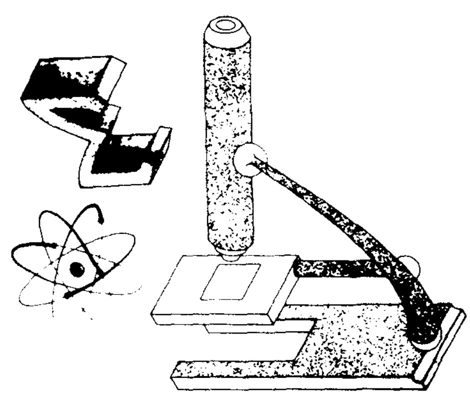
Report No. FHWA/RD-80/199

PB82-180555

SKID RESISTANCE OF PAVEMENT MARKING MATERIALS

Vol. I
March 1981
Final Report



Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

Prepared for
FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Materials Division
Washington, D.C. 20590

FOREWORD

This report presents the findings of an FHWA administrative research study conducted by the Pennsylvania Transportation Institute to assess the skid resistance of the wide variety of pavement marking materials in common use today. Using an extensive data base of field and laboratory results, guidelines are developed by computer simulation techniques for the maximum acceptable differential skid resistance between a pavement and the marking materials on it.

This report is being distributed in sufficient numbers to provide a minimum of one copy to each regional and division office and two copies to each State highway agency. Additional copies of the report for the public are available from the National Technical Information Service (NTIS), Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

Charles F. Scheffey
Director, Office of Research

NOTICE

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/RD-80/199		PB82 180555

4. Title and Subtitle	5. Report Date
SKID RESISTANCE OF PAVEMENT MARKING MATERIALS VOLUME I	March 1981
	6. Performing Organization Code: 075217
7. Author(s): J. J. Henry, D. A. Anderson and G. F. Hayhoe	8. Performing Organization Report No.: 8005
9. Performing Organization Name and Address: The Pennsylvania Transportation Institute, The Pennsylvania State University, University Park, PA 16802	10. Work Unit No.: FCP-No. 31I2-222
	11. Contract or Grant No.: DOT-FH-11-9443
12. Sponsoring Agency Name and Address: U. S. Department of Transportation, Federal Highway Administration, Washington, D.C. 20590	13. Type of Report and Period Covered: Final Report
	14. Sponsoring Agency Code: M/ 0766

15. Supplementary Notes

FHWA Contract Manager: Dr. E. T. Harrigan (HRS-23)
FHWA Implementation Manager: Mr. C. W. Niessner (HDV-22)

16. Abstract

The skid resistance of typical pavement marking materials is determined. A data base of full-scale locked-wheel skid resistance is presented for typical traffic paints of various formulations, hot spray and extruded thermoplastics, cold preformed plastics, temporary tapes, and some two-part systems. A variety of pavement surface types including dense and open graded asphalt and portland cement concrete are used in the study.

In Volume I texture data are presented for field applications and for laboratory samples. Equations are developed for predicting skid resistance from texture measurements. The effects of glass beads, weathering, and polishing are examined in laboratory and field experiments.

Based on a simulation, guidelines are developed for the maximum acceptable differential skid resistance between a pavement and the marking materials on it. Both two- and four-wheel vehicles are treated.

Volume II of this report contains a complete listing of the data compiled in this project and is available in limited quantities to interested researchers. A summary of all the data which was utilized in the formation of the conclusions are included in tables of Volume I.

17. Key Words	18. Distribution Statement
Skid Resistance Microtexture Macrotexture Marking Materials Slip Resistance	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22261

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	131	

Form DOT F 1700.7 (8-69)

TABLE OF CONTENTS

LIST OF FIGURES. iv

LIST OF TABLES vii

NOMENCLATURE ix

1. INTRODUCTION 1
   1.1 Background. 1
   1.2 Experimental Approach 3
   1.2.1 Field Testing 3
   1.2.2 Laboratory Testing. 4
   1.3 The Relationship Between Texture and Skid Resistance. 4
   1.4 Literature Search 5
   1.4.1 State and Other U. S. Agency Specifications 5
   1.4.2 State Programs to Test Skid Resistance of Marking Materials 6
   1.4.3 Overseas Studies and Specifications 6
   1.4.4 Product Specifications by Manufacturer. 7
   1.5 Objectives of the Project 7

2. DATA COLLECTIONS 8
   2.1 Applications of Materials 8
   2.2 Test Procedures 8
   2.2.1 British Pendulum Tester 8
   2.2.2 NBS-Brungraber Portable Slip-Resistance Tester. . . 8
   2.2.3 Texture Profile Measurements. 18
   2.2.4 Reciprocating Pavement Polisher (RPP) 20
   2.2.5 Penn State Drag Tester 20
   2.3 Laboratory Test Program 20
   2.4 Field Test Program. 24

3. DATA ANALYSIS. 50
   3.1 Introduction. 50
   3.1.1 Analysis of Laboratory Data 50
   3.1.2 Determination of Polishing Sequence 50
   3.1.3 Sanding Experiment. 52
   3.1.4 BPN Measurements. 52
   3.1.5 Effect of Bead Application Method and Bead Size on BPN 55
   3.1.6 Brungraber Device 55
   3.1.7 Effect of Compositional Variables on Frictional Properties 55
   3.2 Analysis of Field Data. 58
   3.2.1 Prediction of Skid Resistance from Texture Measurements. 58
   3.2.2 Other Factors Affecting Skid Resistance 68
   3.2.3 Slip Resistance 68

4. RECOMMENDED MAXIMUM LEVELS OF DIFFERENTIAL FRICTION. . . . 74
   4.1 Discussion of the Problem 74
   4.2 Cars in Skidding Maneuver 74
   4.2.1 Vehicle Response During a Skidding Maneuver 74

TABLE OF CONTENTS (continued)

Page

4.2.2 Simulation Model 76
4.2.3 Determination of Criteria for Safe Operation . . 82
4.2.4 Boundaries of Safe Operation 91
4.2.5 Validity of the Results. 94
4.3 Motorcycle Loss of Control on a Marking Stripe . . 100
4.3.1 Loss of Control Maneuver 100
4.3.2 Simulation Model 101
4.3.3 Mechanism of Roll Instability. 101
4.3.4 Simulation Results 102
4.3.5 Conclusions and Recommendations for Motorcycles. 102
4.4 Summary. 109

5. CONCLUSIONS AND RECOMMENDATIONS 110

6. REFERENCES 113

LIST OF FIGURES

Figure		Page
1-1	The Penn State Model for Skid Resistance Speed Behavior	2
2-1	Field Test Installations (layout)	10
2-2	Prismo Cub Tester Liner	11
2-3	Prismo Cub Tester Liner	12
2-4	Schematic of NBS-Brungraber Portable Slip-Resistance Tester	17
2-5	Calibration Curves for the NBS-Brungraber Portable Slip-Resistance Testers	19
2-6	Flow Diagram for Laboratory Testing	23
2-7	Typical Skid Test Traces - 64 km/h Test	31
3-1	Polishing Sequence for Hot Extruded Thermoplastic Panels	51
3-2	Sanding Experiment for Hot Extruded Thermoplastic	53
3-3	Before and After Sanding and Polishing Results	54
3-4	BPN Results for Steel Laboratory Panels	59
3-5	Texture for Weatherometer Samples Before and After Exposure	60
3-6	Skid Resistance Histories of Marking Materials on Dense Graded Asphalt Public Road Sites	70
4-1	Maneuvers Used in the Four-Wheel Vehicle Simulation Study. In Both Cases, Yaw Rate and Lateral Velocity are Initially Zero. Steer Angle is Zero Throughout Both Maneuvers	75
4-2	Vehicle Axis System and Vehicle Parameters	77
4-3	Effective Coefficient of Friction of an ASTM E524 Tire as is Slides Over a 0.3-m Wide Marking Stripe at an Angle of Attack ψ_0. Sliding Speed = 16 km/h	78
4-4	Effective Coefficient of Friction of an ASTM E524 Tire as it Slides Over a 0.3-m Wide Marking Stripe at an Angle of Attack ψ_0. Sliding Speed = 16 km/h	79
4-5	Effective Coefficient of Friction of an ASTM E524 Tire as it Slides Over a 0.3-m Wide Marking Stripe at an Angle of Attack ψ_0. Sliding Speed = 16 km/h	80

LIST OF FIGURES (continued)

Figure		Page
4-6	Effective Coefficient of Friction of an ASTM E524 Tire as it Slides Over a 0.3-m Wide Marking Stripe at an Angle of Attack ψ_0. Sliding Speed = 16 km	81
4-7	Simulation Tire Model Results for Free Rolling and Locked Wheel Sliding	83
4-8	Variables Defining the Kinematics of Four-Wheeled Vehicle Motion	84
4-9	Yaw Rate, Heading Angle, and Drift Angle Response of a Four-Wheeled Vehicle when the Brakes are Released During a Skidding Maneuver Across a 3-m Long Split Coefficient Surface	85
4-10	Yaw Rate, Heading Angle, and Drift Angle Response of a Four-Wheeled Vehicle when the Brakes are Released During a Skidding Maneuver Across a 12-m Long Section of Split Coefficient Surface	86
4-11	Yaw Rate, Heading Angle, and Drift Angle Response of a Four-Wheeled Vehicle when the Brakes are Released During a Skidding Maneuver Across a 24-m Long Section of Split Coefficient Surface	88
4-12	Lateral Deviation During Skidding Maneuvers Where the Brakes are Released 1.5 sec After Initiation of the Skid (Corresponding to Figures 9, 10, and 11)	89
4-13	Lateral Displacement of a Vehicle Travelling Obliquely Across a Road at Steady Forward Speed (t = time)	90
4-14	Vehicle Response at Brake Release and 1 sec After Brake Release During Maneuver (2)	92
4-15	Maximum Drift Angles Attained During Maneuver (1), Angle of Attack = 5°, Initial Vehicle Speed = 88 km/h . . .	93
4-16	Maximum U.β Attained During Maneuver (2), Initial Vehicle Speed = 88 km/h	95
4-17	Maximum U.β Attained During Maneuver (2), Initial Vehicle Speed = 88 km/h	96
4-18	Maximum U.β Attained During Maneuver (2), Initial Vehicle Speed = 88 km/h	97
4-19	Maximum U.β Attained During Maneuver (2), Initial Vehicle Speed = 88 km/h	98

LIST OF FIGURES (continued)

Figures		Page
4-20	Recommended Maximum Lengths of Pavement Marking for Safe Operation of Cars in Skidding Maneuvers. Vehicle Speed at Inception of the Skid = 88 km/h.	99
4-21	Simple Model of the Single-Track Vehicle.	103
4-22	Single-Track Vehicle Roll Response at Increasing Angles of Attack (ψ_0). Marking Material Coefficients of Friction = 0.2, Forward Speed = 65 km/h	104
4-23	Single-Track Vehicle Roll Response at Increasing Marking Material Coefficients of Friction. Pavement Coefficient of Friction = 0.6, Angle of Attack = 5°, Forward Speed = 65 km/h	105
4-24	Single-Track Vehicle Roll Response. Pavement Coefficient of Friction = 0.6, Marking Material Coefficient of Friction = 0.2, Forward Speed = 48.3 km/h	106
4-25	Single-Track Vehicle Roll Response With the Wheels Locked when on the Marking Stripe. Marking Material Coefficient of Friction = 0.2, Forward Speed = 65 km/h	107
4-26	Trajectory of the Center of Gravity of the Single-Track Vehicle at Different Marking Material Coefficients of Friction. Pavement Coefficient of Friction = 0.6, Angle of Attack = 5°, Forward Speed = 65 km/h	108

LIST OF TABLES

Table		Page
2-1	Pavement Description at the Test Sites	9
2-2	Marking Material Applications	13
2-3	Laboratory Mixture Properties	21
2-4	Summary of BPN Measurements for Laboratory Test Panels Before Application of Marking Materials	22
2-5	Laboratory BPN and Microtexture, Before and After Polishing, Metal Plates	25
2-6	Laboratory BPN, Before and After Polishing, Fine Textured Asphalt	26
2-7	Laboratory BPN, Before and After Polishing, Portland Cement Concrete	27
2-8	Laboratory BPN, Before and After Polishing, Coarse -Textured Asphalt	28
2-9	Laboratory BPN, Weatherometer Studies	29
2-10	Microtexture Measurements Before and After Weatherometer	30
2-11a	Full-Scale Skid-Resistance Tests Skid Test Facility - Dense Graded Asphalt Concrete	32
2-11b	Full-Scale Skid-Resistance Tests Skid Test Facility - Dense Graded Asphalt Concrete	34
2-11c	Full-Scale Skid-Resistance Tests Skid Test Facility - Portland Cement Concrete	35
2-11d	Full-Scale Skid-Resistance Tests Skid Test Facility - Jennite Over Dense Graded Asphalt Concrete	36
2-11e	Full-Scale Skid-Resistance Tests Public Highway - Dense Graded Asphalt Concrete	37
2-11f	Full-Scale Skid-Resistance Tests Public Highway - Portland Gement Concrete	39
2-12a	Texture Data Skid Test Facility - Dense Graded Asphalt Concrete	40

LIST OF TABLES (continued)

Table		Page
2-12b	Skid Test Facility - Open Graded Asphalt Concrete	42
2-12c	Skid Test Facility - Portland Cement Concrete	43
2-12d	Skid Test Facility - Jennite Over Dense Graded Asphalt Concrete	44
2-12e	Public Highway - Dense Graded Asphalt Concrete.	45
2-12f	Public Highway - Portland Cement Concrete	47
2-13	Brungraber Portland Slip-Resistance Detector Data from Public Road Sites.	48
3-1	Effect of Bead Size and Application Method on BPN	56
3-2	Comparison of Different Shoes, Brungraber Portable Slip Resistance Detector.	57
3-3	The Effect of Pigment in Formulation of Traffic Paints.	62
3-4	The Effect of Beads in Traffic Paint.	63
3-5	The Effect of Beads in Thermoplastic.	65
3-6	Effect of Winter Exposures on Sprayed and Extruded Thermosplastic.	67
3-7	Skid Resistance of Two-Part Materials	69
3-8	Effect of Temperature on BPN of Unbeaded Marking Materials	71
3-9	Effect of Temperature on BPN of Beaded Marking Materials	72
3-10	Brungraber Portable Slip Resistance Data Survey Public Road Sites	73
5-1	Predictor Equations for Skid Resistance of Marking Materials	112

NOMENCLATURE

Symbol	Description	Typical Units
BPN	British Pendulum Number	-
DTN	Drag Tester Number	-
G	Slope of the skid number - speed curve	h/km
g	Gravitational Acceleration	mk^2
MTD	Mean Texture Depth (sandpatch)	mm
m	Mass of Vehicle	kg
PNG	Percent Normalized Gradient of the skid number.	h/km
RMSH	Root Mean Square Profile Height	mm, μm
r	Yaw Velocity	rad/s
r^2	Correction Coefficient (Coefficient of Determination)	-
SN	Locked Wheel Skid Number	-
SN_0	Zero Speed Intercept Skid Number	-
U	Forward Velocity of Vehicle Center of Gravity	km/h
V	Test Tire Velocity	km/h
W	Weight of Vehicle	N
Y	Longitudinal Tire Force	N
Z	Vertical Tire Force	N
β	Drift Angle	rad
$\dot{\delta}$	Steer Velocity	rad/s
μ	Coefficient of Friction	-
ϕ	Vehicle Roll Angle	rad
ψ	Angle of Attack of Vehicle Tire with Marking Stripe	degree

NOMENCLATURE (Continued)

Subscript	Description
E	Effective
M	Marking Material
MA	Macrotexture
MI	Microtexture
P	Pavement
s	Static
V	Velocity (usually 48, 64, 80 km/h)

Acronym	Description
BWT	Measurement taken between Wheel Track
C	Coarse Graded Asphalt Concrete, Laboratory
DGAFC	Dense Graded Asphalt Friction Course, Field
F	Fine Graded Asphalt Concrete, Laboratory
JEN	Jennite, Tar emulsion with silica sand, Field
Metal	Application of Marking Material to Steel Plates
OGAFC	Open Graded Asphalt Friction Course, Field
PCC	Portland Cement Concrete, Field
W-O Meter	Application of Marking Materials to Aluminum plates for Weather-O-Meter Testing
WT	Measurement taken in Wheel Track

Application Coding

Column 1, 2 Material Code

- AC Alkyd base paint, conventional
- CC Chlorinated rubber base paint, conventional
- AQ Alkyd base paint, quick dry (hot applied)
- CQ Chlorinated rubber base paint, quick dry (hot applied)
- AP Alkyd base paint, premix (beads included in formulation)
- CP Chlorinated rubber paint, premix (beads included in formulation)
- HE Hot extruded thermoplastic (screed plastic)
- HS Hot spray thermoplastic (spray plastic)
- CA Cold applied plastic (preformed plastic with adhesive back)
- TT Temporary Tape (painted metal tape with adhesive back)
- TP Two part materials (polyester and epoxy formulation)

Column 3 Formulation

Numbered 1 - 7

Column 4 Pigment Color

- W White
- Y Yellow

Column 5 Bead Application

- B Surface Application of Beads
- U Unbeaded Surface

Column 6, 7 Replication No. (used in laboratory only)

NOMENCLATURE (Continued)

Example: Designation AC1WB-1 would be as follows:

AC	Alkyd Paint, Conventional
1	Formulation 1
W	White Pigment
B	Beads applied to surface of wet paint
-1	Panel No. 1 (laboratory only)

1. INTRODUCTION

1.1 BACKGROUND

The use of pavement marking materials applied at thicknesses in excess of 1.5 mm has increased significantly in the past 10 years. Hot sprayed and extruded thermoplastic applications with thicknesses ranging up to 3 mm are now commonly used as lane lines on highways. These materials provide longer service life than conventional paints, which offsets their substantially higher application costs [1]. Although preformed plastic materials having thicknesses of about 2.3 mm have been used for crosswalk delineation and for pavement legends for a much longer time, these materials have not been used extensively for lane lines on high-speed highways. Thick applications of marking materials can hide (by filling or covering) the macrotexture of the pavements over which they are applied. Pavement macrotexture describes the surface asperities greater than 0.5 mm [2]. The macrotexture of the surface is the factor that provides good wet skid resistance at high speeds by providing for drainage of water from the tire footprint. Thus, there is a concern that if there is a large difference between the skid resistance of the pavement and that of the marking materials these different skid resistences encountered by the tires of the vehicle as it maneuvers across the marking materials might present a hazard.

Historically [3], marking materials have been tested for skid resistance using techniques, such as the RRL British Pendulum Tester [4], that are indicative only of the low-speed skid-resistance performance of the materials. This practice may be adequate when marking materials are applied to low-speed traffic situations in urban areas. At low speeds, adequate skid resistance can be obtained by providing a high level of microtexture, described by surface asperities less than 0.5 mm [2]; this level of microtexture has been achieved by the inclusion of fine, gritty particles in thick pavement marking materials.

Little is known about the high-speed skid resistance of marking materials. Prior to this research, no data has been available to document the effect of vehicle speed on the skid resistance of marking materials. It may be possible to extrapolate low-speed skid resistance to higher speed performance for marking materials that do not have significant macrotexture, such as the thicker plastic materials.

In contrast to plastic marking materials, conventional traffic paints are applied in thicknesses much smaller than the pavement texture depth. The dry film thickness of these paints range from 0.2 to 0.3 mm, while pavement texture depths range from a comparable 0.2 to 1.0 mm or greater. Thus, the skid resistance of conventional paints reflects to a greater degree the skid resistance of the pavements over which the paints are applied. The paints, however, do alter the microtexture of the pavements, particularly when they are freshly applied; they also reduce but do not obliterate the macrotexture.

Two-part systems (epoxies and polyesters) are applied in film thicknesses ranging from 1.5 to 3 mm and would be expected to produce problems similar to the more common thermoplastic materials.

To develop methods for evaluating the skid resistance of freshly applied marking materials, data on skid resistance and texture were obtained in this research. Changes in the skid resistance of the materials as they wear, age, and polish in service, and changes due to seasonal or climatic variations also have been taken into account. Some materials produce increasing skid resistance as they wear, while others retain low levels throughout their useful life. The identification of the mechanisms that control the expected minimum skid resistance should provide a means for judicious selection of the minimum acceptable levels of skid resistance for freshly applied materials.

The method for evaluating the skid resistance of marking materials ideally should be performed on actual installations ranging from 10-cm-wide lane lines to crosswalks, gore markings, and pavement legends. Special test stripes should be applied with equipment having application characteristics (air pressure, material delivery nozzle, etc.) identical to those of equipment used for actual installations. The method of application can substantially influence the surface characteristics of the marking material and affect the validity of the results from test line applications. Also, it is desirable to have a method which can be used to monitor the skid resistance of the material as it is actually installed in the field.

For skid resistance to be measured on a 10-cm-wide lane marking, for example, alternative methods to the full-scale locked-wheel method [5] are needed. The method should be related to the locked-wheel skid number [5], which is the accepted measurement of pavement skid resistance. The method or combination of methods developed for evaluating marking materials should provide the skid resistance as a function of speed.

For applications at urban crosswalks or other areas where both vehicles and pedestrians may encounter marking materials, both the static and low-speed sliding coefficients of friction are important. The static

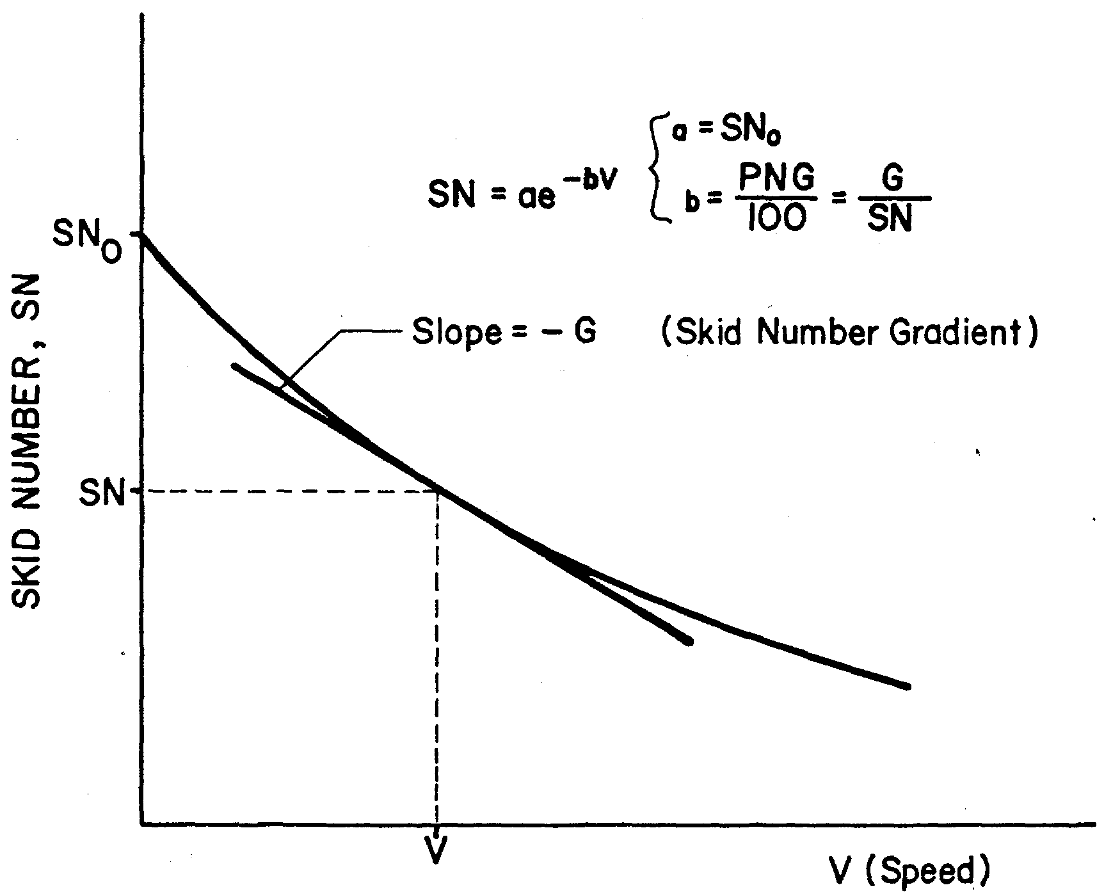


Figure 1.1 The Penn State Model for Skid Resistance Speed Behavior

coefficient of friction controls the pedestrian slip resistance [6] and requires a measurement technique different from that used for the low-speed sliding coefficient. Low-speed sliding coefficients, which affect the stopping distance of vehicles, can be measured by British Pendulum tests [4], low-speed locked-wheel skid tests [5], or transient slip tests [7].

Acceptable skid-resistance levels must be established for pavement marking materials subjected to various service requirements.

To accomplish this objective, it is necessary to ascertain the effects of differential skid resistance between the pavement and its markings, as well as the absolute level of skid resistance required for the operation of four-wheeled and two-wheeled vehicles and for pedestrians.

At high vehicle speeds both the absolute resistance of the marking material and the differential resistance between the pavement and the marking material are important: the first because low skid resistance increases the risk of initiation of an emergency maneuver, and the second because high differential resistance increases the risk of complete loss of control during the maneuver. Also, a high differential resistance exacerbates the effects of any emergency maneuver that includes the crossing of a pavement marking. For high speed application, therefore, it is reasonable to require that the characteristics of the marking material and the pavement surface be compatible. That is, a marking material that is acceptable when the pavement has a medium level of skid resistance may not be acceptable for use on a pavement with high skid resistance. A further important point is that the transition from "low speed" to "high speed" will undoubtedly occur at different speeds for two and four-wheeled vehicles.

1.2 EXPERIMENTAL APPROACH

The specification of minimum skid-resistance values for pavement marking materials would best be accomplished by a study of accidents, as has been attempted for pavements [8]. In the absence of definitive accident data, it is necessary to use analytical and simulation techniques to evaluate the effect of marking materials on vehicle performance. In the case of low vehicle speeds, a promising approach is to compare reductions in skid resistance as a result of pavement marking, averaged over the distance required to stop a vehicle, with skid resistance requirements at intersections [9]. As vehicle speed increases, control and stability of vehicle motion become increasingly important, and a more thorough investigation is required.

1.2.1 Field Testing

To develop a method for evaluating the skid resistance of marking materials which can be related to the skid number, it was necessary to make installations of representative materials upon which locked-wheel tests could be performed. These installations were approximately 30 cm wide with a length dictated by the response of the skid tester. In the case of the PTI Mark III Pavement Friction Tester a 6.5 m length is sufficient. In contrast, conventional skid test equipment requires a minimum length of about 20 m.

Particular attention was taken to apply test materials in such a way that they would be representative of actual installations. Either full-scale application equipment or equipment that accurately duplicates full-scale application should be used. The former is not practical since full-scale equipment is designed for large volume applications. The experience of the researchers indicates that most small machines apply materials, particularly paints, with different results than those obtained from truck-mounted equipment. Equipment developed by Prismo Universal Corporation that duplicates the delivery truck-mounted units was used to apply the test lines. This equipment uses the same delivery systems as those on truck-mounted units, but the systems are mounted on small machines that are supported by a truck with a large air compressor and by other equipment typical of a full-scale system.

In addition to skid-resistance measurements, texture measurements were made on the materials and the pavements to which they were applied. Macrotexture and microtexture profiles were recorded, and the root mean square of the profile height was determined. British Pendulum numbers were also measured. The sand-patch method of measuring texture depth was found to be unsuitable for marking materials. Colored sand was necessary for contrast on white marking materials, but even when contrast was not a problem, such as on the yellow materials, the lack of macrotexture resulted in large, ill-defined circles.

Frequent measurements of skid resistance were necessary to ascertain the degree to which seasonal and short-term weather changes affect the skid resistance of marking materials. Pavement skid resistance is significantly affected by the rainfall history prior to the measurement [10], and similar variations were found for marking materials.

Pedestrian friction is an important factor for some applications of marking materials. The static coefficient of friction is the key measure of pedestrian slip resistance [6]. The static coefficient is not related to the skid resistance of sliding tires, nor to the low-speed skid resistance as measured by the British Pendulum Tester. For this reason, the NBS-Brungraber Portable Slip Resistance Detector was developed. Since all of the pavement marking materials considered in this study could conceivably be used in crosswalk applications, data on the static coefficient of friction were obtained along with skid-resistance measurements.

1.2.2 Laboratory Testing

Laboratory test procedures offer the advantage of controlled test conditions, but they also have the disadvantage of requiring correlation with field experience. Accelerated laboratory polishing is presently performed on aggregates [11] and pavement surfaces [12], but not on pavement marking materials. The Atlas Twin Arc Weatherometer is used by a number of states to evaluate the durability of marking materials but not in relationship to skid resistance. For specification purposes, three hundred hours in the weatherometer is considered equivalent to one year of service. At the present time there is no data base that can be used to correlate friction characteristic measured in the laboratory with field performance.

It would be dangerous to judge the field skid resistance of pavement marking systems solely on laboratory weathering experiments. Instead, laboratory testing can be used to investigate the effect of parameters that are hard to control in the field, such as the effect of test temperature, accelerated wear, embrittlement due to aging, and exposure to UV radiation.

Pavement marking materials are produced in two colors, white and yellow. The pigment particles are extremely small, but since they are of quite different composition (typically lead chromates and rutile titanium dioxide) they may have some effect on surface characteristics, wettability, etc. The study therefore includes the application of some materials in both colors.

1.3 THE RELATIONSHIP BETWEEN TEXTURE AND SKID RESISTANCE

Recent studies of pavement texture and its relation to skid resistance have indicated the importance of the percent normalized gradient (PNG) [2,13]. In Figure 1, the negative slope of the skid number/speed curve is the skid number gradient (G), which varies with velocity and usually decreases with speed. Dividing the speed gradient at a specified speed by the skid number at the same speed and multiplying by 100 produces the PNG. Combining the definitions of the special gradient:

$$G = -\frac{d(SN)}{dV} \qquad (1\text{-}1)$$

and the percent normalized gradient:

$$PNG = \frac{G}{SN} \cdot 100$$

results in:

$$PNG = -\frac{100}{SN}\frac{d(SN)}{dv} \qquad (1\text{-}2)$$

Since both SN and G vary with speed, one would expect that PNG would also vary with speed. However, although a very slight variation with speed is observed, experimental evidence indicates that sometimes the variation is an increase with speed and sometimes a decrease with speed. Thus, it has been concluded that PNG is a very weak function of speed and can, for practical purposes, be considered independent of speed. Rearranging Equation (2) and integrating from zero-speed, where the skid-number zero-speed intercept is defined as SNo, to velocity V, where the skid number is SN, yields:

$$\int_{SN_o}^{SN} \frac{d(SN)}{SN} = -\frac{PNG}{100}\int_{o}^{V} dV$$

$$\ln SN - \ln SN_o = -\frac{PNG}{100} v \qquad (1\text{-}3)$$

$$SN = SN_o e^{-\left(\frac{PNG}{100}\right)V} \qquad (1\text{-}4)$$

Experimental skid number data can be fit to the model by performing a least squares regression analysis of the data in the form of Equation (3) to determine values of PNG and SNo. Note that this model has only two parameters that describe the skid-number speed behavior rather than the three required for the parabolic form which is often used:

$$SN = C_1 + C_2V = C_3V^2 \qquad (1\text{-}5)$$

It has been found [13] that the exponential model (Equation 4) fits the data as well or better than the parabolic model (Equation 5).

It has been shown here that the two skid-resistance parameters, SN_O (the zero-intercept skid number) and PNG (the percent normalized gradient), can be used to determine skid number at any speed (Equation 4). The prediction of SN_O and PNG from texture measurements would therefore permit the determination of pavement friction from texture data.

The zero-intercept skid number (SN_O) can be expected to correlate well with low-speed friction measurements such as the British Pendulum Number (BPN), ASTM Standard Method of Test E303 [4], and the root mean square values of microtexture profiles height

($RMSH_{MI}$). Linear regression of SN_o (derived from skid-test results on pavements) and BPN, and of SN_o and profile $RMSH_{MI}$ produced the following results [2]:

$$SN_o\ 1.32\ BPN - 34.9 \qquad (1\text{-}6a)$$

$$SN_o = 9.44\ (RMSH_{MI}) - 44.4 \qquad (1\text{-}6b)$$

where $RMSH_{MI}$ is expressed in microns.

It should be pointed out that the zero-speed intercept is highly susceptible to short-term variations caused by weather, in particular by rainfall. Surface contaminants removed by rainfall appear to decrease the value of SN_o [10]. BPN measurements are customarily made on cleaned pavements, and texture profile tracers plow through most surface contaminants.

The relationships described above, therefore, would not be expected to apply to other pavements without some correction for seasonal and short-term weather effects.

The percent normalized gradient (PNG) for pavements has been shown [13] to be related to macrotexture data, such as sand-patch mean texture depth (MTD) and macrotexture profile root mean square height ($RMSH_{MA}$). Regressions of PNG values from pavement skid-resistance data with MTD, and profile $RMSH_{MA}$ yield [5]:

$$PNG = 0.45\ (MTD)^{-.47} \qquad (1\text{-}7a)$$

$$PNG = 0.35\ (RMSH_{MA})^{-.52} \qquad (1\text{-}7b)$$

where MTD and $RMSH_{MA}$ are expressed in mm and PNG in (km/h)-1.

The principal effects of pavement marking materials on skid resistance are to alter the microtexture and the macrotexture. The surface chemistry of the marking material also plays a role, and it is therefore not possible to apply the regressions (6) and (7) directly; similar relationships would be expected to exist, but they may be different for each type of marking material.

1.4 LITERATURE SEARCH

1.4.1 State and Other U. S. Agency Specifications

A sampling only of those specifications that mention the problem of skid resistance is given below. This list is not intended to be complete or exhaustive, but contains some typical examples.

North Carolina "Thermoplastic Railroad Pavement Marking" Specification 8.7115002, April 2, 1976, covers railroad-crossing advisory liquids spray and extruded thermoplastic (under traffic). "Shall not be slippery when wet".

Maine Special provision, Section 645, signing and delineation (railroad crossings), March 30, 1976. Covers preformed plastic liquids for use at railroad crossings. "Skid Resistance--The surface friction properties of the plastic shall not be less than 35 BPN, when tested according to ASTM designation E303-74 [4]".

Pennsylvania "Detailed specifications for furnishing labor, material and equipment to install hot thermoplastic pavement markings," covers all applications of thermospheric, September 1974." "The stripe shall not be slippery when wet and shall have a skid resistance approximately equal to that of the adjacent surface."

Federal Aviation Administration "Interim Specification for Runway and Taxiway Painting (Anti-skid)." Supplement to Item P-260 of Advisory Circular 150/53701A, March 5, 1970. Covers all "paint compounds" used for all runway and taxiway markings.

"Skid Resistance" The paint compound, with or without top dressing (which may be required), shall have skid resistant properties as specified in the following. If the skid resistance as specified can be achieved with a pigmented binder and a top dressing, this system will be permitted.

"The contractor shall prove the skid resistance of the marking compound by applying the marking compound on a 100' x 10' test patch which has the same type surface as that which is contracted to be marked. At least one week shall be allowed for thorough curing prior to testing. Before testing, two passes shall be made with a rotary broom to remove any excess loose particles. Tests will be performed by the engineer and shall consist of the following:

The test patch and the adjacent pavement shall be flooded with water and the flooded condition maintained by additional water, if necessary. A water depth of at least 0.1 inches shall be maintained. The engineer shall run tests at 40 miles per hour on the flooded paint test patch and the flooded and unpainted adjacent pavements.

"After sufficient runs to assure reliability, results shall be compared between the painted and unpainted surfaces. The friction values of the paint shall be equal at least to that of the adjacent uncoated surface. If it is, the mix and method of application shall be considered suitable for application on the contract work."

Institute of Transportation Engineers Technical Council Committee 4Q-S: A Tentative Revised Standard covering aspects of pavement marking materials [15] states: "The exposed surface shall be free from tack and shall not be slippery when wet." No mention of "slipperiness" under the section on preformed plastics.

1.4.2. State Programs to Test Skid Resistance of Marking Materials

Massachusetts [16]. On December 11, 1974, thermoplastic marking materials were tested on Route 128 in Needham and on Route 24 in Camton. Tests were at 40 mph. On Route 128, the tests produced an average SN_{40} of 28 while the unmarked pavement had an SN_{40} of 55. The material on Route 128 was approximately six months old. On Route 24 the materials were approximately 18 months old and produced higher skid resistance levels of 42 on a pavement whose SN_{40} was 52. It was noted that the high differential skid resistance measured on the newer material could present problems to motor cycles and vehicles having narrow tires.

Michigan [17]. In April 1976, Michigan reported the results of a study of skid resistance of marking materials. After testing 14 materials in the laboratory and noting low BPN's, three materials were placed on the portland cement concrete pavement in 20 inch wide by 50 foot long installations for full scale skid resistance tests. The results were as follows:

	SN_{40}	BPN
Quick dry paint with beads	37	31
Hot extruded (yellow) thermoplastic with beads	23	35
Cold applied, preformed plastic--no beads	4	14

Pennsylvania. In 1975, any possibility of considering the combining of skid resistance studies with ongoing durability studies of marking materials was rejected because it was observed that the size and placement of the test material would not be amenable to skid testing. It was recommended that two or three of the test materials in the durability study should be placed in an installation large enough for full-scale skid testing.

1.4.3 Overseas Studies and Specifications

France. A technical guide on marking materials has been published by the Ministry of Equipment [18]. The section on "Slipperiness" (pp. 13-14) consists of a general discussion of the problem, which begins with the statement that although there are no data on the consequences of slippery markings, common sense dictates that there should be as little difference between the frictional properties of the pavement as a whole and the markings. The guide states that the majority of European countries specify a minimum of 45 SRT (equivalent to BPN) but no details are given. Although it is conceded that the SRT does not relate well to skid resistance at high speed, the use of SRT is advocated because of the physical difficulty of measuring the slipperiness of markings with any existing high-speed tester.

The effect of paint on skid resistance is said to be minimal. Thermoplastic and similar materials may obliterate texture and should be applied, therefore, only to pavements with good texture. The applied thickness should not exceed 3 mm. Good texture of the underlying pavement is desirable in any event because it enhances light reflection, particularly at night. The marking material should be so applied that water drains readily from it, because a heavy water film tends to submerge the glass beads, hence reducing their effectiveness.

It is mentioned in passing, that 40 "classic paints" applied to glass plates have been tested and that SRTs ranging from 17 to 70 were found. It is not stated who made these tests, nor is any reference given. (There are no references anywhere else in the "Guide"; illustrated machines are not identified and materials are not described.) There is a detailed specification for paint, and a required gradation of glass beads (pp. 22-23).

In section 3 (Certification) the requirement of SRT = 45 is stated as being mandatory (in France). Meeting this requirement does not automatically assure certification, because the "SRT of the marking must also be at least 80 percent of the SRT of the pavment adjoining it". This criterion and all other mandatory properties, except the paint composition and bead gradation, are determined in field applications. Durability is determined every six months , and certification is based on durability ADT for a given texture (sand-patch method) and skid resistance of the pavement. Aside from the mentioned SRT values, acceptable durability requires meeting standards of adhesion, color, and light reflection at night.

South Africa. The study "Research on the Effect of Pavement Markings on Pavement Surface Pigmentation, and Hence on Stopping Distance of Vehicles," was proposed in December 1975. The study had not yet been funded as of April 9, 1979, but funding was still expected.

New Zealand. A report, "Slippery Road Markings-MI-Summary Report" produced by the Road Research Unit lists "good resistance to skidding" among other factors to be considered, and states that a compromise is probably necessary when choosing marking materials. The report recognizes the vulnerability of certain road users (e.g., motorcyclists, tractor/trailer combinations, physically handicapped pedestrians) to variations in skid resistance of the road surface, "especially ...when the situation of a wet road surface is considered."

No quantitative skid resistance requirements are given, and the report concludes:

> "Road markings which are more slippery than the adjacent road surface probably cannot be eliminated, therefore markings should be designed in form and location to minimise the hazard introduced to traffic."
>
> "Especially large continuous areas of potentially slippery road markings should not be placed where traffic is braking, accelerating, or turning at any speed."

1.4.4 Product Specifications by Manufacturer

MMM Stamark. Product Bulletin 99 (Approximately 1976). Covers preformed plastic material. "Skid Resistance on newly applied film, under foot and tire traction when dry or wet with water, will be approximately that of typical pavement markings."

PRISMO Plastix SD. Product Specification SDPX-973-6 (September 1973). Covers preformed plastic material. "Skid Resistance: The surface friction properties of the plastic shall not be less than 35 BPN, when tested according to ASTM Designation E303-66T [4]."

Organization for Economic Co-operation and Development. In 1975, an OECD Road Research Group prepared a comprehensive report on road mark-ing and delineation [3]. Among other desirable qualities of road marking materials, the report states that "it is imperative that they [marking systems] should be skid resistant." Furthermore, "the skid resistance of markings should be at least as good as that of the adjacent road surface" (pp. 23-24).

Skid resistance at low speed is given in terms of an SRT number (equivalent to BPN), and while it is agreed that locked-wheel tests or speeds of 30-140 km/h would be more representative of real conditions, this low-speed test is justified by the observation that "accidents due to skidding on road markings often occur at low speeds" (p. 51).

The report lists the minimum SRT requirements of those countries who attach great importance to skid resistance as a criterion of marking materials (p. 65). A value of 45 for Germany and France, and 55 for Netherlands is given. The report is in agreement with the recommendations given in reference [18], described previously.

1.5 OBJECTIVES OF THE PROJECT

The specific objectives of this project are:

(1) To determine by appropriate measurements the skid resistance of thermoplastic pavement marking materials (both cold and hot-applied), conventional traffic marking paints and tapes in current use.

(2) To recommend a realistic minimum skid resistance for use in specifying these materials for purchase and evaluating materials as applied in the field.

The first objective is dealt with in Chapter 2. Full scale measurements of skid resistances were made in the field and texture measurements were made both in the field and in the laboratory. The second objective is met in Chapters 3 and 4. In Chapter 3, methods for predicting the skid resistance of marking materials are presented and in Chapter 4, criteria for specifying marking materials to achieve acceptable levels of skid resistance are developed.

2. DATA COLLECTION

2.1 APPLICATION OF MATERIALS

In order to obtain full-scale skid-resistance data according to the ASTM Method of Test E 274 [5], marking materials were placed on pavements in 6-m long, 0.3-m wide applications. All of the materials were placed on untrafficked surfaces at the PTI Skid Test Facility, which is not open to the public. In order to assess the skid resistance as they wear, some of the materials were also placed on two public roads. Materials that were expected to have excessively low skid resistance, such as paints without glass spheres, were not placed on the public road sites.

The descriptions of the pavements used for the study are given in Table 2-1. They include typical Pennsylvania dense graded asphalt friction courses, portland cement concrete surfaces, an open graded asphalt friction course and a dense graded asphalt surface over which was applied a heavy application of a coal-tar pitch seal coat. A range of surface textures was thus available to evaluate thin materials which would not hide the pavement textures. The layout of the material applications is shown in Figure 2-1.

The paints and thermoplastics were applied using equipment and personnel supplied by Prismo Universal Corporation. The equipment was designed for testline application and utilizes spray guns and delivery pressures which are similar to full-scale application equipment. It was found that the surface texture of the materials is influenced by the application method, spray pressure, temperatures, etc., sometimes resulting in a rippled surface, at other times in a smooth surface. This behavior is noted also in full-scale applications and, while the skid resistance is affected by these variations, it was not within the scope of this project to perform an exhaustive investigation of variation in application parameters. It may be possible, however to achieve improved skid resistance in some cases by altering these parameters.

For the spray thermoplastic materials a Prismo Cub (Figure 2-2) was used. Hot extruded thermoplastic materials were applied using a Prismo Screed Cart typical of equipment used for crosswalk applications. The conventional, quick dry, and premix paints were applied using a Prismo Testliner (Figure 2-3). The preformed materials, cold applied plastics and temporary tapes, did not require application equipment. One of the two-part polyesters was hand mixed and was doctored onto the pavement manually. The other two-part polyester and the one epoxy (TP1) which was included in the field tests were applied by representatives of the suppliers, using special equipment.

When the field installations were made, the sprayed thermoplastic and paint and the extruded thermoplastic were applied also to panels for the laboratory program. The dry film thickness, therefore, for the field application is assumed to be the same as was measured on the laboratory panels. These film thicknesses are shown in Table 2-2, together with a summary of the locations of the applications. In the case in which glass beads were added to the surface, the applications were made under the same conditions and machine adjustments as the unbeaded applications, so that the film thickness of the binder is assumed to be the same for both beaded and unbeaded applications.

2.2 TEST PROCEDURES

A variety of test procedures were used in the test program. Wherever possible, standard ASTM procedures were followed, and wherever possible, the test procedures were repeated in the laboratory and in the field.

2.2.1 British Pendulum Tester

The British Pendulum Tester is a dynamic pendulum impact-type tester that measures the friction developed when a rubber slider attached to the pendulum is propelled over the surface being tested. The test procedure that was followed in both the laboratory and the field is detailed in ASTM E 303-74 [4], Standard Method of Test for Measuring Surface Frictional Properties Using the British Portable Tester. Seven values were recorded in the laboratory, and each swing of the pendulum, including the first, was recorded. The first swing was included in the analysis of the data, as described in later sections. The temperature of testing in the laboratory was approximately 13°C. Each surface was flushed with clean water before each pendulum swing. No problems were encountered in performing the BPN tests in either the laboratory or the field. Approximately seven readings were required to obtain a uniform BPN value with most of the marking materials tested in the laboratory.

In the field, ten swings were made with no cleaning of the surface prior to the first five swings. The first five values are averaged and reported as the "unscrubbed BPN value". The surface was then cleaned and the average of the next five swings was reported as the "scrubbed BPN value". The purpose of this procedure is to determine whether surface contaminants affect the friction levels.

2.2.2 NBS-Brungraber Portable Slip-Resistance Tester

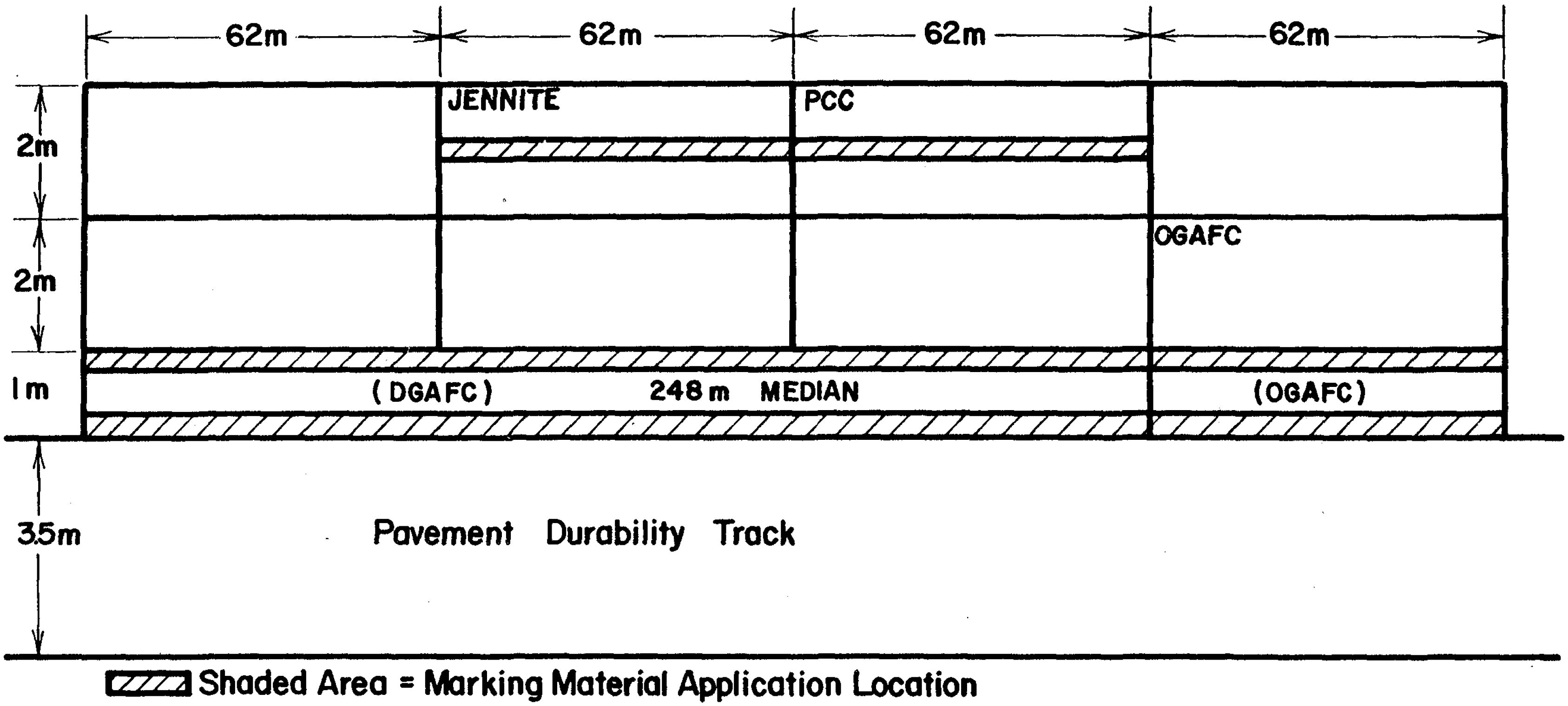
The NBS-Brungraber Tester is designed to measure static coefficient of friction. A schematic of the device is shown in Figure 2-4

Table 2-1. Pavement Description at the Test Sites

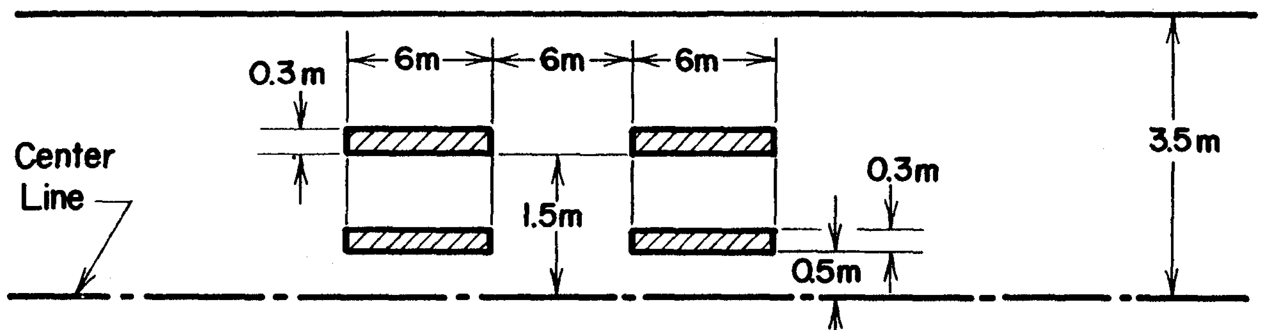
Public Roads (2-lane pavements)

TYPE LOCATION	ADT	YEAR CONSTRUCTED	CONSTRUCTION
Dense Graded Asphalt PA Route 45 LR 14018	800	1964	PA Specification ID-2A asphalt: 5.9 percent, 45 percent aggregate passes No. 8 sieve. Crushed limestone coarse aggregate, silicious river sand, fine aggregate.
Portland Cement Concrete PA LR 14871	1200	1973	Class AA Reinforced cement concrete paving (slip form) using silicious river sand and No. 2B crushed limestone coarse aggregate. Cement factor: 4.75 bags/m^3; 6.5 percent air; slump: 57 mm.

Skid Test Facility Sites Constructed September 1972 Negligible Traffic Exposure	
Dense Graded Asphalt (DGAFC)	Pennsylvania ID-2A bituminous concrete wearing surface consisted of 42 percent Pennsylvania 1-B limestone coarse aggregate, 58 percent crushed stone fines and 5.5 percent AC-20 asphalt cement. The surface was compacted by steel-wheel and pneumatic-tire rollers.
Portland Cement Concrete (PCC)	Burlap drag concrete: The surface was produced on a 20-cm, reinforced portland cement concrete pad constructed by the contractor. As the concrete was placed and hand-finished by smooth float, the surface was given a light application of transverse burlap drag.
Open Graded Asphalt (OGAFC)	Pennsylvania SR-1A experimental hot-mix plant seal was installed by the contractor. The surface, consisting of 85 percent Pennsylvania 1-B coarse crushed river gravel aggregate, 15 percent crushed stone fines and 6.5 percent AC-20 asphalt cement, compacted by steel-wheel and pneumatic-tire rollers.
Jennite	Pennsylvania ID-2A wearing course treated by project personnel with a commercially available coal-tar pitch seal coat applied in two layers: the first, Jennite J-16 (application rate 0.5 l/m^2) and the second, Jennite J-16 mixed 3 to 1 with AFR Plus (application rate 0.4 l/m^2).



a. Skid Test Facility Layout (not to scale)



b. Typical Pattern for Route 871 and Route 45 Installations (not to scale)

Figure 2-1. Field Test Installations (layout)

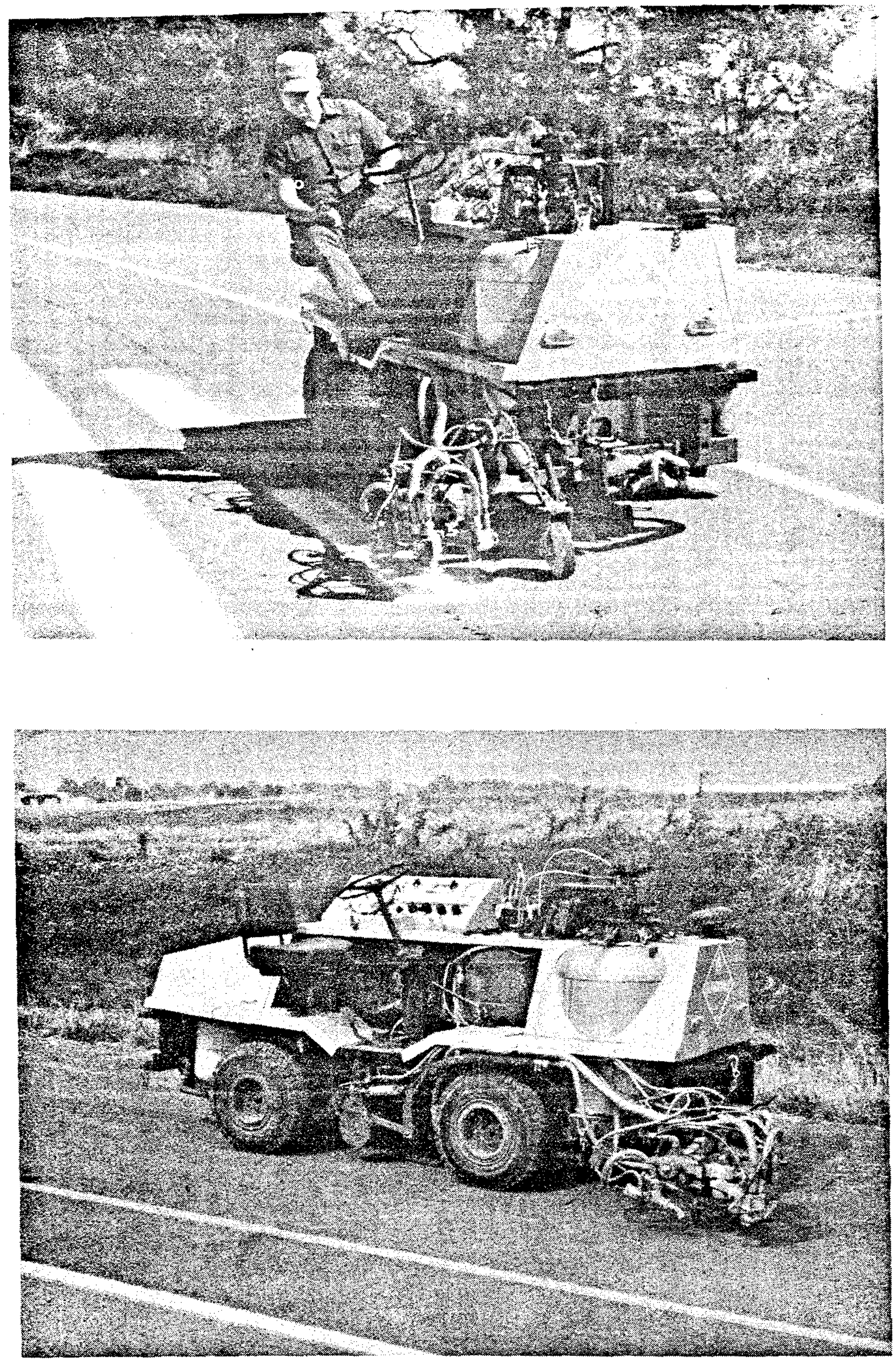


Figure 2-2. Prismo Cub Test Liner

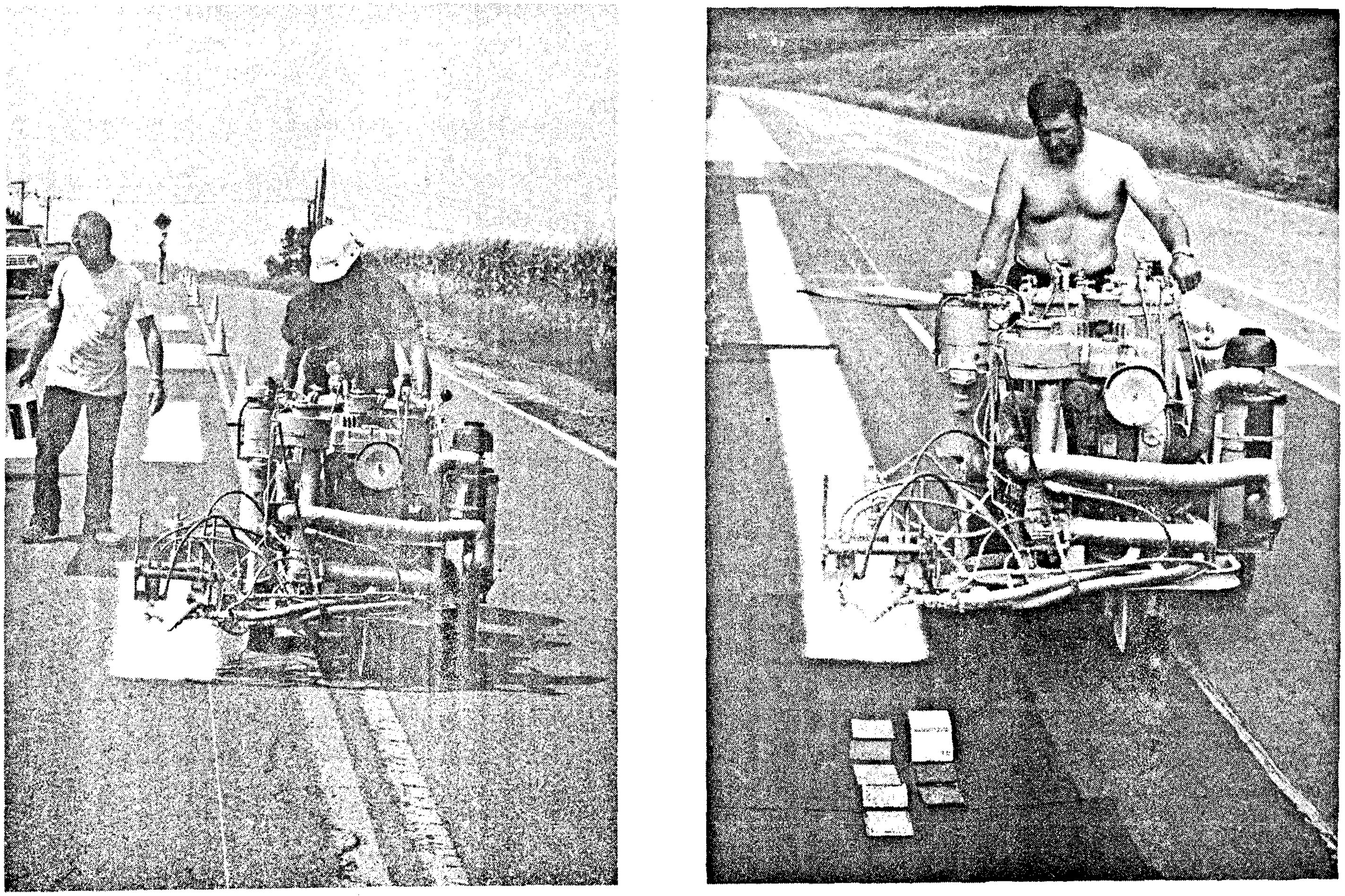


Figure 2-3. Prismo Test Liner

Table 2-2. Marking Material Applications (continued)

MATERIAL CODE	SUMMARY DESCRIPTION	FIELD									LABORATORY					DRY FILM THICKNESS (mm)
		Skid Test Facility				Public Roads				Test Track	Metal	W-O Meter	F	C	P	
						DGAFC		PCC								
		DGAFC	OGAFC	PCC	JEN	WT	BWT	WT	BWT	WT						
TT1WB	Temporary tape:1 white, beads	✓				✓	✓				2	1				} .66
TT1YB	Temporary tape:1 yellow, beads	✓	✓								2					} .66
TT2WB	Temporary tape:2 white, beads	✓				✓	✓				2	1				} .68
TT2YB	Temporary tape:2 yellow, beads	✓	✓								2					} .68
TT3WB	Temporary tape:3 white, beads	✓				✓	✓				2					} .66
TP1WB	Two part epoxy, white, beads	✓	✓													
TP2WB	Two part polyester, white, beads	✓				✓	✓	✓			2	1	2	2	2	} 1.0
TP3WB	Two part polyester, white, beads	✓														
TP3WU	Two part polyester, whte, unbeaded	✓														
TP4WU	Two part epoxy, white, unbeaded										3	1				} 1.3
TP4WB	Two part epoxy, white, beads										3	1				
TP5WU	Two part epoxy, white, unbeaded										10		2	2	2	} .38
TP5WB	Two part epoxy, white, beads										3		2	2	2	
TP5YU	Two part epoxy, yellow, unbeaded										2					} .38
	TOTAL	54	15	10	7	17	18	8	6	5	130	25	57	40	56	

CODES:

DGAFC	Dense Graded Asphalt Friction Course	Metal	Metal Plates
OGAFC	Open Graded Asphalt Friction Course	W-O Meter	Plates for Weathermeter Exposure
PCC	Portland Cement Concrete	F	Fine textured (sand) asphalt panel
JEN	Jennite Treated Asphalt Concrete	C	Coarse textured panel
WT	In the left Wheel Track	P	Portland cement concrete panel
BWT	Between the Wheel		

Table 2-2. Marking Material Applications (continued)

MATERIAL CODE	SUMMARY DESCRIPTION	FIELD: Skid Test Facility DGAFC	FIELD: Skid Test Facility OGAFC	FIELD: Skid Test Facility PCC	FIELD: Skid Test Facility JEN	FIELD: Public Roads DGAFC WT	FIELD: Public Roads DGAFC BWT	FIELD: Public Roads PCC WT	FIELD: Public Roads PCC BWT	FIELD: Test Track WT	LABORATORY: Metal	LABORATORY: W-O Meter	LABORATORY: F	LABORATORY: C	LABORATORY: P	DRY FILM THICKNESS (mm)
CP1WB	Paint:premix chlor. rubber white, beads	✓	✓	✓		✓	✓	✓	✓		11	1	2	4	2	.41
CP1WU	Paint:premix chlor. rubber white, unbeaded	✓									2	1	2		2	
HE1WB	Hot extruded plastic:1 white, beads	✓				✓	✓				4	2	1	1	1	3.5
HE1WU	Hot extruded plastic:1 white, unbeaded	✓									4	2	1	1	1	
HE1YB	Hot extruded plastic:1 yellow, beads	✓									2	1				3.8
HE1YU	Hot extruded plastic:1 yellow, unbeaded	✓									2	1				
HE2WB	Hot extruded plastic:2 white, beads	✓									2	1				3.8
HE2WU	Hot extruded plastic:2 white, unbeaded	✓									2	1				
HE3WB	Hot extruded plastic:3 white, beads	✓				✓	✓									
HE3WU	Hot extruded plastic:3 white, unbeaded	✓														
HE4WB	Hot extruded plastic:4 white, beads	✓				✓	✓									
HE4WU	Hot extruded plastic:4 white, unbeaded	✓				✓	✓	✓								
HE4YU	Hot extruded plastic:4 yellow, unbeaded	✓														
HE4YB	Hot extruded plastic:4 yellow, beads	✓														
HE5WU	Hot extruded plastic:5 white, unbeaded										3					2.8
HE5WB	Hot extruded plastic:5 white, beaded, stud guard	✓	–			✓	✓	✓			3					
HE6WU	Hot extruded plastic:6 white, unbeaded	✓									3					3.2
HE6WB	Hot extruded plastic:6 white, beads	✓									3					

Table 2-2. Marking Material Applications (continued)

MATERIAL CODE	SUMMARY DESCRIPTION	FIELD									LABORATORY					DRY FILM THICKNESS (mm)
		Skid Test Facility				Public Roads				Test Track	Metal	W-O Meter	F	C	P	
						DGAFC		PCC								
		DGAFC	OGAFC	PCC	JEN	WT	BWT	WT	BWT	WT						
HS1WB	Hot spray plastic:1 white, beads												1	1	1	} 2.6
HS1WU	Hot spray plastic:1 white, unbeaded	✓									2	1	3	3	3	
HS1YB	Hot spray plastic:1 yellow, beads	✓									2	1	2	2	2	
HS1YU	Hot spray plastic:1 yellow, unbeaded	✓									2	1	2	2	2	
HS2WB	Hot spray plastic:2 white, beads	✓				✓	✓				2	1	5	3	3	} 2.9
HS2WU	Hot spray plastic:2 white, unbeaded	✓									4	1	4	5	5	
HS3WB	Hot spray plastic:3 white, beads	✓				✓	✓				3					} 2.6
HS3WU	Hot spray plastic:3 white, unbeaded	✓									3		2	2	2	
HS4WB	Hot spray plastic:4 white, beads	✓				✓	✓				3					} 3.0
HS4WU	Hot spray plastic:4 white, unbeaded	✓									3					
CA1WB	Cold applied plastic:1 white, beads	✓								✓	2	1	2	2	2	} 2.7
CA1YB	Cold applied plastic:1 yellow, beads	✓									2					} 2.6
CA2WU	Cold applied plastic:2 white, unbeaded	✓								✓	2	1				} 2.6
CA2YU	Cold applied plastic:2 yellow, unbeaded	✓								✓	2					} 2.7
CA3WB	Cold applied plastic:3 white, beads	✓	✓								2		2	2	2	} 2.7
CA3YB	Cold applied plastic:3 yellow, beads	✓*									2					} 2.7
CA4YU	Cold applied plastic:4 yellow, unbeaded	✓									2					} 2.7
CA5WU	Cold applied plastic:5 white, unbeaded	✓	✓							2	2					} 2.7
CA6WB	Cold applied plastic:6 white, beads	✓									2					} 3.3
CA7WB	Cold applied plastic:7 white, beads	✓									2					} 2.2

* plus an additional four applications set at various angles to the test direction

Table 2-2. Marking Material Applications (continued)

MATERIAL CODE	SUMMARY DESCRIPTION	FIELD: Skid Test Facility DGAFC	OGAFC	PCC	JEN	Public Roads DGAFC WT	DGAFC BWT	PCC WT	PCC BWT	Test Track WT	LABORATORY: Metal	W-O Meter	F	C	P	DRY FILM THICKNESS (mm)
TT1WB	Temporary tape:1 white, beads	✓				✓	✓				2	1				} .66
TT1YB	Temporary tape:1 yellow, beads	✓	✓								2					} .66
TT2WB	Temporary tape:2 white, beads	✓				✓	✓				2	1				} .68
TT2YB	Temporary tape:2 yellow, beads	✓	✓								2					} .68
TT3WB	Temporary tape:3 white, beads	✓				✓	✓				2					} .66
TP1WB	Two part epoxy, white, beads	✓	✓													
TP2WB	Two part polyester, white, beads	✓				✓	✓	✓			2	1	2	2	2	} 1.0
TP3WB	Two part polyester, white, beads	✓														
TP3WU	Two part polyester, whte, unbeaded	✓														
TP4WU	Two part epoxy, white, unbeaded										3	1				} 1.3
TP4WB	Two part epoxy, white, beads										3	1				
TP5WU	Two part epoxy, white, unbeaded										10		2	2	2	} .38
TP5WB	Two part epoxy, white, beads										3		2	2	2	
TP5YU	Two part epoxy, yellow, unbeaded										2					} .38
	TOTAL	54	15	10	7	17	18	8	6	5	180	25	57	40	56	

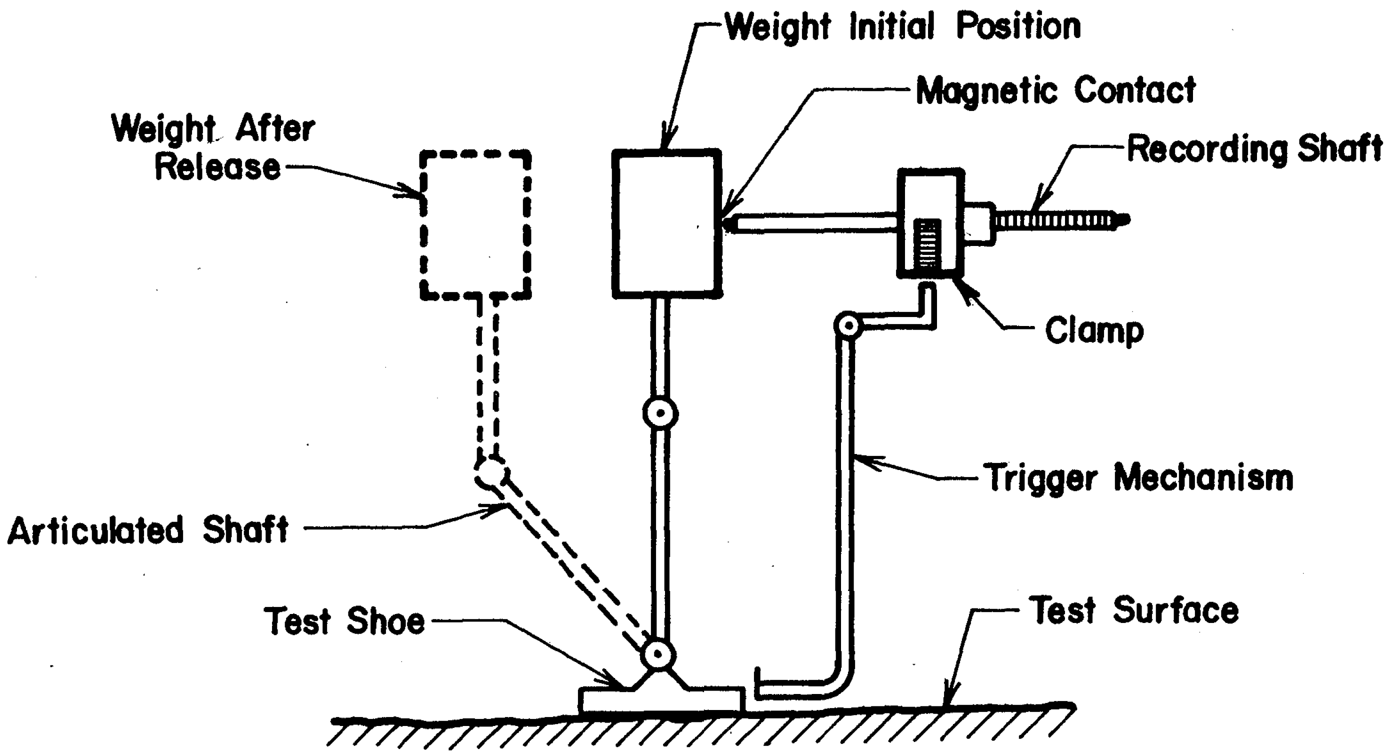


Figure 2-4. Schematic of NBS-Brungraber Portable Slip-Resistance Tester

without the detail of the supporting carriages and framework. A weight is applied to the test shoe through an articulated shaft. When the weight is released from its initial position, the shaft articulates so that a vertical and horizontal force is applied to the shoe. As the weight slides to the left and the shaft articulates, the vertical component of the force applied to the shoe decreases while the horizontal component increases. At the point when the shoe breaks free from the test surface, the ratio of the horizontal and vertical force defines the coefficient of friction. This force ratio is calculated from the geometry of the device. When the test shoe breaks force it trips the trigger mechanism which clamps the recording shaft, breaking it free from its magnetic contact with the sliding weight. Markings on the shaft are then used to calculate the ratio of the horizontal to vertical force on the shoe at the point when sliding is initiated.

The static coefficient of friction, μ_s, is given as:

$$\mu_s = 0.92 \left(\frac{R - I}{100 - (R-I)^2} \right) \qquad (2\text{-}1)$$

where R is the reading on the shaft and I is a calibration factor unique to each test device. Calibration curves for the two test devices supplied by the equipment manufacturers are shown in Figure 2-5.

The NBS-Brungraber Tester is designed as a portable device. To measure the laboratory plates, it was necessary to fabricate an aluminum frame that would hold the test device and the test plates in a fixed position. As manufactured, the tester rests on four rubber feet about 40 mm in diameter. When the coefficient of friction approaches 1.0, the tester tends to slide on its feet rather than on the test shoe. Therefore, in the field it was often necessary to block the device to prevent it from moving during the test.

In the laboratory, five or seven readings were taken for each measurement. The measurements were always in the same direction, along the long dimension of the plate. In the field, ten readings were taken, five in the direction of traffic and five transverse to the direction of traffic. The instrument was furnished with a natural leather test shoe, with the directions that the test be performed with a wet shoe.

2.2.3 Texture Profile Measurements

The PTI macrotexture profile tracer consists of a main platform and a carriage on which the transducer and stylus assemblies are mounted. The platform can be aligned with the plane of the pavement by means of three adjustable legs. Although precise alignment is not necessary, it is desirable to eliminate gross misalignment. The carriage is drawn along the platform by a constant speed synchronous motor, and the towing line is kept under constant tension by means of a counterweight which provides a tension significantly higher than the horizontal force on the stylus under normal conditions. The stylus housing is attached to the traversing carriage by means of two cantilever springs. The stylus housing follows the vertical motions of the stylus in contact with the pavement, as the carriage traverses the platform. The transducer core moves with the stylus housing. A velocity transducer (for profile slope) or a position transducer (for profile height) (LVDT), or both simultaneously may be mounted on the carriage. The traverse rate of the carriage is 3.874 mm/sec, and the total travel is approximately 300 mm. Maximum useful deflection of the stylus is 13 mm.

Macrotexture measurements were not obtained in the laboratory, because macrotexture is related to high-speed skid resistance (SN_{64}), which cannot be measured in the laboratory. Field macrotexture measurements were obtained at selected sites, both at the test facility and at the sites on the public highways. A single 250-mm trace was obtained at each of the test facility applications, and two 250-mm traces were obtained on each of the public highway applications.

The PTI microtexture profile tracer is a modified Gould-Clevite Surface Analyzer with selectable filters to eliminate long wavelength components. The microtexture profiles are analyzed to obtain their spectral components from 1600 to 200,000 cycles per meter. By rejecting components with wavelengths higher than 0.75 mm, a profile for the range 1600-51,200 cycles per meter is obtained; while rejecting wavelengths higher than 0.075 mm produces a trace which is used for the range 40,000-200,000 cycles per meter. It has been demonstrated that agreement is very good in the range where the profiles overlap, and intermediate filtering is unnecessary. The microtexture stylus tip radius is 2.54 mm, providing useful data up to 100,000 cycles per meter. Two microtexture profiles were obtained for each marking material sample that was tested in the laboratory and in the field. A jig was used to index the laboratory panels so that subsequent tests could be made over the same portion of the test panel. Each trace was approximately 25 mm long and was oriented at an angle of 45 degrees through the long axis of the panel. The two traces were parallel and were spaced approximately 25 mm apart. The field traces were taken at randomly chosen locations on the selected applications in the direction parallel to traffic.

The recorded microtexture and macrotexture profile data were processed using the spectrum analysis facility located in the

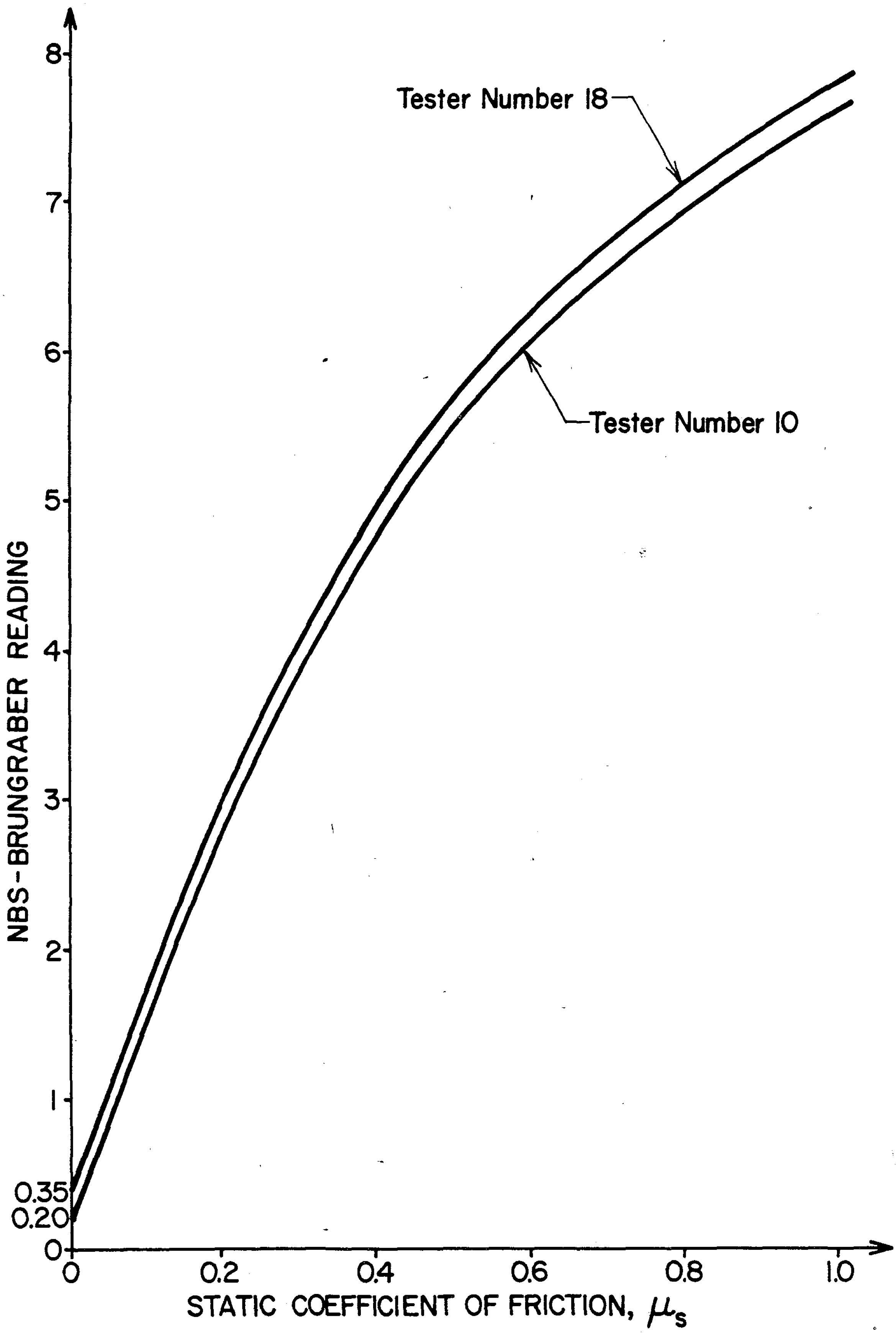


Figure 2-5. Calibration Curves for the NBS-Brungraber Portable Slip-Resistance Testers

Applied Research Laboratory. All profile data were recorded on tape, and at least one macrotexture reading and one microtexture reading were recorded on a strip chart recorder so that a permanent visible profile could be interpreted at the various frequencies. No problems were encountered with either the microtexture or the macrotexture measurements, except for microtexture measurements made on some of the open graded field surfaces where there was an occasional loss of contact between the probe and the surface.

2.2.4 Reciprocating Pavement Polisher (RPP)

This equipment was developed at the Pennsylvania State University in order to polish small test areas rapidly, either in the laboratory or on field pavement sections. In this test method a flat 90 x 140 mm rubber-faced polishing pad is pulled back and forth across the surface to be polished, at a rate of 120 strokes (60 cycles) per minute with a total travel of 25 mm. A slurry of water and abrasive is continuously fed onto the test sample through small holes in the polishing pad. No contact pressure between the pad and the test surface can be varied however, except for a few samples, the pressure was maintained at 700 Pa.

The Reciprocating Pavement Polisher was not used in the field for this project. Most of the laboratory samples were polished using 1000 cycles with 30 mm silica sand abrasive. No problems were encountered using the polisher except on some of the softer materials that tended to tear under the polishing pad. This problem was eliminated by reducing the pressure.

2.2.5 Penn State Drag Tester

The Penn State Drag Tester is a low-speed friction device which utilizes the same slider as the British Pendulum Tester. The slider is loaded with a dead weight, and the unit is pushed along the pavement at a rate of 1-2 km/h. The friction force generated between the pavement and the slider is measured with a force transducer in arbitrary drag tester units. The drag tester is a low-speed friction measuring device and as such is a candidate substitute for the British Pendulum Tester. Its main advantage is convenience, because it requires no set-up time on the pavement surface. On highways with moderate traffic it is possible to use the drag tester without closing the road to traffic. Three tests with the drag tester were made on each of the field installations on October 31, 1978.

2.3 LABORATORY TEST PROGRAM

Laboratory testing was done on small 100 mm by 150 mm panels. Plain metal panels and different pavement surfaces were used: fine-textured asphalt, coarse-textured asphalt, and portland cement concrete. The pavement surfaces were selected to represent the range of textures that might be expected in the field.

The portland cement concrete panels were prepared by casting 300 mm by 300 mm panels, 50 mm thick. These panels were then sawed into individual test panels, 100 mm by 150 mm. The mixture design used in preparing these samples is given in Table 2-3. A broom finish was given to the surfaces to simulate the texture that would be produced by a finishing machine in the field. Testing of the panels was done with the direction of test transverse to the brooming striations.

The fine-textured asphalt concrete test panels were prepared by mixing the hot asphaltic concrete in the laboratory and compacting it in the steel molds with static compaction. Properties of the fine textured asphalt concrete mixture are given in Table 2-3. The mixture was compacted at 135°C using a static pressure of 14 kPa for 2 minutes. The resulting panels were approximately 6.5 mm thick.

The coarse-textured asphalt concrete surfaces were prepared by depositing a film of hot AC-10 asphalt cement on the surface of a heated metal plate and pressing a preweighed quantity of stone into the hot asphalt film. A bead of silicone rubbed around the periphery of the plate was used to retain the asphalt. Excess stone was then brushed from the surface after the plate had cooled. The aggregate used for the coarse-textured surface was from the same source as the fine-textured asphalt surface except that it was graded between the No. 4 and No. 8 mesh sieve.

Aluminum plates (100 mm x 150 mm x 6.4 mm) were used for the weatherometer testing, and steel plates (100 mm x 150 mm x 1.6 mm) were used for the remainder of the test samples. BPN data for the various surfaces before marking material was applied are given in Table 2-4.

The marking materials were applied to the test panels in the field, using the same equipment that was used to apply the field test stripes. The panels were laid in the path of the application equipment over felt roofing paper, as shown in Figure 2-3. Because the hot extruded materials could not be placed on the panels in the field, these panels were prepared in the laboratory using a doctor blade. In all cases the material applied in the laboratory was the same as the material applied in the field. Application temperatures were similar and for practical purposes what was produced in the laboratory was the same as that produced in the field. Cold applied materials and temporary tapes were simply applied to the panel and pressed into place. Duplicate samples were prepared for each laboratory sample. All of the marking

Table 2-3. Laboratory Mixture Properties

1. Portland cement concrete

1B Limestone (passing 9.5 mm)	11.0 kg
River sand	9.1 kg
Cement	5.4 kg
Water:Cement ratio	0.50
Slump	40 mm
Air	5 %

2. Fine-Textured Asphaltic Concrete

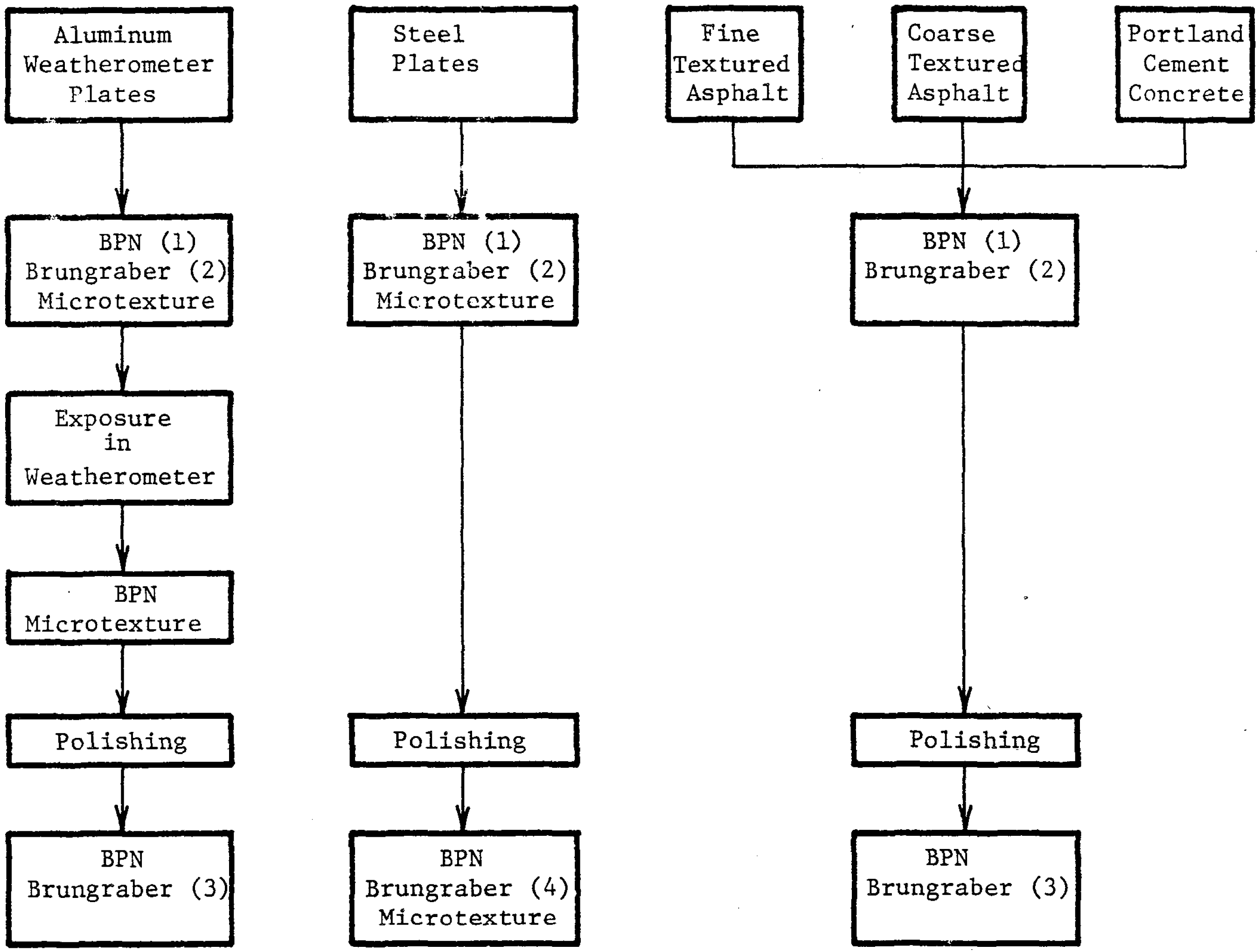
No. 4 Sieve	100 % Passing
8	78
16	60
30	48
50	25
100	11
200	6

Percent Asphalt, AC-10, total weight basic, 12 %

Aggregate: Local Montoursville river sand, heterogeneous, mainly silica sand.

Table 2-4. Summary of BPN Measurements for Laboratory Test Panels Before Application of Marking Materials

Test Surface Description	Average BPN $\bar{X}$	Number of Plates N	Standard Deviations σ
Portland Cement Concrete	96	160	4.0
Fine-Textured Asphalt	86	160	2.4
Coarse-Textured Asphalt	93	68	5.5



(1) Performed by two operators
(2) Wet with natural and synthetic leather
(3) Wet with synthetic leather
(4) Wet and dry with synthetic leather

Figure 2-6. Flow Diagram for Laboratory Testing materials were applied to steel plates. A limited number of materials were applied to the fine-textured asphalt, coarse-textured asphalt and portland cement concrete panels. A summary of the various materials and test surfaces used in the laboratory test program is given in Table 2-2. Testing on the laboratory panels included the British Pendulum Test, Portable Slip Resistance Detector, microtexture and stereo photographs. Accelerated weathering was performed in the Atlas Twin Arc weatherometer at the Pennsylvania Department of Transportation Materials and Testing Laboratory. Laboratory polishing was performed with the Pennsylvania State University reciprocating pavement polisher. A flow diagram showing the generalized testing scheme used in the laboratory is presented in Figure 2-6. In general, texture and friction measurements were made on the laboratory samples (1) after the samples were made and before the application of marking materials; (2) after the application of marking materials and prior to polishing; (3) after polishing; (4) after weathering; and (5) after weathering and polishing.

A complete listing of the data obtained in the laboratory is presented in Appendix A. The BPN and microtexture data obtained in the laboratory for the plain metal plates are presented in abbreviated form in Table 2-5. These data are the average of repeated measurements obtained on several replicate samples. The data in Table 2-5 were obtained before and after polishing with the reciprocating pavement polisher.

Tables 2-6, 2-7, and 2-8, contain data obtained for the texture panels (fine-textured asphalt, portland cement concrete, and open graded asphalt) before and after polishing. Each BPN value reported in Tables 2-6 through 2-8 represents the average of five measurements made on two replicate panels. Microtexture measurements were not performed on these panels.

The results of the weatherometer experiment are presented in Tables 2-9 and 2-10. BPN data, Table 2-9, were obtained before and after exposure in the weatherometer. In addition, after exposure, the panels were polished and BPN data recorded. This was done to find out whether the exposure produced a pattern that was subsequently worn away. Microtexture measurements were obtained before and after exposure, as shown in Table 2-10. Because of time and space constraints it was not possible to replicate the weatherometer experiment. Panels that were replicated are so indicated in Tables 2-9 and 2-10. The weatherometer experiment was performed on aluminum plates to avoid corrosion problems during exposure. The textured panels could not be placed in the weatherometer, because they would be damaged.

2.4 FIELD TEST PROGRAM

The application of the field test materials was completed by August 3, 1978, and skid testing on them was initiated on August 7, 1978. The hot extruded materials and preformed materials were applied during the week of August 21, and the hot spray thermoplastic materials were applied during the third week in September 1978. Such testing continued through November 22, 1978.

Skid testing was performed using a locked-wheel pavement friction tester with response sufficient to measure the skid resistance of 6.2-m long sections. A typical trace from the strip chart recorder for a 64 km/h skid across four test lines is shown in Figure 2-7. Note that the response requirements preclude the use of filters which are customarily used in skid tests systems. The raw data were examined for outliers caused by incorrect lateral placement of the skid tester. These occasional errors were immediately apparent, since the skid resistance of the pavement contributes to the measurement, causing unusually high values for the marking materials. The average of the successful skid tests for each of the test series is shown in Table 2-11, while the individual tests are tabulated in Appendix C. Measurements were made on six days at the Skid Test Facility between August 8 and October 4, 1978, and in 1979 on March 2 and May 14 (Tables 2-11a through 2-11d). Skid-resistance measurements were made at 64 km/h on all days and also at 48 and 80 km/h on May 14, 1979. More frequent tests were performed on the sites exposed to traffic. These sites were tested seventeen times between August 7 and November 22, 1978, and three times in 1979 between March 2 and October 15 (Tables 2-11e through 2-11f).

Texture measurements, British Pendulum tests and Penn State Drag Tester data were obtained on all the field test sites. A complete listing of each measurement is presented in Appendix B. A summary of the data is presented in Table 2-12. Also shown in Table 2-12 are the SN_{40}, SN_0, and PNG calculated from the skid-resistance speed data on May 14, 1979. Microtexture profiles at selected Skid Test Facility sites were recorded and processed as described above in section 2.2.3, for comparison with the laboratory data. Macrotexture profiles were obtained and processed for all the field sites. The reduced profile texture data are summarized in Table 2-12.

British Pendulum tests were performed on all the installations. The data from October 1978 and April 1979 are summarized in Tables 2-12. The Penn State Drag Tester data from October 1978 are also included in Table 2-12. These values are the average of three readings taken along each application.

Table 2-5. Laboratory BPN and Microtexture, Before and After Polishing, Metal Plates

Material	BPN			Microtexture, µm		
	Before	After	Change	Before	After	Change
AC1WB	55.3	49.0	-6.2	1.88	1.63	-0.25
AC1WU	49.0	46.4	-2.6	0.99	2.29	1.30
AC1YB	51.8	44.5	-7.3			
AC1YU	51.4	46.3	-5.1			
CC1WB	46.4	47.2	0.8	8.45	7.85	0.60
CC1WU	28.6	32.5	3.9			
AQ1WB	61.8	53.1	-8.7			
AQ1WU	64.0	57.4	-6.6			
AQ1YB	55.3	51.1	-4.2			
AQ1YU	55.3	53.1	-2.1			
CQ1WB	47.5	44.5	-3.0			
CQ1WU	29.7	52.3	22.6	1.01	1.90	0.89
CQ1YB	47.4	53.1	5.7			
CQ1YU	43.1	57.6	14.5	3.39	3.50	0.11
AP1WB	51.1	52.0	0.8			
AP1WU	53.1	52.1	-1.0			
CP1WB	47.8	49.7	2.0			
CP1WU	43.4	50.6	7.1	2.60	0.51	-2.09
HE1WB	44.5	48.9	3.9	6.18	4.81	-1.37
HE1WU	24.6	42.3	17.6	0.59	2.40	1.81
HE1YB	47.5	52.4	4.9			
HE1YU	58.8	54.5	-4.3			
HE2WB	45.6	54.0	9.3			
HE2WU	21.5	35.4	13.9			
HE5WB	40.0	52.5	12.5			
HE5WU	38.9	32.4	-6.5			
HE6WB	46.7	47.6	1.0			
HE6WU	22.9	26.3	3.4			
HS1WU	19.0	45.5	26.5			
HS1YB	46.1	47.3	1.2			
HS1YU	70.1	58.6	-11.5	3.54	4.08	0.54
HS2WB	53.4	53.1	-0.3	5.93	6.00	0.07
HS2WU	33.9	55.1	21.3	0.54	2.96	2.42
HS3WB	55.1	52.3	-2.9			
HS3WU	35.1	46.2	11.1			
HS4WB	62.8	52.9	-9.9			
HS4WU	45.0	50.7	5.7			
CA1WB	47.5	45.1	-2.4			
CA1YB	42.9	46.9	4.1			
CA2WU	49.6	40.7	-8.9	2.44	1.60	-0.84
CA2YU	53.3	40.0	-13.3			
CA3WB	47.2	42.3	-4.9			
CA3YB	45.4	42.3	-3.1	4.98	5.05	0.07
CA4YU	46.6	63.3	16.7	1.97	2.07	0.10
CA5WU	52.6	41.1	-11.6			
CA6WB	57.6	49.2	-8.4			
CA7WB	56.7	55.3	-1.4			
TT1WB	40.1	38.4	-1.8			
TT1YB	40.9	38.6	-2.3			
TT2WB	52.4	45.7	-6.7	6.08	5.17	-0.91
TT2YB	57.3	53.6	-3.7			
TT3WB	40.9	45.9	5.0	4.23	4.64	0.41
TP2WB	48.6	51.9	3.2			
TP4WB	48.1	42.9	-5.3	5.51	5.18	-0.33
TP4WU	28.0	26.8	-1.2			
TP5WB	44.5	50.0	5.5			
TP5WU	20.5	18.3	-2.2			

Table 2-6. Laboratory BPN, Before and After Polishing
Fine Textured Asphalt

	BPN		
Material	Before	After	Change
AC1WB	46.0	45.2	-0.8
AC1WU	37.9	39.6	1.7
CC1WB	35.1	34.3	-0.8
CC1WU	25.0	31.4	6.4
AQ1WB	51.1	49.4	-1.7
AQ1WU	61.4	65.1	3.7
CQ1WB	41.7	42.3	0.6
CQ1WU	26.4	36.0	9.6
CQ1YB	46.4	44.3	-2.1
AP1WB	44.3	46.8	2.5
AP1WU	46.1	49.9	3.8
CP1WB	47.6	46.1	-1.5
CP1WU	41.9	44.1	2.2
HE1WB	42.3	51.4	9.1
HE1WU	20.7	30.7	10.0
HS1WB	43.9	45.4	1.5
HS1WU	18.7	35.4	16.7
HS1YB	50.6	53.6	3.0
HS1YU	40.1	46.5	6.4
HS2WB	53.0	52.6	-0.4
HS2WU	29.7	38.1	8.4
HS3WU	25.5	33.9	8.4
CA1WB	49.2	48.3	-0.9
CA3WB	45.1	41.5	-3.6
TP2WB	52.5	50.9	-1.6
TP5WB	43.1	44.1	1.0

Table 2-7. Laboratory BPN, Before and After Polishing, Portland Cement Concrete

	BPN		
Material	Before	After	Change
AC1WB	53.5	58.1	4.6
AC1WU	61.2	53.6	-7.6
CC1WB	48.0	45.6	-2.4
CC1WU	40.7	45.8	5.1
AQ1WB	65.0	73.4	8.4
AQ1WU	72.3	76.6	4.3
CQ1WB	49.7	48.7	-1.0
CQ1WU	36.0	48.5	12.5
CQ1YB	42.9	46.7	3.8
AP1WB	51.1	48.9	-2.2
AP1WU	59.9	61.1	1.2
CP1WB	51.0	48.4	-2.6
CP1WU	49.4	55.6	6.2
HE1WB	47.3	49.0	1.7
HE1WU	32.4	53.0	20.6
HS1WB	44.7	45.6	0.9
HS1WU	23.7	45.4	21.7
HS1YB	50.7	58.1	7.4
HS1YU	36.6	49.4	12.8
HS2WB	52.6	50.8	-1.8
HS2WU	29.2	38.4	9.2
HS3WU	31.3	36.3	5.0
CA1WB	50.9	55.4	4.5
CA3WB	45.9	44.2	-1.7
TP2WB	46.1	56.5	10.4
TP5WB	46.9	43.9	3.0

Table 2-8. Laboratory BPN, Before and After Polishing, Coarse Textured Asphalt

	BPN		
Material	Before	After	Change
CC1WB	68.5	61.3	-7.2
CC1WU	56.9	67.3	10.4
CQ1YB	69.9	72.0	2.1
CP1WB	82.2	78.5	-3.6
HE1WB	50.0	51.0	1.0
HE1WU	24.9	27.3	2.4
HS1WB	42.4	44.9	2.5
HS1WU	23.8	40.9	17.1
HS1YB	58.0	60.1	2.1
HS1YU	57.8	64.9	7.1
HS2WB	52.6	51.9	-0.7
HS2WU	32.6	43.4	10.8
HS3WU	32.9	43.2	10.3
CA1WB	49.5	50.3	0.4
CA3WB	53.7	48.5	-5.2
TP2WB	63.3	65.9	2.6
TP5WB	53.1	53.1	

Table 2-9. Laboratory BPN, Weatherometer Studies

	Weatherometer			Weatherometer and Polishing		Overall
Materials	Before	After	Change	After	Change	Change
CC1WB	51.7	46.1	-5.6	40.6	-5.6	-11.1
CC1WU	32.6	28.6	-4.0	28.3	-0.3	-4.3
CP1WB	53.6	52.0	-1.6	45.0	-7.0	-8.6
CP1WU	46.9	53.6	6.7	52.3	-1.3	5.4
HE1WB	48.5	43.3	-5.2	42.9	-0.4	-5.6
HE1WU	26.9	41.1	14.3	34.0	-7.1	7.1
HE1YB	48.6	43.6	-5.0	53.9	10.3	5.3
HE1WU	55.0	68.9	13.9	56.1	-12.7	1.1
HE2WB	49.6	49.7	0.1	48.3	-1.4	-1.3
HE2WU	27.0	32.6	5.6	36.7	4.1	9.7
HS1WU	28.0	51.4	23.4	60.7	9.3	32.7
HS1YB	50.0	46.6	-3.4	47.7	1.1	-2.3
HS1YU	69.9	65.3	-4.6	50.1	-15.1	-19.7
HS2WB	58.0	51.4	-6.6	45.1	-6.3	-12.9
HS2WU	37.1	44.3	7.1	43.3	-1.0	6.1
CA1WB	53.1	46.3	-6.9	52.3	6.0	-0.9
CA2WU	52.7	47.7	-5.0	37.9	-9.9	-14.9
TT1WB	41.6	36.6	-5.0	33.4	-3.1	-8.1
TT2WB	54.1	42.1	-12.0	39.1	-3.0	-15.0
TP2WB	51.4	0.0	-51.4	0.0	0.0	-51.4
TP4WB	49.3	50.3	1.0	50.0	-0.3	0.7

Table 2-10. Microtexture Measurements Before and After Weatherometer

	Microtexture, μm		
Material	Before	After	Change
CC1WU	0.528	0.686	0.158
CC1WB*	1.857	2.187	0.330
CP1WU	2.510	2.479	-0.031
CP1WB	2.911	2.945	0.035
HE1WU*	0.525	0.780	0.255
HE1WB*	7.219	6.677	-0.542
HE1YU	1.610	2.087	0.477
HE1YB	7.873	8.339	0.466
HE2WU	0.325	0.345	0.020
HE2WB	7.531	5.745	-1.786
HS1WU	0.424	1.304	0.880
HS1YU	2.457	2.109	-0.348
HS1YB	4.298	4.373	0.075
HS2WU	0.573	0.706	0.133
HS2WB	7.012	7.201	0.189
CA1WB	7.243	6.582	-0.661
CA2WU	2.506	2.014	-0.492
TT1WB	7.135	6.942	-0.193
TT2WB	3.774	5.130	1.356
TP2WB	7.177		
TP4WU	1.502	0.564	-0.938
TP4WB	6.276	5.428	-0.848

*Average 2 Plates

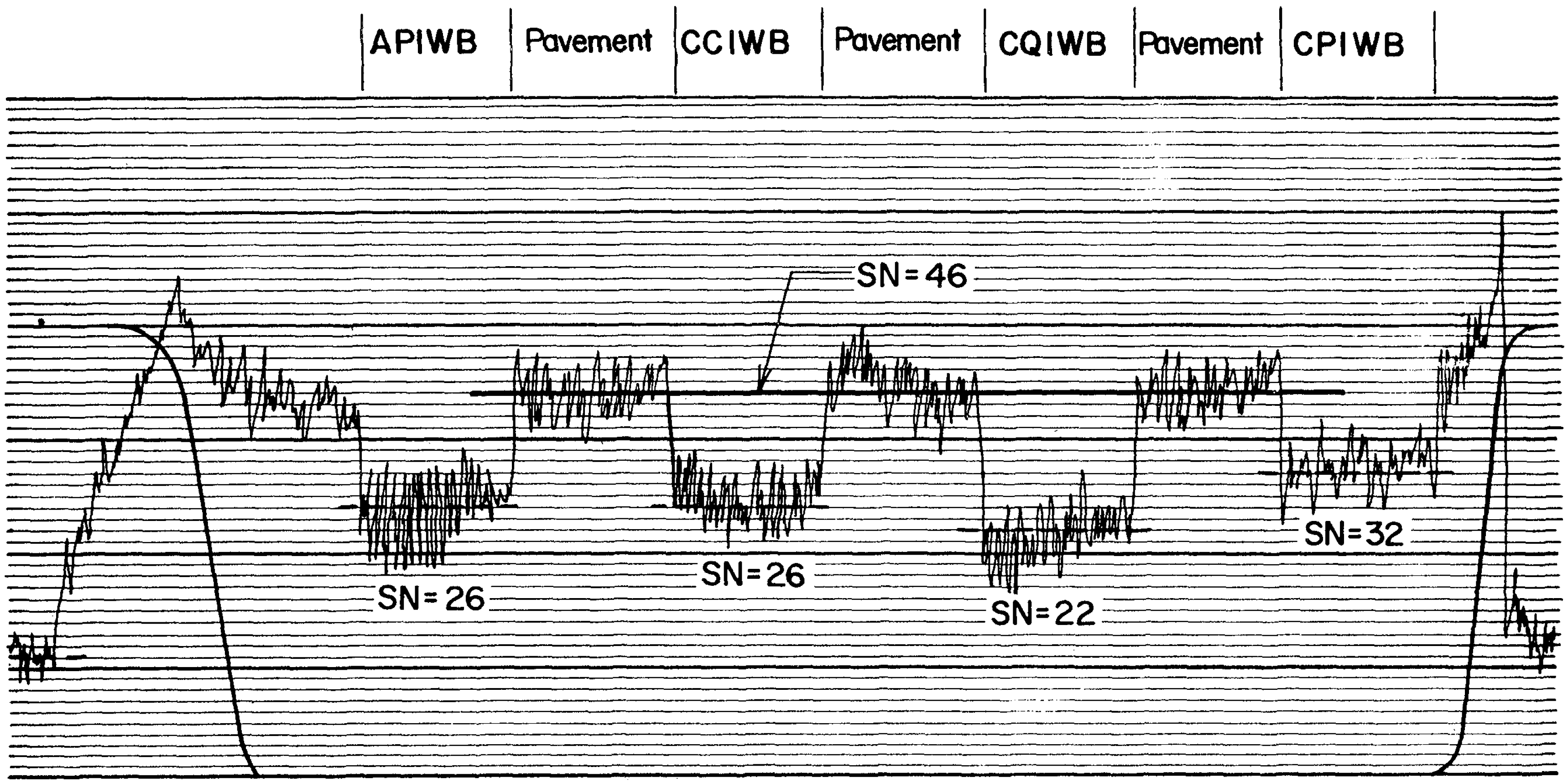


Figure 2-7. Typical Skid Test Traces - 64 km/h Test

Table 2-11a. Full-Scale Skid-Resistance Tests
Skid Test Facility - Dense Graded Asphalt Concrete

	SN_{64}							SN_{48}	SN_{64}	SN_{80}
Material	8220*	8226	8240	8303	8305	8307	9062	9134	9134	9134
AC1WB	22.8	24.7	22.7	26.0	24.0	21.0	22.0	26.0	22.0	21.3
AC1WU	19.2	20.7	14.0	18.0	20.3	14.7	15.5	20.0	17.0	15.0
CC1WB	19.7	19.0	19.5	25.0	24.5	23.7	23.0	26.0	21.0	20.3
CC1WU	13.7	15.0	12.0	14.0	14.0	11.0	13.0	16.0	13.7	11.3
AQ1WB	38.0	36.0	35.0	36.0	36.3	34.3	35.0	38.0	37.0	33.5
AQ1WU	27.5	29.0	27.5	27.7	24.5	25.0	25.3	27.0	25.0	23.3
CQ1WB	30.7	30.0	31.3	37.0	34.5	36.0	34.0	46.0	39.5	33.5
CQ1WU	14.0	17.7	15.0	23.0	22.0	22.5	23.0	36.0	26.0	30.0
AP1WB	31.7	31.0	34.3	36.0	33.5	33.7	30.4	33.0	30.3	25.7
AP1WU	30.5	27.0	28.3	30.7	29.3	27.7	28.0	33.0	28.7	22.3
CP1WB	30.0	30.0	32.0	40.0	39.7	37.3	36.5	45.0	36.0	26.5
CP1WU	23.3	25.0	27.5	32.0	35.0	33.0	27.3	43.3	30.0	24.0
HE1WB			26.0	20.5	19.7	18.0	21.5	34.3	22.7	23.5
HE1WU			20.3	12.3	15.3	13.3	12.0	25.7	16.0	13.5
HE1YB			36.0	31.0	34.7	30.7	30.3	35.3	28.7	26.5
HE1YU			32.8	20.5	28.0	19.5	20.8	29.0	21.7	15.0
HE2WB			41.3	38.0	40.0	35.0	34.5	34.7	32.7	32.3
HE2WU			28.3	30.0	36.0	28.3	30.3	30.5	29.7	26.5
HE3WB			13.7	22.5	20.3	19.5	17.0	33.0	20.0	
HE3WU			6.3	7.0	10.3	8.0	9.5	22.0	11.7	9.0
HE4WB			29.7	24.5	22.7	25.0	26.0	31.5	24.0	22.3
HE4WU			8.0	7.0	8.7	7.0	8.0	25.0	16.0	16.3
HE4YB			24.7	23.0	25.0	27.0	23.8	38.0	28.0	15.0
HE4YU			17.3	13.7	18.7	21.0	18.0	37.0	27.0	21.0
HE6WB			19.3	17.7	19.0	20.5	15.8	23.0	16.0	7.5
HE6WU			5.5	6.7	9.0	8.5	9.3	15.0	8.0	2.0
HS1WU				11.0	9.3	24.0	14.3	33.0	17.0	12.7
HS1YB				36.5	37.0	36.0	32.0	38.0	38.0	26.0
HS1YU				30.5	29.5	32.0	31.5	38.0	37.0	25.0
HS3WB				32.5	39.3	32.7	37.3	40.5	30.5	29.0

Table 2-11a. Full-Scale Skid-Resistance Test
Skid Test Facility - Dense Graded Asphalt Concrete (continued)

	SN_{64}							SN_{48}	SN_{64}	SN_{80}
Material	8220*	8226	8240	8303	8305	8307	9062	9134	9134	9134
HS3WU				20.0	14.8	19.3	20.3	30.0	21.0	22.3
HS4WB				33.0	24.0	34.0				
HS4WU				36.5	36.0	29.0				
CA1WB			27.3	24.0	24.7	47.5	25.0	52.0	50.0	27.0
CA1YB			26.0	24.0	26.0	35.0	26.8	37.7	24.0	14.0
CA2WU			13.3	13.5	16.0	15.3	16.5	27.0	14.0	10.7
CA2YU			16.3	15.0	16.3	14.0	16.7	23.0	14.0	8.0
CA3WB			27.5	30.0	31.0	30.0	29.5	39.0	16.0	
CA3YB			31.0	33.0	30.7	31.5	32.3	36.0	23.0	
CA4YU			16.0	18.7	15.5	16.0	15.3	16.3	12.3	11.0
CA5WU			11.5	11.5	15.5	12.3	16.3	17.3	12.0	8.7
CA6WB			31.3	35.0	33.5	36.0	37.0	41.0	16.5	27.5
CA7WB				35.0	40.5	30.0		30.0	32.5	22.0
TT1WB			31.3	29.7	38.7	30.0	28.3	46.0	35.0	28.0
TT1YB	38.0	35.3	37.5	36.5	44.7	35.3	42.0	39.5	33.3	39.7
TT2WB			37.3	17.0	41.5	41.0	42.0	46.5	27.0	29.0
TT2YB			42.7	37.0	42.0	45.0	43.0	42.0	19.0	29.0
TT3WB				31.7	24.0	28.7	28.3	32.0	24.0	25.3
TP1WB				56.0	55.0	51.0	53.3	57.7	52.7	47.7
TP2WB			33.3	41.0	33.5	40.3	45.7	44.0	38.0	36.0
TP3WB			31.3	32.7	33.0	34.7	36.7	41.0	41.0	32.5
TP3WU			34.0	35.3	37.7	35.3	36.5	47.3	41.7	36.0

*Date: 8220 = 1978 Day 220 = 8/9/78

Table 2-11b. Full-Scale Skid-Resistance Tests
Skid Test Facility - Open Graded Asphalt Concrete

	SN_{64}							SN_{48}	SN_{64}	SN_{80}
Material	8220*	8226	8240	8303	8305	8307	9062	9134	9134	9134
Pavement	64.0	50.7	51.3	46.5	50.3	53.3	53.0	60.3	54.3	56.0
AC1WB	34.5	34.0	33.0	32.0	32.0	35.0	31.0	37.0	34.0	
AC1WU	26.8	23.5	25.8	37.0	23.5	31.0	27.3	33.0	28.7	25.0
CC1WB		29.7	28.3	32.0	30.7	31.0	27.3	42.3	32.0	27.5
CC1WU	20.5	20.5	21.3	15.5	18.3	22.5	17.5	26.7	23.0	15.5
AQ1WB	39.3	38.3	36.8	35.5	36.7	37.5	38.7	48.5	40.0	
AQ1WU	31.3	29.8	29.8	30.0	30.0	34.7	31.3	48.0	35.5	30.0
CQ1WB	32.0	33.0	34.7	44.0	35.7	39.7	35.0	47.0	39.0	33.0
CQ1WU	17.3	18.8	21.3	25.0	24.3	26.3	22.0	32.5	30.0	22.5
AP1WB	37.3	37.0	37.5	38.5	37.0	37.3	34.0	41.0	37.0	
CP1WU	30.5	28.8	35.3	34.0	40.0	40.0	36.3	53.0	49.3	37.0
CA3WB			30.3	31.0	32.5	31.0	30.0	42.5	31.7	26.0
TT1YB	35.0	38.5	47.0	45.3	50.0	42.7	50.0	55.0	46.5	39.0
TT2YB			43.3	38.0	45.0	39.3	41.0	49.0	37.0	38.5
TP1WB				33.0	41.7	33.7	34.0	50.0	34.0	35.0

*Date: 8220 = 1978 Day 220 = 8/9/78

Table 2-11c. Full-Scale Skid-Resistance Tests
Skid Test Facility - Portland Cement Concrete

	SN_{64}							SN_{48}	SN_{64}	SN_{80}
Material	8220*	8226	8240	8303	8305	8307	9062	9134	9134	9134
Pavement	80.3	79.3	74.0	75.0	76.5	76.0	74.3	82.0	81.7	80.5
AC1WB	20.7	20.0	19.7	19.7	16.0	15.7	19.0	26.0	21.0	18.0
AC1WU	13.3	11.7	9.3	12.3	13.0	9.3	10.7	17.7	14.0	9.7
CC1WB	18.0	16.5	20.0	18.0	17.5	17.3	16.0	25.0	20.5	17.5
CC1WU	7.7	7.0	6.0	9.3	10.0	6.7	9.0	17.7	12.3	8.7
AQ1WB	31.3	28.5	25.3	32.7	30.3	29.3	27.3	37.7	31.0	27.5
AQ1WU	24.3	22.0	20.0	22.3	22.0	19.7	18.7	26.0	21.5	20.0
CQ1WB	21.0	23.3	26.3	25.5	25.7	25.3	24.8	37.0	28.7	21.5
CQ1WU	9.0	8.7	7.3	12.5	13.0	11.7	12.3	20.7	14.7	11.0
AP1WB	25.0	23.8	22.5	28.0	28.3	24.3	24.8	32.0	25.7	21.0
CP1WB	25.3	24.3	23.5	29.7	29.0	28.0	31.7	40.0	32.0	23.0

*Date: 8220 = 1978 Day 220 = 8/9/78

Table 2-11d. Full-Scale Skid-Resistance Tests
Skid Test Facility - Jennite Over Dense Graded Asphalt Concrete

	SN_{64}							SN_{48}	SN_{64}	SN_{80}
Material	8220*	8226	8240	8303	8305	8307	9062	9134	9134	9134
Pavement	33.7	29.7	25.3	29.7	25.3	26.7	22.5	27.0	25.0	
AC1WU	12.5	10.0	8.0	13.0	11.0	9.5	7.0	12.5	8.5	7.7
AC1YU	19.0	14.0	13.7	16.0	14.7	14.3	13.8	21.0	16.5	14.0
CC1WU	8.0	7.0	6.0	10.5	10.3	10.7	8.0	13.0	9.0	7.0
AQ1WU	19.7	17.7	15.0	22.0	23.0	19.3	19.5	25.0	20.5	16.0
AQ1YU	14.0	15.5	16.0	23.0		19.0	22.8	25.0	23.0	17.0
CQ1WU	18.0	16.5	12.3	20.0	17.0	17.3	14.0	20.0	16.5	15.7
CQ1YU	15.3	14.3	13.0	15.0	11.3	11.5	11.3	17.5	13.5	15.0

*Date: 8220 = 1978 Day 220 = 8/9/78

Table 2-11e. Full-Scale Skid-Resistance Tests
Public Highway - Dense Graded Asphalt Concrete

		1978																			1979		
	Wheel	SN_{64}																			SN_{48}	SN_{64}	SN_{80}
Material	Track	219	226	240	251	265	272	282	284	289	291	293	298	303	305	307	313	326	062	288	107	107	107
Pavement	IN	42.	40.	42.	40.	37.	38.	39.	36.	36.	37.	38.	32.	37.	34.	36.	33.	35.	42.	37.	38.	38.	38.
Pavement	OUT	47.	48.	44.	48.	41.	48.	49.	46.	41.	42,	46.	41.	42.	45.	49.	40.	44.	48.		55.	49.	43.
AC1WB	IN	31.	29.	29.	28.	27.	26.	32.	27.	28.	28.	27.	26.	26.	26.	26.	25.	27.	32.	31.	31.	29.	30.
AC1WB	OUT	31.	27.	29.	26.	26.	26.	26.	25.	28.	27.	24.	24.	28.	27.	35.	25.	26.	30.		33.	30.	26.
CC1WB	IN	15.	14.	13.	13.	13.	12.	16.	13.	14.	14.	14.	13.	13.	13.	15.	13.	13.	20.	22.	21.	20.	19.
CC1WB	OUT	16.	14.	11.	14.	12.	12.	11.	8.	17.	15.	13.	12.	10.	10.	10.	14.	14.	16.		20.	12.	11.
AQ1WB	IN	27.	29.	31.	30.	30.	29.	29.	30.	29.	27.	28.	26.	29.	28.	30.	28.	29.	35.	31.	35.	28.	25.
AQ1WB	OUT	32.	32.	30.	31.	29.	31.	30.	31.	30.	31.	28.	28.	29.	29.	32.	31.	29.	33.		36.	27.	24.
CQ1WB	IN	18.	17.	18.	16.	17.	16.	21.	16.	17.	16.	16.	15.	16.	17.	21.	16.	19.	24.	23.	24.	21.	20.
CQ1WB	OUT	19.	18.	18.	19.	17.	19.	20.	19.	18.	18.	18.	17.	19.	20.	21.	17.	19.	23.		26.	21.	17.
AP1WB	IN	25.	26.	26.	25.	25.	25.	30.	26.	24.	26.	25.	24.	25.	25.	27.	24.	27.	30.	29.	31.	28.	26.
AP1WB	OUT	24.	23.	22.	21.	21.	23.	24.	24.	23.	21.	20.	20.	23.	25.	26.	21.	22.	24.		26.	24.	18.
CP1WB	IN	27.	28.	28.	27.	29.	27.	31.	27.	28.	27.	27.	25.	26.	29.	29.	27.	30.	32.	30.	33.	28.	28.
CP1WB	OUT	29.	27.	28.	29.	29.	30.	36.	30.	30.	30.	28.	27.	29.	31.	31.	28.	31.	31.		34.	28.	26.
HE1WB	IN			18.	16.	17.	16.	16.	16.	17.	16.	14.	15.	16.	18.	23.	17.	20.	22.	25.	27.	21.	21.
HE1WB	OUT			23.	24.	21.	22.	19.	20.	22.	22.	20.	18.	21.	19.	22.	27.	21.	26.		34.	21.	20.
HE3WB	IN			8.	7.	10.	10.	11.	10.	11.	10.	10.	8.	15.	10.	18.	9.	22.	22.	25.	27.	23.	17.
HE3WB	OUT			9.	10.	10.	12.	12.	11.	14.	12.	11.	13.	12.	12.	13.	13.	15.	23.		27.	23.	17.
HE4WB	IN			14.	14.	15.	14.	15.	14.	15.	15.	13.	11.	15.	14.	20.	14.	19.	23.	25.	28.	23.	21.
HE4WB	OUT			20.	17.	14.	15.	13.	14.	17.	15.	15.	14.	14.	14.	12.	24.	13.	22.		27.	20.	16.
HE5WB	IN			24.	20.	23.	23.	22.	21.	21.	25.	19.	21.	20.	22.	23.	20.	27.	24.	22.	27.	20.	16.
HE5WB	OUT			26.	25.	28.	29.	27.	26.	33.	31.	25.	24.	28.	28.	35.	27.	26.	35.		35.	20.	16.
HS2WB	IN							30.		27.	27.	26.	25.	24.	29.		28.	31.	35.	33.	36.	31.	28.
HS2WB	OUT							28.	30.	28.	30	27.	27.	28.	30.	31.	29.	28.	32.		38.	30.	25.
HS3WB	IN							35.	29.	32.	28.	28.	27.		30.		28.	31.	38.	35.	40.	34.	29.
HS3WB	OUT							30.	32.	29.	30.	27.	28.	29.	28.	29.	30.	28.	32.		35.	31.	28.
HS4WB	IN							30.	30.	27.	27.	27.	25.	27.	29.	34.	27.	32.	34.	32.	35.	31.	24.
HS4WB	OUT							25.	32.	28.	29.	25.	24.	26.	27.	28.	26.	30.	35.		36.	31.	22.

Table 2-11e. Full-Scale Skid-Resistance Tests
Public Highway - Dense Graded Asphalt Concrete (continued)

		1978																	1979				
	Wheel	SN_{64}																			SN_{48}	SN_{64}	SN_{80}
Material	Track	219	226	240	251	265	272	282	284	289	291	293	298	303	305	307	313	326	062	288	107	107	107
TT1WB	IN							31.	29.	30.	31.	29.	27.	27.	28.	32.	28.	29.	36.	31.	37.	34.	29.
TT1WB	OUT							28.	28.	30.	30.	31.	30.	28.	35.	29.	30.	30.	30.		31.	29.	24.
TT2WB	IN							24.	24.	28.	24.	31.	24.	22.	27.		31.	29.	29.	25.	31.	30.	24.
TT2WB	OUT							26.	22.	32.	33.	32.	32.	26.	23.	25.	31.	29.	31.		31.	28.	27.
TT3WB	IN							27.	22.	25.	23.	22.	21.	21.	22.	25.	20.	25.	31.	27.	31.	26.	24.
TT3WB	OUT							24.	27.	16.	18.	19.	21.	22.	28.	26.	24.	24.	24.		36.	28.	19.
TP2WB	IN			30.	27.	27.	28.	26.	27.	27.	26.	25.	25.	26.	29.	28.	25.	30.	30.	28.	32.	26.	23.
TP2WB	OUT			29.	28.	27.	26.	24.	25.	29.	26.	25.	24.	26.	29.	25.	27.	27.	28.		32.	29.	24.

Table 2-11f. Full-Scale Skid-Resistance Tests
Public Highway - Portland Cement Concrete

		1978																	1979			
	Wheel	SN_{64}																		SN_{48}	SN_{64}	SN_{80}
Material	Track	219	226	240	251	265	272	282	284	289	291	293	298	303	305	307	313	326	062	109	109	109
Pavement	IN	50.	46.	49.	52.	45.	55.	46.	48.	43.	45.	47.	47.	50.	46.	42.	43.	43.	54.	59.	45.	44.
Pavement	OUT	60.	60.		62.	59.	64.	55.	60.	53.	58.	52.	54.	52.	53.	51.	57.	56.	55.	60.	53.	47.
AC1WB	IN	33.	22.	21.	19.	21.	21.	25.	22.	21.	20.	19.	21.	23.	22.	19.	22.	21.	33.	35.	33.	29.
AC1WB	OUT	24.	25.		21.	25.	23.	22.	29.	23.	22.	21.	23.	21.	24.	22.	22.	25.	32.	34.	31.	25.
CC1WB	IN	19.	16.	18.	18.	17.	21.	30.	19.	18.	18.	21.	21.	23.	21.	19.	20.	24.	34.	40.	33.	28.
CC1WB	OUT	19.	18.		16.	20.	18.	22.	19.	16.	17.	19.	21.	22.	22.	21.	18.	22.	23.	29.	23.	18.
AQ1WB	IN	27.	25.	26.	25.	26.	28.	34.	24.	25.	24.	24.	27.	26.	27.	24.	27.	28.	33.	41.	30.	25.
AQ1WB	OUT	31.	30.		27.	29.	29.	26.	25.	27.	27.	26.	25.	27.	32.	27.	29.	30.	35.	46.	31.	25.
CQ1WB	IN	24.	20.	23.	20.	21.	22.	22.	19.	20.	20.	19.	21.	20.	21.	19.	21.	21.	27.	32.	24.	23.
CQ1WB	OUT	24.	23.		22.	25.	23.	21.	20.	21.	23.	21.	21.	20.	22.	20.	24.	25.	25.	28.	23.	18.
AP1WB	IN	27.	24.	23.	23.	23.	28.	25.	22.	23.	21.	23.	25.	26.	27.	23.	25.	26.	40.	49.	32.	
AP1WB	OUT	28.	26.		27.	27.	26.	23.	24.	25.	27.	24.	29.	26.	29.	29.	27.	28.	47.			
CP1WB	IN	28.	25.	32.	26.	25.	28.	23.	25.	29.	24.	23.	25.	26.	28.	24.	26.	26.	30.	34.	26.	21.
CP1WB	OUT	30.	27.		25.	27.	28.	28.	27.	26.	28.	27.	27.	26.	26.	27.	27.	30.	31.	36.	28.	24.
HE5WB	IN			22.	18.	21.	24.	20.	24.	22.	20.	18.	20.	22.	22.	19.	20.	22.	20.	28.	18.	12.
TP2WB	IN			29.	25.	25.	26.	24.	28.	25.	24.	23.	26.	26.	26.	24.	25.	24.	32.	41.	31.	25.

Table 2-12a. Texture Data
Skid Test Facility - Dense Graded Asphalt Concrete

Parameter	BPN		Drag-tester	Texture		Skid Resistance			2 Skid Tests
	BPN		Drag-tester	Micro[1]	Macro[2]	SN_{64}	SN_0	PNG[3]	SN_{64}
Material	8304	9113	8304	9120	8313	9134	9134	9134	8303 & 8305
Pavement	77.4		47.0			55.0			55.4
AC1WB	62.4	56.4	38.0		0.378	22.0	34.2	0.62	25.0
AC1WU	52.4	44.6	22.7	1.63	0.394	17.0	30.6	0.89	19.2
CC1WB	60.6	57.8	36.3		0.300	21.0	36.5	0.76	24.7
CC1WU	36.4	38.0	21.7		0.140	13.7	27.0	1.07	14.0
AQ1WB	61.6	58.8	42.0		0.353	37.0	46.5	0.39	36.2
AQ1WU	66.2	69.2	37.0		0.493	25.0	33.8	0.47	26.1
CQ1WB	62.6	58.0	40.3		0.226	39.5	74.2	0.99	35.8
CQ1WU	62.4	57.2	34.0		0.320	26.0	43.8	0.57	22.5
AP1WB	66.2	65.4	36.3		0.579	30.3	48.8	0.78	34.8
AP1WU	69.2	62.6	36.7		0.516	28.7	60.4	1.21	30.0
CP1WB	55.0	54.4	41.0		0.284	36.0	101.0	1.65	39.8
CP1WU	75.2	68.4	41.3	3.14	0.310	30.0	102.6	1.83	33.5
HE1WB	61.8	69.2	32.0	7.31	0.089	22.7	55.9	1.17	20.1
HE1WU	57.6	58.2	19.7	1.99	0.173	16.0	64.0	1.99	13.8
HE1YB	56.6	51.6	37.7		0.104	28.7	52.9	0.89	32.8
HE1YU	61.8	62.4	32.0		0.097	21.7	79.0	2.05	24.3
HE2WB	64.8	66.8	38.0		0.386	32.7	38.2	0.22	39.0
HE2WU	63.4	69.0	49.3		0.363	29.7	38.2	0.43	33.0
HE3WB	54.0	55.6	23.7		0.168	20.0	45.4	0.91	21.4
HE3WU	50.0	50.8	18.0		0.076	11.7	79.0	2.78	8.7
HE4WB	53.0	51.8	40.3		0.193	24.0	51.0	1.07	23.6
HE4WU	43.2	37.0	20.0		0.193	16.0	43.8	1.32	7.8
HE4YB	62.0	58.2	22.7		0.180	27.0	85.6	1.76	24.0
HE4YU	60.0	54.6	30.7		0.378	28.0	161.6	2.89	16.2
HE6WB	51.4	43.6	29.3		0.290	16.0	131.9	3.48	18.3
HE6WU	59.8	65.0	15.0		0.216	8.0	349.6	6.26	7.8
HS1WU	52.6	52.0	18.3		0.112	17.0	130.5	2.98	10.2
HS1YB	72.2	59.8	43.7		0.231	38.0	71.5	1.18	36.8

Table 2-12a. Texture Data
Skid Test Facility - Dense Graded Asphalt Concrete (continued)

Parameter	BPN		Drag-tester	Texture		Skid Resistance			2 Skid Tests
				Micro[1]	Macro[2]	SN_{64}	SN_0	PNG[3]	SN_{64}
Material	8304	9113	8304	9120	8313	9134	9134	9134	8303 & 8305
HS1YU	73.8	75.4	43.7	1.87	0.323	37.0	75.7	1.30	30.0
HS2WB	56.8	52.4	20.0	4.11	0.196				32.8
HS2WU	67.4	54.4	23.3	1.69	0.389				18.5
HS3WB	52.4	51.8	35.0		0.338	30.5	64.3	1.04	35.9
HS3WU	64.6	71.0	32.3		0.264	21.0	43.6	0.92	17.4
HS4WB	49.6	45.8	21.0		0.269				28.5
HS4WU	40.4	32.4	21.0		0.353				36.3
CA1WB	48.4	41.8	31.3		0.084	50.0	153.0	2.04	24.4
CA1YB	49.6	57.4	27.7		0.109	24.0	168.7	3.08	25.0
CA2WU	51.8	48.8	20.0	2.38	0.099	14.0	102.0	2.88	14.8
CA2YU	53.2	51.0	20.7		0.061	14.0	113.3	3.28	15.7
CA3WB	56.0	57.2	44.3		0.269	16.0	60.8	1.38	30.5
CA3YB	52.4	52.4	49.3	4.95	0.295	23.0	39.8	0.47	31.9
CA4YU	64.2	57.0	27.3	1.54	0.053	12.3	28.7	1.23	17.1
CA5WU	51.6	53.2	22.7		0.079	12.0	48.7	2.16	13.5
CA6WB	63.2	58.0	50.3		0.188	16.5	58.9	1.24	34.3
CA7WB	61.8	56.0			0.401	32.5	51.7	0.96	37.8
TT1WB	59.6	66.0	42.3		0.244	35.0	96.1	1.54	34.2
TT1YB	48.2	54.2	35.3		0.191	33.3	37.1		40.6
TT2WB	65.2	54.2	48.3	4.13	0.239	27.0	85.2	1.47	29.3
TT2YB	62.8	66.6	45.3		0.305	19.0	59.8	1.15	39.5
TT3WB	63.2	61.6	47.7	4.42	0.302	24.0	42.9	0.73	27.9
TP1WB	71.0	61.2	51.7		0.196	52.7	76.9	0.59	55.5
TP2WB	52.2	59.2	40.3		0.328	38.0	58.5	0.62	37.3
TP3WB	72.8	66.6	47.0		0.076	41.0	60.4	0.72	32.9
TP3WU	78.6	73.2	41.7		0.284	41.7	71.4	0.84	36.5

[1] Micro RMS (μm)

[2] Macro RMS (mm)

[3] PNG (hr/km)

Table 2-12b. Texture Data
Skid Test Facility - Open Graded Asphalt Concrete

Parameter	BPN		Drag-tester	Texture		Skid Resistance			2 Skid Tests
				Micro[1]	Macro[2]	SN_{64}	SN_0	PNG[3]	SN_{64}
Material	8304	9113	8304	9120	8313	9134	9134	9134	8303 & 8305
Pavement	93.8		58.3			54.3	66.0	0.23	48.4
AC1WB	74.6	66.0	52.3	1.11	0.691	34.0	35.2		32.0
AC1WU	61.4	49.4	41.0		1.709	28.7	50.0	0.86	30.3
CC1WB	71.0	63.6	50.3	2.40	0.688	32.0	79.1	1.34	31.4
CC1WU	47.0	54.2	40.3		0.691	23.0	62.7	1.68	16.9
AQ1WB	72.2	68.8	39.3		1.326	40.0	46.8		36.1
AQ1WU	70.6	72.0	42.7		0.770	35.5	95.0	1.46	30.0
CQ1WB	72.2	68.0	35.7		0.541	39.0	79.6	1.10	39.9
CQ1WU	64.0	59.6	52.7	2.14	0.630	30.0	58.4	1.14	24.7
AP1WB	71.8	63.6	53.3		0.605	37.0	40.4		37.8
CP1WU	76.0	75.0	43.3		1.227	49.3	94.2	1.12	37.0
CA3WB	57.2	51.4	48.7		0.330	31.7	87.4	1.53	31.8
TT1YB	51.2	57.0	48.7			46.5	92.2	1.07	47.7
TT2YB	66.8	67.0	51.0		0.538	37.0	66.7	0.75	41.5
TP1WB	59.8	36.6	47.3		0.297	34.0	79.7	1.10	37.4

[1] Micro RMS (μm)

[2] Macro RMS (mm)

[3] PNG (hr/km)

Table 2-12c. Texture Data
Skid Test Facility - Portland Cement Concrete

Parameter	BPN		Drag-tester	Texture		Skid Resistance			2 Skid Tests
				Micro[1]	Macro[2]	SN_{64}	SN_0	PNG[3]	SN_{64}
Material	8304	9113	8304	9120	8313	9134	9134	9134	8303 & 8305
Pavement	58.8		60.0			81.7	84.4		75.8
AC1WB	51.8	50.4	23.3	1.85	0.104	21.0	44.7	1.14	17.9
AC1WU	49.2	49.8	21.0	1.05	0.084	14.0	44.7	1.88	12.7
CC1WB	51.2	46.4	22.7	1.66	0.089	20.5	42.4	1.11	17.8
CC1WU	48.6	35.6	16.7		0.198	12.3	51.4	2.21	9.7
AQ1WB	51.8	49.6	34.0		0.127	31.0	59.6	0.98	31.5
AQ1WU	66.6	62.6	24.7		0.074	21.5	37.8	0.81	22.2
CQ1WB	61.0	55.2	24.7		0.112	28.7	84.0	1.68	25.6
CQ1WU	48.6	47.0	18.3	2.27	0.135	14.7	52.7	1.96	12.8
AP1WB	52.2	47.6	23.0		0.107	25.7	60.0	1.31	28.2
CP1WB	56.2	47.4	25.7		0.082	32.0	93.4	1.72	29.4

[1] Micro RMS (μm)

[2] Macro RMS (mm)

[3] PNG (hr/km)

Table 2-12d. Texture Data
Skid Test Facility - Jennite Over Dense Graded Asphalt Concrete

Parameter			Drag-	Texture		Skid Resistance			2 Skid Tests
	BPN		tester	Micro[1]	Macro[2]	SN_{64}	SN_0	PNG[3]	SN_{64}
Material	8304	9113	8304	9120	8313	9134	9134	9134	8303 & 8305
Pavement	66.4		37.7			25.0			27.5
AC1WU	42.6	44.4		1.25	0.086	8.5	24.8	1.52	12.0
AC1YU	48.0	50.6	28.7		0.584	16.5	38.1	1.26	15.4
CC1WU	42.0	38.8	22.3		0.132	9.0	32.3	1.93	10.4
AQ1WU	62.0	61.8	33.7		0.244	20.5	49.2	1.39	22.5
AQ1YU	56.6	58.4	20.7		0.351	23.0	46.2	1.20	23.0
CQ1WU	59.4	56.4	22.7	1.57	0.117	16.5	28.2	0.76	18.5
CQ1YU	45.0	41.8	22.7	1.61	0.169	13.5	20.8	0.48	13.2

[1]Micro RMS (μm)

[2]Macro RMS (mm)

[3]PNG (hr/km)

Table 2-12e. Texture Data
Public Highway - Dense Graded Asphalt Concrete

Parameter				Drag-	Macro	Skid Resistance			2 Skid Tests
	Wheel	BPN		tester	RMS[1]	SN_{64}	SN_0	PNG[2]	SN_{64}
Material	Track	8310	9110	8303	8306	9107	9107	9107	8303 & 8503
Pavement	IN	63.6				37.7	38.7		35.5
Pavement	OUT	68.0		46.2		49.0	79.7	0.76	43.5
AC1WB	IN	73.0	46.4	33.3	0.641	29.0	32.0	0.10	26.0
AC1WB	OUT	56.2	51.8	40.6	0.274	30.0	46.6	0.70	27.5
CC1WB	IN	48.6	45.4	34.6	0.516	19.7	24.1	0.32	13.0
CC1WB	OUT	36.4	39.4	38.6	0.204	12.0	47.5	1.95	10.0
AQ1WB	IN	71.4	51.2	45.0	0.493	28.3	55.9	1.01	28.5
AQ1WB	OUT	61.8	44.6	35.3	0.338	27.0	64.3	1.26	29.0
CQ1WB	IN	46.0	40.2	32.3	0.296	21.3	32.3	0.61	16.5
CQ1WB	OUT	51.2	44.8	40.3	0.232	21.0	45.5	1.20	19.5
AP1WB	IN	51.8	49.4	33.3	0.519	28.0	41.0	0.58	25.0
AP1WB	OUT	53.4	49.6	46.0	0.297	24.0	44.7	1.08	24.0
CP1WB	IN	66.4	51.2	37.0	0.442	28.0	43.3	0.60	27.5
CP1WB	OUT	61.0	61.2	47.3	0.415	28.0	49.2	0.83	30.0
HE1WB	IN	42.8	50.4	42.0	0.217	20.7	36.6	0.73	17.0
HE1WB	OUT	52.4	56.0	43.3	0.160	21.3	70.8	1.67	20.0
HE3WB	IN	39.4	44.4	35.3	0.185	23.0	53.6	1.38	12.5
HE3WB	OUT	47.2	53.6	35.3	0.102	23.3	55.6	1.44	12.0
HE4WB	IN	43.8	49.0	38.0	0.102	23.3	43.8	0.93	14.5
HE4WB	OUT	54.2	51.4	39.3	0.102	19.7	58.1	1.63	14.0
HE5WB	IN	60.6	56.2	42.3	0.156	19.7	58.1	1.63	21.0
HE5WB	OUT	61.4	61.0	44.3	0.179	19.7	100.6	2.34	28.0
HS2WB	IN	80.0	57.2	46.3	0.607	31.3	52.3	0.78	26.5
HS2WB	OUT	71.6	58.6	55.0	0.387	29.7	68.9	1.27	29.0
HS3WB	IN	79.6		50.0	1.161	33.7	63.3	0.96	30.0
HS3WB	OUT	56.6	62.6	49.3	0.429	31.0	48.6	0.70	28.5
HS4WB	IN	63.4	62.6	56.3	0.734	30.7	62.8	1.17	28.0
HS4WB	OUT	65.6	59.2	47.0	0.420	30.7	77.5	1.53	26.5

Table 2-12e. Texture Data
Public Highway - Dense Graded Asphalt Concrete (continued)

Parameter				Drag-	Macro	Skid Resistance			2 Skid Tests
	Wheel	BPN		tester	RMS[1]	SN_{64}	SN_0	PNG[2]	SN_{64}
Material	Track	8310	9110	8303	8306	9107	9107	9107	8303 & 8305
TT1WB	IN	49.0	53.0	49.0	0.363	34.0	51.9	0.70	27.5
TT1WB	OUT	48.4	51.0	59.3	0.272	28.7	46.2	0.81	31.5
TT2WB	IN	66.6	45.2	54.0	0.345	30.3	48.3	0.84	24.5
TT2WB	OUT	63.4	43.2	51.0	0.315	28.0	37.0	0.39	24.5
TT3WB	IN	74.2	46.4	49.0	0.563	26.0	43.8	0.70	21.5
TT3WB	OUT	59.8	40.4	52.3	0.218	28.0	96.1	1.99	25.0
TP2WB	IN	51.0	56.6	42.6	0.575	26.3	50.7	0.99	27.5
TP2WB	OUT	47.2	54.2	44.3	0.382	29.0	48.8	0.86	27.5

[1] Macro RMS (mm)

[2] PNG (hr/km)

Table 2-12f. Texture Data
Public Highway - Portland Cement Concrete

Parameter						Skid Resistance			2 Skid Tests
	Wheel	BPN		Drag-tester	Macro RMS[1]	SN_{64}	SN_0	PNG[2]	SN_{64}
Material	Track	8310	9110	8303	8306	9107	9107	9107	8303 & 8305
Pavement	IN	72.4				45.0	87.9	0.90	48.0
Pavement	OUT	77.0		47.5		52.7	88.5	0.79	52.5
AC1WB	IN	51.2	53.8	43.3	0.164	32.5	48.7	0.65	22.5
AC1WB	OUT	52.2	49.6	48.3	0.136	31.3	55.2	0.96	22.5
CC1WB	IN	46.2	52.6	44.0	0.205	33.3	66.2	1.07	22.0
CC1WB	OUT	51.4	43.2	42.6	0.172	22.5	55.0	1.37	22.0
AQ1WB	IN	55.0	62.6	44.3	0.165	30.0	83.7	1.54	26.5
AQ1WB	OUT	55.0	60.2	45.3	0.317	31.3	107.6	1.83	29.5
CQ1WB	IN	54.0	51.2	39.6	0.146	24.0	50.4	1.04	20.5
CQ1WB	OUT	53.2	49.2	44.3	0.164	22.7	54.5	1.37	21.0
AP1WB	IN	53.2	58.2	43.3	0.098	32.0	71.1	0.96	26.5
AP1WB	OUT	53.2	66.4	43.0	0.376				27.5
CP1WB	IN	53.8	52.8	41.3	0.225	26.3	71.3	1.53	27.0
CP1WB	OUT	57.2	48.4	40.6	0.149	28.3	63.9	1.23	26.0
HE5WB	IN	60.4	54.8	39.3	0.117	18.0	96.5	2.60	22.0
TP2WB	IN	48.6	47.4	40.3	0.175	31.0	81.0	1.46	26.0

[1] Macro RMS (mm)

[2] PNG (hr/km)

Table 2-13. Brungraber Portable Slip-Resistance Detector Data from Public Road Sites

PAINT	WHEEL TRACK	Brungraber No. (Date: 9171) DGAFC SURFACE	PCC SURFACE
AC1WB	IN	.719	.779
AC1WB	OUT	.762	.708
AP1WB	IN	.774	.701
AP1WB	OUT	.791	.783
CC1WB	IN	.762	.755
CC1WB	OUT	.808	.697
CQ1WB	IN	.743	.705
CQ1WB	OUT	.779	.698
CP1WB	IN	.739	.783
CP1WB	OUT	.839	
AQ1WB	IN	.750	.779
AQ1WB	OUT	.804	.775
HE1WB	IN	.809	
HE1WB	OUT	.858	
HE4WB	IN	.853	
HE4WB	OUT	.826	
HE3WB	IN	.804	
HE3WB	OUT	.791	
HE5WB	IN	.882	.770
HE5WB	OUT	.867	
HS4WB	IN	.808	
HS4WB	OUT	.835	
HS2WB	IN	.844	
HS2WB	OUT	.804	
HS3WB	IN	.812	
HS3WB	OUT	.800	
TT2WB	IN	.720	
TT2WB	OUT	.712	
TT3WB	IN	.738	
TT3WB	OUT	.787	
TT1WB	IN	.716	
TT1WB	OUT	.727	

As in the laboratory, a large amount of Portable Slip-Resistance Data was collected in the field. Similar problems were encountered in the field with the leather shoe in that the leather never reached an equilibrium condition when exposed to water over a large series of tests. Data obtained on the public road sites with the composition shoe are shown in Table 2-13. These data were obtained using a different Brungraber Portable Slip-Resistance Detector than used earlier in this project. Although both machines were calibrated and operated in a similar manner and used the same shoe, this second machine consistently produced higher readings. Thus, any conclusions based on Brungraber data must be made from a single data set and should be confined to relative effects rather than absolute effects.

Attempts with the sand patch method of measuring texture depth were unsuccessful for marking materials. It was not possible to obtain distinct circles on the thicker marking materials. The sand became embedded in and the plastic materials and could not be spread reliably. The data obtained for the paints were too scattered to be useful.

3. DATA ANALYSIS

3.1 INTRODUCTION

The laboratory and field experiments were designed to:

1. Determine the skid resistance properties of typical traffic marking materials in current use.

2. Develop an understanding of the variables affecting the skid resistance of traffic marking materials so that a realistic minimum skid resistance can be specified for these materials.

The experimental data have been analyzed in two parts: a laboratory, and a field analysis.

3.1.1. Analysis of Laboratory Data

The variables evaluated in the laboratory included the type of marking material, the substrate over which the marking material was applied, and bead application:

1. marking material type (see Table 2.2)

2. substrate = plain metal plates (PM)
   portland cement concrete (PCC)
   fine textured asphalt concrete (FT)
   coarse textured asphalt concrete (CT)

3. bead application = none
   sprayed, dropped

4. polishing = before polishing
   after polishing

5. weathering = before weathering
   after weathering

3.1.2 Determination of Polishing Sequence

A number of preliminary experiments were conducted. The first of these was to establish a polishing sequence for use with the reciprocating pavement polisher. In previous resarch at The Pennsylvania State University, the reciprocating pavement polisher has been used to polish aggregate, and a series of grit sizes has been used in the polishing process. In the previous research, a coarse grit, 74 μ_m, was used initially, followed by 30, 15, and 5 μ_m grit. Polishing was continued with each grit size until the BPN number stabilized. Several thousand passes of the polisher were required at each grit size to stabilize the BPN number.

For this project, because of the large number of samples to be polished, the effect of polishing sequence and grit sizes was evaluated to determine whether the polishing sequence could be simplified. Five different grit sizes, 105, 74, 30, 15, and 5 μ_m grit were used to polish beaded and unbeaded panels. Representative panels were selected from the thin materials (paints) and the thick materials (hot extruded thermoplastics), and a variety of polishing sequences were used. The results of a typical test are shown in Figure 3-1.

The hot extruded beaded marking material increased in BPN after the first 1,000 cycles. This initial increase is apparently due to a conditioning of the beads, most likely a removal of paint overspray. After 1,000 cycles the BPN changes little with increasing polishing cycles or increasing width size. The hot extruded unbeaded material showed little effect from the polishing. In some instances, the thick unbeaded materials increased in BPN after initial polishing, most likely due to a roughening of the paint surface. The results shown in Figure 3-1 represent the equilibrium BPN value obtained after seven swings of the BPN pendulum.

The size of the grit used for the polishing did not affect the equilibrium BPN of the polished surface except when the finer grit sizes were used on the softer unbeaded thermoplastics. The thermoplastics tended to pick up or tear when the finer grit sizes were used, increasing the BPN values. The 30 μ_m grit was selected as a compromise, and was used in all of the polishing work.

Terminal polishing was reached rapidly, and after 1000 passes there was little change

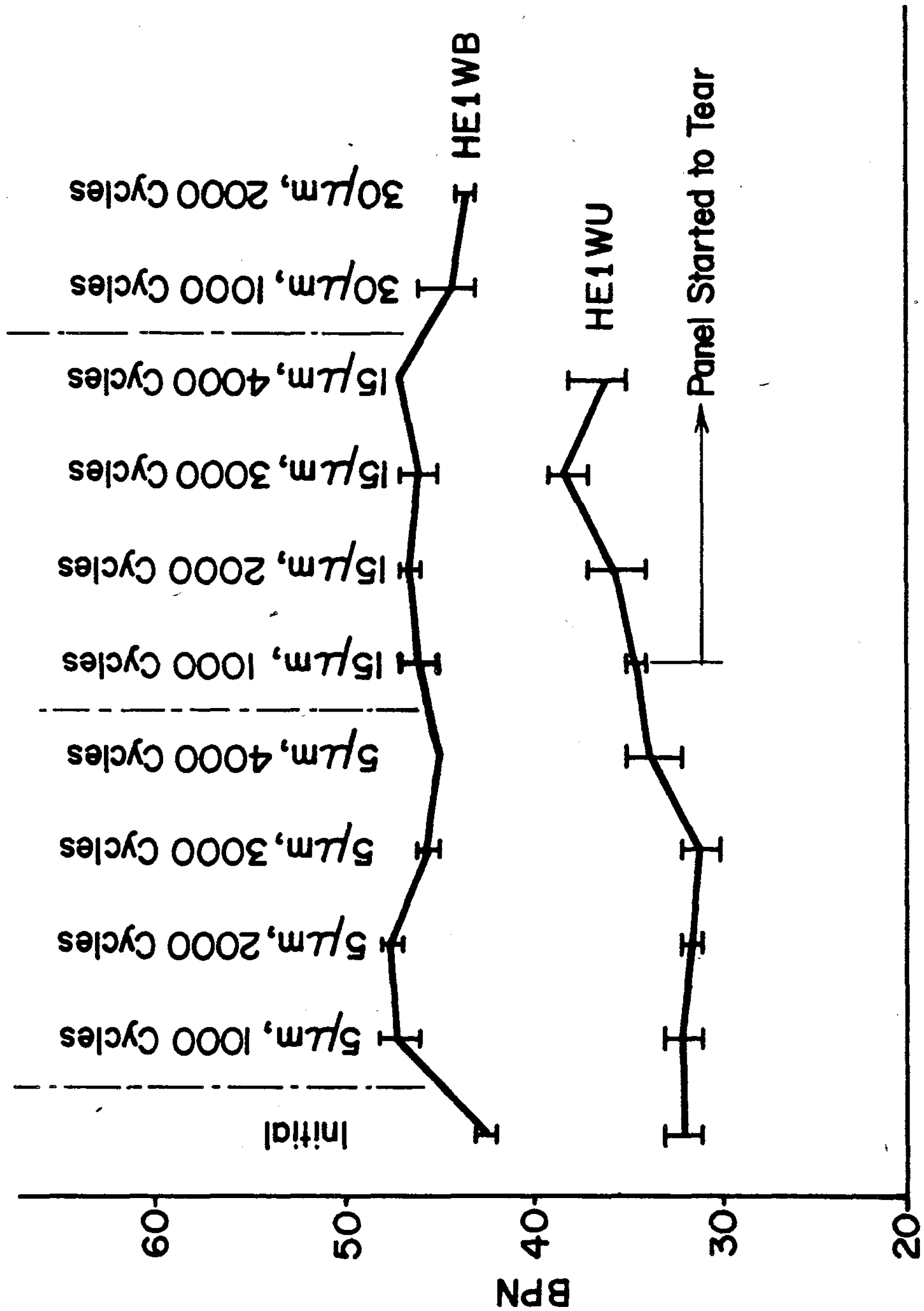


Figure 3-1. Polishing Sequence for Hot Extruded Thermoplastic Panels.

in the BPN measurements. Tearing on the soft thermoplastics generally occurred after 1000-2000 passes. Therefore, 1000 passes were used in all the polishing work. The grit was a ground silica, Min-U-Sil supplied by the Pennsylvania Glass Sand Corporation, Berkely Springs, West Virginia.

The polishing mechanism was different for the beaded and unbeaded surfaces. There was no wearing of the beads due to the polishing. Apparently, the polishing does remove surface contaminants, essentially cleaning the beads. In many instances the polishing increased the BPN values of the unbeaded surfaces by removing the surface sheen or glaze. Therefore, the polishing procedure was more a conditioning procedure than a true polishing procedure. In the field the surfaces are conditioned by the action of traffic or the skid trailer. In order to duplicate field conditions the development of a specification test procedure should include a conditioning step. The purpose of this step would be to condition the surfaces and duplicate the surface that would be expected in the field. A polishing procedure such as the reciprocating pavement polisher, Torque Device (ASTM E 510), full scale wheel (ASTM E 450) or similar device is not appropriate for the conditioning step. The development of new test procedures was outside the scope of the project however a simple conditioning procedure such as brushing with a soft bristle brush and a mild abrasive should be adequate.

3.1.3 Sanding Experiment

Because the polishing did not produce any appreciable wear of the surfaces, a more drastic approach was taken to establish the effect of wear. A number of panels with thick thermoplastic were sanded with 100 grit sandpaper using a 20-cm (4-in.) belt sander. Figure 3-2 shows the results with HE6WU, a hot-extruded, unbeaded thermoplastic. The initial BPN reading was 31, but after 7 passes of the BPN pendulum the reading decreased to 18. This reduction in BPN with subsequent swings of the pendulum was much more noticeable with the smooth, glassy unbeaded surfaces than with the dull or satin surfaces. Approximately 7 swings of the pendulum were required before the BPN equilibrated .

The sanding roughened the surface of the unbeaded HE6WU panel and gave a dramatic increase in the BPN, from 18 to 39. Some of the improvement was lost with subsequent swings of the pendulum (39 to 30). Resanding roughened the surface and restored some of the BPN, which again was lost with increasing swings of the pendulum. After sanding, the panels were polished with 15 μm grit and BPN readings were taken. The 15 μm grit had little effect on the BPN readings although the loss in BPN with subsequent swings of the pendulum was still apparent. The sanding sequence is not necessary to condition the surfaces. Although not shown, a number of HS panels with a dimpled surface were sanded until their surfaces were smooth. The sand did not significantly effect the BPN readings on the panels.

The results from a number of materials are shown in Figure 3-3. The height of the vertical bar indicates the range in value between the first swing of the pendulum and the final swing after the BPN values had equilibrated (usually after 7 swings). The top of the bar represents the initial value, the bottom of the bar represents the equilibrium value. For the purpose of comparison the terminal value or the lower extremity of the bar should be used. In general, even though the sanding roughened the surfaces and increased the BPN values, this effect was lost after the surfaces were polished. The sanding was not sufficient to cut through the beads but merely roughened their surface. Of particular note is panel HS3WU which had a very rippled surface initially. The sanding completely removed the ripple effect and produced a flat, smooth surface. After sanding the BPN increased by only 7 points.

The unbeaded surfaces that contained a micro aggregate were rippled. Based upon the observation that the BPN values for these materials changed little after sanding (removal of the ripple) it was concluded that the higher BPN values for these surfaces resulted from the micro aggregate rather than the texture. The BPN values for the three smooth, glassy materials increased dramatically after sanding (HE6WU, HE1WU, TP5WU). The roughening that occurred for HE6WU and HE1WU was retained after polishing, however the roughness produced on panel TP5WU was lost after polishing. The increase in roughness or texture that was produced by the 100 grit belt sander was much greater than would be expected from polishing in the field. From this experiment it was concluded that wearing of the marking material is not an important consideration and that surface polishing as done with the reciprocating polisher is more than adequate to condition the surface.

3.1.4 BPN Measurements

The initial and final reading for each set of BPN measurements on the uncoated (control) panels were within a few points while the readings on the majority of the marking materials decreased with an increase in the number of swings. Approximately seven readings were required to obtain a uniform value. ASTM Method E 303-74, which governs the use of the British Pendulum Tester, requires only five readings and the first reading is disregarded because the BPN readings can change dramatically with each succeeding swing

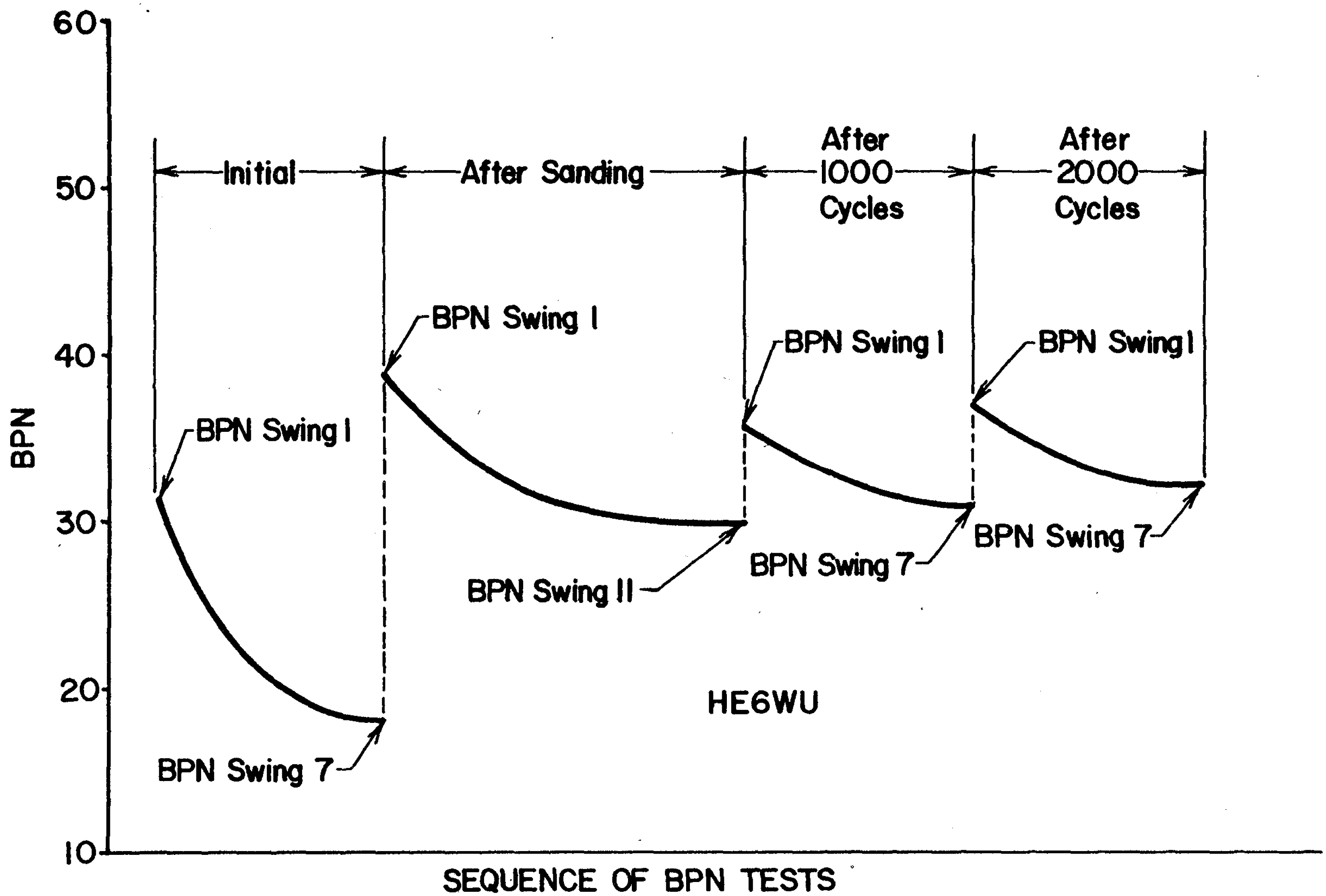


Figure 3-2. Sanding Experiment for Hot Extruded Thermoplastic

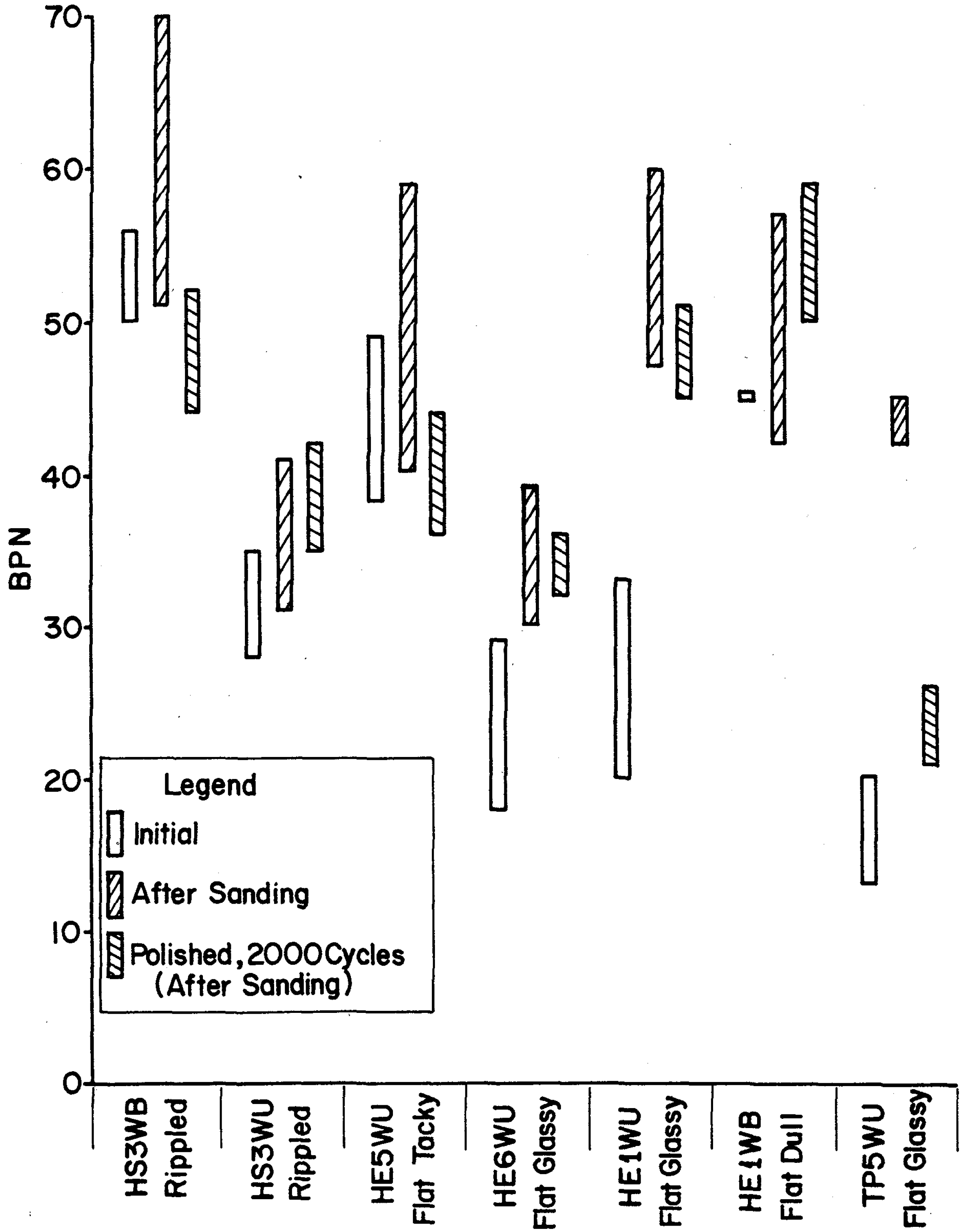


Figure 3-3. Before and After Sanding and Polishing Results

of the pendulum, if ASTM E 303 is adopted for use with marking materials, it may be necessary to amend section 5.2 of ASTM E 303 to read:

> 5.2 Without delay, make additional swings, rewetting the test area each time. Record the results of each swing and continue the testing until the results of four consecutive swings vary by no more than three points. Report the average of the last four swings as the BPN value.

3.1.5 Effect of Bead Application Method and Bead Size on BPN

An experiment was performed to determine the effect of application method and bead size on the BPN number of paint. The results of this experiment are given in Table 3-1. Paint was sprayed on 10 cm x 15 cm masonite panels and beads were either sprayed or dropped onto the wet paint. Two different bead sizes 20/100 mesh and 40/80 mesh beads were used. Visual evaluation of the texture produced by the sprayed on beads indicated a much rougher surface than that produced by the dropped on beads. Apparently, the energy imparted to the beads causes the beads to penetrate into the film causing a dimpling effect that increases the texture of the surface. This is reflected in the BPN numbers for the dropped on beads versus the sprayed on beads. From results in Table 3-1, it was concluded that the method of application has a more significant influence on the BPN value than the size or gradation of the beads. Three different panels were prepared for each test condition. A total of four trials, or applications, were performed on each panel. Each trail consisted of four BPN values. The results in Table 3-1 indicate a small variability both between panels and within trial. The excellent repeatability shown in this experiment is due to the smooth surface offered by the masonite panel.

3.1.6 Brungraber Device

The Brungraber device was furnished initially with a leather shoe. Based on experience with tire materials the initial Brungraber readings were taken with the wet condition. During the initial testing considerable variation was observed in the data. In particular, after the machine had been used for a certain period of time, it was noticed that the slider would no longer slide or break away from the surface of the marking material. Considerable effort was spent trying to find the source of the malfunction within the machine; it was finally determined, however, that the problem was caused by the leather shoe literally grabbing the surface being tested.

Leather softens with time and becomes soggy. The leather fibers act as suction cups, giving a false indication of the friction characteristics of the tested surface. Subsequent to this initial testing, a number of other sliders were obtained and evaluated in the laboratory. Based on limited testing, a composition leather slider was chosen for future testing. The researchers believe that considerable developmental work is needed to develop a standard slider if this machine is to be used for future testing and research with pavement marking materials. Based on the limited testing that was done, it is further evident that the critical condition may be the dry condition rather than the wet condition. This will depend largely on the type of slider material that is used.

Since developmental work on the Brungraber device was outside the scope of the project, the composition leather slider was chosen for testing. The results of the data, given in Table 32, indicate that the natural leather slider gives consistently higher coefficients of friction than the composition leather slider. The lowest coefficient of friction, the critical condition, is with the composition leather slider in the dry condition. The Brungraber device is not furnished with a standard shoe or calibration surface and the Brungraber data should be used to rank the different marking materials and should not be used as an absolute measure of coefficient of friction. Limited testing was done on some other experimental sliders provided by the manufacturer. The data indicated that additional variability would be observed with these sliders.

3.1.7 Effect of Compositional Variables on Frictional Properties

The SAS statistical package was used extensively to test for the effect of factors such as polishing, beads, and pigment type on BPN. In many instances statistically significant effects were established, however, many of these effects were not significant from an engineering standpoint. The average BPN standard deviation was 2.2 for the beaded panels and 3.9 for the unbeaded panels. The average standard deviation for the Brungraber device was 2.4 and 1.4 units for the beaded and unbeaded panels respectively.

Differences in the average BPN, before and after polishing, were not significant for the metal plates. The mean BPN for the metal plates increased by 0.72 points for the beaded surfaces but increased 3.5 points for the unbeaded surfaces. Closer examination of the data, Table 2-5, indicates that the BPN values for a few of the surfaces increased by 10-27 points after polishing. Except for HE5WB all of these increases were for unbeaded surfaces. If the panels with the larger increase in BPN are ignored then the average BPN value for the unbeaded panels decreased by 5.2 points a significant decrease. After a visual examination of the surfaces of the polished panels,

Table 3-1. Effect of Bead Size and Application Method on BPN

Beads	Panel	BPN Trial 1	2	3	4	Average
20/100 Mesh	A	63.8	62.8	61.5	61.8	62.5
Spray On	B	63.8	59.3	58.8	62.8	61.2
	C	60.0	61.8	58.3	60.8	60.2
	Average	--	--	--	--	61.3
20/100 Mesh	A	47.8	48.0	47.8	47.5	47.8
Drop On	B	47.5	47.5	47.8	46.5	47.3
	C	49.0	47.8	47.8	47.8	48.1
	Average	--	--	--	--	47.7
40/80 Mesh	A	50.8	50.8	48.3	50.5	50.1
Drop On	B	51.3	50.8	51.3	49.3	50.7
	1	51.8	50.3	51.0	50.5	51.2
	Average	--	--	--	--	50.7

Table 3-2. Comparison of Different Shoes, Brungraber Portable Slip Resistance Detector.

Material	Composition Leather		Natural Leather	
	Wet	Dry	Wet	Dry
AC1WB-1	0.68	0.52	0.87	0.76
AC1WB-2	0.58	0.51	0.95	0.83
AC1WB-3	0.65	0.53	0.84	0.83
AC1WB-4	0.68	0.55	0.87	0.83
AC1WB-5	0.65	0.56	0.80	0.81
Average	0.65	0.53	0.87	0.81
CC1WB-1	0.57	0.49	0.87	0.72
CC1WB-2	0.59	0.51	0.90	0.78
Average	0.58	0.50	0.89	0.75
CC1WU-1	0.65	0.50	>1.00	0.70
CC1WU-2	0.67	0.48	>1.00	0.72
Average	0.66	0.49	>1.00	0.71

it was concluded that two mechanisms occured during the polishing of the unbeaded panels: Increases in BPN were associated with smooth, glassy surfaces while decreases were associated with surfaces that had some initial texture which was removed during polishing. When the entire data set was analyzed, it was often possible to show a statistical difference between the BPN values for the yellow and white materials. The texture difference was especially noticeable for the thick hot spray materials. Comparing AC1WU-AC1YU, AW1WU-AQ1YU and CQ1WU-CQ1YB after polishing (Table 2-5) there is little difference in the yellow and white materials. The two thermoplastics, HW1WU-HE1YU, and HS1YB-HS1YU show significant differences after polishing.

The effect of the beads is summarized in Figure 3-4. The leveling affect of the breads is very apparent. The beads improved the BPN values of the chlorinated paints by approximately 15 points and the hot extruded thermoplastics by approximately 17 points.

Changes in texture due to exposure in the weatherometer were not statistically significant. These results are summarized in Figure 3-5.

3.2 ANALYSIS OF FIELD DATA

The field test program provides the data base for accomplishing the objectives of this project. The full-scale skid resistance tests provide locked-wheel skid numbers (SN) which are the most appropriate measures for skid resistance because they can be compared directly with the same measures routinely made on pavements. The field program also provides, for each material tested, sets of data including texture measurements and full-scale locked-wheel skid numbers at 20-40 mph. These data sets provide a basis for the prediction of full-scale skid resistance data (skid numbers) from texture measurements which can be performed on smaller sample applications.

3.2.1 Prediction of Skid Resistance from Texture Measurements

It was anticipated that the skid resistance of all pavement marking materials could be predicted from texture measurements alone, using one set of prediction equations for all types of materials, including paints, thermoplastics, preformed plastics, temperary tape, and two-part systems. The initial analyses, however, showed that the marking materials do not exhibit skid-resistance values that are predictable solely from microtexture and macrotexture data, such as is the case for pavements. Apparently, surface chemistry differences are greater for the various types of marking materials and are an important factor; therefore each type must be treated as a different data set. Although a vast quantity of data was collected in this project, there were only a few cases for which the data set was large enough to permit the derivation of meaningful predictor equations. The data sets for the other types, however, do not exhibit a wide range of performance in skid resistance within any one type of material; consequently, general guidelines for the expected level of performance can be given. Predictor equations, or when these are not possible, guidelines for estimating skid-resistance of materials are given below for each type of material.

Traffic paints. Traffic paints have the smallest film thickness of the marking material applications and therefore reflect, to the greatest extent, the texture of the substrate. In the field, they were applied to all the test surfaces and hence produced the largest data set of any type of material in this study. Fortunately, the data set also produced the most reliable prediction equations for skid variations as a function of macrotexture and microtexture, for all the data regardless of formulation or pavement type. Two prediction equations were necessary, however--one for unbeaded paints and one for beaded paints.

Unbeaded traffic paints. There were 22 applications of unbeaded paints applied to four surfaces at the test track. The skid resistance-speed behavior was measured on April 1979 (Julian day 9134 in Tables 2-12) and the resulting Percent Normalized Gradient (PNG) and Zero Speed Intercept (SN_0) were obtained. An attempt to perform correlation of the form (1-6a) and (1-7b) yielded poor correlations but the resulting equations were in the correct form:

$$SN_0 = 1.33\ BPN-23 \qquad (3\text{-}1)$$

$$r^2 = 0.44 \text{ (22 points)}$$

The value of r2 here and in the subsequent regressions is the correlation coefficient which is a coefficient of determinations which gives the proportion of variation of the dependent variable (in this case SN_0) explainable by linear regression with the independent variable (in this case BPN).

$$RNG = 1.06\ (RMSH_{MA})^{-0.07} \qquad (3\text{-}2)$$

$$r^2 = .02 \text{ (22 points)}$$

where PNG is the percent normalized gradient in h/km and $RMSH_{MA}$ is the root mean square of the macrotexture profile in mm.

In these correlations, the SN_0, PNG, and BPN data were all from April 1979, while the macrotexture data were from November 1978, which explains, in part, the poor correlation obtained in (3-2) above. Macrotexture measurements were not repeated in 1979, but it was not

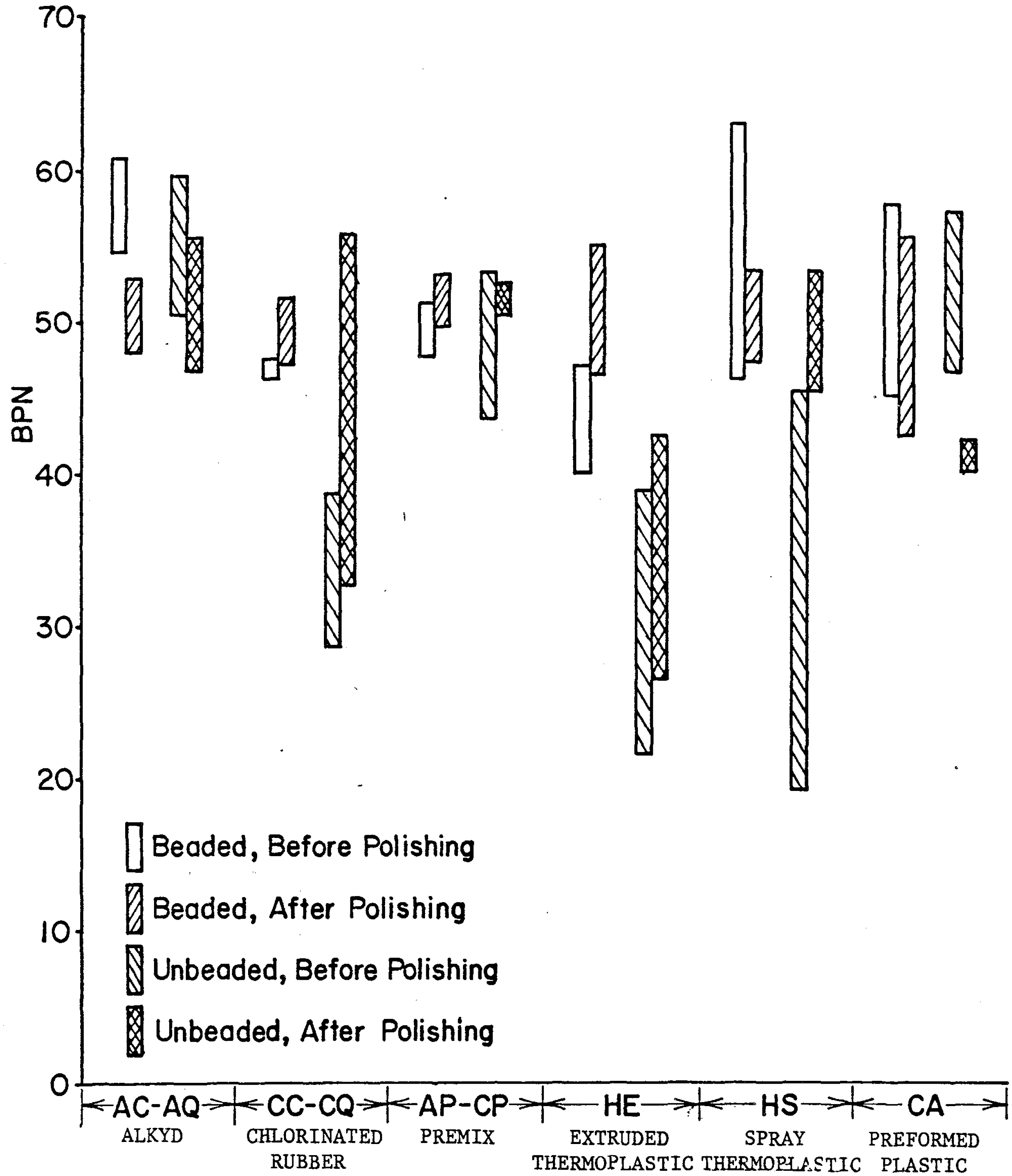


Figure 3-4. BPN Results for Steel Laboratory Panels

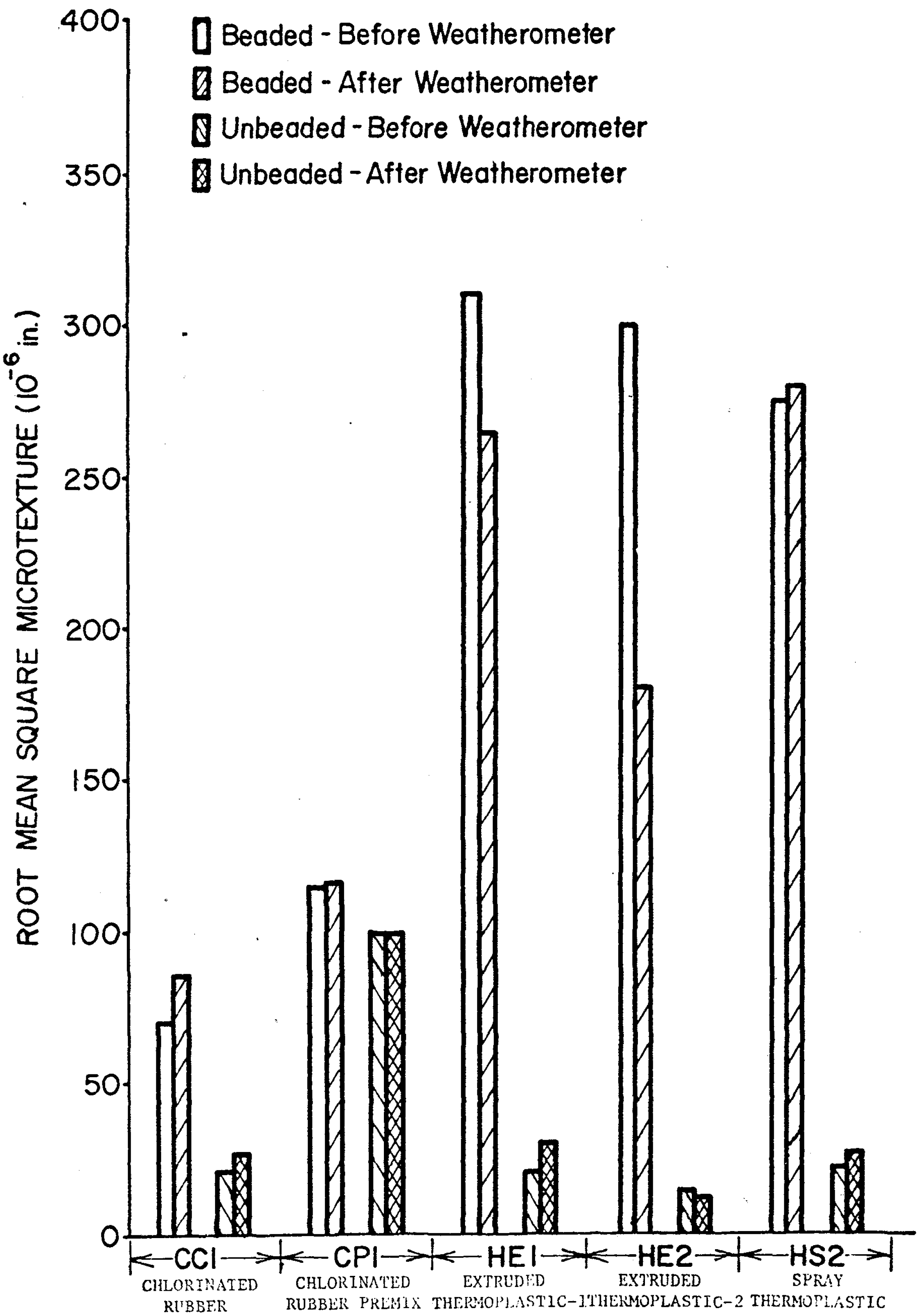


Figure 3-5. Texture for Weatherometer Samples Before and After Exposure

anticipated that the macrotexture would change significantly at the test track in the absence of traffic.

An attempt to use BPN as the sole predictor for SN_{64} was somewhat more successful. In the 1978 data:

$$SN_{64} = .64\ BPN-15.6 \quad (3\text{-}3a)$$

$$r^2 = .44\ (22\ \text{points})$$

and for the 1979 data:

$$SN_{64} = .70\ BPN-16.6 \quad (3\text{-}3b)$$

$$r^2 = .69\ (22\ \text{points})$$

For the combined dates, 1978 and 1979:

$$SN_{64} = .66\ BPN-15.5 \quad (3\text{-}3c)$$

$$r^2 = .73\ (44\ \text{points})$$

Since these data do not account for macrotexture, the data for fine surfaces which exhibited extremely high or low macrotexture in 1978 were eliminated. The data eliminated had values for $RMSH_{MA}$ outside the range $0.1<RMSH_{MA}<1.0$. The results showed improved correlation coefficients. For the 1978 data:

$$SN_{64} = .60\ BPN-13.5 \quad (3\text{-}3d)$$

$$r^2 = .86\ (17\ \text{points})$$

For the 1979 data:

$$SN_{64} = .58\ BPN-10.3 \quad (3\text{-}3e)$$

$$r^2 = .79\ (17\ \text{points})$$

It should be noted that the 1979 data that were eliminated were rejected on the basis of their 1978 macrotexture. For the combined 1978-79 data:

$$SN_{64} = .58\ BPN-11.3 \quad (3\text{-}3f)$$

$$r^2 = .81\ (34\ \text{points})$$

For the 1978 data both BPN and $RMSH_{MA}$ data* were available, and a two-way linear regression was attempted with good results:

$$SN_{64} = .546\ \ BPN + 6.10\ RMSH_{MA} - 12.82 \quad (3\text{-}4)$$

$$r^2 = .92\ (22\ \text{points})$$

*Throughout this chapter the unit of macrotexture root mean square ($RMSH_{MA}$) is in millimeters (mm).

For unbeaded traffic paints, equation (3-4) predicts the skid resistance well for the wide variety of formulations and pavement surfaces included in this study.

The Penn State Drag Tester was proposed as a surrogate for the British Pendulum Tester. The Drag Tester measures low-speed friction and is more convenient to use than the Pendulum Tester. A correlation of Drag Tester Number (DTN) and British Pendulum Number (BPN) yields, for the 1978 data:

$$BPN = .876\ DTN + 30.5 \quad (3\text{-}5)$$

$$r^2 = .68\ (21\ \text{points; one outlier rejected})$$

The Drag Tester also is a fair predictor of skid resistance (SN_{64}). For the 1978 data:

$$SN_{64} = .730\ DTN - 1.0 \quad (3\text{-}6)$$

$$r^2 = .68\ (21\ \text{points})$$

An experiment to test the effect of pigment in the formulation on skid resistance was conducted on a smooth (Jennite) surface with unbeaded paints. Three pairs of white and yellow paints were applied to the Jennite surface. The results are shown in Table 3-3. The skid resistance did not show any consistent dependence on pigment when the paints were freshly applied (1978 data, 8304), but the skid resistance of all the white paints decreased significantly during the winter, while that of the yellow paints stayed about the same. Thus the 1979 data (9134) indicate that the white formulation has lower skid resistance than the yellow.

Beaded traffic paints. There were 41 applications of beaded traffic paint, 17 at the test track and 24 on the public road sites. The effect of the beads is to increase the skid resistance (SN_{64}) by about six skid numbers. For the unbeaded paints the mean SN_{64} was 20.7, with a standard deviation of 8.0 for the 22 applications; while for the beaded paints the mean was 26.7, with a standard deviation of 6.8 for 41 applications. These figures are based on the overall averages. There were 14 applications of pairs of beaded and unbeaded material on the same surface. The data shown in Table 3-4 are the skid-resistance differences between beaded and unbeaded application for 1978 and for 1979, after the exposure to one winter. Initially the beads increased the skid resistance by 9.0, and after exposure to the winter they still maintained a level of 8.0 skid numbers above that of the unbeaded paints. These applications were exposed to weather but not to traffic. A similar experiment on public roads to test the effect of traffic would have been interesting, but was rejected because of the low skid resistance of the unbeaded paints.

Table 3-3

The Effect of Pigment in Formulation
of Traffic Paints on Skid Resistance

	(SN_{64} White)		(SN_{64} Yellow)		(SN_{64} White) - (SN_{64} Yellow)	
PAINT	8304	9734	8304	9134	8304	9134
AC1	12.0	8.5	15.4	16.5	-3.4	-8.0
AQ1	22.5	20.5	23.0	23.0	-0.5	-2.5
CQ1	18.5	16.5	13.2	13.5	+5.3	+3.5
DIFFERENCE OF THE MEANS					-0.47	-2.5

Table 3-4

The Effect of Beads in Traffic Paint on Skid Resistance

		Increase Due To Beads [SN_{64}(Beaded) - SN_{64}(Unbeaded)]	
Paint	Surface Date:	8304	9134
AC1W	Dense Graded Asphalt	5.8	5.0
CC1	Dense Graded Asphalt	10.7	7.3
AQ1	Dense Graded Asphalt	10.1	12
CQ1	Dense Graded Asphalt	13.3	13.5
AP1	Dense Graded Asphalt	4.8	1.6
CP1	Dense Graded Asphalt	6.3	6.0
AC1	Open Graded Asphalt	1.7	5.3
CC1	Open Graded Asphalt	14.5	9.0
AQ1	Open Graded Asphalt	6.1	4.5
CQ1	Open Graded Asphalt	15.2	9.0
AC1	Portland Cement Concrete	7.2	7.0
CC1	Portland Cement Concrete	8.1	8.2
AQ1	Portland Cement Concrete	9.3	9.5
CC1	Portland Cement Concrete	8.1	8.2
AQ1	Portland Cement Concrete	9.3	9.5
CQ1	Portland Cement Concrete	12.8	14.0
	Mean/Standard Deviation	9.0/4.0	8.0/3.5

The beads provide macrotexture to the marking materials and have the effect of evening out differences between the skid resistances of the different materials. A difference in the behavior of chlorinated rubber and alkyd resin-based formulations was noted; when BPN is used to predict SN_{64}, the results differ as follows (based on 1978 data):

Chlorinated Rubber Paints with Beads

$$SN_{64} = .725 \text{ BPN} - 15.4 \qquad (3\text{-}7a)$$
$$r^2 = .61 \text{ (20 points)}$$

Aklyd Resin Paints with Beads

$$SN_{64} = .356 \text{ BPN} + 7.10 \qquad (3\text{-}7b)$$
$$r^2 = .36 \text{ (21 points)}$$

All Paints with Beads

$$SN_{64} = .555 \text{ BPN} - 5.38 \qquad (3.7c)$$
$$r^2 = .50 \text{ (41 points)}$$

When macrotexture ($RMSH_{MA}$) and BPN were used to predict SN_{64}, there was little improvement in the correlation. It may also be noted that there are fewer extreme macrotexture data, again probably due to the effect of the beads.

The results of the two-way regressions were:

Chlorinated Rubber Paints with Beads

$$SN_{64} = .80 \text{ BPN} - 7.67 \text{ RMSH}_{MA} - 17.5 \qquad (3\text{-}8a)$$
$$r^2 = .63 \text{ (20 points)}$$

Alkyd Resin Paints with Beads

$$SN_{64} = .357 \text{ BPN} + .002 \text{ RMSH}_{MA} + 7.02 \qquad (3\text{-}8b)$$
$$r^2 = .36 \text{ (16 points)}$$

The negative coefficient of macrotexture in the chlorinated rubber results, and the very small value in the alkyd resin results, indicate the small role of marcotexture in beaded paints. Therefore the preferred predictor equations for beaded paints would be equations (3-7).

The Penn State Drag Tester data (DTN) do not correlate well with skid resistance (SN_{64}) as they did for the unbeaded paints. The glass beads in the surface do not produce the same results with the Drag Tester as they do with the Pendulum Tester.

Thermoplastics. Hot extruded thermoplastic and hot spray thermoplastic materials were applied both with and without beads. As with the paints it was necessary to treat the beaded and unbeaded applications separately.

Unbeaded thermoplastic. Twelve unbeaded applications were made at the Skid Test Facility on dense graded asphalt. Since the unbeaded materials possess a very low skid resistance, they were not applied to the public road sites. The best correlations of skid resistance with texture were obtained when the hot extruded and hot spray materials were treated separately. The hot spray materials possess an irregular surface which depends strongly on the conditions of application. These irregularities provide macrotexture which results in higher skid resistance for the sprayed material. Both unbeaded extruded and sprayed materials increased the skid resistance by about 3 skid numbers over the winter (in the absence of traffic), and the sprayed material had a skid resistance of about 6 skid numbers higher than that of the extruded material. Due to the small size of the data sets, the resulting correlations are not very reliable, but they can be used as an estimate until a more extensive study of thermoplastic skid resistance can be performed.

For the hot extruded thermoplastic, using BPN to predict skid resistance:

$$SN_{64} = .91 \text{ BPN} - 35.3 \qquad (3\text{-}9)$$
$$r^2 = .48 \text{ (7 points)}$$

Introducing macrotexture improves the correlation only slightly:

$$SN_{64} = .817 \text{ BPN} + 13.3 \text{ RMSH}_{MA} - 33.1 \qquad (3\text{-}10)$$
$$r^2 = .50 \text{ (7 points)}$$

For the hot spray thermoplastic, the best correlation obtained was with macrotexture ($RMSH_{MA}$):

$$SN_{64} = 64.4 \text{ RMSH}_{MA} + 3.9 \qquad (3\text{-}11)$$
$$r^2 = .45 \text{ (5 points)}$$

Beaded thermoplastic. A total of 23 applications of thermoplastic with beads was placed, 9 at the Skid Test Facility on dense graded asphalt, 13 on the dense graded asphalt public road site, and one on the portland cement concrete public road site. The application on the public road site included 6 pairs of material in and out of the wheel track. After five months exposure, including the winter months, the mean skid resistances in the wheel track were slightly higher by 0.72 skid numbers and thus are not significantly different statistically (student's t-test). Had there been a higher traffic volume, the differences might have been greater.

Nine pairs of applications with and without beads were placed at the Skid Test Facility. Table 3-5 shows the effect of beads in thermoplastic marking material.Initially, the

Table 3-5

The Effect of Beads in Thermoplastic on Skid Resistance

	SN_{64} (B) - SN_{64} (U)	
Material	8304	9134
HE1W	6.3	6.7
HE1Y	8.5	7.0
HE2W	6.0	3.0
HE3W	12.7	8.3
HE4W	15.8	8.0
HE4Y	7.8	1.0
HE6W	10.5	8.0
HS1Y	6.8	1.0
HS3W	17.5	9.5
Mean/Standard Deviation	10.2/4.2	5.8/3.3

All data were from applications on the dense graded asphalt surface of the Skid Test Facility.

effect of the beads is greater (about 10 skid numbers); after five months exposure, without traffic, the difference decreases to about 6 skid numbers. This decrease results from some loss of beads due to exposure alone, but also partially results from the fact that the skid resistance of the unbeaded material increases by about 3 skid numbers over the winter.

As noted for the unbeaded material, the beaded hot spray materials produced higher skid resistance than the hot extruded materials, by about 9 skid numbers. This effect also persisted through the winter as evidenced by the fact that the beaded thermoplastic materials were all changed relatively little after the winter, even those which were exposed to traffic. The means and standard deviation are shown in Table 3-6 for beaded and unbeaded extruded and sprayed materials in November 1978 and April 1979. As can be seen from the standard deviations, the data have a considerable degree of variability, and because of the small sample sizes, particularly for the sprayed materials, the conclusion should be used only qualitatively.

The use of British Pendulum Numbers (BPN) to predict the skid resistance (SN_{64}) of hot extruded materials produces the following result for the 1978 data:

$$SN_{64} = .68\ BPN - 15.4 \qquad (3\text{-}12)$$

$$r^2 = 0.50 \text{ (16 data points)}$$

The correlation can be improved by introducing macrotexture data:

$$SN_{64} = 0.623\ BPN + 36.4\ RMSH_{MA} - 18.7 \qquad (3\text{-}13)$$

$$r^2 = 0.66 \text{ (16 data points)}$$

The data set for the hot spray materials was too small to provide meaningful correlation. It has been noted that the hot spray materials have generally higher skid resistance than the hot extruded materials.

Preformed plastics. Eleven preformed plastic (cold applied) applications were placed at the Skid Test Facility, ten different materials on the dense graded asphalt and one repeated on the open graded asphalt pad. The one application on the open graded surface produced skid resistance about one skid number higher than its counterpart on the dense graded surface. This limited experiment tends to support the hypothesis that the pavement surface texture is completely masked by the preformed plastic. Exposure over the winter showed a tendency for the skid resistance of these materials to decrease by about 2.8 skid numbers, but the data variability was such that this decrease is not significant at the 95% confidence level (student's t-test). Three pairs of materials in white and yellow colors were placed, and the results show a skid resistance one skid number higher for the yellow material. Although the data set is small, this difference was found to be significant at the 95% confidence level (student's t-test), but it is not of practical significance.

British Pendulum Tester data (BPN) alone is not able to predict skid resistance; it produces a correlation coefficient of 0.39 (r^2 = .15) for the 1978 data. However, the BPN data combined with macrotexture data ($RMSH_{MA}$) produced a satisfactory model:

$$SN_{64} = .158\ BPN + 58.4\ RMSH_{MA} + 5.95 \qquad (3\text{-}14)$$

$$r^2 = .76 \text{ (11 data points)}$$

The Penn State Drag Tester appears to be the best predictor for these data:

$$SN_{64} = 0.616\ DTN + 0.285 \qquad (3\text{-}15)$$

$$r^2 = .91 \text{ (10 data points)*}$$

The preformed material which produced the highest skid resistance exhibited the highest macrotexture. Under traffic this advantage may disappear as the macrotexture is worn away. However, it was not deemed wise to expose the public to large test applications of this material, and testing was performed only at the Skid Test Facility.

Temporary tapes. Thirteen applications of temporary tapes were made, seven at the Skid Test Facility and six at the dense graded asphalt public road site. Two of the applications at the Skid Test Facility were on the open graded surface, while all eighteen other applications were on dense graded surfaces. The skid resistance of the two applications on the open graded surface was consistently higher than that of their counterparts on the dense graded surface, and this advantage improved with traffic, even the small amount of traffic at the Skid Test Facility. The conformance of the tapes to the coarse texture of the open graded asphalt was noticeable and increased as testing across them proceeded.

Three pairs of tapes were placed in and out of the wheel track on the public road site. After five months of exposure, the application in the wheel track averaged 1.8 skid numbers higher than those out of the wheel track, but, due to the small data size, this difference was not significant at the 95% confidence level (student's t-test). It was also necessary to reject on the same basis a slight decrease (about 1.4 skid numbers) of the mean skid numbers between November 1978 and April 1979.

*Does not include one application which was missed during testing.

Table 3-6

Effect of Winter Exposures on Sprayed and Extruded Thermoplastic

	Mean and Standard Deviation(s) of Skid Numbers				
	1978		1979		
	$\overline{SN}_{64}$	s	$\overline{SN}_{64}$	s	Number of Samples n
Extruded Unbeaded	15.9	9.6	18.7	8.1	7
Sprayed Unbeaded	22.5	10.5	25	10.6	5
Extruded Beaded	21.3	7.3	22.8	4.2	16
Sprayed Beaded	30.3	3.7	31.7	2.8	7

The skid resistance of the tapes on the dense graded surface ranged from 21.5 to 40.6 when new (1978), and from 19 to 35 after five months' exposure. Most of the data was clustered in the mid-20's, and therefore there were no meaningful correlations of skid resistance with texture data. On the dense graded surfaces the mean skid resistance of all tapes when new was 29.6 with a standard deviation of 6.2. In 1979, after five months of exposure, the mean was 28.5 with a standard deviation of 4.7.

Two-part materials. Three of the two-part materials were applied to the field sites, one epoxy and two polyesters. Of these, one (TP3) was applied in a very thick film and, because of rapid setting, produced a hard, coarse textured surface. The other two were applied in relatively thin applications which reflected the pavement texture to a large extent. No further comparisons are possible with this small data set. The results of the skid tests are given in Table 3-7. Since these materials were applied by hand and their performance is highly dependent on the film thickness and application conditions, conclusions about actual performance should not be drawn from these data.

3.2.2 Other Factors Affecting Skid Resistance

The skid-resistance histories of the marking materials at the dense graded public road sites are shown in Figure 3-6. The marking materials can be seen to behave much like the pavement, which exhibits a behavior similar to other pavements currently being studied for seasonal and short-term variations. Rainfall and temperature are thought to be two important factors in causing the short-term variation, while polishing and wear affect the long-term seasonal variations. The winter recovery of skid resistance results from the depolishing effects of winter snow and ice removal activities. During the winter of 1978-79, studded snow tires were illegal in Pennsylvania, so that their effects are not reflected here.

The skid numbers plotted in Figure 3-6 are the averages for each type of material. It is noteworthy that the thin materials continue to have low skid resistance after the winter, when they have visibly deteriorated. It had been anticipated that they would approach the skid resistance of the pavement more rapidly than the thick materials. The chlorinated rubber base paints performed as poorly as the hot extruded thermoplastic and are significantly lower than the other materials tested.

To determine the role of surface contaminants in the seasonal and short-term variations, the British Pendulum Tests were performed on the surfaces without any preparation or "conditioning" as required in the ASTM Method of Test E303 [4]. These values are reported in Appendix B as "prescrubbed". Ordinary BPN numbers are denoted as "scrubbed," meaning that the requirements of the ASTM Method of Test have been met. Eighty-four pairs of BPN data in November 1978 show the mean of the difference between the prescrubbed and scrubbed values to be 0.25 with a standard deviation of 2.14 BPN. The difference is insignificant at the 95% confidence level (student's t-test), and therefore the prescrubbed BPN values are not useful in accounting for short-term variations.

A limited experiment was performed to test the effect of temp-erature on skid resistance of the marking materials. British Pendulum Tests were performed at the Skid Test Facility applications where the surfaces were 18°C and 40°C. The results are shown in Tables 3-7 and 3-8. The unbeaded materials (Table 3-7) show an increase with temperature averaging about 0.25 BPN/°C. The beads (Table 3-8) have an opposite effect, showing a decrease with temperature of about .15 BPN/°C. This result reinforces the earlier finding that the beaded and unbeaded materials should be treated separately.

3.2.3 Slip Resistance

The slip resistance data measured with the NBS-Brungraber Portable Slip Resistance Detector are shown in Table 2-13. Only the data using the composition shoe are considered valid. The leather shoe did not stabilize, but kept increasing in readings until they were out of range of the device regardless of the surface being tested. The data were taken on the public road site in and out of the wheel tracks. There was no significant difference in the data in and out of the wheel tracks; the values in the wheel tracks averaged .012 less than that out of the wheel tracks, with a standard deviation of .044. Therefore the data for both are treated here as a single data set. The means and standard deviation of the slip resistance of the various materials are summarized in Table 3-9. The paints and temporary tapes have similar slip resistance values, or the test does not discriminate between them. The thermoplastics, both extruded and sprayed, exhibit higher slip resistance values.

Table 3-7

Skid Resistance of Two-Part Materials

		SN_{64}	
		1978	1979
TP1WB	Skid Test Facility/Dense Graded	55.5	52.7
	/Open Graded	37.4	34.0
TP2WB	Skid Test Facility/Dense Graded	37.3	38.0
	Public Road/Dense Graded/In Wheel Track	27.5	26.3
	/Out of Wheel Track	27.5	29.0
	Public Road/Portland Cement/In Wheel Track	26.0	31.0
TP3WB	Skid Test Facility/Dense Graded	32.9	41.0
TP3WU	Same without Beads	36.5	41.7

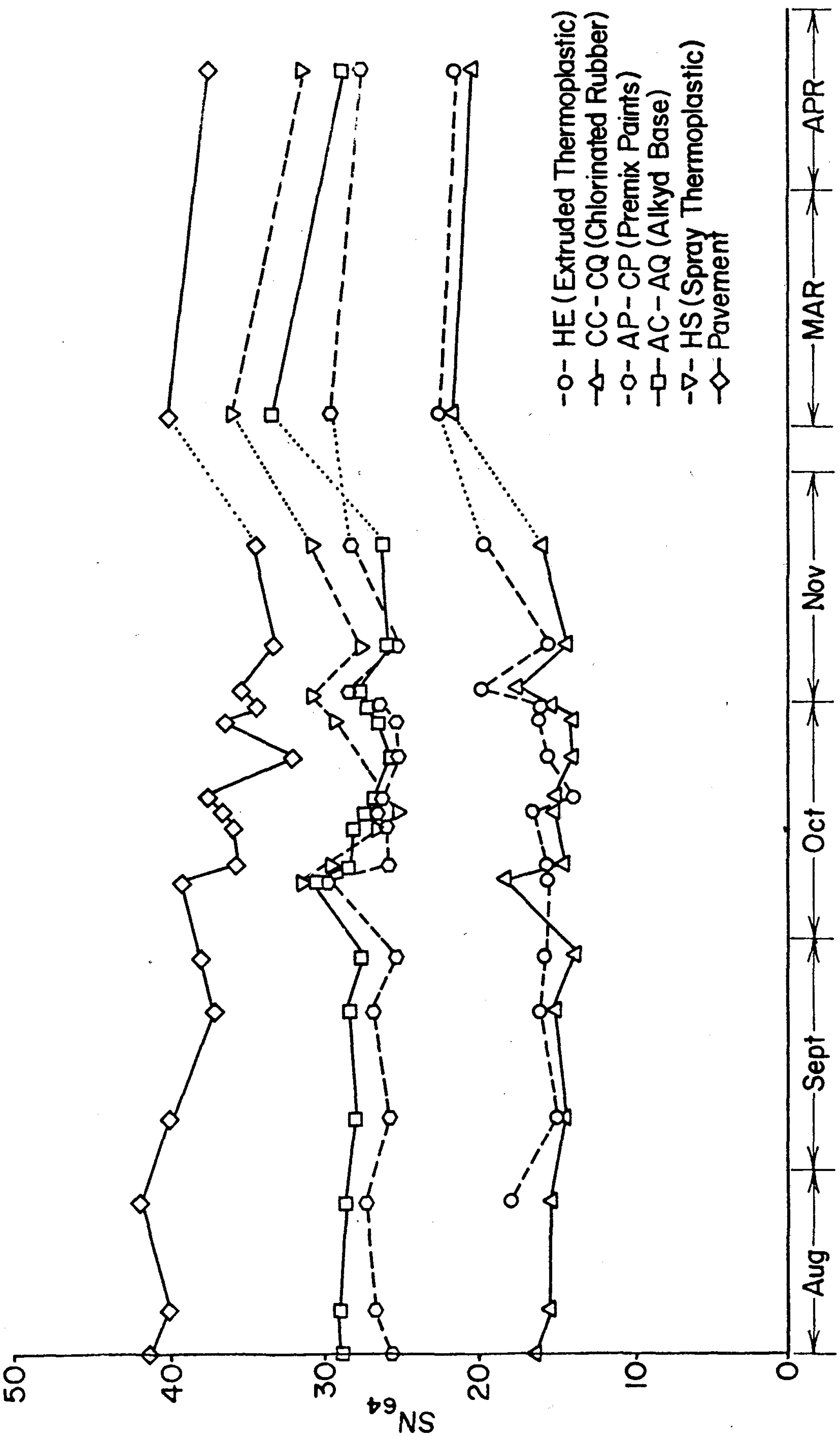


Figure 3-6. Skid Resistance Histories of Marking Materials on Dense Graded Asphalt Public Road Sites

Table 3-8

Effect of Temperature on BPN of Unbeaded Marking Materials

Paint	Average BPN 18°C	Average BPN 40°C	$BPN_{40°}-BPN_{18°}$
	Jennite		
AC1WU (alkyd resin - white)	39	49	+10
AC1YU (alkyd resin - yellow)	46	53	+7
CC1WU (chlorinated rubber - white)	30	36	+6
AQ1WU (alkyd, hot applied - white)	60	65	+5
AQ1YU (alkyd, hot applied - yellow)	56	58	+2
CQ1WU (chlorinated rubber, hot applied - white)	56	55	-1
CQ1YU (chlorinated rubber, hot applied - yellow)	61	63	+2
		Average	4.4
	Portland Cement Concrete		
AC1WU (alkyd resin - white)	39	45	+6
CC1WU (chlorinated rubber - white)	30	36	+6
AQ1WU (alkyd, hot applied - white)	65	70	+5
CQ1WU (chlorinated rubber, hot applied - white)	41	43	+2
		Average	4.7
	Dense Graded Asphalt		
HE1WU (extruded thermoplastic - white)	57	69	+12
HS2WU (spray thermoplastic - white)	44	46	+2
HS4WU (spray thermoplastic - white)	35	38	+3
CA2WU (cold applied white plastic)	52	60	+8
		Average	6.2
		Overall Average	5.0
		Standard Deviation	3.4

Table 3-9

Effect of Temperature on BPN of Beaded Marking Materials

Paint	Average BPN 18°C	Average BPN 40°C	$BPN_{40°}-BPN_{18°}$
	Portland Cement Concrete		
AC1WB (alkyd resin, white)	53	50	-3
CC1WB (chlorinated rubber, white)	46	47	+1
AQ1WB (alkyd, hot applied, white)	54	55	+1
CQ1WB (chlorinated rubber, hot applied, white)	57	53	-4
AP1WB (alkyd premix, white)	56	53	-3
CP1WB (chlorinated rubber, premix, white)	54	50	-4
		Average	-2.0
	Dense Graded Asphalt		
HS2WB (spray thermoplastic, white)	61	56	-5
HS4WB (spray thermoplastic, white)	50	49	-1
TT3WB (temporary tape, white)	53[a]	64[b]	(+11)
TT3WB (temporary tape, white)	61[b]	64[b]	(+3)
		Average (Excluding TT3WB)	-1.0
	Open Graded Asphalt		
CC1WB (chlorinated rubber, white)	65	59	-6
TP1WB (two-part polyester, white)	54	51	-3
		Average	-4.5
		Average (Excluding TT3WB)	-2.2
		Standard Deviation	2.8

a - no beads were present on the surface

b - a few beads were present on the surface

Table 3-10

Brungraber Portable Slip Resistance Data Survey
Public Road Sites

Material	no. tests	Dense Graded Slip No Mean	Dense Graded Slip No s	Portland Cement Slip No Mean	Portland Cement Slip No s
Alkyd Resin Paints	6	.767	.030	.754	.039
Chlorinated Rubber Paints	6	.778	.039	.728	.039
Hot Extruded Thermoplastics	8	.836	.033	-	
Hot Spray Thermoplastics	6	.817	.018	-	
Temporary Tapes	6	.733	.028	-	

4. RECOMMENDED MAXIMUM LEVELS OF DIFFERENTIAL FRICTION

4.1 Discussion of the Problem

The presence of marking materials on pavements tends to create areas of non-uniform tire/pavement friction across the pavement surface. During many vehicle maneuvers, differential friction caused by marking materials can either exacerbate the effects of an emergency maneuver (a locked-wheel skid, for example) or precipitate an emergency during an otherwise normal maneuver (due to the unexpected locking of a wheel, for example). The purpose of this part of the study was to set limits on the tolerable differential friction for the safe operation of cars and motorcycles, and thus to establish procedures for choosing marking materials suitable for roadway delineation. Computer simulations were used to study the behavior of cars and motorcycles under the prescribed conditions.

A common response of car drivers to an emergency is simply to lock the wheels of the car. Locked-wheel skidding maneuvers are relatively easy to analyze, and the skidding behavior of a car on delineated sections of a highway was therefore studied first. A measure of the likelihood of a driver being able to regain control of the vehicle, should he release the brakes at some point during the maneuver, was used to determine whether a particular marking material/pavement configuration was acceptable.

Non-skidding maneuvers, or those where independent locking of one or more of the wheels of the vehicle occurs, usually involve complex interaction between the driver and the vehicle. In these cases a simple analytic examination of the vehicle motion is not possible, because realistic models of driver behavior have not been formulated. This problem in the study of car performance was avoided by assuming that locked-wheel skidding gives worst case behavior, while still being a common and, in a restricted sense, a stable maneuver.

Two maneuvers (see Figure 4-1) were chosen as general cases of four-wheeled vehicle trajectories and roadway delineation likely to be met in practice:

(1) The vehicle slides obliquely across a 150-mm-wide stripe. Simulation results showed that, for all combinations of pavement and marking material friction, this configuration does not provide a significant hazard.

(2) The vehicle skids, with the wheels on one side sliding onto a solid block of marking material, and the wheels on the other side sliding on bare pavement. In this case, certain combinations of length of marked area, pavement friction, and marking material friction were found to create a definite hazard. Boundaries of safe operation are given in a design chart presented in section 4.2.4. The chart was constructed from the simulation results and illustrates the boundaries of safe operation for a specified set of conditions. Additional charts may be constructed for other conditions by the highway engineer.

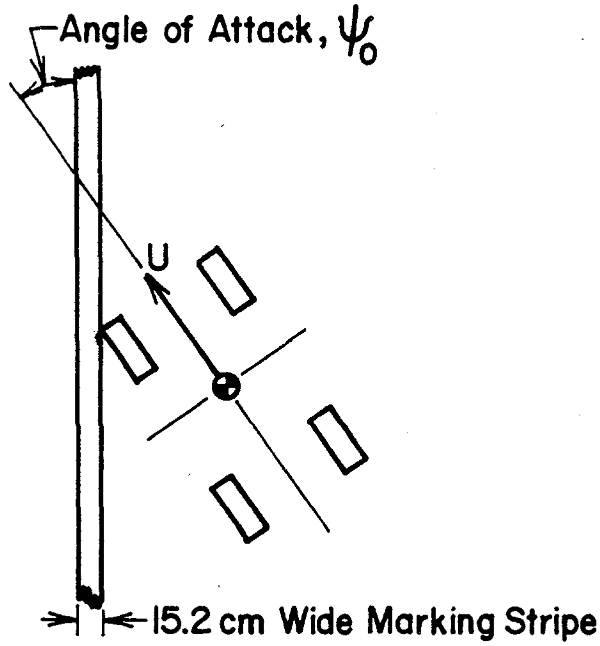
In the motorcycle study, simple locked-wheel skidding could not be used as the base maneuver because, as will be shown later, locking either or both of the wheels of a motorcycle causes rapid instability which is very difficult to correct, even if the brakes are released quickly. A steering controller (which should not be considered a "driver model") was therefore used in the motorcycle simulation study so that some assessment of system stability could be made. The general conclusion of the motorcycle study is that a rational procedure for choosing marking materials for motorcycle operation can best be obtained from a human factors study which would determine the excess available friction usually allowed by riders in braking and cornering maneuvers.

In this chapter the parameter describing the ability of a surface to provide frictional forces is referred to as "coefficient of friction" rather than "skid number". This nomenclature emphasizes the fact that the results are given in terms of the vehicle tire/pavement properties and not in terms of pavement properties as described by an SN_{40} measurement. Skid numbers are used for ranking assumed uniform sections of pavement in terms of their "skid resistance", and are not intended to describe the true coefficient of friction experienced by a typical highway vehicle. In contrast, the present work aims at assessing the relative hazard associated with different levels of suddenly changing friction on a pavement surface. Estimates of the true coefficients of the pavement and marking material surfaces are therefore required.

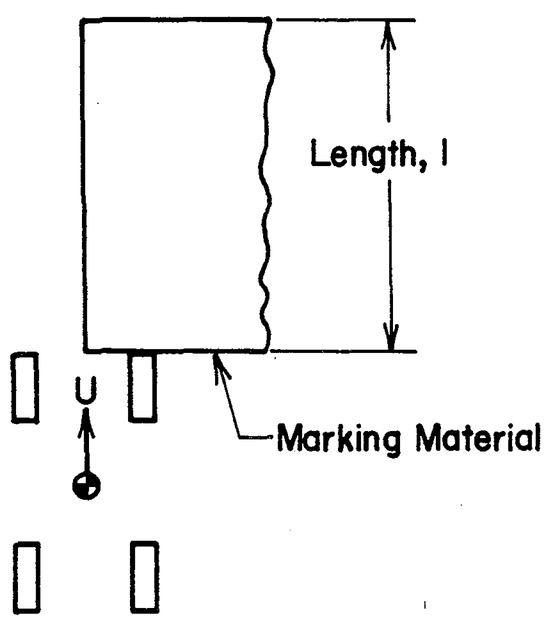
4.2 CARS IN SKIDDING MANEUVERS

4.2.1 Vehicle Response During a Skidding Maneuver

In a pure skidding maneuver the presence of marking material on the pavement causes, in general, yawing of the vehicle and an increase in stopping distance dependent on the change in effective total friction. If the vehicle is maintained in a skid (i.e., the wheels are kept locked), the trajectory of the center of



Maneuver (1) - Vehicle Sliding With Locked Wheels
Across a 6-in Wide Marking Stripe



Maneuver (2) - Vehicle Sliding With Locked Wheels Across a
Solid Block of Marking Material

Figure 4-1. Maneuvers Used in the Four-Wheel Vehicle Simulation Study. In Both Cases, Yaw Rate and Lateral Velocity are Initially Zero. Steer Angle is Zero Throughout Both Maneuvers.

gravity is very close to a straight line; the only difference in vehicle responses on pavement surfaces with and without differential friction is the increased stopping distance and vehicle yaw. In this case, the procedures presently used for acceptable skid-resistance determination can be applied by estimating the "effective" coefficient of friction and by allowing for the increased hazard of an increase in effective vehicle width as the vehicle rotates. The effective friction and rotational hazard would have to be determined for each individual site, which would make a general design procedure for marking materials very difficult to formulate. However, the full skidding maneuver is a special case of the general maneuver in which a driver locks the wheels, skids for some distance, and then releases the brakes. If the coefficient of friction is uniform over the pavement surface, the vehicle will not rotate during the skid and the driver can reapply the brakes while maintaining steering control. If the friction is non-uniform, the vehicle will rotate during the skid and, upon release of the brakes, will travel in a direction different from the original. If the yaw angle is large enough, the driver may not have steering control.

4.2.2 Simulation Model

The effect of differential friction on safe car operation was studied by means of a digital computer simulation in which the vehicle was given an initial velocity, direction, and position relative to the marked-out portion of the pavement. By an extension of the argument given in the previous section, the particular pavement configuration was considered to be unsafe if:

(a) At some point during the skid the heading of the vehicle changed by more than 20 degrees from its original direction, or

(b) at some point during the skid the product of drift angle and forward velocity exceeded a value of 3.66 m/s.

The first condition expresses the fact that the driver has no steering control over the vehicle at large yaw angles and that the vehicle will mot continue to travel in the original direction when the brakes are released. The second condition expresses the fact that, subsequent to releasing the brakes, the vehicle is likely to travel off the highway before the driver has an opportunity to take control and change the vehicle heading.

The simulation model has three degrees of freedom: forward velocity (U), lateral velocity (V), and yaw velocity (r). Figure 4-2 shows the variables and the general layout of the model. The vehicle model has four wheels; the tire forces at each wheel are found by using a comprehensive tire model [1] which calculates the forces under all conditions of lateral and longitudinal slip.

The coefficient of friction in the contact patch is required by the tire model. If the tire is wholly on the pavement or wholly on the marking material, then the coefficient of friction is taken as the value for the appropriate surface. If the tire contact patch covers portions of both surfaces, then the coefficient of friction is given by the average of the friction of the two surfaces in direct proportion to the surface areas. This may be expressed as:

$$\mu_E = \frac{(\mu_P A_P + \mu_M A_M)}{A_T} \tag{4-1}$$

where: μ_E = effective coefficient of friction

μ_P = pavement coefficient of friction

μ_M = marking material coefficient of friction

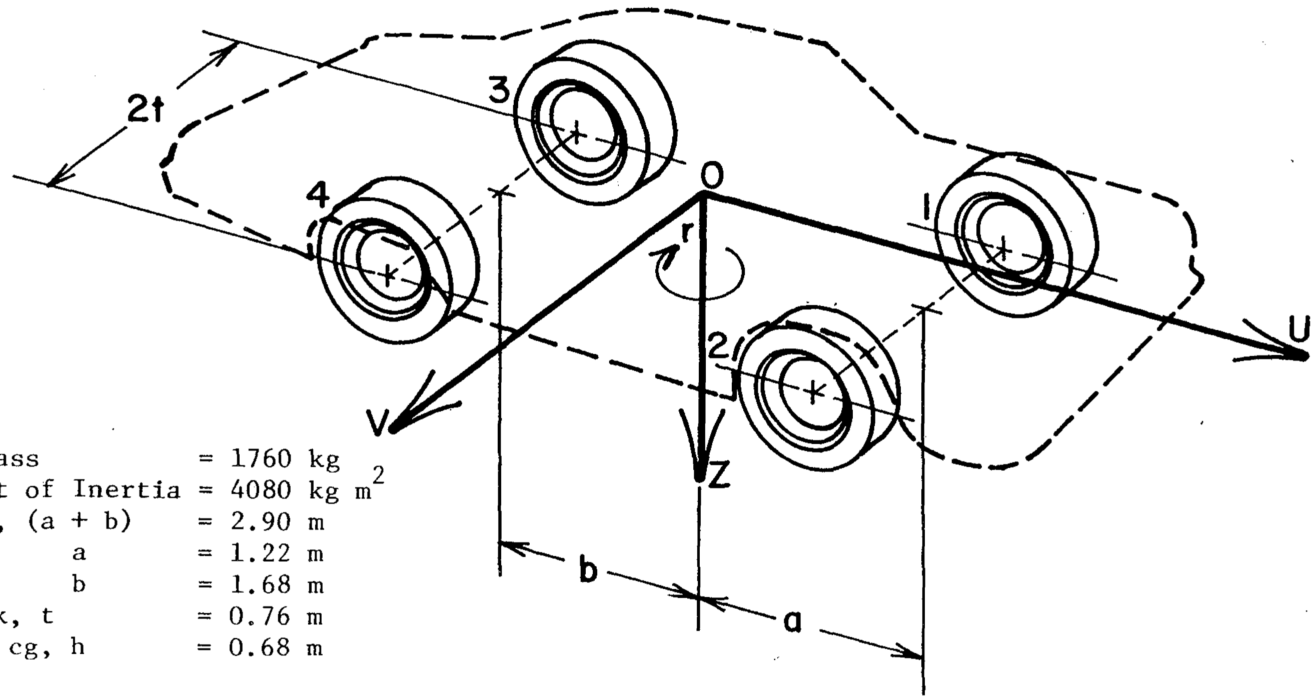
A_T = total area of the contact patch

A_P = area of the tire in contact with the pavement

A_M = area of the tire in contact with the marking material.

A regular contact patch was assumed, with dimensions taken from an ink-print of an ASTM E 524 [19], tire contact patch. The coefficient of friction was assumed to be constant with respect to load and velocity.

In order to check the accuracy of the determination of the coefficient of friction for locked-wheel sliding, a series of tests was conducted with the Penn State Mark III road friction tester. Strips of 0.3 m wide cold applied plastic with glass beads were placed on site 8 (open-graded asphalt) of the PTI Skid Test Facility at angles of 22.5, 45, 67.5, and 90 degrees to the direction of travel. An ASTM E 524 [19] blank test tire was skidded over the surfaces at 16 and 32 km/h, and the results were compared with those of the tire model. Figures 4-3 through 4-6 show the results for a test speed of 16 km/h; it can be seen that there is reasonable correlation for all angles except 22.5 degrees. The probable reason for the discrepancy is that the pressure in the contact patch of the tire model is implicitly assumed to be constant, whereas the pressure in the contact patch of the ASTM tire is reduced at the edges. This effect becomes more evident as the angle of attack decreases, because the rate of increase of tire area in contact with the marking stripe also decreases. Also, it was difficult to determine the tire force accurately as the tire encountered and left the



Vehicle Mass	= 1760 kg
Yaw Moment of Inertia	= 4080 kg m^2
Wheelbase, (a + b)	= 2.90 m
a	= 1.22 m
b	= 1.68 m
Half-Track, t	= 0.76 m
Height of cg, h	= 0.68 m

Figure 4-2. Vehicle Axis System and Vehicle Parameters

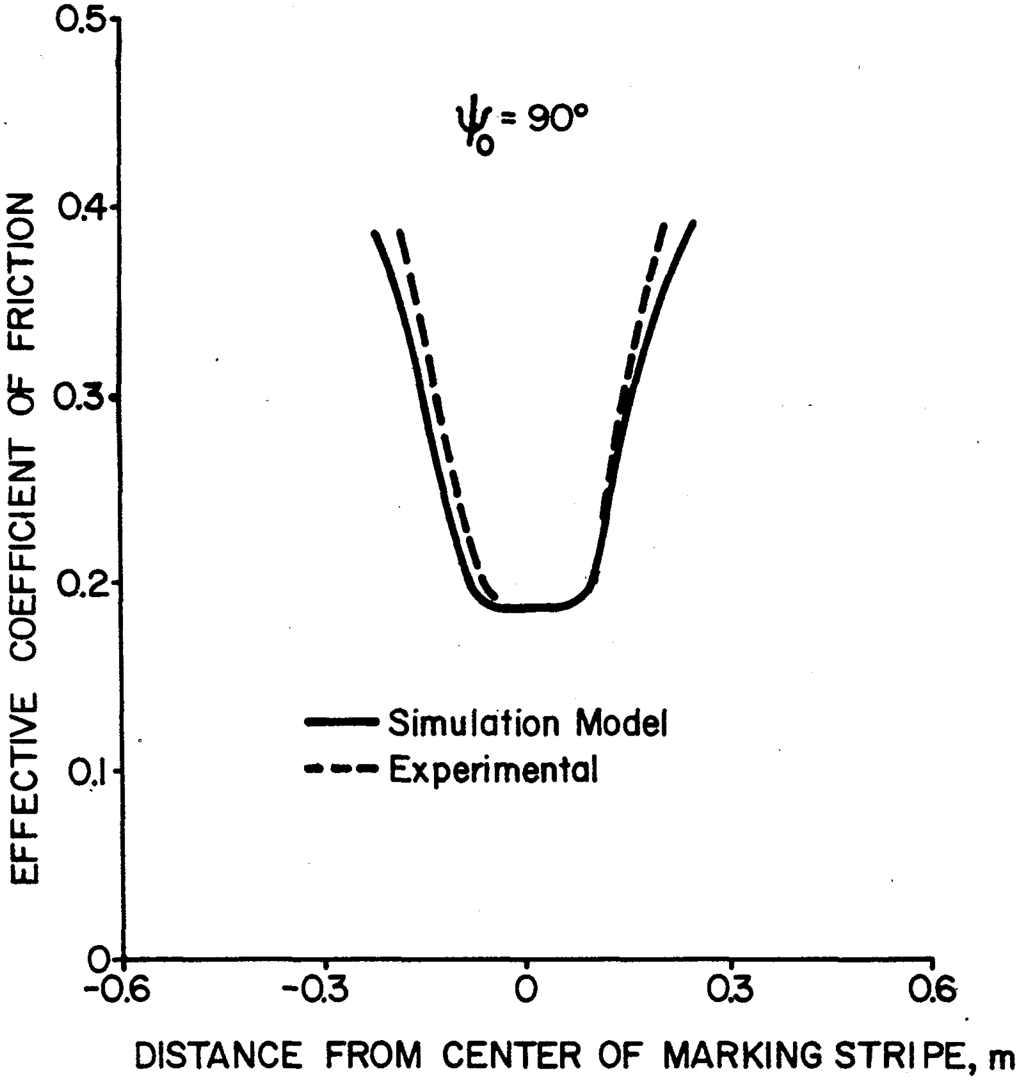


Figure 4-3. Effective Coefficient of Friction of an ASTM E524 Tire as it Slides Over a 0.3-m Wide Marking Stripe at an Angle of Attack ψ_0. Sliding Speed = 16 km/h.

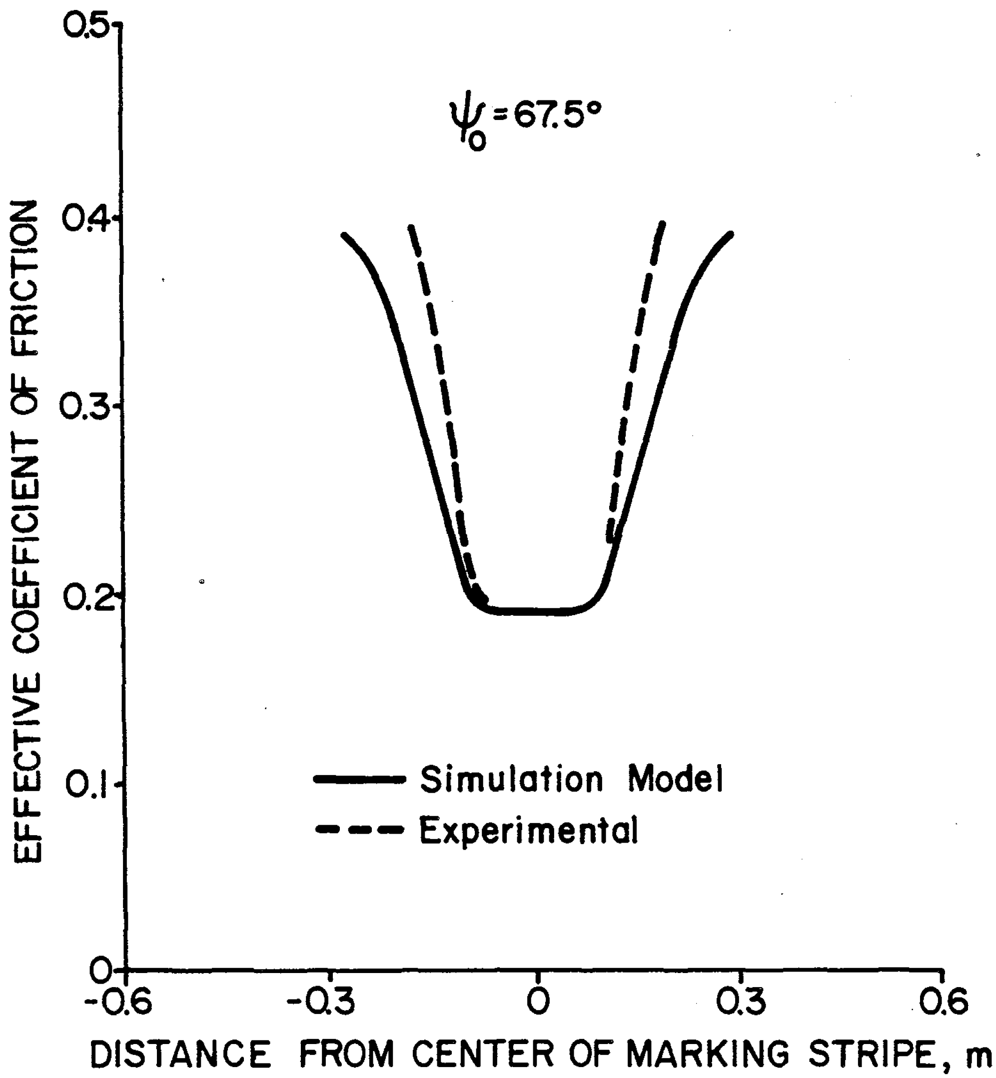


Figure 4-4. Effective Coefficient of Friction of an ASTM E524 Tire as it Slides Over a 0.3-m Wide Marking Stripe at an Angle of Attack ψ_0. Sliding Speed = 16 km/h.

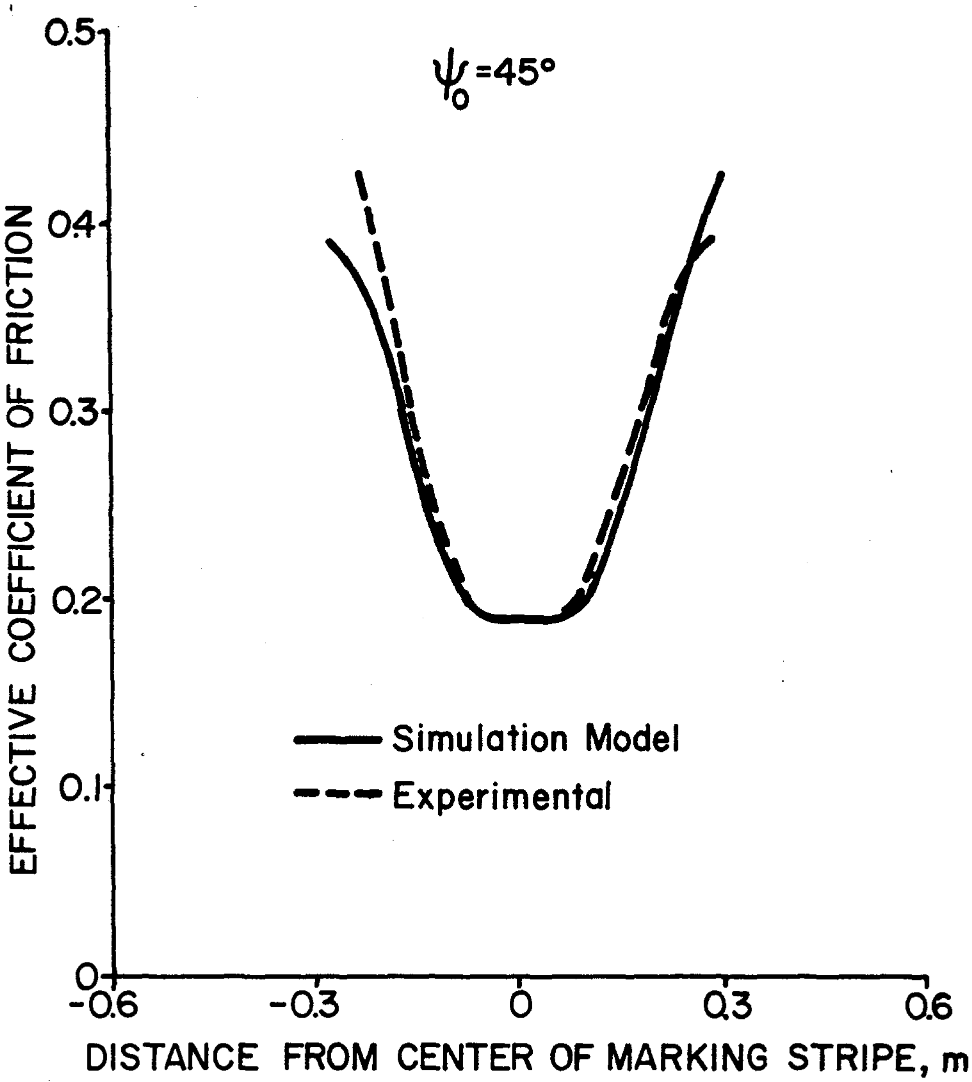


Figure 4-5. Effective Coefficient of Friction of an ASTM E524 Tire as it Slides Over a 0.3-m Wide Marking Stripe at an Angle of Attack ψ_0. Sliding Speed = 16 km/h.

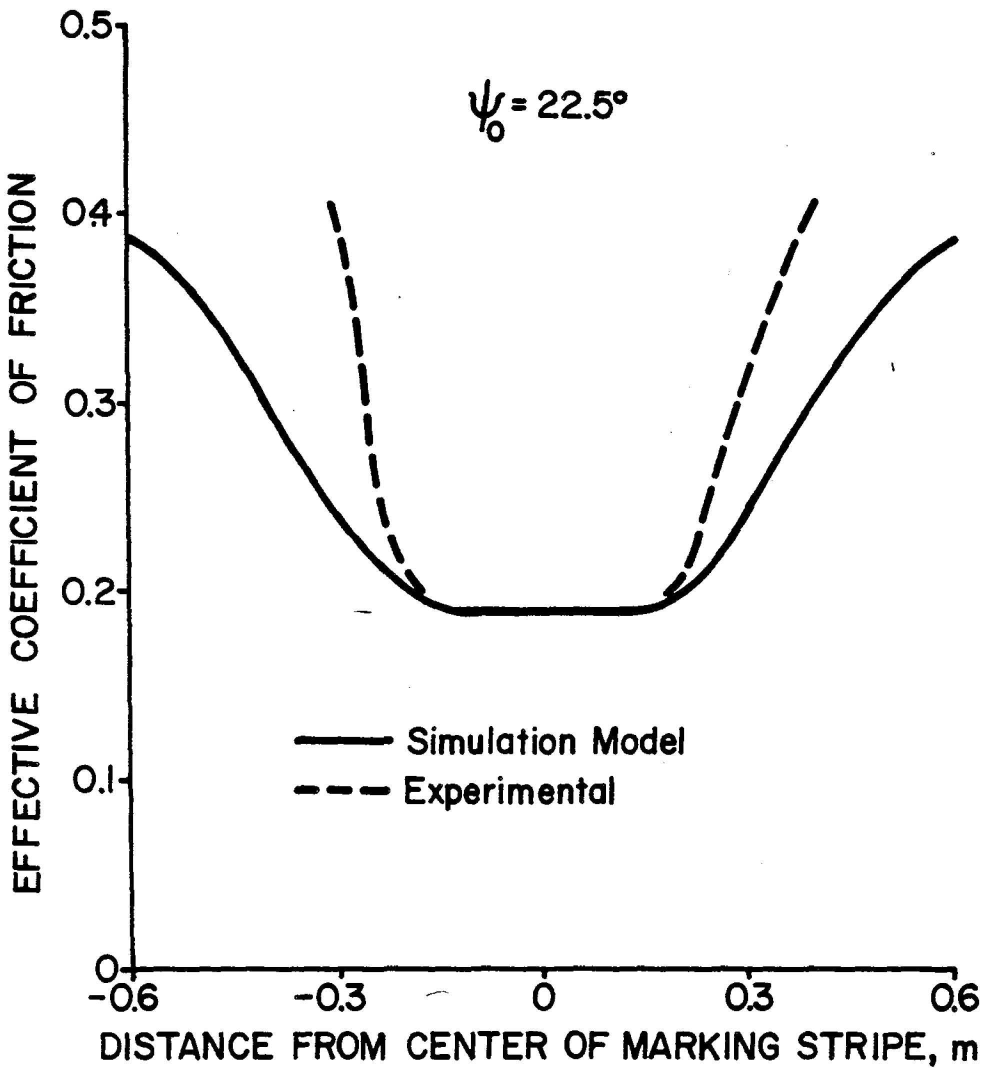


Figure 4-6. Effective Coefficient of Friction of an ASTM E524 Tire as it Slides Over a 0.3-m Wide Marking Stripe at an Angle of Attack ψ_0. Sliding Speed = 16 km/h.

of oscillations excited in the test trailer by the change in skid resistance. However, since the model gives slightly lower average friction than the experimental results indicate, conservative simulation results will be obtained. The model was therefore considered suitable for use without modification.

4.2.3 Determination of Criteria for Safe Operation

Vehicle control is, in general, a process in which the driver turns the steering wheel to modify the lateral forces generated at the front tires of the vehicle. Whether the front tire forces can be changed by small steering motions is therefore of fundamental importance to efficient control, and, by extension, so is the shape of the lateral tire force characteristic. Figure 4-7 shows plots of lateral tire force against slip angle for a free rolling and a locked wheel at coefficients of friction of 0.8 and 0.3. (Slip angle is the angle between the diametral plane of the wheel and the resultant velocity vector [in the horizontal plane] of the wheel axle.) The plots were taken from results of the tire model with the coefficient of friction constant with speed. But, since coefficient of friction generally decreases with increasing speed, experimental free-rolling lateral tire force characteristic curves typically show a peak in lateral force at a slip angle between 10 and 20 degrees. This somewhat unrealistic aspect of the plots does not influence the following discussion; the important characteristic is that, for a free-rolling tire, the slope of the curves at large slip angles (greater than about 5 degrees) is small compared to the slope at small slip angles.

Consider a vehicle sliding with locked wheels on a surface with uniform coefficient of friction at a given drift angle (β), yaw rate (r), and sliding velocity (V_r), as shown in Figure 4-8. Under these conditions the vehicle will rotate about its center of gravity and travel in the direction of the V_r vector at decreasing rates until it stops.

At small drift angles, lateral velocity at the cg of the vehicle (V) will be of the same order of magnitude as the lateral velocity at the front and rear tires (a.r and b.r in the tire slip angle expressions given in Figure 4-8). Locked-wheel side force will also be very small. If the brakes are now released, the tire side forces will rapidly attain the values given by the free-rolling curve, and the front tire force will be smaller than the rear tire force. This creates a negative yaw moment about the center of gravity which decreases the yaw rate and stabilizes the vehicle motion at some final heading angle (to the original direction of V_r). When the front tire force is on the part of the tire curve having high slope (small α_f) it is clear that vehicle yaw rate will always go to zero when there is no control action by the driver, and that the front tire force can easily be changed by the driver if he turns the steering wheel.

At large drift angles, lateral velocity (V) will be the dominant term in the slip angle expressions except when yaw rate is unreasonably large. Upon release of the brakes, the magnitude of the lateral tire forces at the front and rear will be determined almost wholly by the drift angle and will therefore give approximately equal and opposite yaw moments about the center of gravity while both front and rear tires are operating at large slip angles. Modification of the slip angles by the yaw-rate terms will have little effect because of the small slope at large slip angles. The result is that the vehicle will maintain an approximately constant yaw rate while moving laterally under the influence of the large lateral tire forces.

Figures 4-9, 4-10, and 4-11 show yaw rate, drift angle and heading angle responses for maneuver (2) on marking material lengths of 3, 12.2, and 24.4 m, with the brakes released 1-1/2 seconds after the start of the maneuver. The pavement coefficient of friction (μ_p) is 0.6, and the marking material coefficient of friction (μ_m) is 0.2. (Drift angle is defined as the angle between the longitudinal vehicle axis and the resultant velocity vector at the cg; heading angle is the angle through which the vehicle rotates from the start of the maneuver (t = 0) to time t. The different scales on the vertical axes of the three plots should be noted.)

In Figure 4-9, yaw velocity, drift angle, and heading angle increase while the vehicle is sliding on the split coefficient surface. Yaw rate then decreases when the vehicle is sliding on the uniform coefficient surface, while drift and heading angle continue to increase. When the brakes are released and the wheels allowed to turn freely, drift angle is 5-1/2 degrees; this is a small value which causes the yaw rate and drift angle to decrease rapidly to zero through the mechanism described previously. The heading angle goes to a constant value, and the final vehicle trajectory is a straight-line motion at the steady-state headin angle. Full steering control is available to the driver as soon as the brakes are released.

In Figure 4-10, the vehicle motion follows the same pattern as Figure 4-9 until brake release, except that the three variables reach larger values because of the increased length of time on the split coefficient surface. Upon brake release, the drift angle has a value of 20 degrees and the yaw rate decreases much more slowly than in Figure 4-9. The yaw rate does not begin to decrease at a significant rate until the drift angle has become less than 10

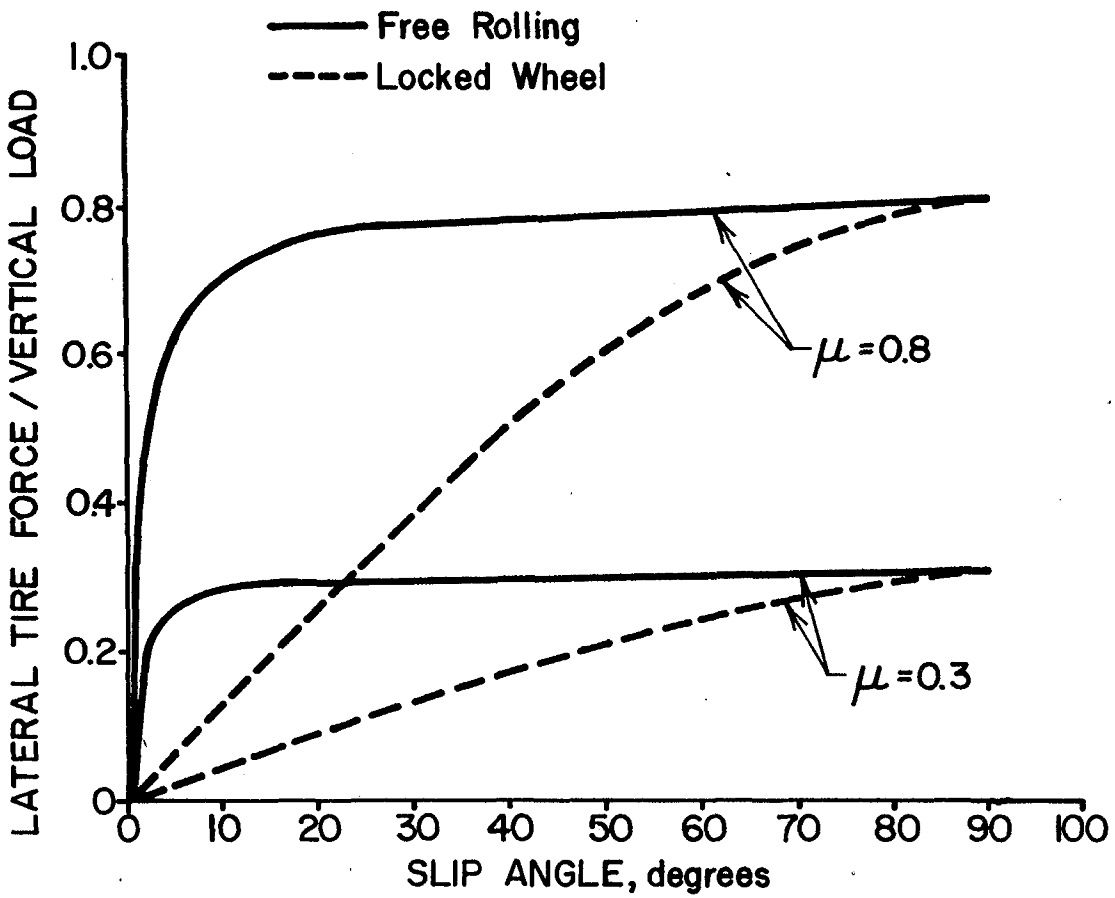
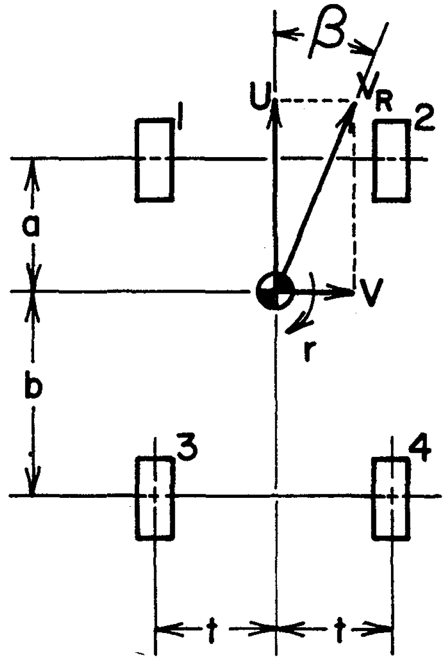


Figure 4-7. Simulation Tire Model Results for Free Rolling and Locked Wheel Sliding



U = Forward Velocity

V = Lateral Velocity

V_r = Resultant Velocity = $\sqrt{U^2 + V^2}$

β = Drift Angle = Arctan (V/U)

r = Yaw Rate = Angular Velocity about a Vertical Axis Through the cg

Tire Slip Angles (α):

$$\alpha_1 = \text{Arctan}\left(\frac{V + a.r}{U + t.r}\right)$$

$$\alpha_2 = \text{Arctan}\left(\frac{V + a.r}{U - t.r}\right)$$

$$\alpha_3 = \text{Arctan}\left(\frac{V - b.r}{U + t.r}\right)$$

$$\alpha_4 = \text{Arctan}\left(\frac{V - b.r}{U - t.r}\right)$$

Figure 4-8. Variables Defining the Kinematics of Four-Wheeled Vehicle Motion

a = Locked wheel sliding on a split coefficient surface (pavement and marking material).

b = Locked wheel sliding on a uniform coefficient surface (pavement only).

c = Free rolling wheels on a uniform coefficient surface (pavement only). Brake release is at 1.5 sec.

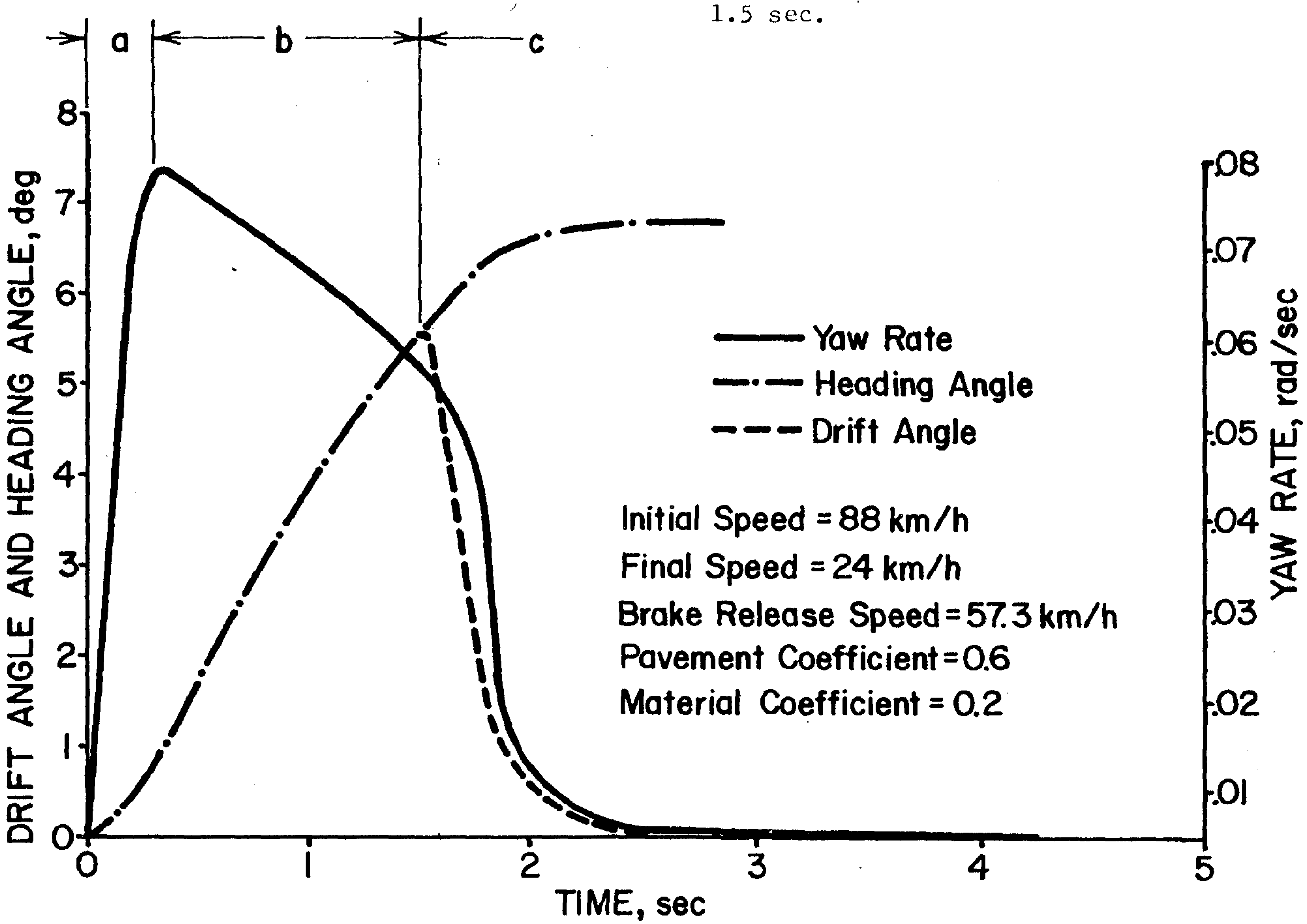


Figure 4-9. Yaw Rate, Heading Angle, and Drift Angle Response of a Four-Wheeled Vehicle when the Brakes are Released During a Skidding Maneuver Across a 3-m Long Split Coefficient Surface

a = Locked wheel sliding on a split coefficient surface (pavement and marking material).

b = Locked wheel sliding on a uniform coefficient surface (pavement only).

c = Free rolling wheels on a uniform coefficient surface (pavement only). Brake release is at 1.5 sec.

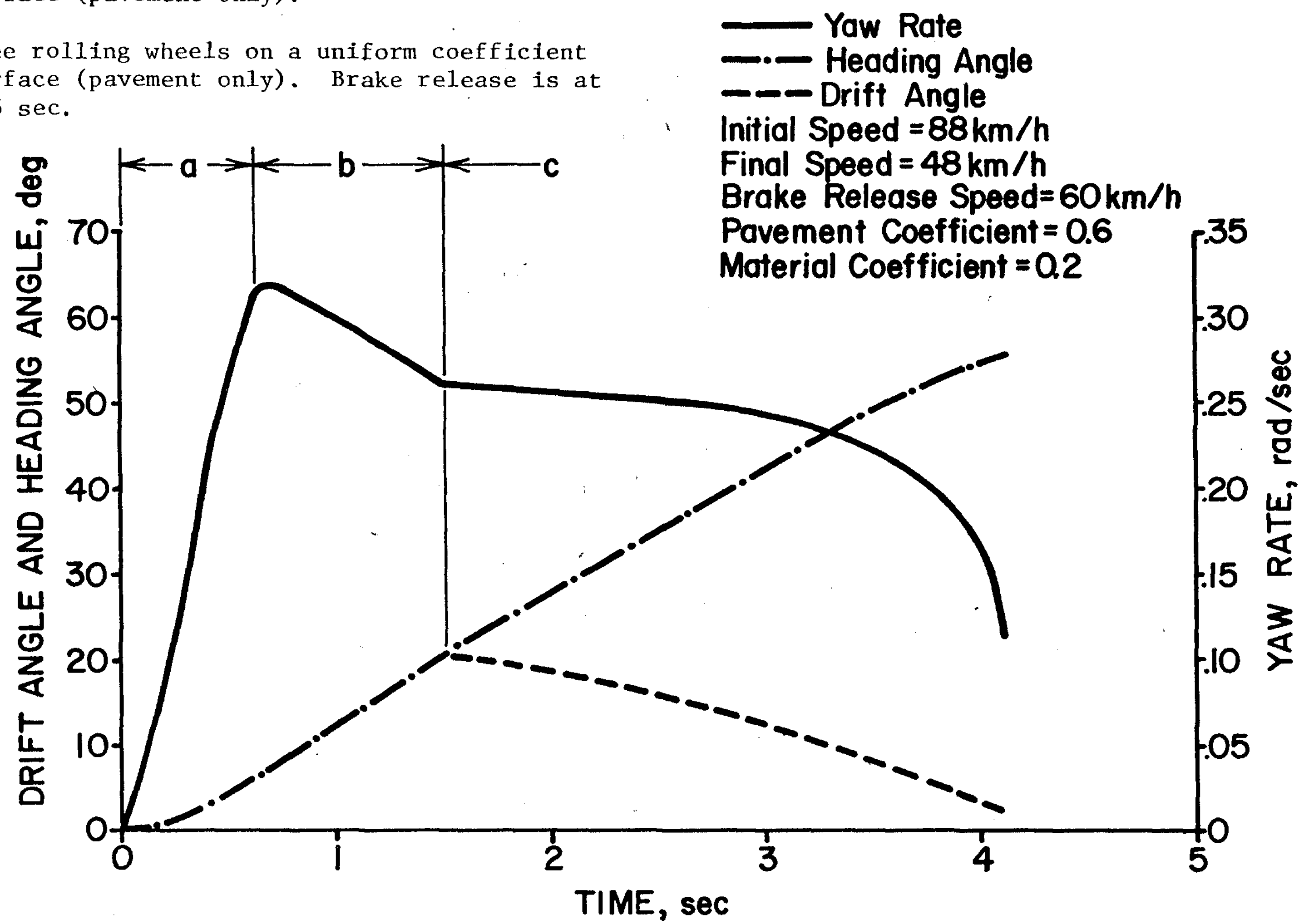


Figure 4-10. Yaw Rate, Heading Angle, and Drift Angle Response of a Four-Wheeled Vehicle when the Brakes are Released During a Skidding Maneuver Across a 12-m Long Section of Split Coefficient Surface

degrees two seconds after brake release. If the driver is to gain sufficient steering control to stabilize the vehicle, he must reduce the front-wheel slip angle to less than 5 degrees. For a drift angle of 20 degrees he must therefore turn the steering wheel through at least 300 degrees (assuming a steering gear ratio of 20:1). The upper limit of steering wheel rotation rate for a typical driver is approximately 400 degrees/sec [2]. Thus, if driver response time is ignored, about one second will pass after brake release before the driver can begin to significantly influence the behavior of the vehicle. This analysis also assumes that the driver makes the correct response.

In Figure 4-11, drift angle is 33 degrees upon brake release, and the vehicle continues to spin at a constant yaw rate through the remainder of the maneuver. The drift angle also continues to increase in this case, because the increase in lateral velocity due to vehicle rotation exceeds the decrease due to lateral acceleration. It is clear that the vehicle motion is completely unstable and that the driver cannot influence vehicle behavior during either the locked-wheel or the freely rolling wheel phases by turning the steering wheel.

Figure 4-12 shows the lateral deviation of the vehicle perpendicular to the initial heading. Lateral deviation in the last two cases (l = 12 m and l = 24 m) is in excess of 3 m 1-3/4 seconds after brake release. However, driver control action may be expected to reduce this for l = 12 m, since the drift angle is at all times less than 20 degrees.

From these results, and from the general description already given of vehicle response in skidding maneuvers, it is clear that releasing the brakes is the most hazardous response that a driver can make in a skidding maneuver where all four wheels are locked and the vehicle is sidesliping at a large drift angle. Once the brakes are released, the ability of the driver to regain control before colliding with another vehicle or with a roadside obstacle depends in the first case on the drift angle of the vehicle. Consequently, a roadway delineation scheme was considered to be unsafe if, at any point during either of the simulated locked-wheel skidding maneuvers, the vehicle drift angle exceeded a value of 20 degrees. Twenty degrees was chosen partly because it represented the transition between a decrease or an increase in the drift angle after brake release in the maneuvers used to produce the results shown in Figures 4-9 through 4-11. A further reason was that 20 degrees is an upper limit on the angle through which a driver can reasonably be expected to turn the road wheels of a car in one second. A delay longer than this will probably result in the vehicle passing into a potential collision zone before the driver can regain full control.

The 20-degree drift angle limit is independent of speed, but experience suggests that vehicle control becomes more difficult as speed increases. A full explanation of this effect cannot be given, although important to the present work is the fact that a vehicle travelling at a non-zero heading angle will travel sideways, relative to the center line of the road, at a rate in direct proportion to forward speed times the sine of the heading angle ($U. \sin \psi$), as demonstrated in Figure 4-13. The parameter $U. \sin \psi$ is given in terms of steady-state forward speed and heading angle with free-rolling wheels, but the desired parameter should be expressed in terms of vehicle variable values measured during a locked-wheel skid. The substitution of drift angle (β) for heading angle is later shown to be a reasonable transformation. Also, if $U. \sin \beta$ is taken as a limiting factor in vehicle response, it will be the deciding factor only when drift angle is less than 20 degrees. The expression may therefore be simplified to $U.\beta$ with little change in the numberical values.

An upper limit of 3.66 m/s was placed on $U.\beta$; if this value was exceeded during a simulated maneuver, the delineation scheme was considered hazardous. (U has the units 'm/s' and β 'radians'.) The choice of $U.\beta = 3.66$ assumes: (1) that the vehicle must travel 3.66 m laterally to enter a potential collision zone, (2) that the yaw rate reduces instantaneously to zero and the vehicle travels in the direction of its heading at brake release, and (3) that the driver is allowed one second to regain control and steer the vehicle to a safe path. The third assumption is the most difficult to justify, since both driver response time and time to regain control must be taken into account. For example, if the driver makes no steering correction at all, he will exceed the 3.66-m allowed lateral displacement in one second. But if he begins steering action at, say, 1/2 second after brake release, the heading angle will decrease during the remaining time, thus effectively allowing more time to steer the vehicle to a safe path within the 3.66-m lateral displacement limit.

The allowance of just one second for the driver to respond and control the vehicle would probably be too short if yaw rate did indeed reduce to zero instantaneously. But Figures 4-9 through 4-11 show that this assumption becomes less true as the drift angle at brake release increases. Figure 4-12 shows the effect on lateral displacement. For example, when l = 3 m, $U.\beta = 1.55$ m at brake release and lateral displacement one second later is 1.43 m. Laterial displacement one second after brake release is therefore slightly over-predicted by $U.\beta$. In contrast, $U.\beta$ over-predicts lateral

a = Locked wheel sliding on a split coefficient surface (pavement and marking material).

b = Locked wheel sliding on a uniform coefficient surface (pavement only).

c = Free rolling wheels on a uniform coefficient surface (pavement only). Brake release is at 1.5 sec.

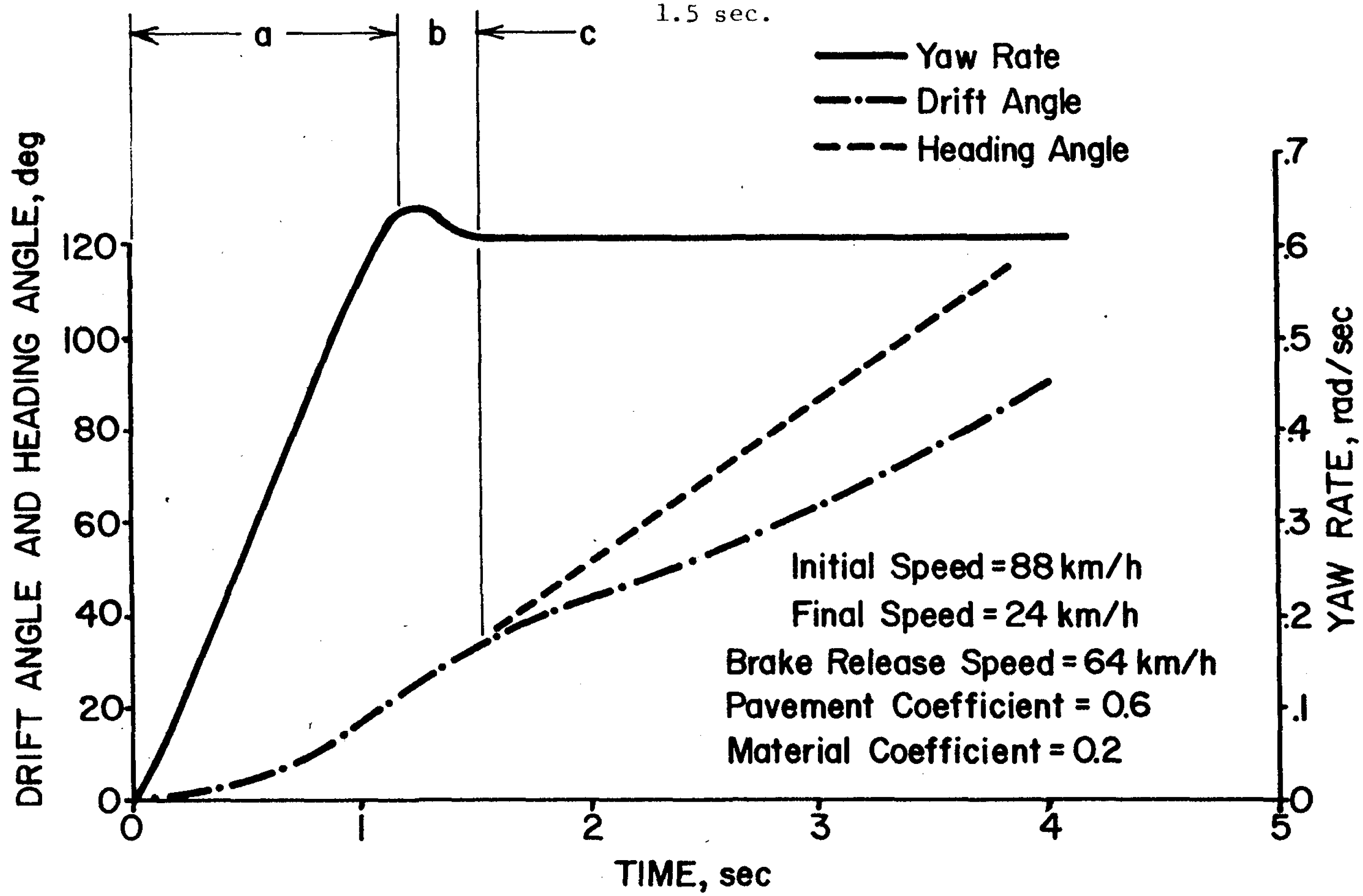


Figure 4-11. Yaw Rate, Heading Angle, and Drift Angle Response of a Four-Wheeled Vehicle when the Brakes are Released During a Skidding Maneuver Across a 24-m Long Section of Split Coefficient Surface

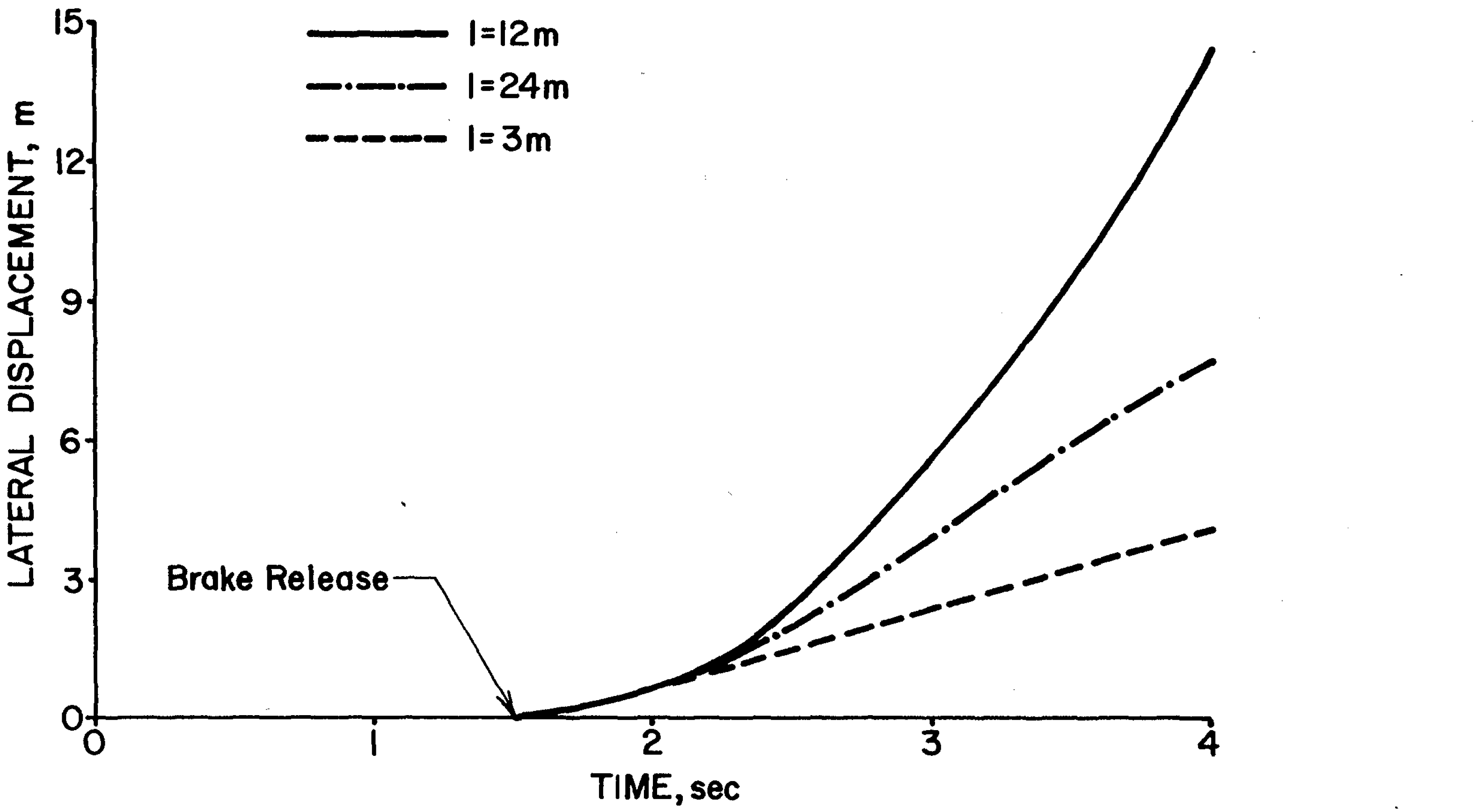


Figure 4-12. Lateral Deviation During Skidding Maneuvers Where the Brakes are Released 1.5 sec After Initiation of the Skid (Corresponding to Figures 9, 10 and 11)

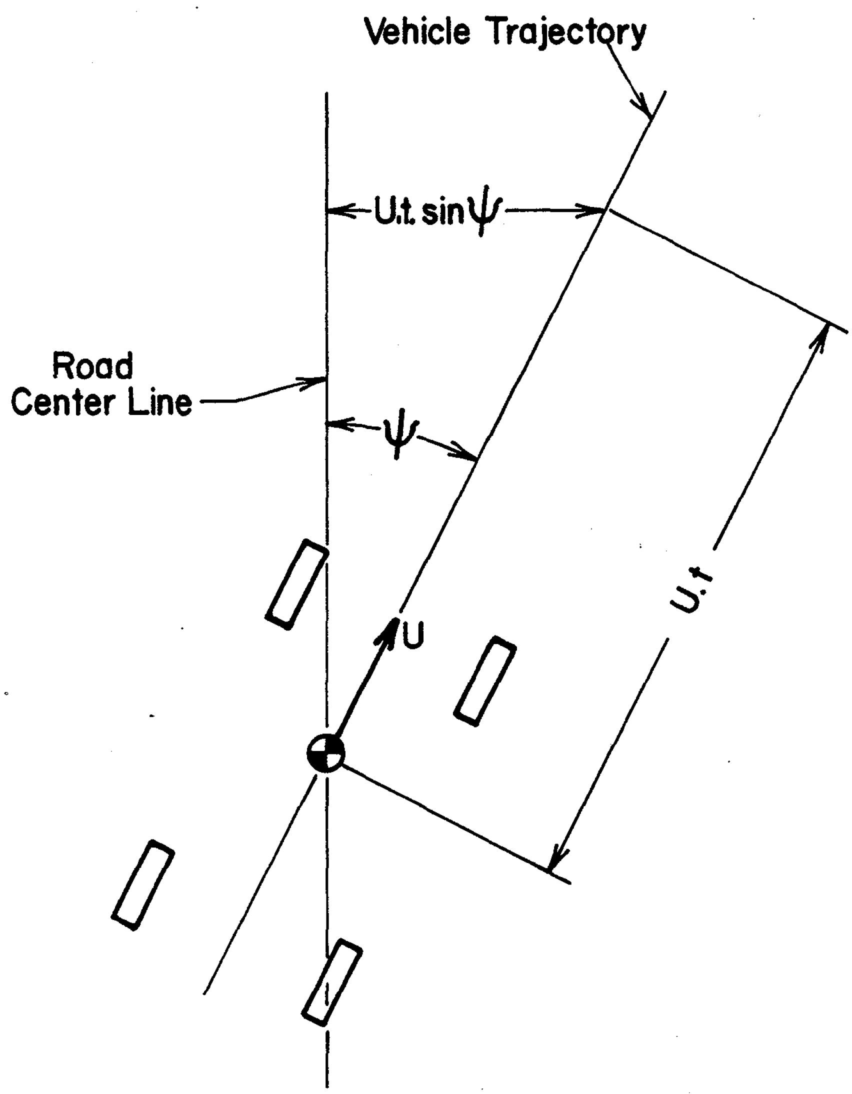


Figure 4-13. Lateral Displacement of a Vehicle Travelling Obliquely Across a Road at Steady Forward Speed (t = time)

displacement by more than a factor of two when 1 = 12.2 m. Drift angle, heading angle, and U.β at brake release, and drift angle and lateral displacement one second after brake release are plotted in Figure 4-14.

The maximum allowable lateral deviation of 3.66 m was chosen to conform with Reference [3], where a vehicle is considered to have entered a potential collision zone when it moves from the center of a lane 3.66 m in width to the center of an adjacent lane also 3.66 m in width. The maximum allowable lateral deviation may be increased or decreased according to the location of a marked-out section of roadway.

Reference [3] also gives an experimental justification for some of the conclusions drawn from the simulation. The report describes a series of experiments in which a professional driver locked the wheels of a car on a split coefficient surface and then released the brakes after the car had rotated through a specified angle. Specific findings were that: (1) a rotation in excess of 30 degrees caused the vehicle to be completely uncontrollable; (2) the permissible angle of rotation at brake release, without loss of control, decreased as vehicle speed increased; and (3) the vehicle entered a potential collision zone after release of the brakes at a rotation of 10 degrees and a vehicle speed of 80 km/h. These results are important because they are based on the only full-scale experimental data on vehicle loss of control on split coefficient surfaces. However, the number of tests conducted was small, and the experienced driver's performance may not be typical of that of the general driving population confronted with an unexpected maneuver. Direct correlation of the simulation results with the experimental results therefore was not possible. (Reference [4] gives a plot of a typical trajectory for a scale model car sliding with locked wheel on a split coefficient surface, but the effect of releasing the brakes was not considered.)

A study of vehicle/driver behavior after brake release by including a steering controller in the simulation was not attempted because none of the available models (for example, References [5] and [6]) accurately reproduce the behavior of a human driver, particularly in emergency maneuvers.

4.2.4 Boundaries of Safe Operation

Maneuver (1) This maneuver consisted of the vehicle sliding obliquely across a 150-mm wide marking stripe, thus simulating a car skidding across a lane delineation stripe. Vehicle deviation during a maneuver increased with decreasing angle of attack. An angle of attack of 5 degrees was selected as a typical value for presentation of results.

Figure 4-15 shows the maximum drift angle attained by the vehicle during the maneuver for a marking material coefficient of friction (μ_m) varying between 0.1 and 0.8 on pavements with coefficients of friction (μ_p) of 0.2, 0.4, 0.6, 0.8. The worst case of $\mu_p = 0.8$ and $\mu_m = 0.1$ gave a maximum value of U.β of 1.2. The values are all within the boundaries of safe operation, and it was concluded that a lane delineation stripe presents little hazard to a four-wheeled vehicle, whatever the values of pavement and marking material coefficients of friction. Additional simulation runs made with stripes of up to 300 mm in width resulted in the same conclusion.

Maneuver (2) This maneuver simulates a car sliding onto a section of roadway of which a significant proportion of the surface area is covered with marking material. The simulation model assumed that the marked-out section of roadway was completely covered with marking material and that the vehicle entered the section as shown in Figure 4-1. Heavily marked sections of roadway, such as gore areas, are generally patterened with alternating stripes of marking material and pavement. In this case the simulation results may be applied by calculating an equivalent marking material coefficient of friction according to the proportion of marking material area to the pavement area as suggested in Reference [7]. For example, if the marking pattern consists of regular stripes, this may be expressed as:

$$\mu_{MEC} = \frac{W_p \mu_p + W_M \mu_M}{W_p + W_M} \qquad (4\text{-}2)$$

where

μ_{MEQ} = marking material coefficient of friction, if the marked-out area of pavement is considered to be completely covered

W_M = width of marking material stripes

W_p = width of bare pavement stripes

If the marking pattern is irregular, this may be expressed as:

$$\mu_{MEQ} = \frac{A_p \mu_p + A_m \mu_m}{A_p + A_m} \qquad (4\text{-}3)$$

where

A_m = area of marking material

A_p = area of bare pavement within the marked area

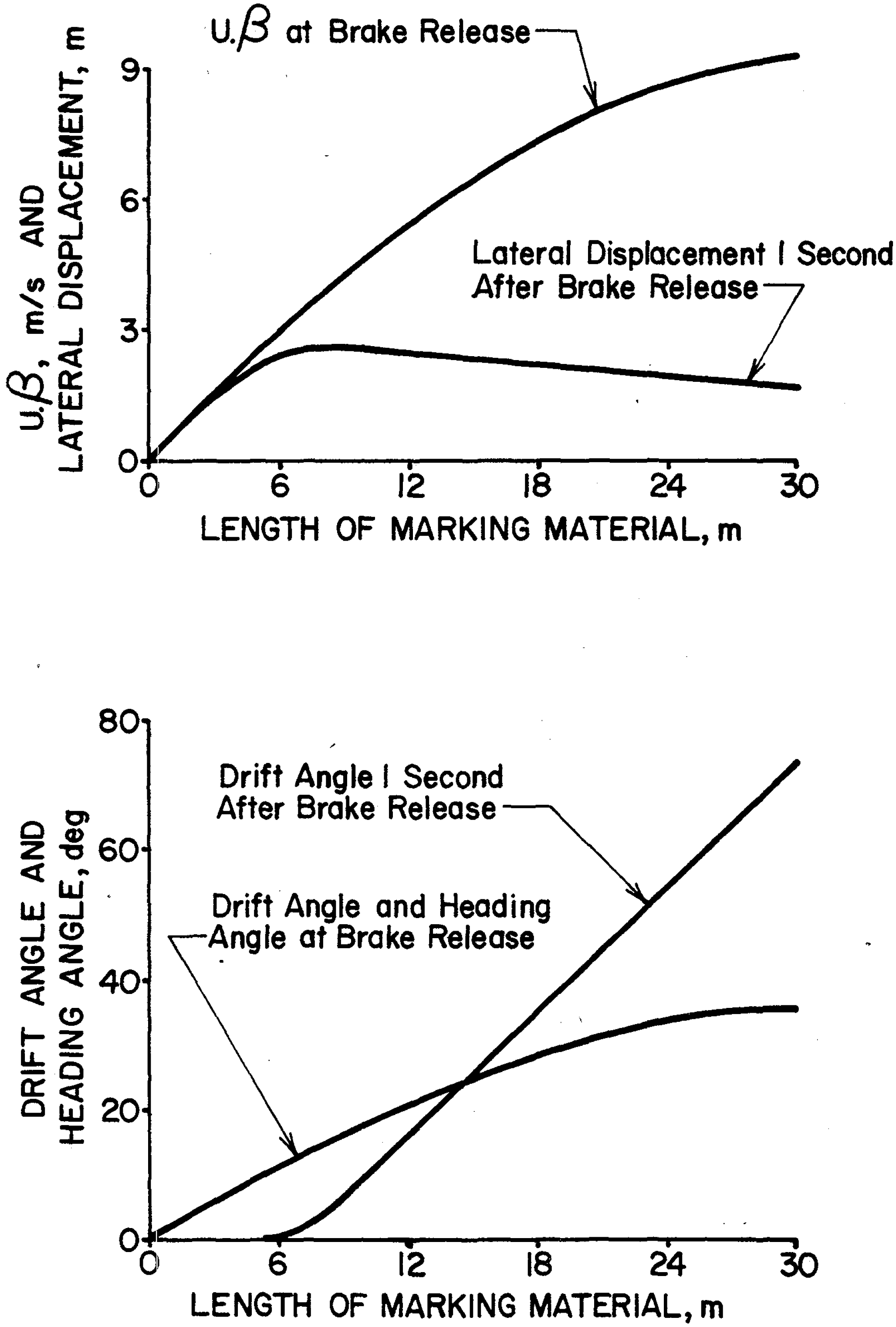


Figure 4-14. Vehicle Response at Brake Release and 1 sec After Brake Release During Maneuver (2)

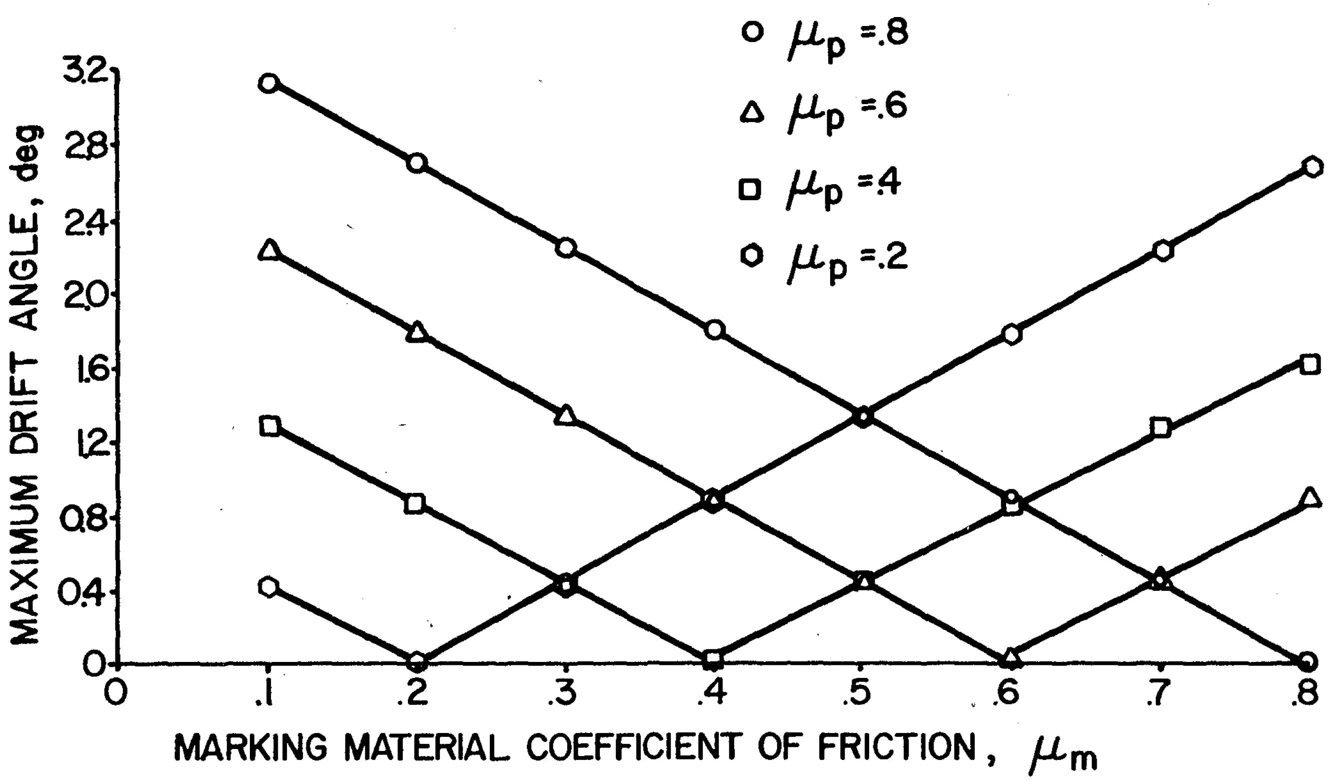


Figure 4-15. Maximum Drift Angles Attained During Maneuver (1), Angle of Attack = 5°, Initial Vehicle Speed = 88 km/h

When the pattern is highly irregular and asymmetric, specific guidance cannot be given on the hazard presented by the marking material. The highway engineer must either estimate the equivalent coefficient of friction or have a simulation run made for the specific pattern.

The simulation runs were made with an initial vehicle speed of 88 km/h. In most cases, either the U.β limit was exceeded before the drift angle limit or neither of the two limits was exceeded. However, in some runs U.β reached a maximum value which was less than 3.66, while drift angle exceeded its limit at a relatively low speed. When this occurred, the maneuver was considered to be hazardous if drift angle exceeded 20 degrees at a vehicle speed of 32 km/h or less. It should be noted that changing the vehicle parameters or the initial speed may reverse the order in which the parameters are exceeded, as will changing the specified safe limit for U.β or β.

Figures 4-16 through 4-19 show the maximum values of U.β attained during the simulation runs, plotted as a function of marked pavement length at each combination of pavement and marking material coefficients of friction. The length of pavement marking where each curve crossed the U.β = 3.66 line was plotted in Figure 4-20 as a function of the marking material coefficient of friction for each of the four values of pavement coefficient of friction considered. Also shown in Figure 4-20 are curves indicating when drift angle exceeded 20 degrees at a vehicle speed of 32 km/h or less. The procedure for using the chart is as follows:

(a) To find the maximum recommended length of pavement marking for specified pavement and marking material surfaces:

(1) Determine a value for the vehicle tire/pavement coefficient of friction, μ_p.

(2) Determine a value for the vehicle tire/marking material coefficient of friction, μ_m.

(3) Draw a vertical line on Figure 4-20 at the value of μ_m found in (2).

(4) Where the line cuts the curve corresponding to the value of μ_p found in (1), read off length of pavement marking. Interpolate if necessary.

(b) To find a recommended marking material given the length of pavement marking and the pavement surface:

(1) Determine μ_p.

(2) Draw a horizontal line on Figure 4-20 at the length of pavement marking.

(3) Where the line cuts the curve for the value of μ_p found in (1), read off the value of μ_m. Interpolate if necessary.

(4) Convert mm to a value of SN_{40} (or whichever skid resistance measurement is standardized for marking materials).

(5) Select a marking material which has a skid resistance higher than the value determined in (4).

(c) To determine whether an existing section of pavement marking is potentially hazardous:

(1) Measure the skid resistance of the pavement and marking material surfaces by the standardized methods.

(2) Convert to values of μ_p and μ_m.

(3) Draw a vertical line on Figure 4-20 at the value of μ_m and draw a horizontal line at the length of pavement marking.

(4) If the intersection of the lines lies above the curve for μ_p, then the pavement marking is potentially hazardous and corrective maintenance may be necessary.

When using Figure 4-20, a first estimate of the coefficients of friction may be obtained by taking values of SN_{40} for the respective surfaces, dividing by 100, and entering directly. If it is required to account for the fact that an SN40 measurement (made with an ASTM E 501 [20] tire) overestimates the skid resistance of a low macrotexture surface as seen by a worn tire, the coefficient of friction may be estimated values of skid resistance mwasured with an ASTM E 524 [5] blank tread tire or from macro and microtexture measurements. However, skid resistance measurements made by the ASTM E 274 [5] method should be used with care. The transformation and interpretation of such measurements should be made at the discretion of the design engineer.

4.2.5 Validity of the Results

The results presented in Figure 4-20 are applicable only to skidding maneuvers in which the skid was initiated by some factor other than the presence of roadway marking. Maintaining the vehicle in the skid is then considered to be the safest course of action for the driver if the roadway marking causes the vehicle to exceed a given value of angular deviation from the original path. The previously defined angular

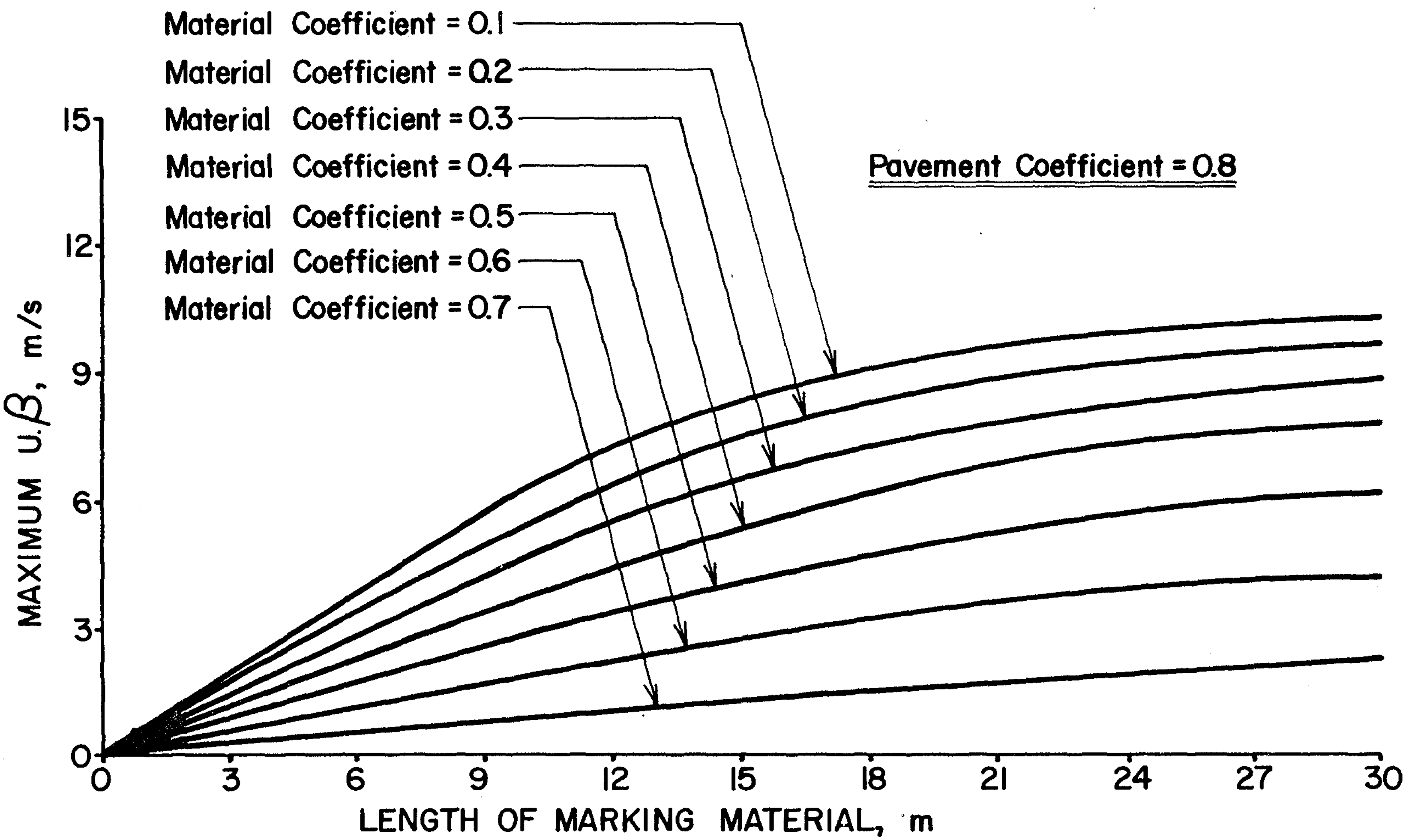


Figure 4-16. Maximum U.β Attained During Maneuver (2),
Initial Vehicle Speed = 88 km/h.
(See Text for Definition of U.β.)

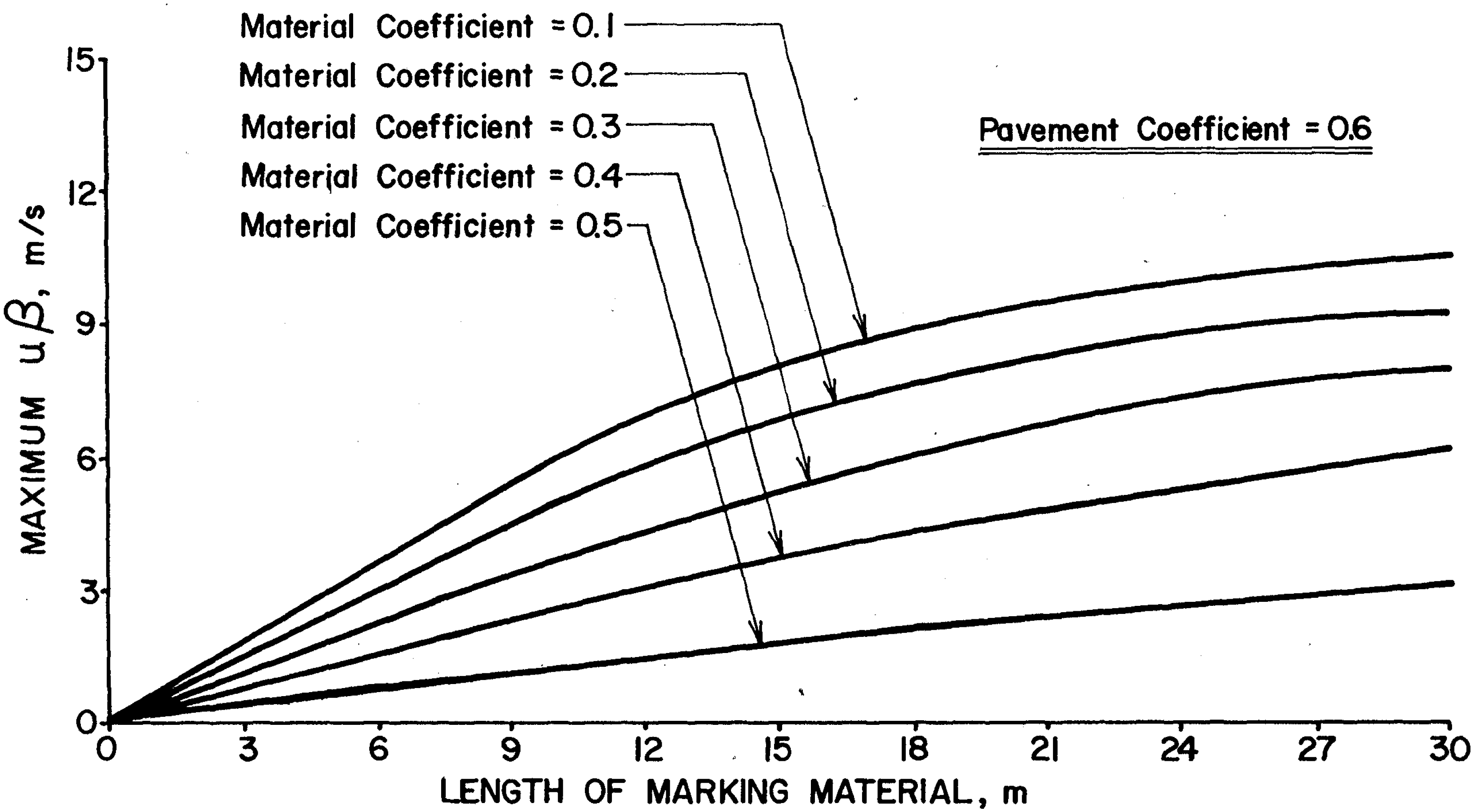


Figure 4-17. Maximum U.β Attained During Maneuver (2),
Initial Vehicle Speed = 88 km/h
(See Text for Definition of U.β.)

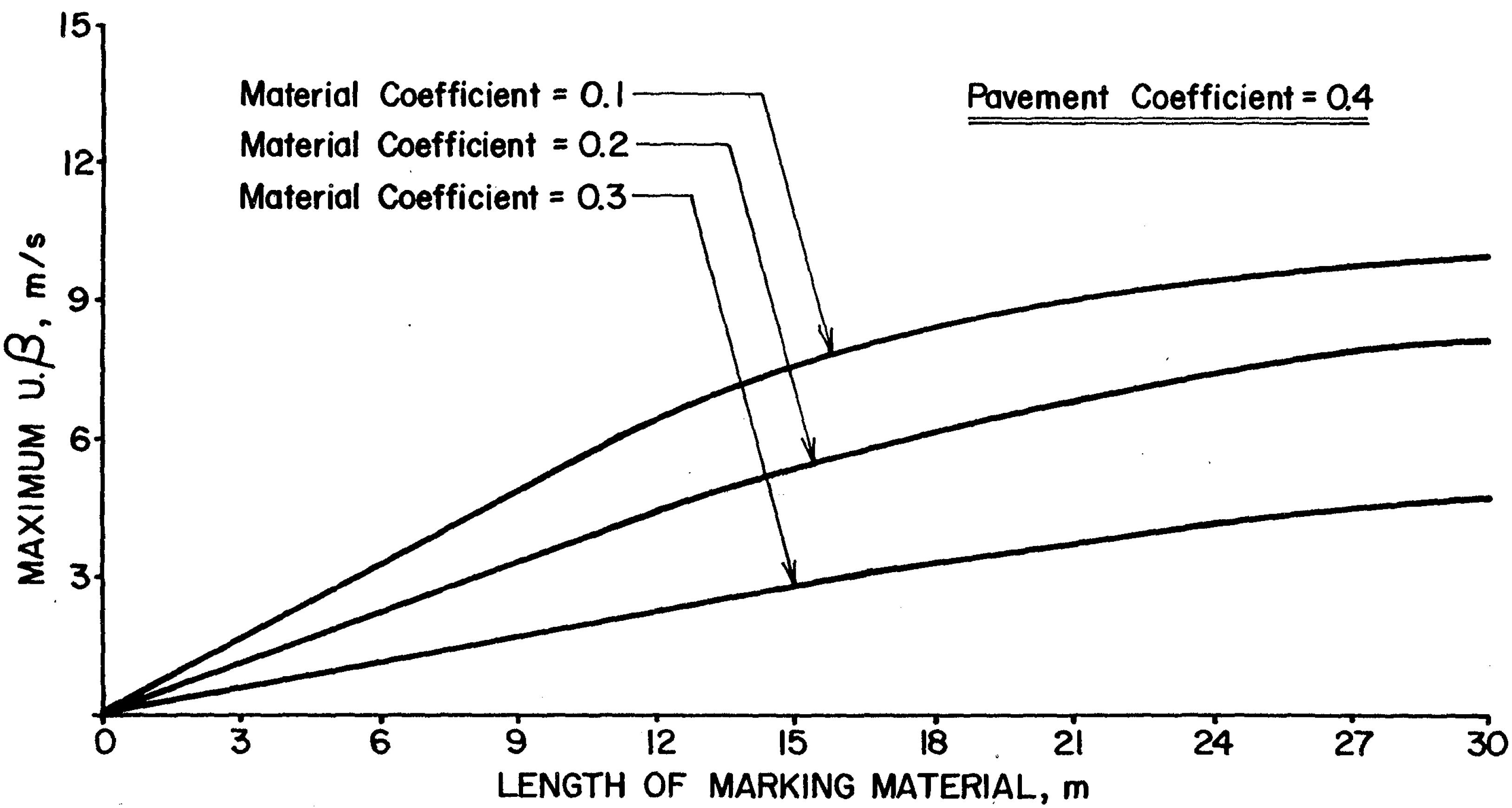


Figure 4-18. Maximum U.β Attained During Maneuver (2),
Initial Vehicle Speed = 88 km/h
(See Text for Definition of U.β.)

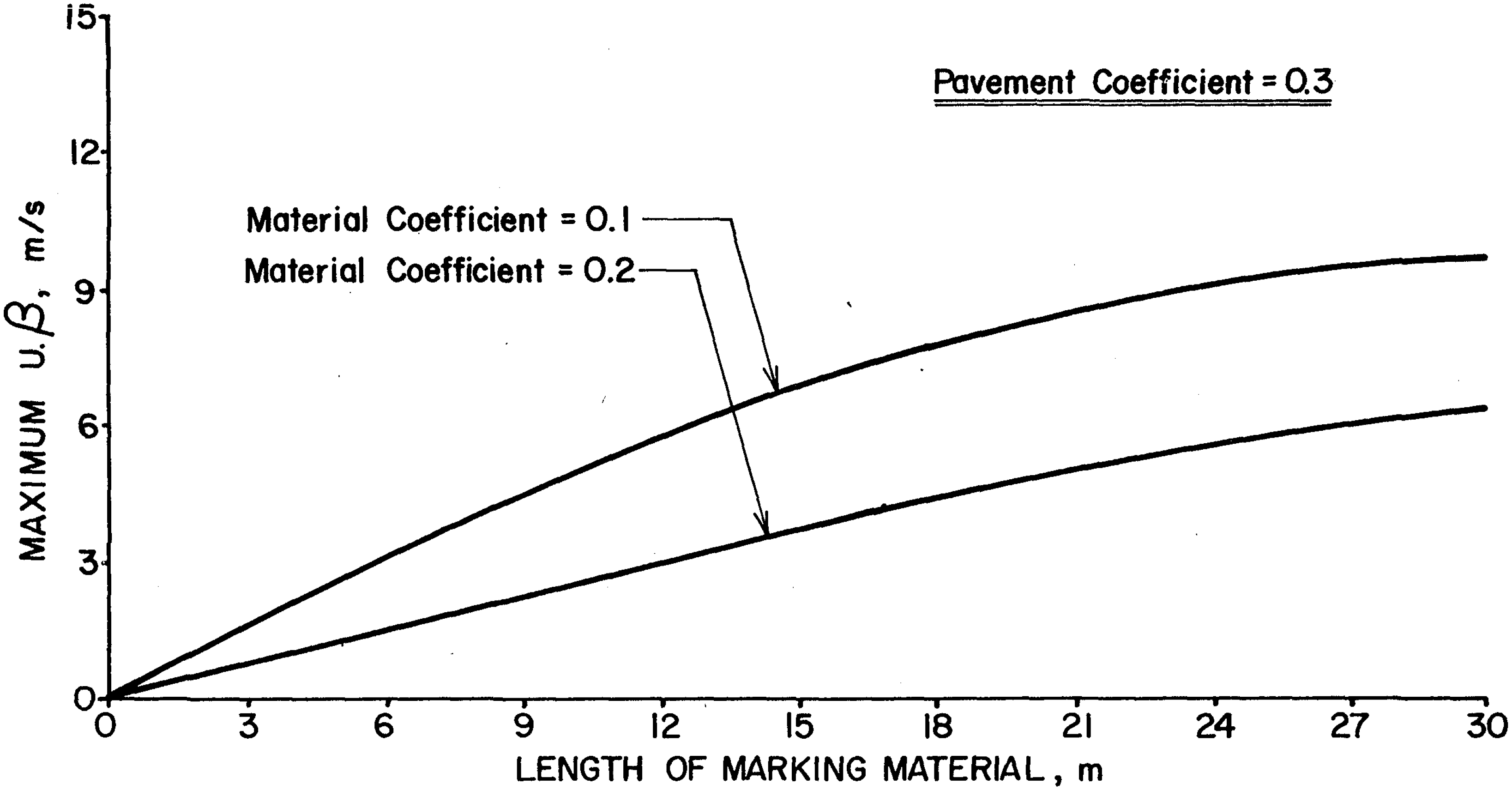


Figure 4-19. Maximum U.β Attained During Maneuver (2),
Initial Vehicle Speed = 88 km/h
(See Text for Definition of U.β.)

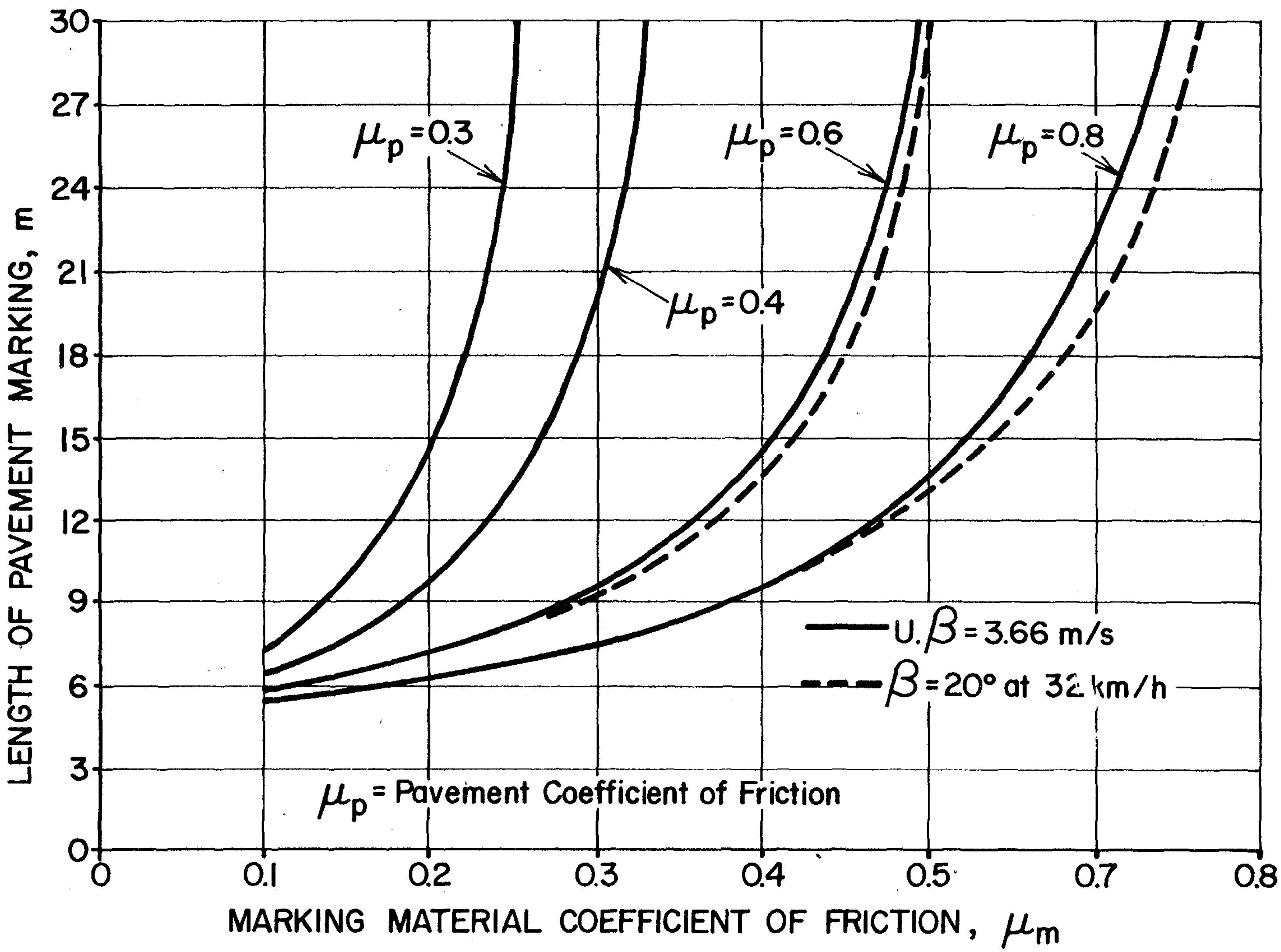


Figure 4-20. Recommended Maximum Lengths of Pavement Marking for Safe Operation of Cars in Skidding Maneuvers. Vehicle Speed at Inception of the Skid = 88 km/h. (See Text for Definition of the Design Criteria.)

deviation parameters are measures of how difficult it will be for the driver to regain control and subsequently steer the vehicle on a path within the roadway boundaries should he release the brakes at some point during the skid. Only tangent sections with 3.66 m of allowable lateral maneuvering space were considered, although smaller lateral distances and curved sections could also be included by changing the allowable limit of the parameter U.ß.

However, the extremely complex and variable nature of human behavior and a lack of experimental data make it very difficult to set numerical values for the parameter limits. This constitutes the most serious source of error (or uncertainty) in the design recommendation of Figure 4-20. Further studies of driver behavior and an analysis of accidents occurring on marked sections of roadway are required to validate: (1) the choice of parameters for indicating potential loss of control and (2) the numerical parameter values which give the boundaries of safe operation.

The chart given in Figure 4-20 is therefore a first approximation to the boundaries of safe operation and should be used only as a guide. It should also be noted that a "boundary of safe operaton" implies an acceptable level of risk rather than a definite boundary below which no accidents will occur.

Roadway marking materials may also initiate an emergency when a vehicle is being braked and passes over a section of marking material, since the wheels on the marking material will lock if the surface cannot generate sufficient tire friction force. The locking of three or fewer of the wheels will yaw the vehicle in much the same manner as will a four-wheel skid on a split coefficient surface, except that the driver retains a measure of lateral control through the wheels that are not locked. Skidding maneuvers initiated by pavement markings may therefore not be as serious as maneuvers which result from the release of the brakes of a vehicle during a four-wheel skid. But this consideration should be weighed against the fact that the emergency has been caused by the roadway marking.

Other factors contributing to differences between the simulated trajectories from which Figure 4-20 was generated and the trajectory of a car on the highway involve modeling simplifications and estimation of coefficients of friction. In view of the difficulty in predicting human behavior during emergencies, improving the accuracy of modelling would probably not give a significant improvement in the degree of uncertainty associated with the use of Figure 4-20. Estimation of the effective coefficients of friction is a practical matter which depends on the procedure used to measure skid resistance and on the vehicle tire configuration (worn, mixed, winter tread, etc.) that is to be considered as typical or representative.

The most important factors likely to contribute to discrepancies in the simulation results are:

(1) The vehicle parameters used in the simulation were for a full-size sedan. Other vehicle configurations or off-design values will give different results.

(2) The coefficient of friction was modelled as being independent of tire sliding speed. Low speed skid resistance and the skid resistance against speed relationship for different tire/pavement pairs are to a large extent independent. Allowing the coefficient of friction to vary with speed would therefore have greatly increased the number of simulation runs because of the increased number of possible combinations of pavement and marking material parameters.

(3) The roadway was considered to be flat and horizontal. A vehicle sliding on a superelevated roadway will tend to slide laterally, and changes in grade will change the distance required for the vehicle to stop.

(4) The vehicle model did not have a roll degree of freedom. Probably the most serious aspect of this restriction is that there is some evidence of coupling between vehicle roll and driver steer input, during severe maneuvers, which may lead to instability. At present, such complications cannot be modelled.

4.3 MOTORCYCLE LOSS OF CONTROL ON A MARKING STRIPE

4.3.1 Loss of Control Maneuver

An analysis of the motion of a motorcycle passing over an area of marking material is more difficult than an analysis for a car, since single track vehicles are fundamentally unstable in roll. Without active control by the rider, the vehicle will simply fall over. Also, locking one or both of the wheels leads to rapid roll instability which cannot be corrected by the rider. Locked-wheel skidding maneuvers similar to those used in the four-wheeled vehicle study were therefore not applicable. Rather, a maneuver in which the marking material caused a disturbance in the trajectory of the vehicle was required. An active steering controller, modelled in the simulation to stabilize the vehicle in roll, was a further departure from the methodology used in the four-wheeled vehicle study.

The maneuver chosen was as follows: set the vehicle in a steady state turn and then allow it to pass over a 150-mm-wide stripe of marking material at a given angle of attack. If the disturbance caused by the marking stripe was corrected by the steering controller, and the vehicle returned to the original steady state roll angle, the pavement/marking material configuration was acceptable. Otherwise, the configuration was not acceptable.

4.3.2 Simulation Model

A constant forward speed simulation model which had four degrees of freedom was used: roll (ϕ), lateral velocity (V), yaw velocity (r), and steer velocity ($\dot{\delta}$). The vehicle roll angle was constrained to follow a prescribed trajectory by a feedback controller with the law:

$$\dot{\delta} = k_1 (\phi - \phi_c) + k_2\dot{\phi} + k_3\dot{\phi} \qquad (4\text{-}4)$$

where: $\dot{\delta}$ = steer velocity
ϕ = vehicle roll angle
ϕ_c = command (desired) roll angle
k_1, k_2, k_3 = constants

The simulation included an empirical, curve-fit tire model which gave free rolling lateral tire force as a function of slip angle, camber angle, and vertical load, for camber angles of up to 40 degrees. The effect of longitudinal slip was not included in the tire model, and the simulation runs were made by modifying the shape of the tire characteristic curves according to the value of the coefficient of friction or by assuming full locked-wheel sliding. These two cases were implemented as follows:

(1) As the tires passed over the marking stripe the coefficient of friction was changed from μ_m to μ_m.

(2) It was assumed that the rider was braking at a level which could be sustained by the pavement but not by the marking material, i.e.,

$$\mu_p > \frac{a_x}{g} > \mu_m \qquad (4\text{-}5)$$

where: a_x = vehicle deceleration, m/s^2

g = gravitational constant
= 9.81 m/s^2

This was modelled by assuming that the wheel locked as soon as it passed onto the marking material and that it returned to its free rolling speed as soon as it passed back onto the pavement. Forward speed was held constant during the maneuver despite the assumed braking. But unstable maneuvers were terminated in less than 0.5 sec, and it was felt that errors from holding speed constant were no more serious than errors arising from other deficiencies in the simulation model.

The vehicle simulated was a 650-cc street model with a curb mass of 210 kg. Full details of the vehicle model, tire model, and steering controller are given in reference [20].

4.3.3 Mechanism of Roll Instability

When a four-wheeled vehicle executes a steady state turn and its wheels are locked, the vehicle continues to rotate in yaw, but travels in a straight line in the direction of its tangential velocity vector at the point of wheel lockup. The maneuver is therefore not catastrophic, unless another object is in the path of the vehicle; and there is always a chance that control can be regained if the brakes are released. But locking both of the wheels on a single track vehicle will almost always lead to complete roll instability.

If the simplified vehicle model shown in Figure 4-21 is considered, then summing the forces in the lateral direction and moments about point 0, the lateral (V) and roll (ϕ) equations of motion are:

$$M(Ur = \dot{V}) = Y \qquad (4\text{-}6)$$

$$m(Ur + \dot{V})\, h \cos\phi + I.\ddot{\phi} = Wh \sin\phi \qquad (4\text{-}7)$$

In a steady state turn, $\dot{V} = \ddot{\phi} = 0$, and $Y = mUr$. Therefore, the steady state roll angle is given by:

$$\phi_0 = \arctan\left(\frac{Ur}{g}\right) = \arctan\left(\frac{Y}{W}\right) \qquad (4\text{-}8)$$

(since W = mg)

If both wheels are locked when the vehicle is in a steady state turn, then $Y \to 0$, and

$$m(Ur + \dot{V}) = 0 \qquad (4\text{-}9)$$

$$\dot{V} = -Ur \qquad (4\text{-}10)$$

which means that, as the vehicle rotates, lateral velocity increases at the expense of forward velocity.

Also, $\ddot{\phi} = \frac{Wh \sin\phi}{I_0}$, and roll acceleration is positive (unstable), increasing as a function of sin ϕ.

As time increases, the tire forces will increase because drift angle (arctan V/U) increases but it should be noted that the tire force required to right the vehicle increases as tan ϕ. Also, the rider cannot influence vehicle motion by turning the steering.

If it is assumed that sin $\phi = \phi$, then, for the vehicle parameters used in the simulation, the roll equation with locked wheels has the solution:

$$\phi = \frac{\phi_0}{2} (e^{15t} = e^{-15t}) \qquad (4\text{-}11)$$

The unstable motion is clearly very rapid.

Returning to the steady state roll equation:

$$\tan \phi_0 = \frac{Ur}{g} = \frac{Y}{W} = \text{lateral acceleration of the vehicle in the turn gravity units} \qquad (4\text{-}12)$$

and considering a vehicle travelling in a steady state turn on a pavement with $\mu_p > Y/W$. If the vehicle passes onto a section of marking material with $\mu_m < Y/W$, the tires will not be able to generate sufficient side force to maintain the vehicle at its original lateral acceleration. However, since the roll moment due to the weight of the vehicle is now larger than the maximum opposing roll moment that can be generated by the tires, the vehicle will not only change its trajectory but will also be unstable in roll. This is, of course, an extreme simplification of what might occur in reality where coefficient of friction is a function of sliding velocity and various stabilizing actions (such as dragging a foot on the ground) are available to the rider if he has adequate skill and experience. Nonetheless, the argument is probably sufficient to demonstrate that at some limiting combination of coefficient of friction and vehicle acceleration, the rider is completely helpless against a rapidly unstable roll motion of the vehicle.

4.3.4 Simulation Results

Figures 4-22 through 4-25 show roll angle response for the vehicle passing over the 150-mm-wide marking stripe with free rolling wheels. Steady state roll angle is 18.5 degrees and steady state lateral acceleration is 0.3 g in all cases. Forward speed is 65 km/h in Figures 4-22 and 4-24, and 48.3 km/h in Figure 4-25.

Figure 4-22 shows the effect of angle of attack (the angle between the longitudinal vehicle axis and the marking stripe at the instant the front tire touches the marking stripe) with a pavement coefficient of friction (μ_p) of 0.6 and a marking material coefficient of friction (μ_m) of 0.2. For angles of attack of 15 and 10 degrees, the steering controller satisfactorily regained control after the vehicle had passed over the stripe. But at an angle of attack of 5 degrees the roll angle had exceeded 40 degrees within 0.6 seconds in a completely unstable motion. Increasing μ_p to 0.8 at an angle of attack of 5 degrees produced a roll motion which was stable but had large excursions about the steady state value. This change from instability to stability with an increase in pavement friction is consistant with the discussion of the previous section.

Figure 4-23 shows the effect of different values of μ_m. The second disturbance evident in the curves for $\mu_m = 0.3$ and $\mu_m = 0.4$ is due to the vehicle continuing in its curved trajectory and passing over the marking stripe a second time. Figure 4-26 shows the vehicle trajectories corresponding to the results of Figure 4-23. With $\mu_m = 0.4$, the roll motion is stable throughout the maneuver; for $\mu_m = 0.3$, the second passage over the marking stripe caused an unstable motion. The motion for $\mu_m = 0.2$ is the same as that given in Figure 4-22.

The results given in Figure 4-24 are for the same conditions as Figure 4-22 except that the forward speed is 25 percent lower. A significant decrease in stability is evident, which may be due to an increase in the time that the tires are on the marking material. Vehicle dynamic factors may also be important, however, and further investigation is necessary.

Figure 4-25 shows conditions similar to those in Figure 4-22 except that the wheels are assumed to be locked while on the marking stripe. The results follow the same trend but with a decrease in the level of stability.

4.3.5 Conclusions and Recommendations for Motorcycles

For a single track vehicle passing over a road delineation marking stripe, the results of the analysis indicate that the following factors tend to increase the risk of loss of control:

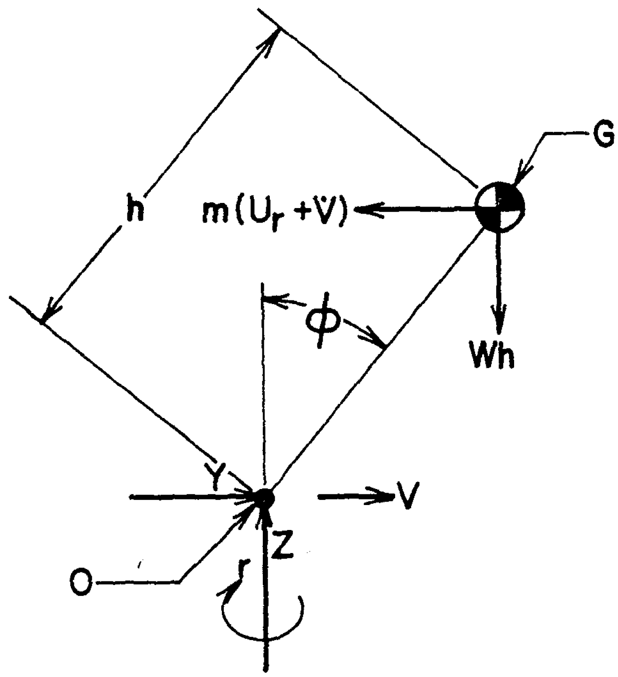
(1) decreasing the angle of attack,

(2) decreasing the pavement and marking material coefficient of friction,

(3) allowing the vehicle to pass over the stripe more than once or to run over a number of stripes in succession, and

(4) decreasing forward speed.

Acceptance of these results depends on the confidence that can be placed in the procedure adopted for determining loss of control, i.e., whether or not the simulation steering controller was capable of generating a stable motion. Vehicle motion on a more extensive area of marking material than a single stripe was not investigated, but it seems reasonable to infer that a higher level of risk will prevail. Rider skill and experience clearly play a considerable role in the probability of an accident occurring on a given section of roadway, both as regards the rider's ability to



G = center of gravity of the combined vehicle/rider mass

0 = intersection of a line through G in the 0_{yz} plane and the ground plane
= effective point of application of the tire forces assuming that the tires have zero cross section radius

ϕ = roll angle

U = forward speed (positive into the page)

V = lateral velocity of point 0

r = yaw velocity

Y = lateral tire force (front + rear)

Z = vertical tire force (front + rear)

m = mass of vehicle plus rider

W = weight of vehicle plus rider
= mg

I_0 = moment of inertia about a longitudinal axis through 0

Figure 4-21. Simple Model of the Single-Track Vehicle

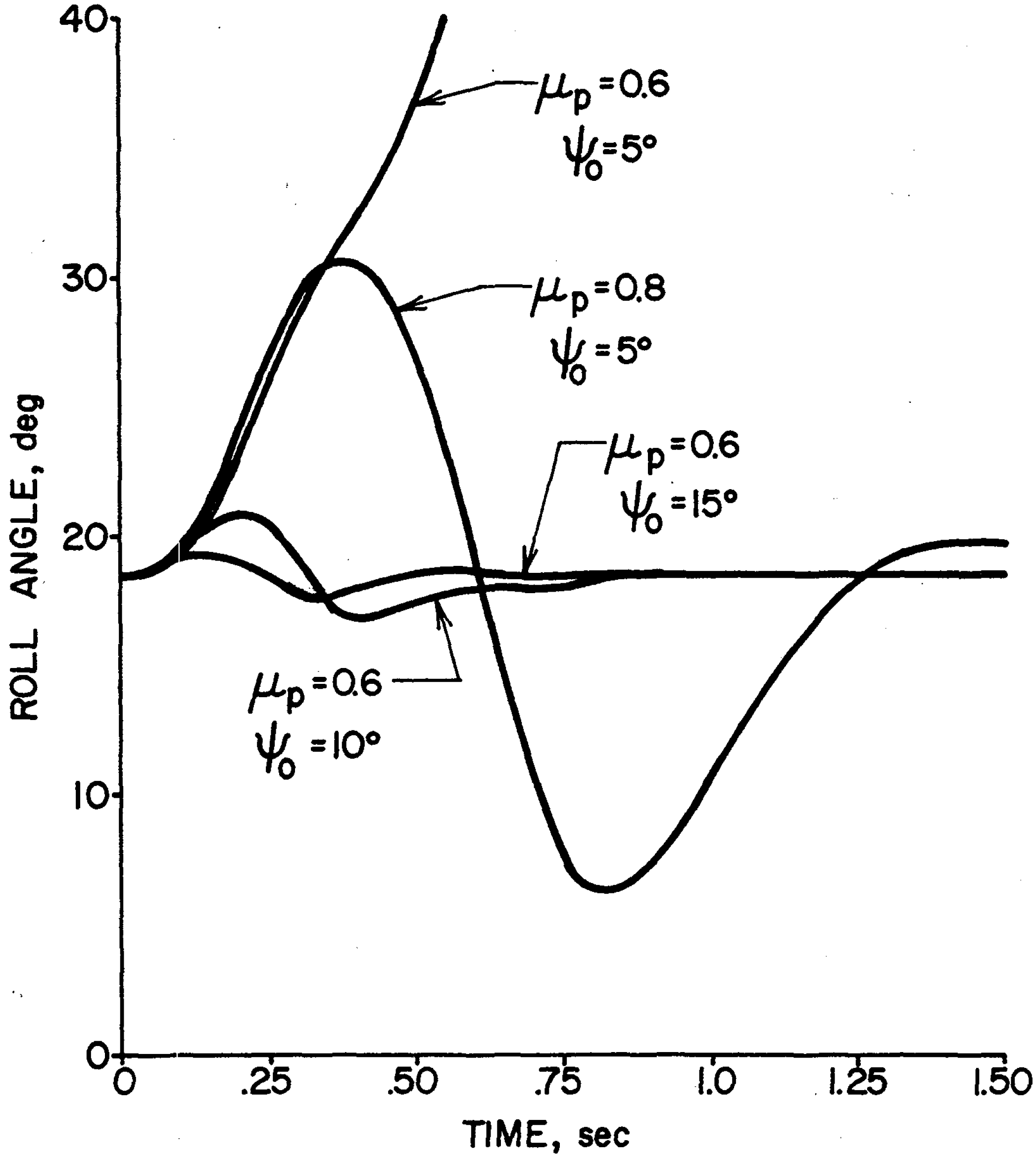


Figure 4-22. Single-Track Vehicle Roll Response at Increasing Angles of Attack (ψ_0). Marking Material Coefficients of Friction = 0.2, Forward Speed = 65 km/h.

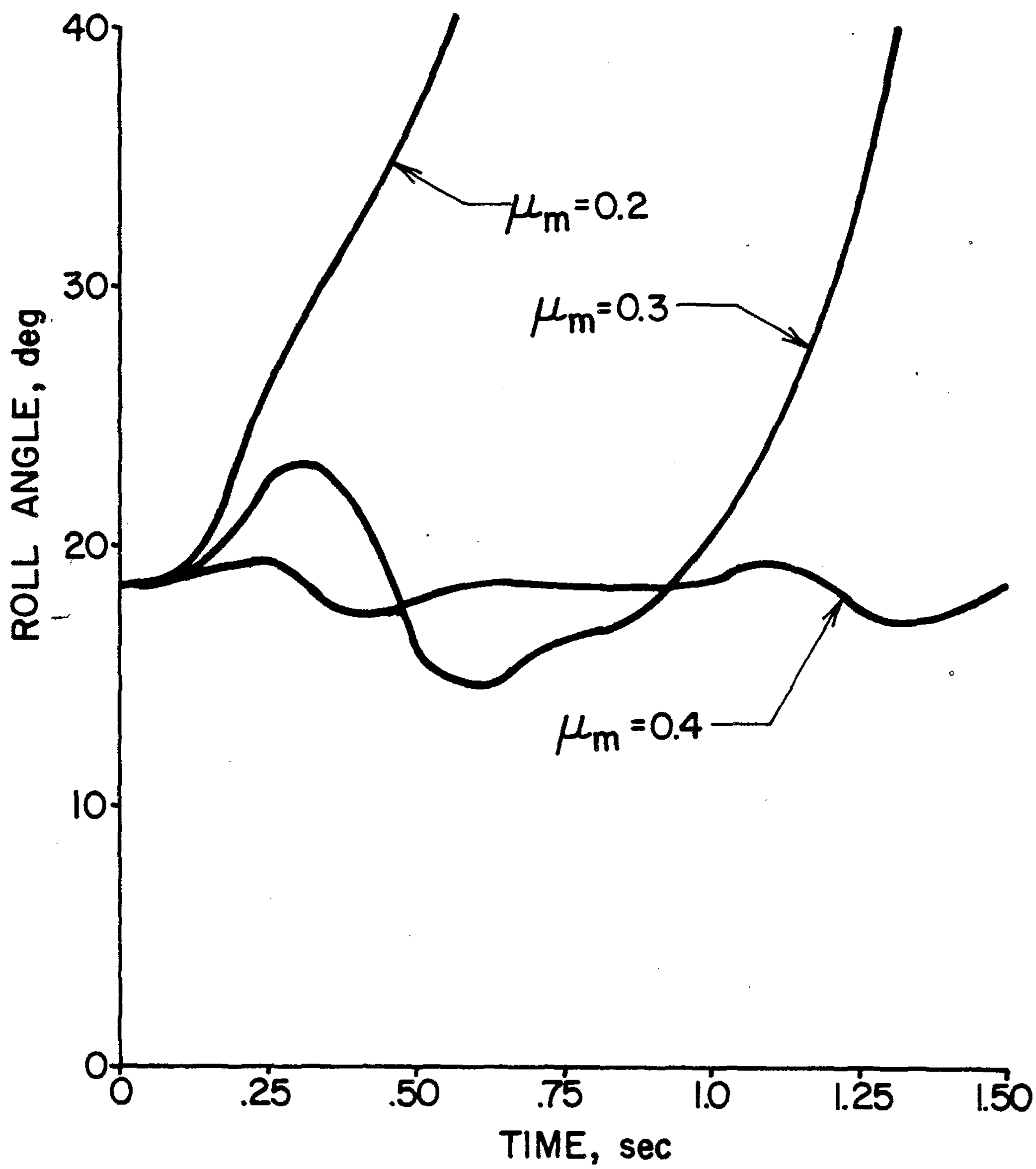


Figure 4-23. Single-Track Vehicle Roll Response at Increasing Marking Material Coefficients of Friction. Pavement Coefficient of Friction = 0.6, Angle of Attack = 5°, Forward Speed = 65 km/h.

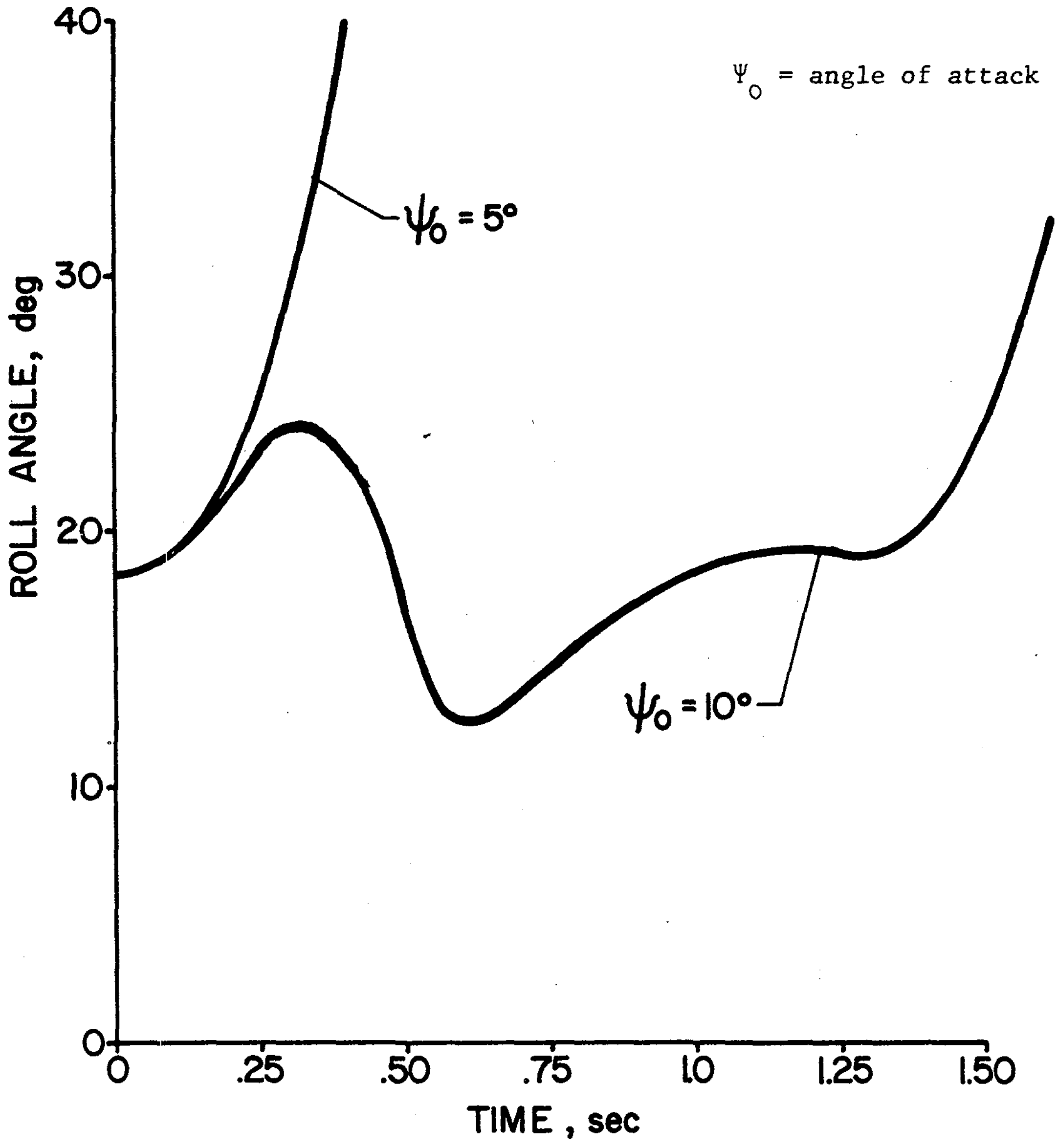


Figure 4-24. Single-Track Vehicle Roll Response. Pavement Coefficient of Friction = 0.6, Marking Material Coefficient of Friction = 0.2, Forward Speed = 48.3 km/h.

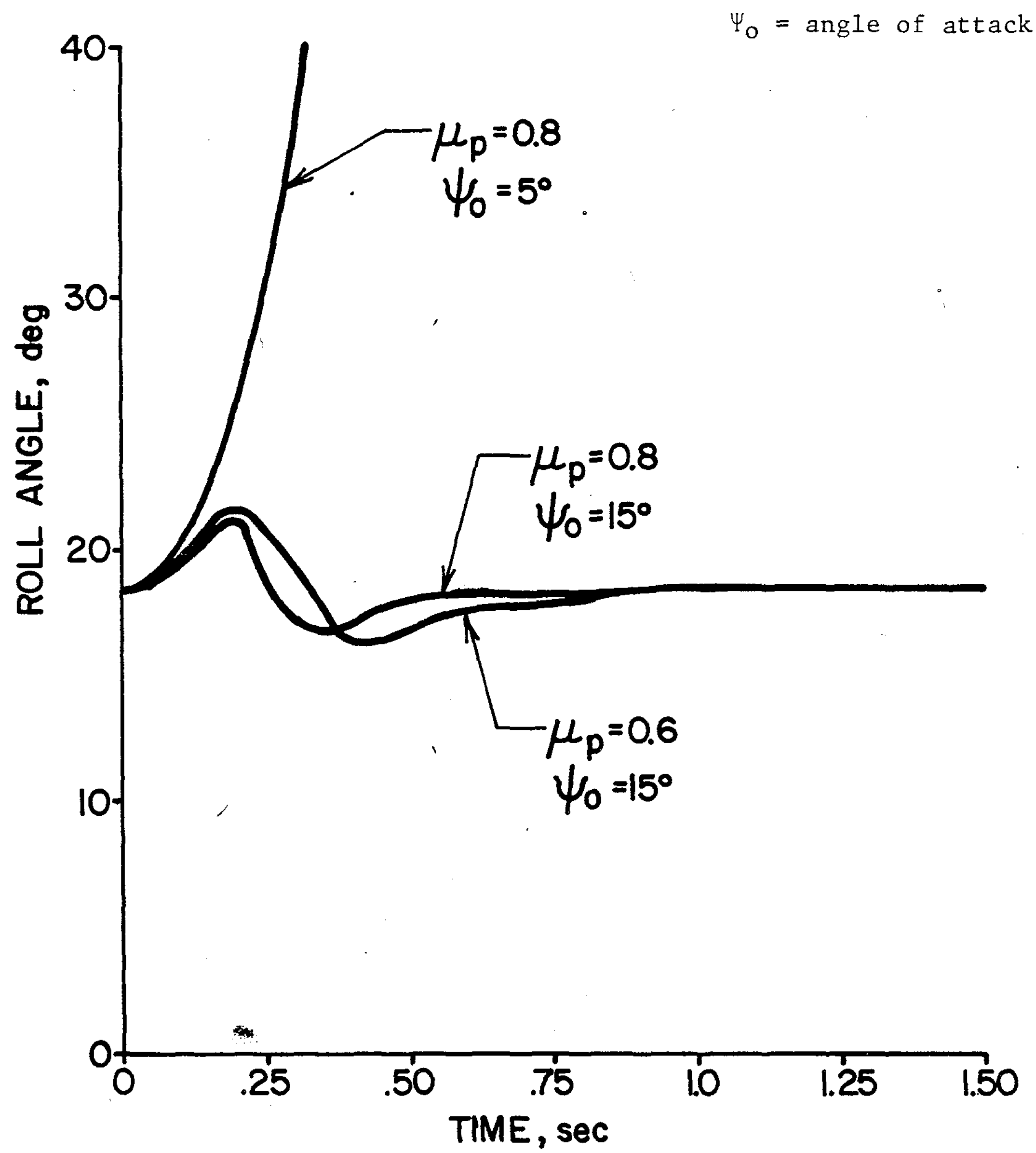


Figure 4-25. Single-Track Vehicle Roll Response With the Wheels Locked when on the Marking Stripe. Marking Material Coefficient of Friction = 0.2, Forward Speed = 65 km/h.

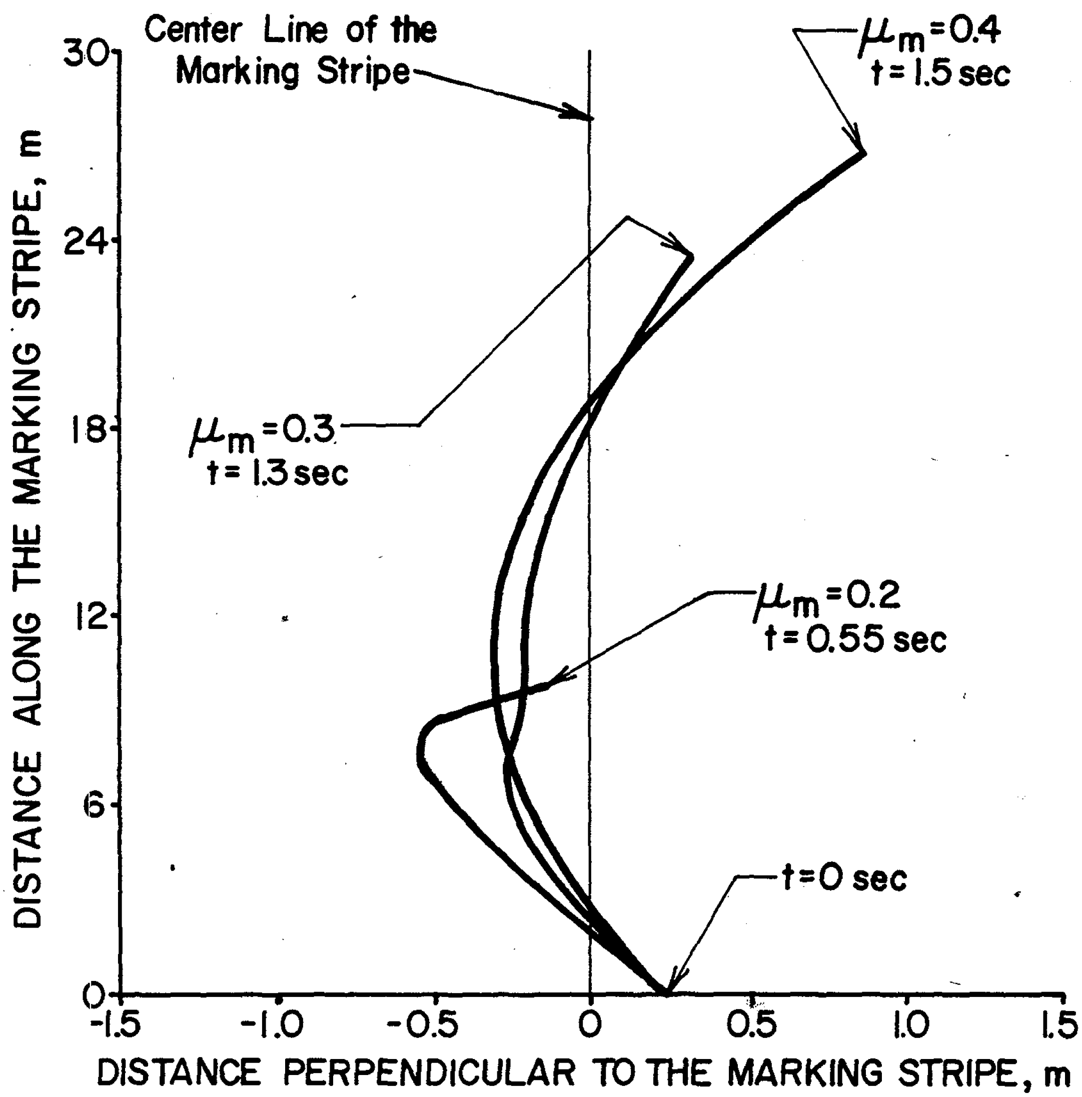


Figure 4-26. Trajectory of the Center of Gravity of the Single-Track Vehicle at Different Marking Material Coefficients of Friction. Pavement Coefficient of Friction = 0.6, Angle of Attack = 5°, Forward Speed = 65 km/h.

anticipate road conditions and his ability to retain control once an emergency maneuver has been initiated. These considerations make it extremely difficult to formulate even the beginning of a general procedure for specifying pavement marking materials for safe motorcycle operation.

However, one statement can be made with a fair degree of certainty: a single track vehicle operating on a pavement at a given level of acceleration (whether due to driving traction, braking, cornering, or any appropriate combination) is likely to become completely unstable if it passes across a marking material surface which has a coefficient of friction equal to or less than the vehicle acceleration measured in gravity units. There are two problems in trying to apply this statement: (1) How should the "coefficient of friction" of a typical motorcycle be defined and measured? and (2) Is a significant amount of differential friction allowable and, if so, how can safe levels be determined?

The first problem has already been discussed in connection with four-wheeled vehicle operation, and a procedure developed for car tires would probably be equally applicable to motorcycle tires. The second problem is essentially concerned with human behavior relatively independent of vehicle behavior or vehicle/rider interaction. It depends mainly on whether a rider allows a consistent margin of safety against sliding when operating on various pavement surfaces. For example, when operating on a surface with a coefficient of friction of 0.8, he might restrict vehicle accelerations to 0.6 'g'; on a surface with a coefficient of friction of 0.6 he might restrict vehicle accelerations to 0.4 'g'. Other relationships, such as the variation of safety margin with pavement friction, can also be postulated.

If such a relationship could be established, the minimum allowable marking material coefficient of friction for safe motorcycle operation would be given by a function of pavement coefficient of friction (and, probably, by other highway design factors such as geometry), so that the vehicle would never operate on a surface whose coefficient of friction is lower than the maximum vehicle acceleration likely to be attained. On the other hand, if a consistent relationship is found not to exist, or cannot be established, the minimum allowable marking material coefficient of friction could be given as the minimum allowable pavement friction for the section of highway under consideration, irrespective of the existing or design pavement surface friction. In either event, the problems inherent in fixing minimum levels of friction or skid resistance will have to be resolved.

4.4 SUMMARY

To emphasize the reasons for the different approaches taken when considering two- and four-wheeled vehicles, a brief summary of the major arguments is given.

On a surface with a uniform coefficient of friction, a locked-wheel skid is hazardous for a four-wheeled vehicle only if there is an object in the path of the vehicle. Passing over a section of differential friction during the skid, however, will cause rotation of the vehicle and the driver may not be able to regain control should he release the brakes. Locking of the wheels when passing from a high friction surface to a lower friction surface is likely to initiate an emergency maneuver, but locking of all four wheels will probably not occur, and at least a measure of control will be retained by the driver.

Locking either one or both of the wheels of a two-wheeled vehicle is likely to result in complete loss of control. A differential friction surface is hazardous in this case since it may precipitate a locked-wheel skid. Under these circumstances it becomes difficult to differentiate between a normal maneuver and a controlled, but rapid maneuver caused by reaction to an emergency situation. Similar arguments may be applied to loss of lateral tire traction in single track vehicle operation.

5. CONCLUSIONS AND RECOMMENDATIONS

A data base for a number of different pavement marking materials has been obtained. A very wide range of skid resistance levels was found, the lowest of which were for the hot extruded thermoplastics and the chlorinated rubber-base traffic paint used in this study.

Glass spheres were found to increase significantly the skid resistance of the marking materials. The beneficial effect of the beads lasted throughout the test period for the project (seven months including a winter season). The reduced skid resistance levels of the pavement resulting from the application of paints persisted well into the useful life of the marking material, that is, until degradation of the material was noticeable. The use of unbeaded materials is rare and should be avoided. Chlorinated rubber-base traffic paints exhibited skid resistance levels significantly lower than alkyd resin paints. Spray thermoplastics provided higher skid resistances than hot extruded thermoplastics, due in part to the coarser macrotexture levels produced by the spray applications.

The marking materials studied in this project were grouped into six types: traffic paints, hot spray thermoplastics, hot extruded thermoplastics, preformed plastic, temporary tapes, and two-part systems. In analyzing the data and developing the predictor equations for skid resistance in terms of texture and British Pendulum data it was necessary to treat each type separately. This resulted in six data sets, some of which were too small to provide significant correlations. A summary of the predictor equations is given in Table 5-1. This table contains correlation coefficients (r^2) for each predictor equation which gives the proportion of the variation in the dependent variable, skid number (SN_{64}), explainable by linear regression with the independent variable British Pendulum Number (BPN). In some instances the prediction of skid number is improved by the inclusion of a second independent variable, macrotexture profile root mean square ($RMSH_{MA}$).

The British Pendulum Number (BPN) in these equations was found to be affected by the pavement temperature. The temperature effects were more pronounced for the unbeaded materials (0.25 BPN per °C increase with temperature) than for the beaded materials (0.15 BPN decrease with temperature). There was, in the field data, no significant difference between the first five BPN readings and the second five taken after the surface was scrubbed. It would be desirable to study in depth each type of material, particularly the paint, thermoplastics, and preformed materials, so that a wider variety of material formulations could be included.

Based on the testing of samples in the Atlas Twin Arc Weatherometer ir was concluded that accelerated weathering is not necessary to predict the frictional characteristics of marking material surfaces. Weathering did not significantly alter the texture of either the beaded or the unbeaded surfaces. Although a surface patina may develop on some unbeaded surfaces after weathering, this patina is quickly worn away and cannot be relied upon to improve skid resistance.

The effect of polishing the surfaces of marking materials with abrasive grit is different for marking materials than for aggregate surfaces or unmarked pavement surfaces. Little wear occurs during the polishing: the polishing removes overspray from the beads but has little effect on the beads themselves. Polishing increases the frictional resistance of the unbeaded surfaces by removing the glaze from these surfaces. However, because unbeaded surfaces are not practical in the field, it was not considered necessary to develop a special test procedure for unbeaded surfaces.

The laboratory BPN values decrease exponentially with an increasing number of swings, so that up to seven swings are required to reach equilibrium. The standard procedures of eliminating only the first swing is not appropriate for marking materials; seven swings are recommended, with the last four swings averaged and recorded as the BPN value.

Although polishing per se is not recommended, some sort of conditioning procedure should be used to obtain an equilibrium BPN value.

Beads tend to mask differences in the marking material and serve to level the texture (BPN) measured for different surfaces. Additional work is required on bead systems to optimize the trade off between skid resistance and reflectivity. The method of bead application is significant in developing texture, and consequently in developing skid resistance. Any procedure that increases texture will increase skid resistance. Spray-on beads are preferred to drop-on beads.

The aggregate (sand) in the thick thermoplastic, hot extruded, hot spray and cold applied materials does influence skid resistance. Additional research is needed to quantify the aggregate properties that maximize skid resistance. The thick hot-spray materials tend to have a rougher surface than the extruded materials and hence a higher level of skid resistance. This is in part due to the roughness created in the spraying operation.

There is almost no correlation between the Brungraber Portable Slip Resistance Detector and the BPN device. This is not surprising, because the Brungraber measurement is a static measurement whereas the BPN is a dynamic measurement. Additional developmental work is needed before the Brungraber device can be used for specification purposes (improved shoe material and test procedure). The lowest skid resistance or critical condition occurs with a hard shoe on dry pavement. In general, the thermoplastics have higher skid resistance than the temporary tapes.

When applied to pavements, marking materials cause a local reduction in skid resistance. The resulting differential frictions can create problems for drivers of automobiles and other four-wheel vehicles if the materials are applied to large areas such as gores, legends, and stop bars. Such applications should be avoided when possible. Current standards for such configurations should be reviewed in light of this finding. Some criteria have been developed for selection of materials to determine the maximum allowable differential friction. Four-inch lane delineation lines do not cause problems for drivers of four wheel-vehicles, but can for motorcyclists if they brake during lane changes.

Table 5-1

Predictor Equations for Skid Resistance of Marking Materials

Traffic Paints

Unbeaded — 22 applications — $\overline{SN}_{64} = 20.7$ (s = 8.0)

$SN_{64} = .58\ BPN - 11.3$ — $r^2 = .81$ (3-3f)

$SN_{64} = .546\ BPN + 6.10\ RMSH_{MA} - 12.82$ — $r^2 = .92$ (3-4)

Beaded — 41 applications — $\overline{SN}_{64} = 26.7$ (s = 6.8)

Chlorinated Rubber Base (20 applications) $\overline{SN}_{64} = 25$ (s = 8)

$SN_{64} = .725\ BPN - 15.4$ — $r^2 = .61$ (3-7a)

Alkyd Resin Base (21 applications) $\overline{SN}_{64} = 28.3$ (s = 5.1)

$SN_{64} = .356\ BPN + 7.10$ — $r^2 = .36$ (3-7b)

Thermoplastics

Unbeaded — 12 applications — $\overline{SN}_{64} = 18.7$ (s = 10.1)

Hot Extruded (7 applications)

$SN_{64} = .91\ BPN - 35.3$ — $r^2 = .48$ (3-9)

$SN_{64} = .817\ BPN + 13.3\ RMSH_{MA} - 33.1$ — $r^2 = .50$ (3-10)

Hot Spray (5 applications)

$SN_{64} = 64.4\ RMSH_{MA} + 3.9$ — $r^2 = .45$ (3-11)

Beaded — 26 applications — $\overline{SN}_{64} = 24.7$ (s = 7.5)

Hot Extruded (16 applications)

$SN_{64} = .68\ BPN - 15.4$ — $r^2 = .50$ (3-12)

$SN_{64} = .623\ BPN + 36.4\ RMSH_{MA} - 18.7$ — $r^2 = .66$ (3-13)

Hot Spray (10 applications)

No acceptable correlation found

SN_{64} Hot Spray > SN_{64} Hot Extruded

Preformed Plastics — 11 applications — $\overline{SN}_{64} = 25.2$ (s = 8.7)

$SN_{64} = .158\ BPN + 58.4\ RMSH_{MA} + 5.95$ — $r^2 = .76$ (3-14)

$SN_{64} = .616\ DTN + 0.285$ — $r^2 = .91$ (3-15)

Temporary Tapes — 13 applications — $\overline{SN}_{64} = 29.6$ (s = 6.2)

No meaningful correlations

Note: The macrotexture profile root mean square ($RMSH_{MA}$) is expressed in mm in all the above expressions.

6. REFERENCES

1. Harrigan, E. T. "New Materials and Systems for Improved Traffic Lane Delineation." Public Roads, December 1977, 6 p.

2. Leu, M. C. and Henry, J. J. "Prediction of Skid Resistance as a Function of Speed from Pavement Texture." Presented at the 57th Annual Meeting of the Transportation Research Board, Washington, D. C. January 1978, 19 p.

3. Organization for Economic Co-Operation and Development, Road Research Group. "Road Maring and Delineation." Paris, February 1975, 156 p.

4. American Society for Testing and Materials. "Standard Method for Measuring Surface Frictional Properties Using the British Portable Tester--E303-74." 1980 Annual Book of ASTM Standards, Part 15, 1980.

5. American Society for Testing and Materials. "Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire--E274-79." 1980 Annual Book of ASTM Standards, Part 15, 1980.

6. Brungraber, Robert J. "An Overview of Floor Slip-Resistance Research with Annotated Bibliography." NBS Technical Note No. 895, National Bureau of Standards, U. S. Department of Commerce, Washington, D. C., January 1976, 113 p.

7. Shah, V. R. and Henry, J. J. "The Determination of Skid Resistance--Speed Behavior and Side Force Coefficients of Pavements." Presented at the 59th Annual Meeting of the Transportation Research Board, Washington, D. C., January 1980, 3 p.

8. Rizenbergs, Roland L. et. al. "Accidents on Rural Interstate and Parkway Roads and Their Relation to Pavement Friction." Transportation Research Record No. 584, pp. 22-36.

9. Farber, E. et. al. "Determining Pavement Skid-Resistance Requirements at Intersections and Braking Sites." National Cooperative Highway Research Program Report, 154, Transportation Research Board, Washington, D. C., 1974, 64 p.

10. Dry, D. R., Henry, J. J., and Dahir, S. J. Seasonal Skid Resistance Variations. Interim Report, Project 75-10, Report PTI 7705, the Pennsylvania Transportation Institute, University Park, PA, April 1977, 82 p.

11. Dahir, S. H. and Meyer, W. E. "The Polishing Characteristics of Common Rock Types Used as Aggregate in Bituminous Pavement Surfaces." ASTM Journal of Testing and Evaluation, November 1977, 32 p.

12. American Society for Testing and Materials. "Tentative Recommended Practice for Accelerated Polishing of Aggregates Using the British Wheel--D 3319." 1977 Annual Book of ASTM Standards, Part 15, 1977.

13. Hegmon, R. R. and Henry, J. J. "Pavement Texture Measurement and Evaluation." ASTM Special Technical Publication, 583, 1975.

14. Henry, J. J. and Dahir, S. H. Seasonal Skid Resistance Variations. Second Interim Report, Contract No. 53384, Pennsylvania Department of Transportation. Report PTI 7804, The Pennsylvania Transportation Institute, University Park, PA, May 1978.

15. Institute of Transportation Engineers, Technical Council Committee 4Q-S. "A Model Performance Specification for the Purchase of Thermoplastic and Preformed Plastic Pavement Marking Materials" (Tentative Revised Standard).

16. Turo, M. D. Interoffice correspondence from "Skid Testing Reflective Markings." Department of Public Works, Commonwealth of Massachusetts, December 23, 1974.

17. Richard, C. L. "Skid Testing of Pavement Marking Materials." Michigan Department of State Highways and Transportation, Final Report, Project TSD-284-76, April 1976, 9 p.

18. "Les Produits de Marquage et Leur Mise en Oeuvre" (Marking Materials and Their Application). Technical guide published by Service d'Etudes des Routes et Autoroutes (SETRA) and Laboratoire Central des Ponts et Chaussees (LCPC), (French) Ministry of Equipment, Paris, November, 1975, 68 p.

19. American Society for Testing and Materials. "Standard Specification for Smooth-Tread Standard Tire for Special-Purpose Pavement Skid-Resistance Tests--E524-76." 1980 Annual Book of ASTM Standards, Part 15, 1980.

20. American Society for Testing and Materials. "Standard Specification for Standard Tire for Pavement Skid-Resistance Tests--E501-76." 1980 Annual Book of ASTM Standards, Part 15, 1980.

21. Dugoff, H., Fancher, P. S., and Segel, L., "An Analysis of Tire Traction Properties and Their Influence on Vehicle Dynamic Performance." SAE Transactions, Vol.79 (1970), Paper 700, 377.

22. Lincke, W., Richter, B., and Schmidt, R., "Simulations and Measurement of Driver Vehicle Handling Response." SAE Paper No. 730, 489, 1973.

23. Burns, J. C., "Differential Friction: A Potential Skid Hazard." Transportation Record 602 (1977), pp. 46-53.

24. Zuk, W., "The Dynamics of Vehicle Skid Deviation as Caused by Road Condition". Report of the Virginia Council of Highway Investigation and Research, Charlottesville, Virginia, June, 1958.

25. Hayhoe, G. F., "A Driver Model Based on the Cerebellar Model Articulation Controller." Vehicle System Dynamics 8 (1979), pp. 49-72.

26. McRuer, D. T., and Klein, R. H., "Automobile Controllability. Driver/Vehicle Response for Steering Control, Vol. 1--Summary Report." U.S. DOT Report No. TR-1040-1-I (Avail. NTIS PB-240 208), 1975, 269 pp.

27. Ellis, J. R., and Hayhoe, G. F., "The Steady State and Transient Handling Characteristics of a Motorcycle." Proceedings of the 2nd International Congress on Automotive Safety, San Francisco, July 1973.

*U.S. GOVERNMENT PRINTING OFFICE: 1981-0-728-482/1856

FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.