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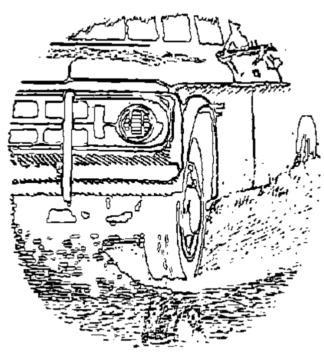
PAVEMENT AND GEOMETRIC DESIGN CRITERIA FOR MINIMIZING HYDROPLANING

A Technical Summary

December 1979

Final Report



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

FOREWORD

The report presents a summary of the research conducted on pavement design criteria to reduce or mitigate highway hydroplaning. It covers pavement texture, cross slope, rutting, rainfall probability analysis, drainage, vehicle control, traction studies, and pavement finishes.

Laboratory and full scale tests were conducted for a variety of roadway conditions to develop realistic evaluation of the hydroplaning phenomena. These experiments were followed by analytic analyses and interpretation of data to provide a sound treatise.

This technical summary is being widely distributed. Copies for State highway agencies are disseminated through the Division Offices.

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

Notice

Technical Report Documentation Page

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16. Abstract

This technical summary presents in concise detail the findings contained in the full reports of Phases I and II of the development of pavement and geometric design criteria for minimizing hydroplaning. The full-length report numbers are: Phase I FHWA-RD-75-11 and Phase II FHWA-RD-79-31.

The authors have covered the empirical indications of hydroplaning as determined from hard data. Precise measurements of surface drainage were examined, and equations relating pavement texture and cross slope and rainfall intensity were developed.

Vehicle control as related to variation in cross slope was simulated with the HVOSM.* A determination of the deficiencies in existing surface drainage design methodology for sag vertical curves was conducted, and innovative solutions to these problems are presented.

From a detailed study of state rainfall records a method is presented for determining a design rainfall intensity.

Field studies of open-graded friction courses included water depths in simulated and natural rainfall, the effects of tire type, tread depth, inflation pressure, vehicle speed and accumulated traffic.

*Highway-Vehicle-Object Simulation Model

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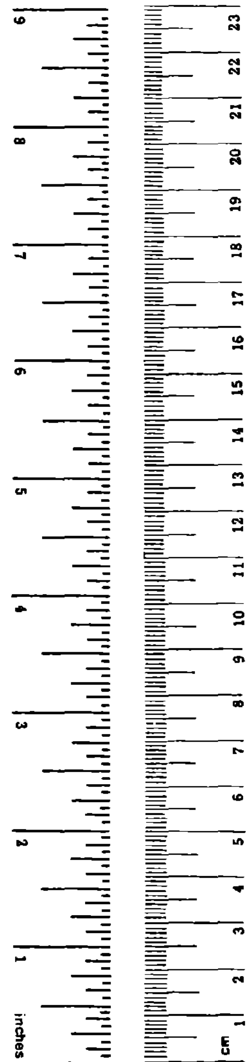
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

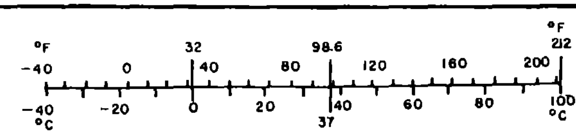
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This is a technical summary of a two-phase study performed under DOT Contract FH-11-8269. The study deals with "Pavement and Geometric Design Criteria for Minimizing Hydroplaning".

The report summarizes the findings of the entire study and concisely presents criteria developed by an eight-man team for pavement surface texture and cross slope, design rainfall intensity, drainage concepts for sag vertical curves, performance of open-graded friction courses in simulated and natural rainfall and suggestions for the modification of pavement geometrics to minimize hydroplaning.

Since this document was purposely condensed for short-time review by technical personnel, the use of references is minimized. Both Phase I and Phase II reports are thoroughly referenced to the appropriate literature.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Mr. Glenn G. Balmer, contact representative of the Federal Highway Administration, for his assistance in securing vital background information for the study and for his counsel and devoted interest in assuring the successful execution of the objectives of the study.

Mr. Balmer's patient and careful review of the various segments of the report during the draft stage has been most helpful to the authors.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF TABLES

EXECUTIVE SUMMARY

The several chapters of this report cover in detail those pavement surface properties, environmental conditions and highway geometrics that are considered inputs to vehicle control via tire-pavement interactions.

Because full dynamic hydroplaning represents essentially complete loss of vehicle directional control, it has therefore been considered a critical aspect of this study even though the occurrence of this phenomenon is rare. Research in tire hydroplaning has been extensive but until this study was carried out, only limited information existed on full-scale field tests which examined a reasonably complete array of variables including vehicle speed, pavement surface texture and cross slope, water depth, tire inflation pressure and tread depth and two modes of tire slip.

Previous data developed at the Texas Transportation Institute in the area of vehicle hydroplaning have been reexamined taking into account the information developed by other researchers, and all of these data have been reanalyzed in light of new information obtained in this study. This complete review considers those references of the spindown trailer, the skid number trailer by both drag link and torque and also includes past and new data on cornering slip for a variety of pavement surface types tested in simulated and natural rainfall.

Traction tests under controlled conditions have included a large array of pavements (among which are 17 different textures formed in portland cement concrete while it was plastic), grooved portland cement concrete, open-graded friction courses and free standing puddles or pools of water. Concrete pavements with both transverse and longitudinal texturing were tested at various degrees of tire slip with other variables of water depth, tread depth, tire type, tire tread depth and vehicle speed.

The torque effect of free standing puddles was measured by continuous recording of forces on the wheels of a specially instrumented full-scale trailer. Dangerous levels of torque were measured. As expected, free standing puddles which engage only one side of the vehicle present a greater danger potential than puddles wide enough to include both sides of the vehicle. Puddles investigated varied in length and depth including lengths to more than 30 ft (9.1 m) and depths up to 1.5 in (38 mm).

In the natural driving environment, pavement surface water is considered a most critical element, hence the probability of the occurrence of rain of given intensity and duration must be considered and examined. It was found, for example, that rainfall intensities of 0.2 in/h (5 mm/h) or greater occur less than one percent of the time for the States of Alabama, Illinois and Texas. Rainfall records for selected states were carefully examined and a method was developed which allows one to calculate a design rainfall intensity for any state or region. This design rainfall intensity is then utilized with other parameters that require consideration in the design and construction of a safe and functional roadway system. It was also found that rainfall in the range of 0.01 in/h (0.25 mm/h) is ample to keep a pavement completely wetted.

For given conditions of wind direction and velocity and given geometrics and pavement cross slope, water depth on the pavement surface becomes a function of the drainage capacity of the pavement. This capacity is lodged in both surface and interconnected internal voids, and these two avenues of water flow join hands with tire tread to minimize the development of hydrostatic uplift at the tire pavement interface. It was found, contrary to the claims of some earlier researchers, that natural drainage of open-graded friction courses was not as effective as was hypothesized. Tests on field cores from properly designed and constructed open-graded surfaces indicate that many of the laboratory measured internal voids are cul de sacs or roundabouts that are only partially effective in the natural drainage of the surface. However, the interconnected fraction of the total measured voids functions more efficiently under the action of a tire, aiding in the relief of hydrostatic pressure buildup.

Factors affecting accident frequency, driver maneuvering and vehicle control were examined; and these included pavement texture, tire inflation pressure, tread depth and vehicle speed. Cross slope was examined as it interacted with vehicle control in passing maneuvers and lane changes. Steering torque and friction demand were examined in light of safe passing speeds and lane change operations utilizing the Highway-Vehicle-Object Simulation Model (HVOSM). For a cross slope of 4 percent and a speed of 60 mph (97 km/h), required aligning torque during a passing maneuver for a tangent path was 750 lbf·in (85 Nm) with a coefficient of friction demand of 0.36. It was concluded from the model study that cross slope values up to 2 percent show no significant detrimental effects on friction demand or driver effort.

Since open-graded friction courses offer the best currently known method of assuring adequate and controlled surface macrotexture and the added bonus of some internal drainage, more extensive evaluations of the accident reduction potential of this tool were considered wise investments. Hence, extensive additional research was conducted in this area in Phase II of the study.

This effort included the usual variables of a well designed study of hydroplaning, i.e., speed, water depth, tire pressure and tread depths and tire design. Four percentages of internal voids were included in the pavements tested. Each pavement had essentially the same surface macrotexture of about 0.10 in (2.5 mm). Overlay thickness was held constant at the recommended 1 in (25 mm) with measured voids from 15 to 25 percent. A pavement cross slope of 1 percent was used throughout the job.

Performance of these surfaces was thoroughly examined in simulated rain, the intensity of which was varied from about 0.2 to 2.0 in/h (5 to 51 mm/h). The most recently published literature in the subject area was reviewed in depth, and the experiments were intermeshed to supplement and complete the data bank in this critical area. It was found, for example, that even the most open surface was flooded in the outside wheel path of the outside lane (a 24-ft (7.3 m) pavement with 1 percent cross slope) at rainfall intensities of about 0.2 to 0.4 in/h (5 to 10 mm/h). However, for the mixture designs and aggregates used on these pavements, the friction developed at 55 mph

(88 km/h) was completely adequate for vehicle control provided tire pressure was at or above 18 psi (124 kPa) and the tread depth was above about 0.2 in (5 mm). This depth roughly represents the median tread depth for vehicles operating on highways.

On flooded surfaces of the open-mix type there are decided advantages in addition to higher friction. Splash and spray are reduced. Of course, in light rains and even in heavier rains of short duration, little or no superficial water collects on any of the pavement surface; that is, the pavement performs essentially as a dry surface.

Various state agencies in the United States have considerable mileage of open-graded friction courses, some of which have been in service for several years. Most of these surface courses are thinner than those examined in this detailed study. A primary factor in establishing thickness is initial cost. The authors consider economic factors relating to raising levels of texture and/or skid resistance of pavement surfaces. The analysis emphasizes long-term costs which include not only the initial costs of the surface but the effects of increased macrotexture and higher friction on tire wear and vehicle rolling resistance.

Rolling resistance is directly related to macrotexture when construction methods and aggregate particle shape are fixed. For a given macrotexture, rounded aggregates offer less rolling resistance than crushed particles. Aggregates of approximately equal microtexture appear to produce tire wear at a rate proportional to the pavement macrotexture, with crushed materials producing somewhat higher wear rates than the more rounded materials. Mixing sequential pavements of high and low friction may represent a decrease in the safety of some drivers.

Sag vertical curves offer areas for special consideration in any accident reduction program whether in the wet or the dry condition. One facet of this study dealt with the performance of sag vertical curves during wet weather. In particular, typical problem situations were studied; and suggested alternative solutions for surface and/or internal drainage are presented.

Innovative concepts for improving the wet weather performance of sag vertical curves are presented and include special surface drainage devices positioned to intercept water and divert it to supplemental subsurface conduits. Open-graded friction courses are used to reduce surface water and to act as subsurface drainage devices. However, excessive rainfall creates water depths that do not lend themselves to economical and/or practical removal. Fortunately, such rains are rather local and quite infrequent and, indeed by their intensity usually limit speeds to safe levels.

In summary this report offers the design engineer the tools and sufficient background information to develop a logical system for improved tire-pavement interaction during wet weather conditions. Implementation of these findings will reduce the number and severity of accidents during wet weather.

INTRODUCTION

Hydroplaning is an event that has been widely misunderstood. In relation to its importance to highway safety, published opinions vary widely. One extreme is that hydroplaning has no significant influence on accidents due to relatively low traffic speeds. The other extreme is that hydroplaning has a great influence on wet weather accidents. The truth must be that both of these opinions are correct at different specific highway sites. In the general case, the truth must lie somewhere between these extremes. Hydroplaning will be shown to be a fairly low probability event, primarily due to the fact that high intensity rainfalls necessary to flood a pavement are low probability events. The nature of the event, however, is so hazardous when it does occur that criteria for surface design to reduce the probability of hydroplaning are warranted.

Some of the earliest investigations and technical reports on hydroplaning came from NACA and its successor NASA and were primarily concerned with hydroplaning of aircraft during landings. In this connection, the U. S. Army Air Corps and its successor U. S. Air Force also did valuable work. Later the Road Research Laboratory in Great Britain began investigations related to automobiles. Concurrent with this research, the Americans and Germans studied tires and road surfaces to seek their own answers. Most recently, the Highway Research Board (now the Transportation Research Board), the National Cooperative Highway Research Program and the Federal Highway Administration have encouraged and are financing studies related to tire-pavement interaction and hydroplaning, studies that are bringing the "state of the art" to a most respectable level.

The following subjects cover the main areas where good information has been found or developed.

1. The definition of full dynamic hydroplaning conditions.
2. The definition of changes in available friction as full hydroplaning is approached as a function of a variety of textural conditions, both random and patterned.
3. The definition of road surface geometry and how it affects the accumulation of water under various environmental conditions.
4. The interrelationship of different methods of measuring hydroplaning.
5. The performance of open-graded friction courses during rainfall conditions.
6. The probability of different conditions relating to hydroplaning such as tire condition and rainfall intensity.
7. The influence of various pavement cross slopes on driver workload and performance, as indicated by vehicle accelerations and friction demand levels.
8. Determination of the drainage properties of sag vertical curves and innovative drainage concepts for these geometric situations.

In Chapter IX indications of the range and frequency of important factors such as tread depth, tire pressure, surface texture, cross slope and rainfall intensity are used to develop design criteria.

The implementation of criteria and recommendations for surface texture and pavement cross slope to minimize hydroplaning has the potential for a significant impact on the high wet weather accident toll. The information contained in this report justifies this action. Further, it is hoped that the means used to accomplish this reduction may be extended to other nations that are now experiencing similar problems.

CHAPTER I

THE PHENOMENON OF HYDROPLANING

Hydroplaning is the separation of the tire from the road surface by a layer of fluid. On a microscopic scale all operational conditions may involve some degree of partial hydroplaning as long as there is any significant amount of water present. On a macroscopic scale, however, this zone can be defined as occurring during those operational conditions when there is some significant degree of penetration of a water wedge between the tire and pavement contact area.

Hydroplaning of pneumatic-tired vehicles has been divided into three categories by Horne (1). These categories are

1. viscous hydroplaning,
2. dynamic hydroplaning and
3. tire tread rubber reversion hydroplaning.

Viscous and dynamic hydroplaning are the important types of hydroplaning insofar as passenger cars are concerned as tire-tread-reversion hydroplaning occurs only when heavy vehicles such as trucks or airplanes lock their wheels when moving at high speeds on wet pavements with macro but little microtexture. Viscous hydroplaning may occur at any speed and with extremely thin films of water. Browne (2) states that wet friction hydroplaning occurs only on surfaces where there is little microtexture. A thin film of water remains between the tire and pavement since there is insufficient pavement microtexture to promote the breakdown of the water film.

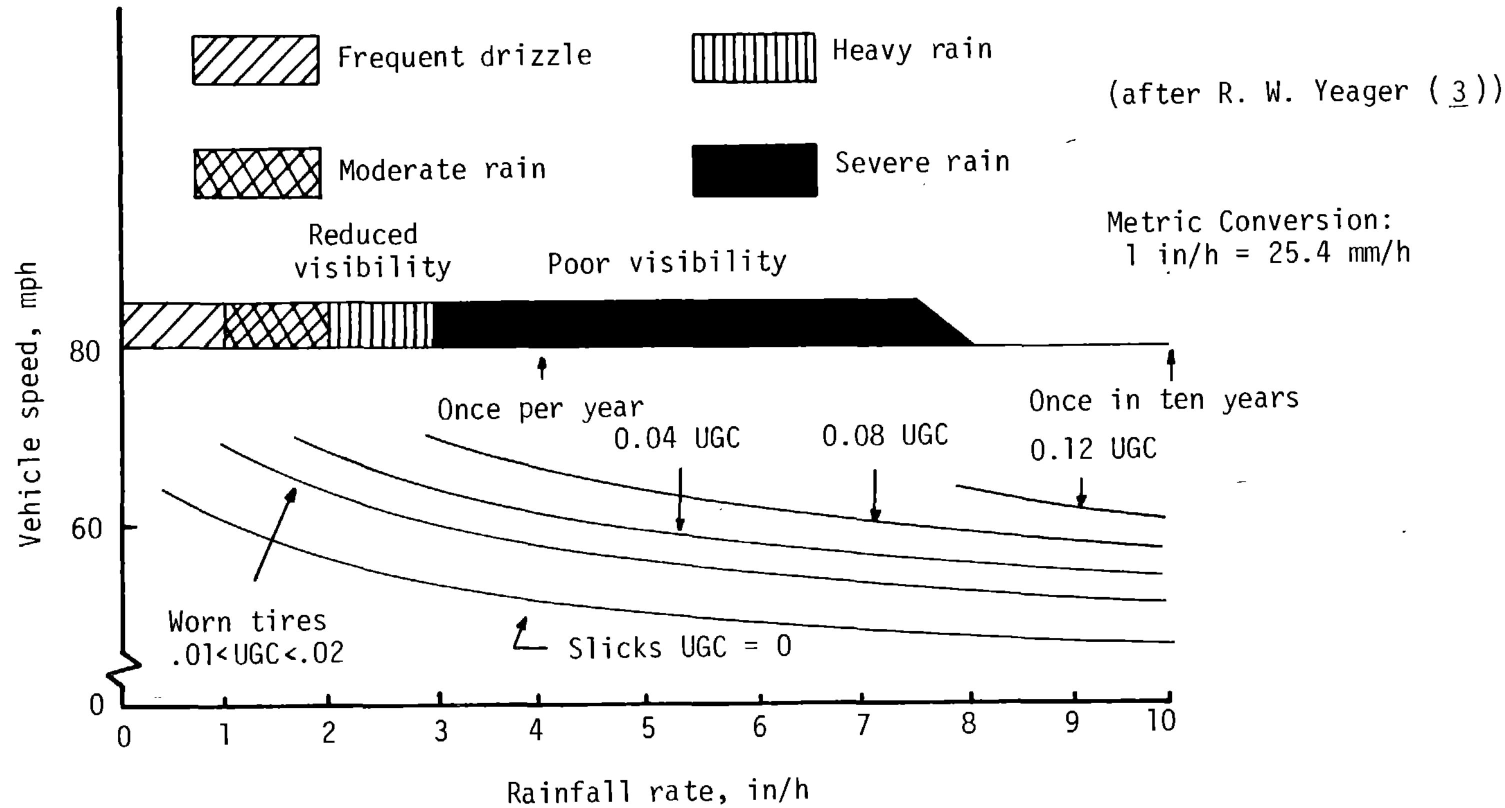
A variety of equations has been developed to predict the speed at which hydroplaning will occur. These equations are summarized in Table 1. The first equation is of value primarily as a definition of the phenomenon of viscous hydroplaning rather than as a prediction of viscous hydroplaning speeds. Equations 2 through 5 predict hydroplaning minimum speed. Equations 1, 2, and 3 have limitations, primarily because they were derived independently of the surface texture characterization. Equation 4 does consider one aspect of pavement texture through the factor K_1, but K_1 must be determined empirically if the equation is expected to be accurate. Equation 4 must be used in conjunction with Figure 1 in order to estimate hydroplaning speed. The procedure is to determine the unit groove capacity (UGC), then determine the proper position on the chart for either of the two stated combinations of cross slope and drainage path length by selecting a specific rainfall intensity. It should be noted that this predictive method is not comprehensive in terms of combinations of cross slope, pavement texture and drainage path length, but is limited to the two combinations tested. Another aspect of the wet weather safety problem which has a definite interaction with the speed most drivers are content to drive is that of visibility. Yeager (3) includes an estimate of this characteristic for different intensities of rainfall in Figure 1.

One of the most significant studies of the influence of tread design on hydroplaning speed was conducted by Gengenbach (4). In this study he

Table 1. Equations to predict hydroplaning speed

Equation	Definition of Variables	References
1. $V_H \geq L/\Delta T_{sf}$	V_H = minimum speed necessary for viscous hydroplaning L = the length of the tire footprint region ΔT_{sf} = the amount of time necessary for the water film thickness to be sufficiently reduced so that contact is made between the tread rubber and the pavement microasperities	Browne (2)
2. $V_H = 1.8\sqrt{P_{IN}}$ * $V'_H = 6.35\sqrt{P_{IN}}$	V_H = the limiting dynamic hydroplaning speed in m/s V'_H = the limiting dynamic hydroplaning speed in km/h P_{IN} = the tire inflation pressure in kilopascals (kPa)	Horne and Joyner (5)
3. $V_P = 0.592\sqrt{\frac{228F_v}{\rho A_G C_{L,S}}}$	V_P = hydroplaning speed in mph F_v = vertical ground force ρ = fluid density A_G = tire contact area $C_{L,S}$ = hydroplaning lift coefficient	Horne and Dreher (6)
4. $V_H = f(UGC)$ $UGC = \frac{K_1}{W_T}\sum_{i=1}^{n} w_i d_i$	V_H = hydroplaning speed in mph (The function of UGC, f(UGC), is given graphically by Yeager.) K_1 = weighting factor to consider lateral grooving and blading n = number of ribs w_i and d_i = individual widths and depths of each groove as obtained dynamically on a wet glass plate W_T = effective width of tread	Yeager (3)
5. $V = 508\sqrt{\frac{Q}{B\ t\ C_H}}$	V = hydroplaning speed in km/h Q = wheel load in kg B = maximum width of contact patch in mm t = thickness of water film in mm C_H = hydroplaning lift coefficient	Gengenbach (4)

*Metric conversion of $V_P = 10.35\sqrt{P}$ in which P is the tire inflation pressure in psi and V_P is in mph (5,2).



Water depth (in)											
	0.030	0.045	0.057	0.067	0.075	0.082	0.088	0.093	0.097	0.101	2.1% Slope, 11 ft drainage length
	0.045	0.060	0.072	0.082	0.092	0.102	0.110	0.117	0.124	0.130	1.56% Slope, 22 ft drainage length

Figure 1. Estimated free rolling minimum full dynamic hydroplaning speed for passenger tires. (Conditions: relatively smooth surface, rounded footprint, and rated inflations and loads.)

compared seven conventional bias-ply tires with a variety of tread patterns designed and cut into the tire so that the total volume of grooves was constant (groove area ratio was 20 percent).

One conclusion not drawn by Gengenbach seems appropriate here. While for bald tires hydroplaning was observed at water depths as low as 0.01 in (0.3 mm) for treaded tires, no hydroplaning data have been found in the report for water depths less than 0.08 in (2 mm). Evidently, for the low values of texture between 0.005 and 0.008 in (0.13 and 0.20 mm), depending on embedment of the grains in the retaining cement, treaded tires did not hydroplane at water depths less than 0.08 in (2 mm). It is noted that there was space for almost all the water in the contact patch within the grooves. It should be understood that Gengenbach's tests were conducted in a drum facility where very small water depths could be controlled with extreme precision. On highway surfaces dynamic hydroplaning by tires with minimal $<\frac{2}{32}$ in (<1.6 mm) tread depths was not achieved whenever the average water depth was less than 0.06 in (1.5 mm).

In addition to the findings of research efforts already cited, the authors are fortunate in that several research projects relating either directly or indirectly to hydroplaning have been recently completed. These projects proved to be useful in the development of a quantitative definition of partial hydroplaning conditions.

The study directly related to hydroplaning, HPR-147 (7), is an extensive empirical study of tires, pavements and water depths which compare closely to real highway conditions. The water depths are all over 0.1 in (2.5 mm) and therefore extend the information available to the larger water depth conditions. These tests show a range of full dynamic hydroplaning speeds from 45 to 77 mph (72 to 124 km/h).

In developing the body of data in HPR-147 the indication of hydroplaning which was used was the spindown of a test wheel when moved in a freely rolling condition across a section of pavement covered by a significant layer of water. Spindown is usually given in percent as dictated by the following equation:

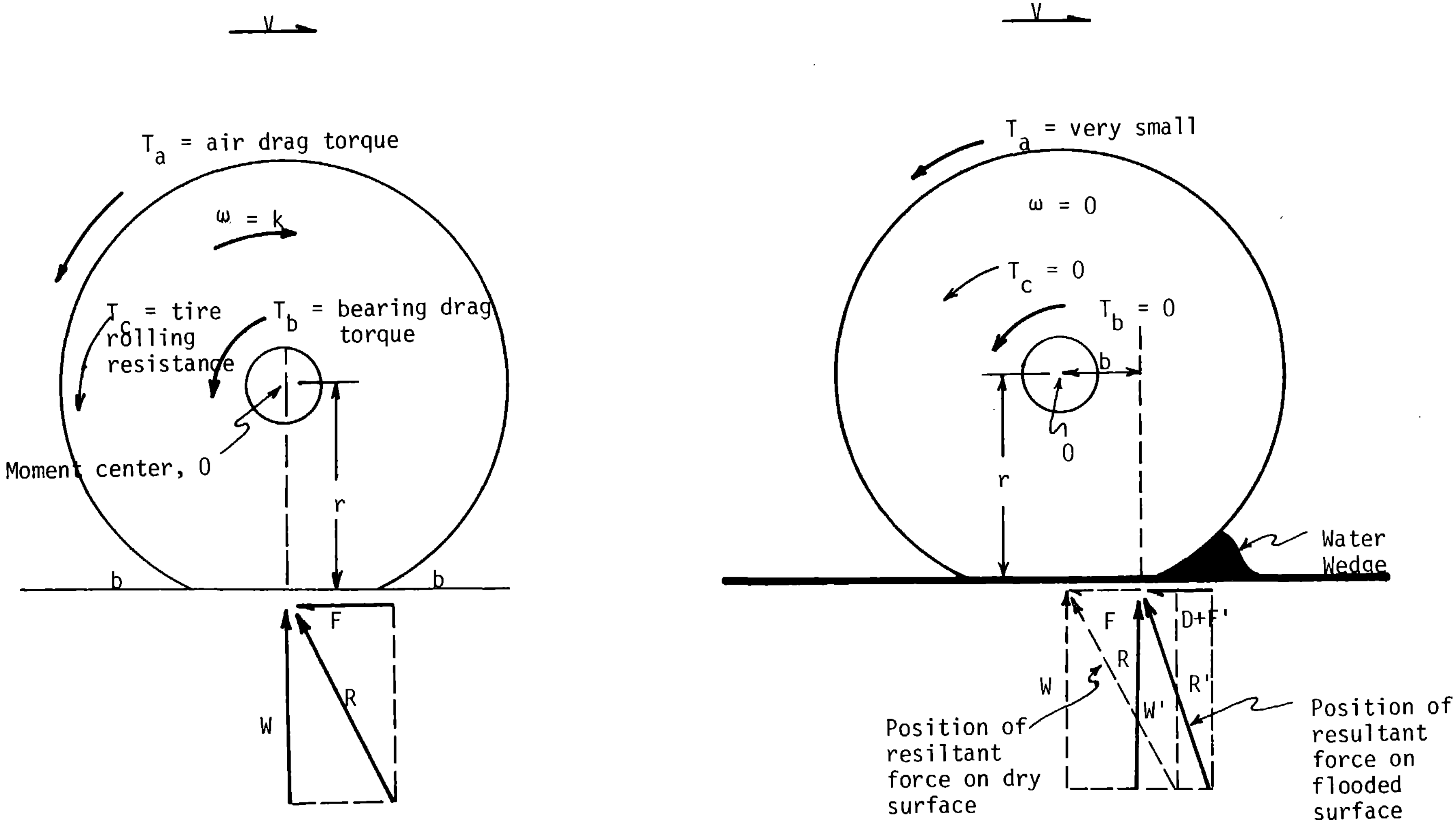
$$SD = \frac{\omega_d - \omega_w}{\omega_d} (100) \qquad \text{Eq. (6)}$$

where

ω_d = rotational velocity of the rolling wheel when on a dry surface

ω_w = rotational velocity of the wheel after spinning down due to contact with a flooded pavement.

Figure 2 will be used to illustrate the forces acting on the tire in two extreme conditions: (1) freely rolling on a dry surface and (2) the condition of 100 percent spindown when the tire is sliding across a water surface with little, if any, direct contact between tire and pavement surface. At 100 percent spindown, the rotational velocity of the tire is equal to zero.



(a) Wheel freely rolling on dry surface.

(b) Wheel not turning, 100 percent condition.

Figure 2. Forces acting on tire in two extreme conditions.

In the freely rolling condition with the rotational velocity a constant, K, a summation of moments about the center of the wheel is given by

$$Ta + Tb + Tc = Fr$$

when the vertical component, W, of the resultant force, R, is assumed to pass through the moment center, O, or to pass so close to it that the torque induced by W is negligible. Thus, in order for the tire to rotate at the constant value of ω, without significant contact zone slip, only enough friction needs to be developed to overcome the retarding effects of rolling resistance, which includes bearing friction and air drag. Thus, the value of F is small with respect to W. Up to 60 mph (97 km/h) the rolling resistance is generally less than 2 percent of W (8).

In the 100 percent spindown condition, a condition considered to be indicative of full dynamic hydroplaning, the resultant force, R, changes to some degree in magnitude; but the major change is in its line of action. These changes are caused by (1) the destruction of friction between tire and pavement surface, (2) the development of pressure on the tire in the region of contact with the water wedge and (3) the development of a hydrodynamic drag force on the tire-water interface.

The resultant force, R', can still be resolved into two components, the vertical, W', equal to the weight supported by the wheel and the horizontal force, D + F'. Hydrodynamic drag, D, is due to the inertia of the water over and through which the tire is sliding. F' is some small remaining value of tire-pavement friction. Now the moment summation gives

$$W'b = (D + F')r$$

Thus, the change in line of action of R' produces a counterclockwise torque due to W which counteracts the torque due to D. Stated another way, the line of action of R' moves to a position which includes the moment center, O, resulting in negligible torque on the wheel.

In interpreting the meaning of hydroplaning data developed under HPR-147, it was concluded that significant control forces between the tire and the pavement did not exist at high values of wheel spindown, i.e., over 50 percent. Further, the difference between 10 percent spindown and 50 percent spindown when expressed in mph (test vehicle speed) was so small that 10 percent spindown was chosen as the indicator of hydroplaning. Further testing during this study indicated that almost full dynamic hydroplaning was present with as little as 10 percent spindown. In order to make maximum use of the test data, it was necessary to develop a general equation that would allow the vehicle speed to be predicted as a function of SD and of the variables denoting test conditions. These parameters were as follows:

1. V, vehicle speed in mph ((km/h)/1.609)
2. TD, tread depth in 32nds of an inch (mm x 32/25.4)
3. TXD, texture depth in inches (mm/25.4), Silicone Putty Method

4. WD, water depth (above the asperities in inches (mm/25.4))
5. P, tire pressure in psi (kPa/6.895)*
6. SD, spindown percent.

Based on data from approximately 1,300 tests and the curves of SD vs. V which fit these data for specific test conditions, 1,038 points were selected at SD values of 10, 30 and 60 percent. The equation which produced the best fit of these data is as follows:

$$V = SD^{0.04} P^{0.3} (TD + 1)^{0.06} A \qquad \text{Eq. (7)}$$

where A is the greater of

$$\frac{10.409}{WD^{0.06}} + 3.507 \quad \text{and} \quad \left[\frac{28.952}{WD^{0.06}} - 7.817\right] TXD^{0.14}.$$

In this case the greater value of A would always be used.

Figure 3 shows how the data are fit by Equation 7. Approximately 99 percent of the observations lie within plus or minus 5 mph (8 km/h) of the predicted value. The value of the calculated correlation coefficient is 0.85.

Further evaluation of this equation by comparison to full-scale tests of vehicle control is presented in the full report (9). At this stage, it represents the most comprehensive estimate of dynamic hydroplaning speed. It can be combined with methods of estimating water depths, presented in Chapter V, to predict critical speed for specific tire tread, tire pressure and texture depth conditions.

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*Throughout this Technical Summary equations generally appear in English units with suitably associated constants. Where metric measurements are utilized for input to these English unit equations, the metric values must first be converted to English units then inserted in the equation. Metric-to-English unit conversions appear in parentheses as shown above. This approach prevails throughout the report.

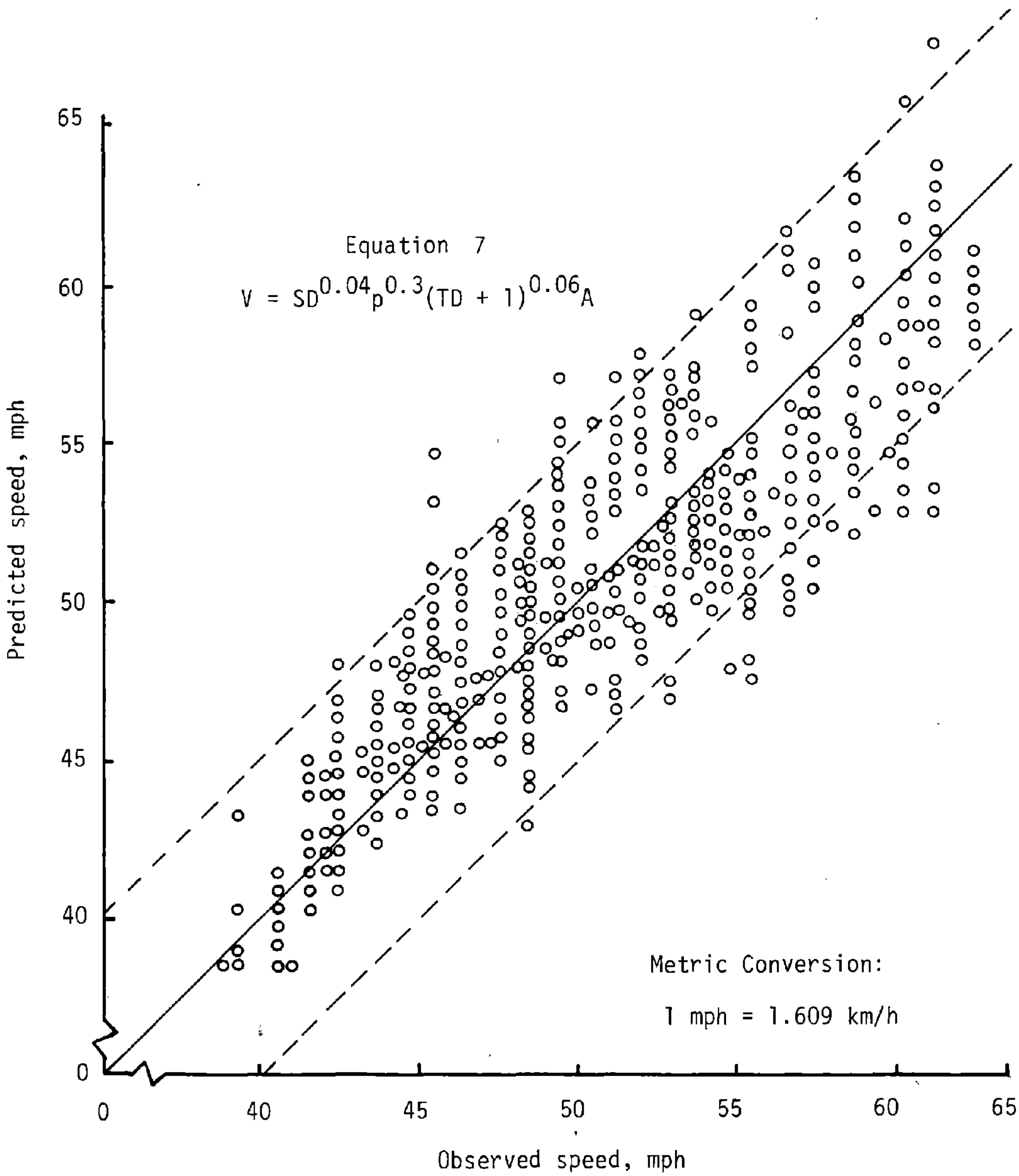


Figure 3. Data scatter for hydroplaning equation.
(Data points at 10, 30 and 60 percent spindown.)

CHAPTER II

HYDROPLANING AND TRACTION TESTS UNDER CONTROLLED CONDITIONS

A series of tests were performed under relatively controlled conditions in the "hydroplaning trough". This facility consists of a pair of rails 2.5 ft (0.76 m) apart and 800 ft (244 m) long. The underlying surface has a longitudinal slope of about 1 percent, and water can be injected at the upper end and allowed to slowly flow over the surface contained by the rails. Various flow rates permit the water depth throughout the trough to be varied, and different surfaces can be installed within the trough.

The tests were performed with the TTI research trailer which, in addition to the capability of measuring ASTM E274 locked-wheel skid numbers, can measure test wheel rotational speed referenced to a fifth wheel which measures forward speed. Horizontal force, vertical force and torque can be measured with the test wheel locked or freewheeling.

Test Conditions

The primary test matrix was as follows:

SURFACES: Open-graded hot mix and lightweight aggregate slurry seal.
TIRES: ASTM E501 and B. F. Goodrich FR 78-14 steel-belted radial.
TIRE PRESSURE: 24 and 18 psi (165 and 124 kPa).
TREAD DEPTHS: 11/32 and 2/32 in (8.7 and 1.6 mm).
WATER DEPTHS: 3/32 and 8/32 in (2.4 and 6.4 mm).
NOTE: All combinations of tire, tread depth, tire pressure and water depth were used on each surface.

A longitudinally grooved portland cement concrete (PCC) surface was in the trough at the time testing began. Preliminary tests were conducted on this surface. This was followed by overlaying a coarse open-graded surface, and the full test matrix was performed. This surface was then overlaid with a uniform lightweight aggregate slurry seal of medium texture, and the tests were repeated.

Locked-wheel "skid numbers" were determined both in the external water conditions and using internal water (ASTM E274 procedure) on this dense, medium-textured surface.

As an adjunct, freewheeling spindown and horizontal drag forces were measured while traversing "puddles" of various lengths and depths.

Preliminary Tests on Grooved PCC

The TTI research skid measurement system was adjusted and calibrated, and an exploratory test program was conducted on the existing surface. These tests were run in 3/8 in (9.5 mm) (average) water depths using an ASTM E501 tire with 2/32 in (1.6 mm) tread depth and 24 psi (165 kPa) (cold) inflation pressure. The runs were conducted in the following three speed conditions: while accelerating, during deceleration and at incremented constant speeds.

Both freewheeling and locked-wheel data were obtained from the horizontal force and torque transducers. In addition, standard ASTM E274 skid numbers (and traction forces) were obtained in the trough using the internal watering system and a fully treaded but broken-in ASTM E501 tire.

With external watering, there was a smooth, though not necessarily linear, loss of traction with increased speed until the tire lost contact with the pavement, at which time the horizontal force leveled out at that produced by hydrodynamic drag (see Figure 4). In addition, it appears that horizontal force, F_H, for a given speed is not dependent on whether the vehicle is accelerating or decelerating through the speed, or travelling at a constant speed. This fact allows data points to be obtained at several speeds during one run. In general, a speed change of about 10 mph (16 km/h) was used in succeeding tests. It takes about 15 minutes between runs for the water depth to restabilize, so this technique results in considerable time saved. At speeds above "full hydroplaning", the horizontal force under these conditions is about the same (~90 lbf) (~400 N) whether locked-wheel or freewheeling.

Figure 5 shows that the horizontal force measured on the torque transducer, F_T, exhibits the same trend but is consistently about 70 lbf (311 N) lower than that measured on the horizontal force transducer. These transducers read the same under static (force plate) calibration. A simple analysis of the force and torque mechanisms indicates that the lower torque force can be explained by a 0.8 in (20.0 mm) dynamic forward shift at the "center of effort" as opposed to the force plate condition. The wedge of water in front of the tire in the dynamic test condition could very well cause this degree of shift.

It is also interesting to note that the total rolling resistance, both dry and with internal watering, is about 20 lbf (89 N) while the drag in 3/8 in (9.5 mm) of water is about 90 lbs (400 N), a difference of 70 lbf (311 N). In addition, the freewheeling drag forces above are relatively speed independent except at low speeds in the external water condition. Again, accelerating, decelerating or constant speed seems to make no difference within the band of precision.

Figure 6 compares the locked-wheel "coefficients" using ASTM E274 procedure (full tread tire and internal watering) with a similar procedure for a 2/32 in (1.6 mm) thin tread and 3/8 in (9.5 mm) external watering. The "traction coefficients" are equivalent at about 35 mph (56 km/h).

Figure 7 indicates the percent spindown as a function of vehicle speed. The spindown starts to occur at about 46 mph (74 km/h), the speed at which the horizontal force becomes constant and equal to the freewheeling drag force. The curves for accelerating, decelerating and incremented constant speeds cannot be significantly resolved. Apparently, when spindown is detected, the tire has lost contact with the pavement and only hydrodynamic forces, which seem to be speed independent in the test conditions, are present.

Figure 8 shows the time as a function of speed for the wheel to reach zero spindown after unlocking the brake. Obviously it takes a finite time for this to occur even on dry pavement. However, the rather sharp divergence

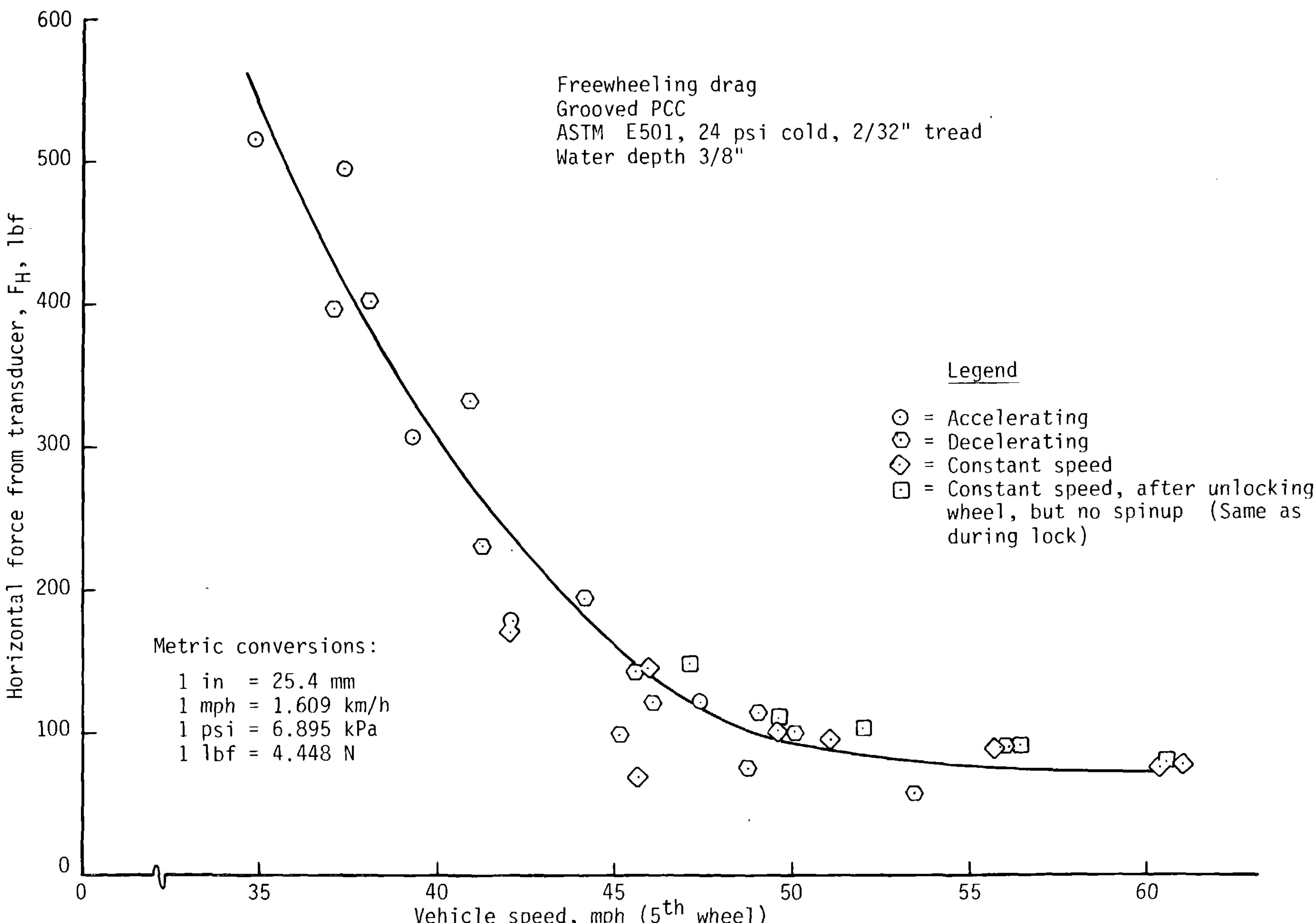


Figure 4. Locked-wheel horizontal force from force transducer vs. 5th wheel vehicle speed.

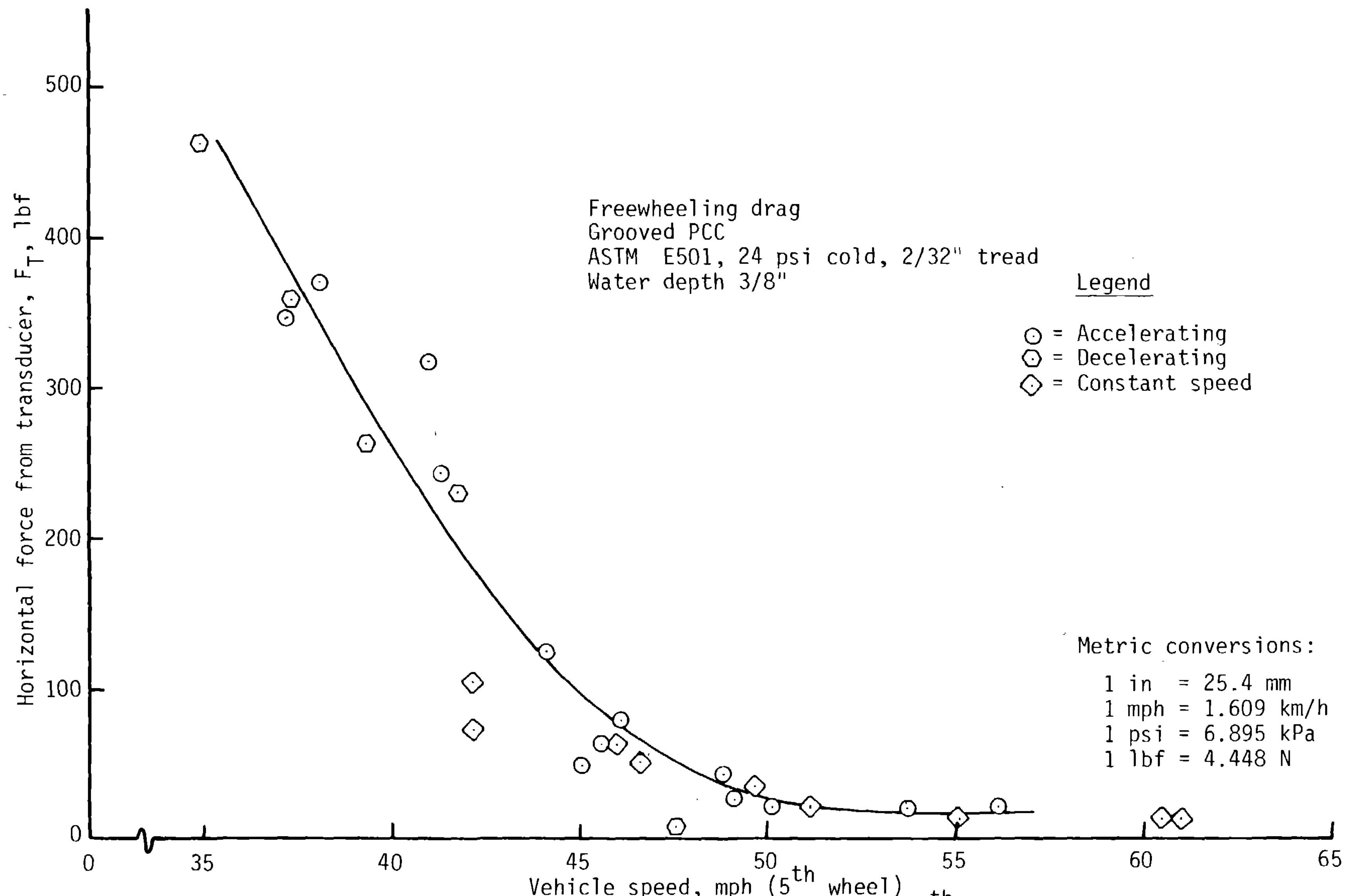


Figure 5. Horizontal force from torque transducer vs. 5th wheel vehicle speed.

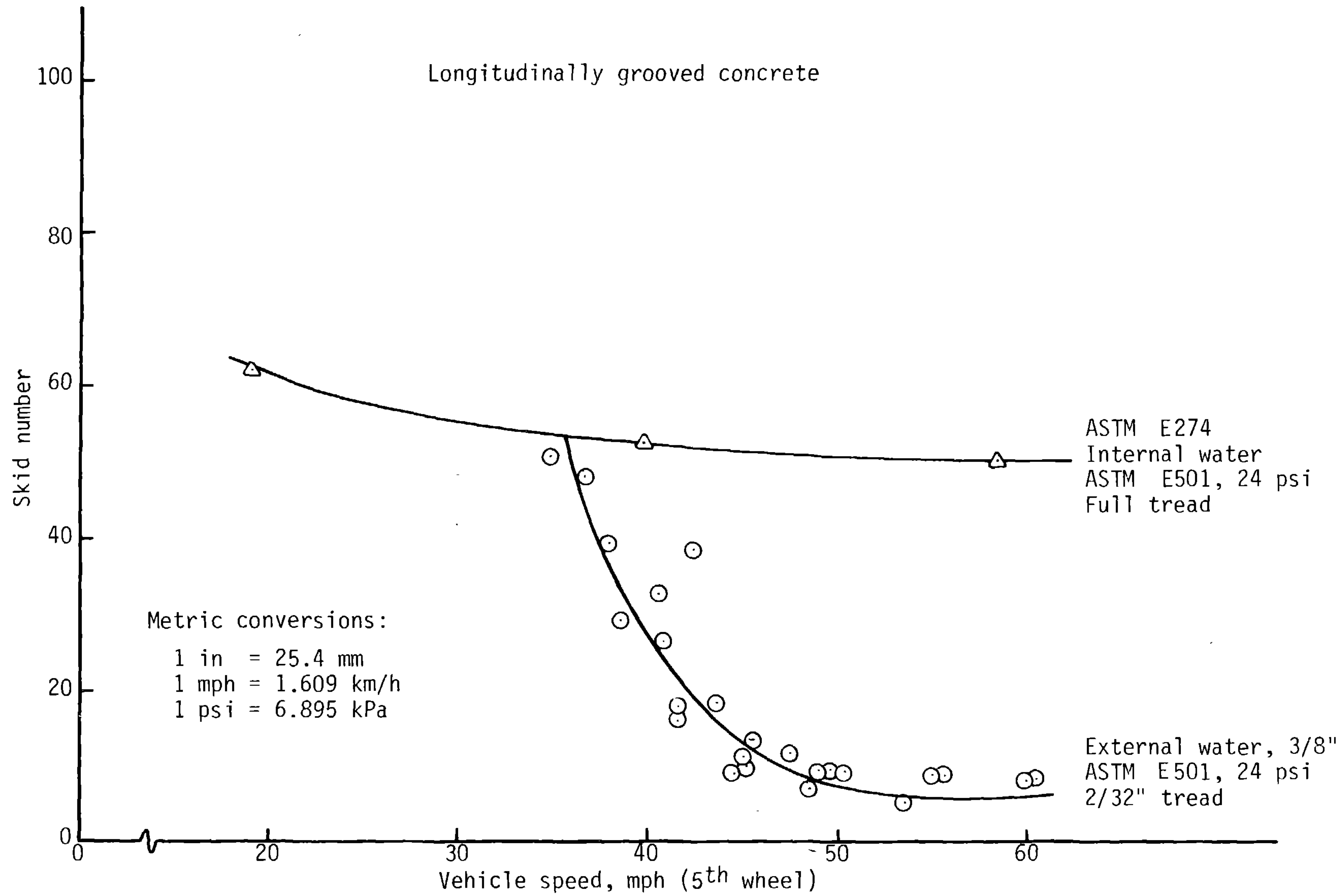


Figure 6. Locked-wheel skid number vs. speed.

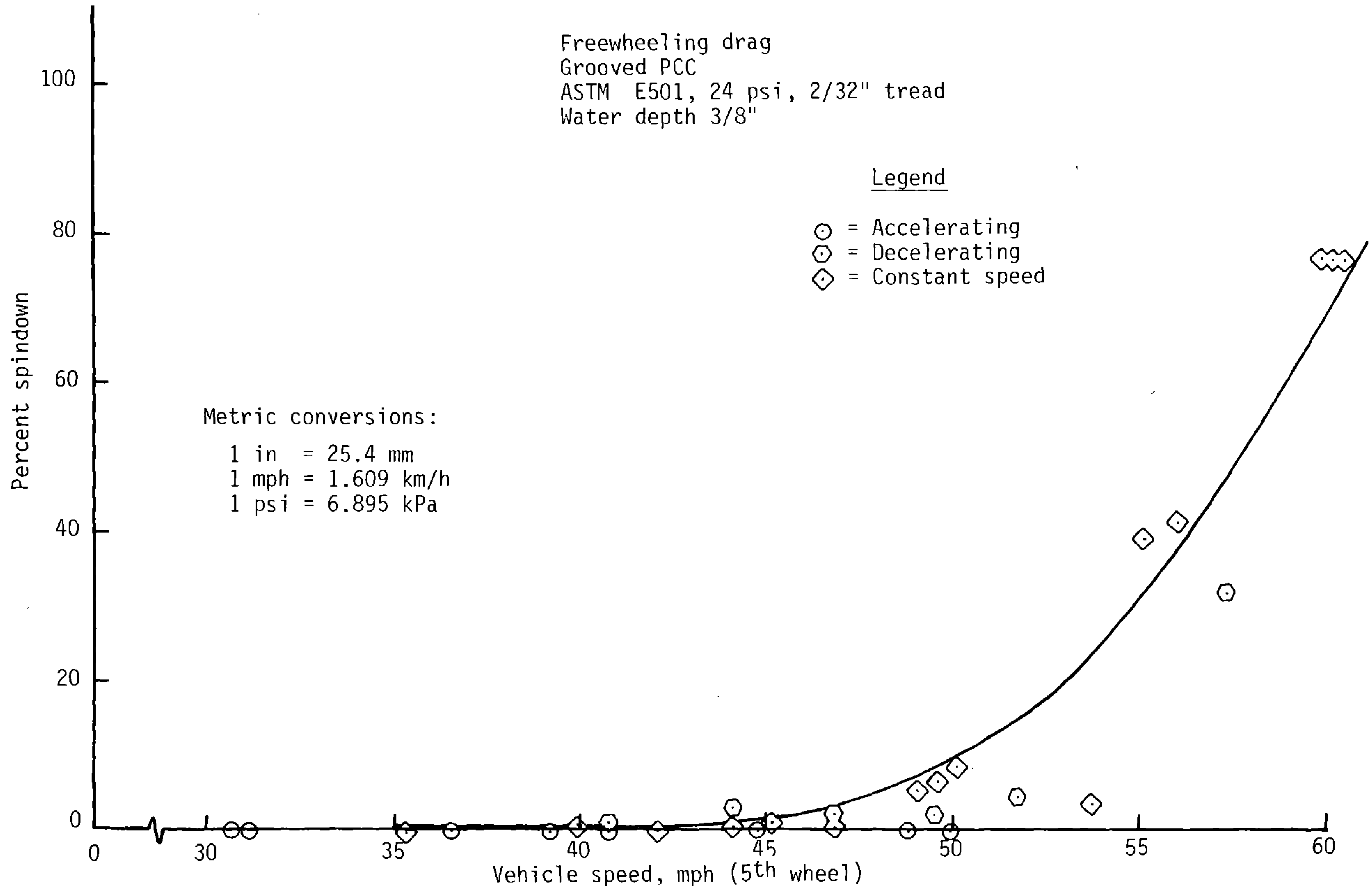


Figure 7. Percent spindown vs. vehicle speed.

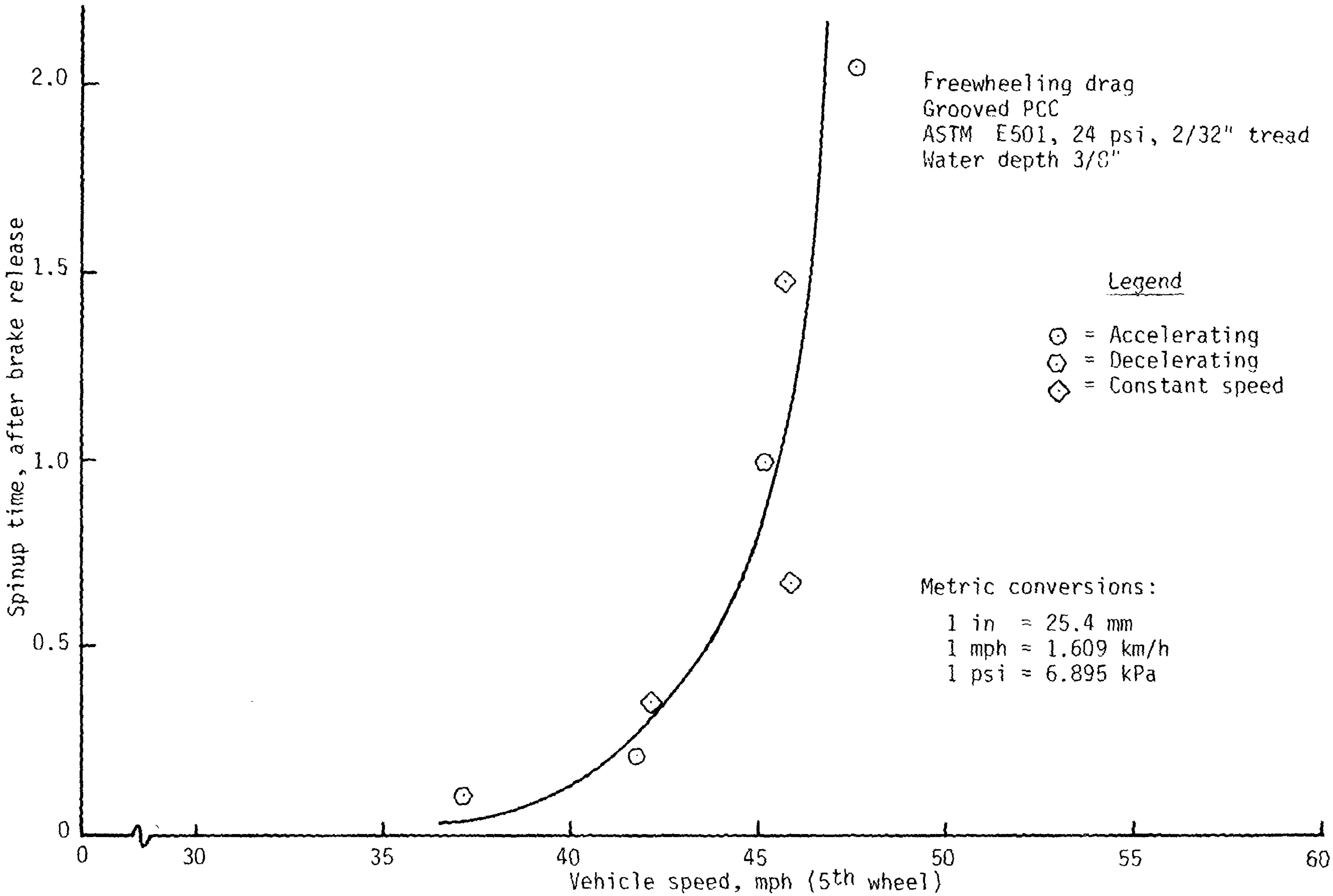


Figure 8. Spinup time vs. 5th wheel vehicle speed.

of spinup time near 46 mph (74 km/h) indicates that this may be a more sensitive indicator of "full hydroplaning" speed, or the speed at which essentially all pavement contact is lost, than is spindown.

Summary of Observations from Preliminary Tests on Grooved PCC

1. Under the stated test conditions, the freewheeling drag force is approximately constant at 90 lbf (400 N), and is the same as the locked-wheel horizontal force above the apparent "full hydroplaning" speed of 46 mph (74 km/h). If asymmetrically distributed, this could cause unstabilizing yaw forces on a vehicle.
2. Except for hydrodynamic drag, the locked-wheel horizontal force is the same as the internal water horizontal force at about 35 mph (56 km/h) and below, but it decreases smoothly to a minimum at "loss of contact" where it equals the freewheeling drag at 46 mph (74 km/h) and above.
3. Percentage spindown and spinup times as functions of speed diverge from the horizontal at about 46 mph (74 km/h), but spinup time does so more dramatically and may be a more sensitive indicator of full loss of physical contact.
4. In 3/8 in (9.5 mm) water, the force from the torque transducer is consistently about 70 lbf (311 N) lower than the force from the horizontal force transducer when calibrated to read the same statically on the force plate. This can be accounted for by a shift of the "center of effort" forward about 4/5 in (20 mm) when in the 3/8 in (9.5 mm) deep water.
5. No significant difference was apparent in any case if the data were taken at different speeds while accelerating or decelerating, or at different speeds using discrete constant speed runs. This allows a significant saving in number of individual runs and time consumed.
6. The freewheeling drag force is about 20 lbf (89 N) dry or with internal water, about 90 lbf (400 N) in 3/8 in (9.5 mm) water and about 90 lbf (400 N) either locked or freewheeling above full hydroplaning speed.
7. No quantitative estimate of the effect on cornering was made, but one can assume that at full hydroplaning the directional control would be negligible. This is an area that needs investigation.

Tests on Asphalt Surfaces

Figure 9 is an example of the results on the two surfaces with the various combinations of tire inflation pressure and water depth. The ordinate is labeled "Skid Number", but technically the upper pair of curves are the ASTM E274 skid number with E501 tire, full tread and 24 psi (165 kPa) cold inflation pressure. These are the values that would be measured on the two surfaces under contemporary road skid resistance inventory techniques. The lower pair of curves are results under the stated conditions using the FR 78-14 steel-belted radial tire which is an example of the current real-world tire population.

Again, we see that with water covering the asperities, loss of traction begins to occur as low as 20 mph (32 km/h). The open-graded surface has a

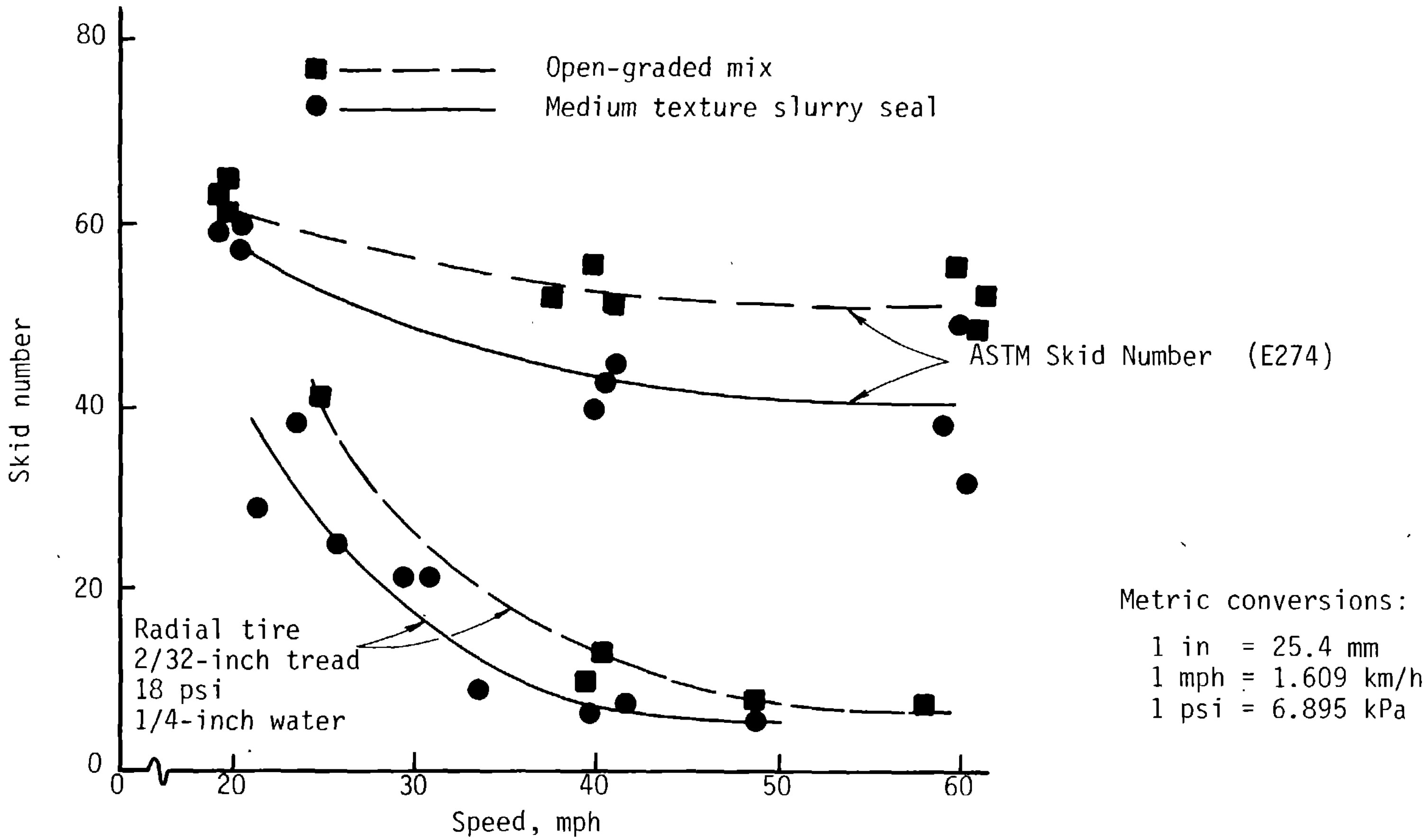


Figure 9. Comparison of open-graded and slurry seal surfaces.

higher skid number and in general provides more traction under "partial hydroplaning" conditions. Usually, as would be expected, the curves tend to converge at higher speeds where loss of pavement contact occurs.

On the slurry seal surface, spindown is first detected at the point where "SN" curve flattens out. The spindown on the open-graded mix was only detected in two cases, and then only briefly. This surface was not as smooth as the slurry seal, and the tire may have been contacting enough high points to prevent spindown in the freewheeling condition but not in contact firmly enough to generate higher traction at the higher speeds.

On the slurry seal surface which usually produced a definite spindown, comparisons were made of the speeds at which some spindown began to appear. With both water depths, the lowest speed at which spindown began was, expectedly, with low tire pressure and low tread depth; and the highest initial spindown speed occurred with high tread and pressure. The combinations of high tread and low pressure and low tread and high pressure fell in between.

Within the range of test conditions used, the speed at which spindown began to occur decreased with increasing water depth; and the largest decrease due to increasing water depth occurred with the combination of higher tire pressure and lower tread depth. Similarly, the largest change in "onset" speed due to changing tire pressure occurred with low tread depth and low water depth. Finally, the largest change due to decreasing tread depth occurred with the combination of higher tire pressure and greater water depth.

Comparing the effects of changing tire pressure alone and water depth alone showed no clear-cut and consistent variation in traction. However, the higher tire tread depth seemed to consistently improve traction, at least at some speed, under all conditions.

Figure 10 represents data using the ASTM E501 tire only. Again, the upper curves represent ASTM E274 skid numbers on the two surfaces. The lower pair of curves compare results on the two pavements using various combinations of tire pressure, tread depth and average water depth.

The results using external water were much more consistent with the ASTM tire in all combinations of conditions. Usually, the open-graded surface provides significantly more traction at lower speeds, with the traction converging at hydroplaning speeds. (Actually, at these speeds the "traction" is primarily hydrodynamic drag.)

The effect of tire inflation pressure with other parameters constant is not consistent, and only in some cases does increased pressure significantly improve the traction on one or the other of the surfaces. The same can be said of the effect of water depth in the range used. However, increased tread depth, for a given inflation and water depth, causes a significant improvement on both surfaces except at higher speeds where full hydroplaning occurs.

Tests in Free-Standing Pools ("Puddles")

A limited number of freewheeling runs was made on the PCC surface through puddles of standing water following a rain. The puddles ranged from 30 to 50 ft (9 to 15 m) in length and 1/4 to 1-3/4 in (6 to 44 mm) in depth.

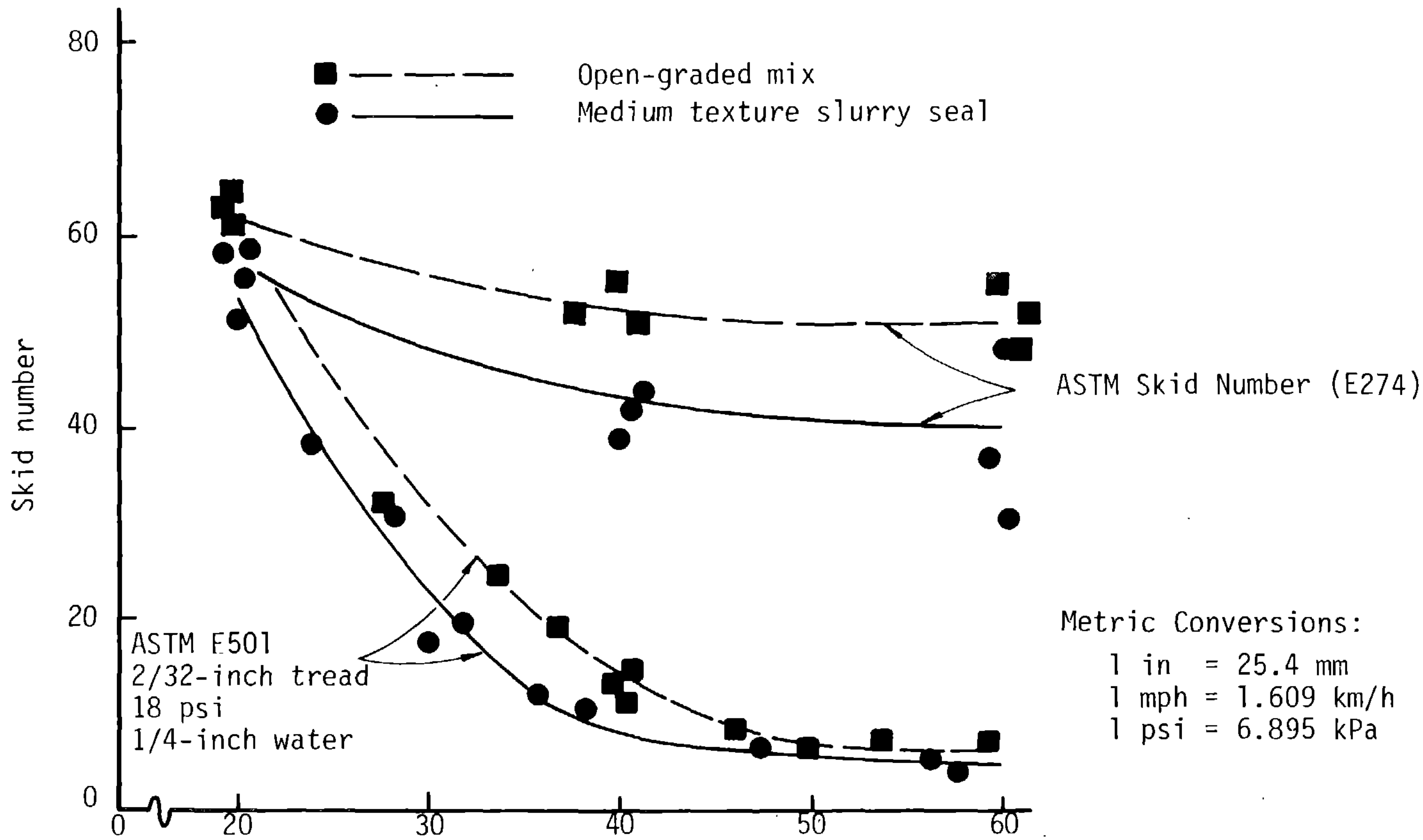


Figure 10. Comparison of open-graded and slurry seal surfaces.

The test wheel was centered between the two vehicle tracks. The effect of tow vehicle wake on the water condition at the test wheel is unknown, so these tests can only be interpreted qualitatively in regards to water depths.

The data were not highly reproducible because of some water loss or redistribution following a run, and possibly because of the short duration of the interaction. The tire used was the FR 78-14 radial, with 2/32 and 11/32 in (1.6 and 8.7 mm) tread depths and 24 psi (165 kPa) inflation pressure.

Some spindown began between 40 and 49 mph (64 and 79 km/h) in all cases.

Peak longitudinal drag forces were as high as 300 lbf (1.3 kN) on the test wheel. If this force were applied to one vehicle front wheel only, it could have a significant vehicle destabilizing effect. Such an event might occur in a situation in which water collects along a curb due to cross slope and/or poor drainage.

To obtain a rough estimate of the potential real-world effect, some simple computations were made using a hypothetical vehicle weighing about 3400 lbs (1.5 Mg), with a wheel base of 112 in (2.84 m) and track width of 60 in (1.52 m). A conventional American automobile of this size would have a vertical load on each front wheel of about 1000 lbs (454 kg). If we neglect inertial effects and compute the produced torque about the center of gravity (not necessarily where it should be computed), then it would take a corresponding opposing torque to counteract it to maintain directional stability.

Now if we assume that the opposite front wheel were on pavement that is only wetted, with no standing water, this opposing torque could be applied by developing a cornering slip angle by steering. Data for a typical tire on wetted pavement indicate that a front wheel slip angle of about 2 degrees would be required. For a typical steer ratio of about twenty-to-one, this would require a steering wheel correction of about 40 degrees. If such a correction were made, and full pavement contact were suddenly regained, it could cause a divergence toward the opposing traffic lane before appropriate steering recorrection is possible.

In this case in which both front wheels are fully hydroplaning, but unequal water depths exist laterally, the unequal drag forces would cause yaw instability with little or no corrective steering capability available to the driver.

Irrespective of the accuracy or validity of the example computation, there is little doubt that the kind of drag forces generated by positive water depths distributed unevenly would pose a hazard to unwary drivers.

General Observations

The following observations were based on results of the tests described in this chapter. Obviously, sweeping generalizations cannot be made based on a small fraction of the possible real-world conditions. However, valuable insights can be obtained, and areas that seem to be worthy of further consideration can be identified from tests under controlled conditions.

1. Under all test conditions, the open-graded pavement provided as much, and usually more, traction than the asphalt slurry seal

except at full hydroplaning where they are about equal. The open-graded surface has the added advantage of reducing the probability of positive water depths in the field.

2. With externally applied water, the difference in traction between the two pavements was more dependent on test conditions (water depth, tire pressure and tread depth) for the radial tire than for the ASTM E501 tire. That is, the ASTM tire produced a more consistent "ranking" of the pavements with various combinations of tire parameters and water depths.

3. With positive water depths, traction becomes less than that for ASTM E274 skid numbers as low as 20 mph (32 km/h). It continues to decrease, usually smoothly, until full loss of contact with the pavement occurs, at which speed it becomes equal to the freewheeling hydrodynamic drag.

4. Within the boundaries of the test matrix, tread depth has a greater influence on traction and hydroplaning speed than either tire inflation pressure or positive water depth.

5. Spinup after unlocking the test wheel may be a more positive and precise indicator of full hydroplaning speed than spindown. Complex hydrodynamic forces are involved, with subtle interactions of tire, tread, inflation pressure, water depth, pavement and speed.

6. No consistent difference in skid numbers was observed whether accelerating slowly, decelerating slowly or at constant speed. This permits data points to be taken at several speeds during one variable-speed run, which in turn results in savings of time and cost.

7. Loss of contact can occur between 40 and 45 mph (64 and 72 km/h) in "puddles" of about 1 in (25 mm) maximum depth and about 30 ft (9 m) in length. In addition, horizontal drag forces up to 300 lbs (1.3 kN) were observed. Three-eighths inch (9.5 mm) of water can produce about 90 lbf (400 kN) of drag. If unevenly distributed laterally by pooling against a curb or raised shoulder on a cross slope, these forces could cause hazardous directional instability.

CHAPTER III

MINIMIZING HYDROPLANING CONDITIONS ON PORTLAND CEMENT CONCRETE SURFACES

The parameters involved in this study which influence hydroplaning of portland cement concrete (PCC) surfaces fall into two groups: those associated with the pavement surface and those associated with the vehicle. These parameters, together with their abbreviations as used in this report, are summarized elsewhere.

This phase of the study involved two separate investigations. The first was to determine the validity of the predicted water depth for drainage lengths to 48 ft (15 m) (simulating multilane facilities now in use), and the other was to examine skid resistance and cornering slip on textured PCC surfaces. In the following paragraphs, the results from each investigation are presented.

To determine the applicability of predictive equations for water depth as a function of relatively long drainage lengths, water depths were determined for a number of different textures for drainage lengths, L, up to 48 ft (15 m) under rainfall intensities up to 2 in/h (51 mm/h) and slopes up to 8 percent. All measurements were statistically analyzed in the computer using a two-step regression technique to develop the best fit equations for the data. By combining all previously obtained data (11) with the data gathered on this study, the following equation was developed (using 1059 data values) for drainage lengths, L, up to at least 48 ft (15 m):

$$WD = 3.73 \times 10^{-3}[TXD^{0.13}\ L^{0.52}\ I^{0.56}\ (1/S)^{0.36}] - TXD \qquad \text{Eq. (8)}$$

where
- WD = Water depth above asperities in inches (mm/25.4)
- TXD = Pavement texture depth in inches (mm/25.4) (putty test)
- L = Length of flow in feet (m/0.305)
- I = Rainfall intensity in inches per hour ($\frac{mm}{25.4}$/h)
- S = Slope of drainage path.

Equation 8 was an independent derivation of the equation reported previously (see Equation 9). The new coefficients of Equation 8 are not significantly different. Equation 8 is considered simply a verification of Equation 9. The use of Equation 9 is recommended in all computations of water depth.

$$WD = 3.38 \times 10^{-3}[TXD^{0.11}\ L^{0.43}\ I^{0.59}\ (1/S)^{0.42}] - TXD. \qquad \text{Eq. (9)}$$

Furthermore, it was shown that neither texture direction (longitudinal or transverse) nor texture type (brush, broom, burlap drag or tines) affected the resulting water depth to any significant degree.

No analysis of hydroplaning would be complete without investigating both skid resistance and cornering slip of wetted pavements. To accomplish this, the standard ASTM skid trailer was used to measure skid resistance, and the HSRI Mobile Tire Tester was utilized with a number of tires to measure cornering slip at various vehicle speeds and tire slip angles.

Results from a previous study (10) in which seventeen test sections were subjected to standard skid testing under simulated rainfall are fully reported in our earlier hydroplaning report (11). Analysis of the data using statistical correlation techniques reveal that, even for the very deep textured pavement (0.060 in or 1.5 mm in this example), transverse texturing results in significantly higher skid numbers at higher speeds where hydroplaning is most likely. Furthermore, deeper transverse textures do result in higher skid values at every speed.

The obvious question is, do these findings hold true for cornering slip? To answer this question a total of 504 observations was made on seven PCC test sections under conditions of both artificial and natural rainfall. These measurements were made with the HSRI Mobile Tire Tester, which consists of a retractable test wheel mounted on the rear of a modified tandem-axle commercial tractor which serves as the test bed. To analyze the data, statistical regresssion computations were performed with the aid of the computer, and the following variables had no significant influence on cornering slip (CS):

Cross slope (S) (about 2 percent) (only varied in these tests)

Tire inflation pressure (P) (between 18 and 24 psi (124 and 165 kPa))

While the other values overshadowed the influence of these two variables, it should not be construed that these variables are not important in hydroplaning. Rather, it means that only under the conditions of the experiment reported were these variations undefined. To illustrate the meaning and import of the statistical equations (developed from the data) certain assumed conditions were taken, and the cornering slip (CS) numbers were calculated from the equations.

The combined effects of water depth and texture direction are shown in Figure 11. Here, for the 16 degree slip angle, the calculated CS numbers for longitudinal and transverse textures as a function of texture depth are compared with the three pieces of data obtained under more nearly hydroplaning conditions. The data under the more nearly hydroplaning conditions (flooded pavement with shallow tread depths) are frighteningly lower than the calculated values from data obtained under natural rainfall conditions in which the pavement did not have positive water depths and using deeper tread depths. Note that the transverse textures, under both conditions, exhibited higher CS numbers. This is in agreement with the ASTM E274 SN_{40} numbers obtained under simulated rainfall and other CS data. The dotted curves through the three data points obtained for positive water depths are only suggestive of what might be the shapes of the curves based on all the other data obtained. Once again, however, the extremely reduced CS values on flooded pavements using reduced tread depths point up the dangers of hydroplaning under these conditions.

A large amount of data was gathered and analyzed in this phase of the investigation. In some cases questionable results were obtained. The phenomenon of hydroplaning on highway surfaces is exceedingly complex and

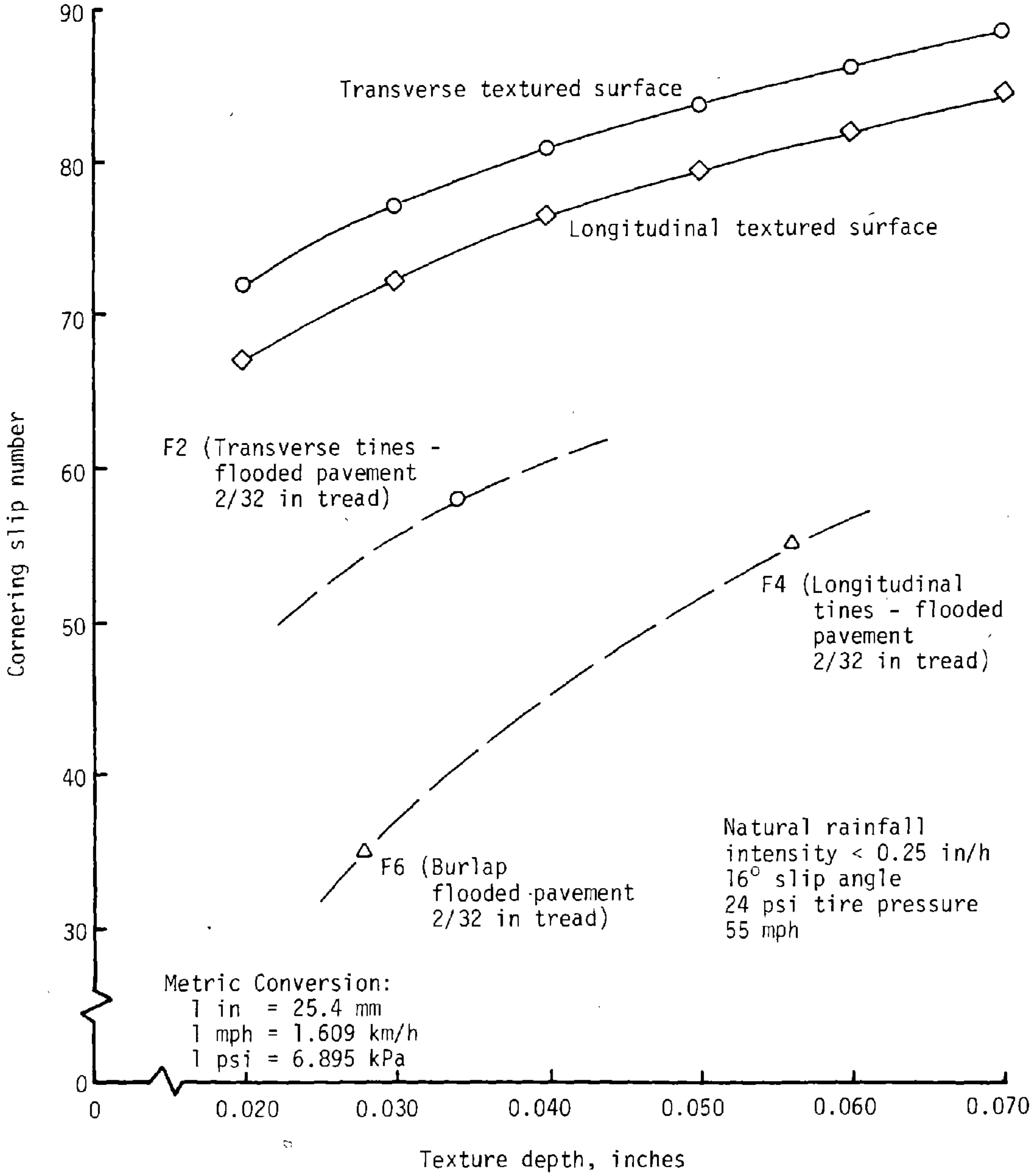


Figure 11 Cornering slip number vs. texture depth for ASTM standard tire E501 with full (11/32 in) and low (2/32 in) tread depth at hydroplaning conditions.

involves many variables. Although most of the data obtained were for conditions which did not approach full dynamic hydroplaning, the findings are extremely important because they relate to frequently occurring conditions in which the pavement is completely wetted and thus potentially hazardous to the motorist. Those data obtained under hydroplaning conditions verify the types of relationships developed between CS, speed, tread depth and texture direction.

From the data the following conclusions have been drawn:

1. Water depth as a function of cross slope, texture depth and rainfall intensity can be reliably predicted for drainage lengths up to 48 ft (15 m), and probably considerably beyond. The direction of the texturing does not appreciably influence the resulting water depth.

2. Under both skid number measurements and cornering slip measurements on wetted surfaces, transverse textures yield higher values than do longitudinal textures. Thus the logical recommendation would seem to be to require transverse textures for both tangent and horizontally curved sections of the roadway. But, it should be pointed out that this reserach, as detailed as it was, did not investigate the potentially hazardous maneuver of full dynamic hydroplaning of an automobile around a horizontal curve! Here the conditions are not approximated by either skid numbers or cornering slip numbers. Logic would strongly suggest that vehicle tracking could be very influential in keeping the vehicle in its respective lane. This tracking could best be obtained by providing longitudinal texturing, rather than transverse, throughout the horizontal curves. Certainly the dramatic decreases in accident rates documented (12) in California (and elsewhere) after longitudinal grooving attests to the validity of this approach. What is not known is whether or not transverse grooving would have been as good as, worse or better than longitudinal grooving in terms of accident reduction on horizontal curves.

   California DOT (12) uses longitudinal grooves on horizontal curves, and they report 90 to 95 percent reduction of spinout type of accidents. California has one installation which utilizes transverse grooves on horizontal curves and one installation with "diamond" grooves. Accident records are not currently available on these.

   Recently California DOT has used transverse texturing of plastic concrete. Accident data on these installations are being collected, but a conclusion at this time is premature.

   Skid number and cornering slip data clearly establish the validity of requiring transverse textures on tangent sections; but on horizontal curves the jury is still out!

3. Increasing texture depth provides the greatest increase in either skid number or cornering slip values. Thus adequate textures should always be constructed. From a construction viewpoint, texture depths of 0.060 in (1.5 mm) can be easily constructed utilizing tines spaced 1/4 in (6 mm) clear distance (11). Therefore, initial

texture depths of 0.060 in (1.5 mm) should be required as an average minimum and in no case should the construction of texture depths below 0.050 in (1.3 mm) be permitted (as measured by the silicone putty or sand patch method).

4. The type of tire and tread depth significantly influence cornering slip values. At elevated speeds and relatively high slip angles the wide oval tire developed the lowest cornering slip values while the radial developed the highest cornering slip values. Shallow tread depths produced significantly lower cornering slip values than did deeper tread depths.

CHAPTER IV

DETERMINING THE PROBABILITY OF SELECTED RAINFALL INTENSITIES

General

The development of design criteria that will preclude hydroplaning under most wet weather conditions necessitates an understanding of those factors related to hydroplaning, the interdependence of those factors and the occurrence probability of certain critical combinations of those factors. This probability is, in turn, a function of the probability of the existence of each individual factor. The purpose of this section is to develop guidelines that will determine the incident chance of influential environmental factors.

It has been shown by Gallaway (13), Yeager (3) and Horne (14) that the amount of water on the pavement (or water depth) is primarily a function of the rainfall intensity and wind velocity, neglecting transient conditions. It has also been shown that a significant positive water depth (above the asperities) is necessary before hydroplaning can occur. Therefore, the selection of highway surface characteristics that would disallow positive water depths in all but the more extreme conditions of heavy rainfall would prevent most cases of hydroplaning. "Most" must be defined in probabilistic terms for particular rainfall intensities that occur in conjunction with specific wind velocities; but is wind velocity really needed to develop antihydroplaning criteria? Horne (14) has shown that as long as the water depth is not above the asperity tops there seems to be little wind effect on the flow path and speed of draining water. Therefore, if a criterion of zero water depth is preselected, the influence of wind becomes largely academic, although it is difficult to ignore some influence even on intra-asperity flow if the direction of the falling raindrops is not nearly vertical. The neglect of wind speed and direction seems sound when their effect on surface flow is so slight although it may be argued that wind could make the difference in some cases between a water depth of height coincident with the tops of the pavement asperities and water depths that are very slightly higher than the asperities. The critical environmental factor, and possibly the only important one, is the intensity of rainfall. The remainder of this chapter will be dedicated to defining the probability of specific intensities.

It would be of little value to determine the average relationship between rainfall intensity and its probability for the U.S. as a whole as rainfall is so highly variable over this vast continent; a comparison between Yuma, Arizona and New Orleans, Louisiana, shows great contrast. The other extreme would be to determine this relationship for every part of the proposed roadway with antihydroplaning surface characteristics changing from milepost to milepost, an extreme that is obviously not justified even if such extensive rainfall data were available.

The National Climatic Center in Asheville, North Carolina, the focal point for all climatic data developed by the National Oceanic and Atmospheric Administration (NOAA), has extensive data from over 300 weather stations throughout the country. In general, the number of weather stations is a function of the geographic size of the state, although there are some exceptions. In many of the larger states wide intrastate variations in rainfall may indicate the need for several zones of rainfall intensity/probability; whereas, in many states a single statewide relationship may be quite sufficient.

The States of Alabama and Illinois were selected for the purposes of this study for several reasons. Extensive current and historical climatic data were available from a number of stations in each of these states. The State of Illinois was seen to be representative of the average moderate conditions across the continental United States. Alabama was chosen for study because the state is located in an area which experiences hurricanes and rainfall of very high intensity and was considered to be one of the most critical states with respect to the need for road surface design criteria to prevent flooding. Rainfall data from Texas stations in Austin and Fort Worth had been acquired on a previous study and published (15). The reduced data have been included later in this report for purposes of comparison.

The outline shown in Table 2 gives the sequence of operations used to arrive at an appropriate relationship between rainfall intensity and the probability of the event for a specific state or geographic area. The full report details the procedures used to derive the desired relationship for the State of Illinois.

Table 2. Sequence of operations.

I. Determination of Rainfall Data for a State

II. Selection of Representative Stations

III. Selection of Representative Years

IV. Confirmation of Availability and Acquisition of Detailed Rainfall Data

V. Analysis of Detailed Rainfall Data

Determination of Rainfall Characteristics

A listing from the U.S. Department of Commerce showed seven recording stations in Illinois. Figure 12 shows the variation in annual rainfall across the state is relatively small, leading to the conclusion that the state need not be subdivided into different regions for purposes of rainfall analysis.

A definite criterion for acceptable variation is given in Figure 13. This curve of acceptable percentage and absolute variation was developed from an understanding of different regional extremes in Texas. Study of the isohyetal map of Texas, Figure 14, indicated that the state should be divided into at least four zones to prevent the necessity of large data extrapolations. The variations of these four zones were plotted on Figure 13. The line of definition between acceptable and unacceptable variations was then placed to include these points in the acceptable zone. These points are defined by determining from the isohyetal map the absolute variation in annual rainfall in a region and the percentage variation in annual rainfall

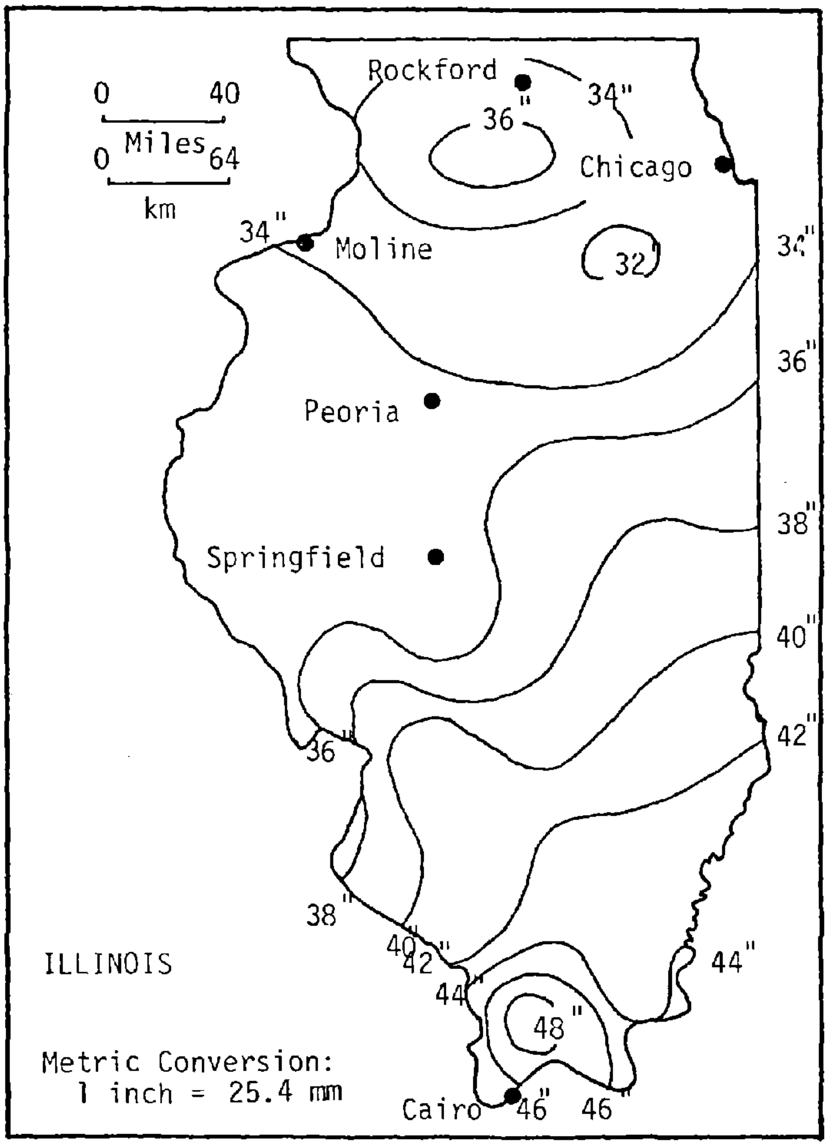


Figure 12. Isolines of mean annual precipitation (U.S. Dept. of Commerce, Environmental Sciences Services Administration, Environmental Data Services, Climatography of the U.S. No. 60-11, Climates of the States)

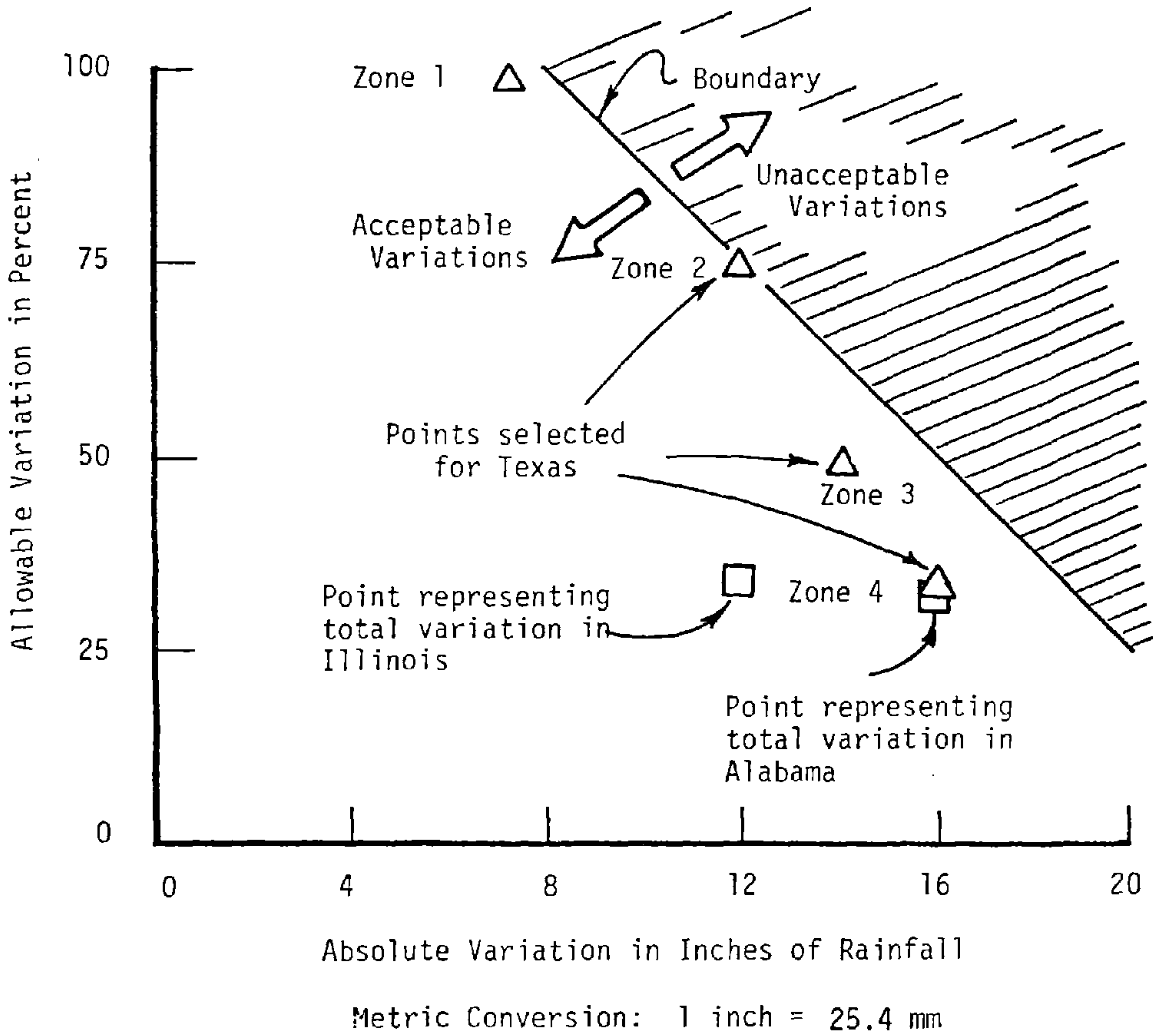


Figure 13. Tentative criterion for acceptable variation in annual precipitation (The major variation in Illinois is from 34 to 46 inches. The difference is 12 inches, which is absolute variation. The ratio of 12 to 34, times 100 is the percentage variation of 35.)

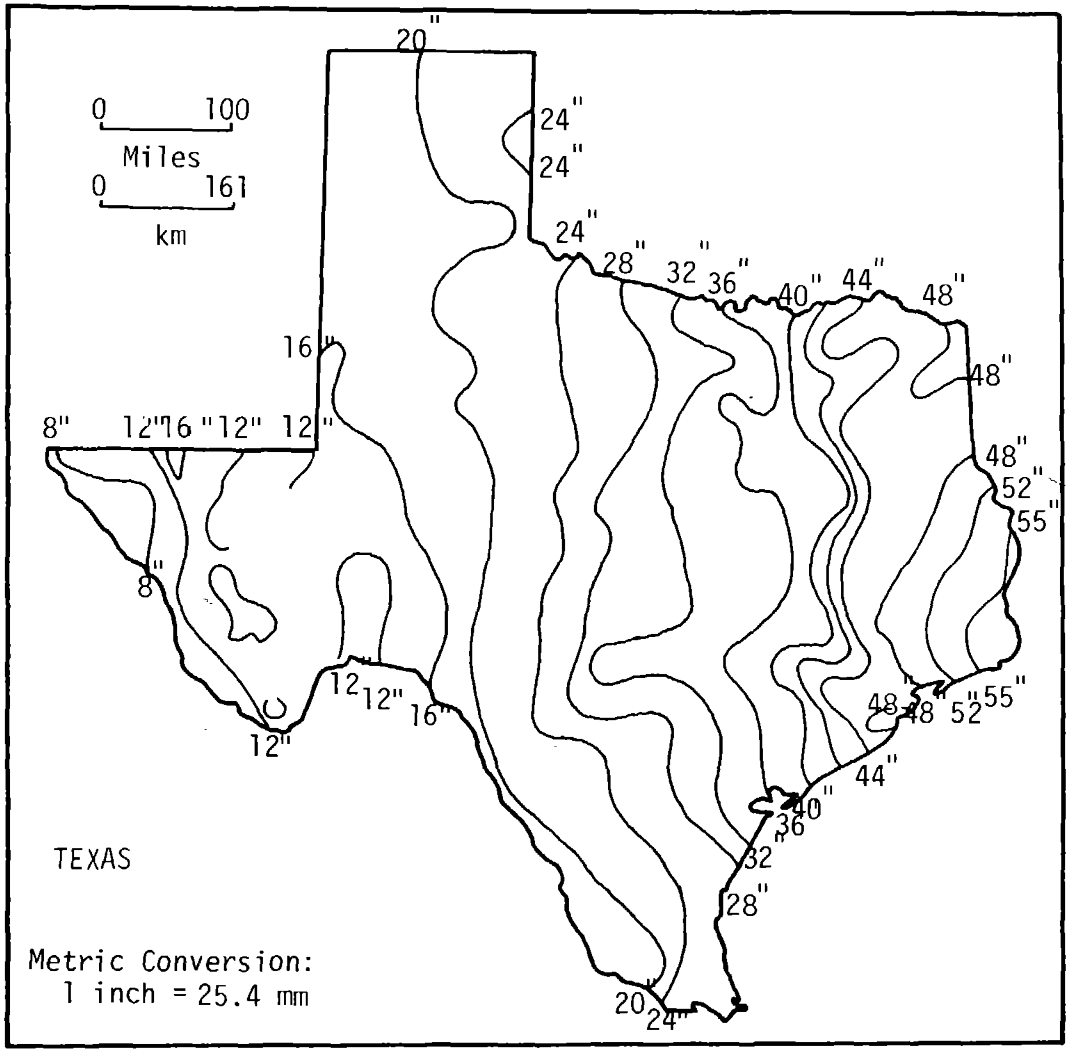


Figure 14 Isolines of mean annual precipitation (U.S. Dept. of Commerce, Environmental Sciences Services Admin., Environ. Data Serv., Climatography of the U.S. No. 60-11, Climates of the States).

in the same region, as can be seen in Figure 13. The variation in the entire State of Illinois does not represent as critical a variation as is seen in each of the four subdivisions of Texas.

Selection of Representative Stations

Once the operating weather stations have been shown on isohyetal maps, it is possible to select the most representative stations for more detailed data analysis. Such geographic characteristics as mountain ranges, valleys or relatively large differences in elevations should be considered in selecting typical stations. The stations at Rockford, Springfield and Cairo were selected from the isohyetal map in Figure 12 to represent the high and low rainfall conditions that are geographically representative of the state. A similar process was used in selecting the Alabama stations of Birmingham, Mobile and Montgomery.

Based on the detailed analyses of nine station-years of rainfall data in Illinois and nine station-years in Alabama, the data presented in Tables 3 and 4 were acquired. Traces of total rainfall versus time were analyzed in increments of time from two to fifteen minutes depending on the variability of the trace. The resulting data shown in these tables can be plotted as shown in Figure 15. This figure contrasts the data from Alabama and Illinois and gives the probability of occurrence of a specific intensity of rainfall during a period of rainfall.

These probability curves for Illinois and Alabama appear similar, but this graph may be somewhat misleading since it is a normalized curve which does not account for the total amount of rainfall or for the total amount of exposure time. Figure 15 contrasts two states which are quite different in terms of annual rainfall. The nine station-years analyzed for Alabama averaged 57.3 in/year (145 cm/year), one of the highest rainfall areas on a statewide basis in the U.S.; and one where tropical storms, and their associated high intensities, play an important part in the rainfall environment. In contrast, Illinois has an annual rainfall of slightly less than 40 in (101 cm) with a fairly low variation across the state, thus more closely representing the national average.

It is seen that the curves cross at the 0.20 in/h (5 mm/h) intensity level. For any intensity greater than 0.20 in/h (5 mm/h) the probability of its occurrence is higher in Alabama than in Illinois, perhaps a somewhat less than startling conclusion to Mobile residents. The converse is also true. The probability is higher, that intensities less than 0.20 in/h (5 mm/h) will occur during a given rainfall period in Illinois than in Alabama.

A different perspective can be achieved by comparing the percentage of total time (both dry and wet) that a rainfall of a given intensity or greater is falling. Table 5 gives these data for Texas, Illinois and Alabama. The data from Texas were developed in a previous study (15). Of some importance is the fact that all three states are subjected to rainfall intensities of 0.5 in/h (12.7 mm/h) or more for approximately 1/4 of 1 percent of the time. This is approximately 24 h/year. Intensities greater than 1 in/h (25.4 mm/h) occur more on the order of 10 h/year.

Table 3. Summary of individual rainfall analyses from nine data stations in Illinois.

Rainfall Intensity Range in/h From	To	Total Number of Minutes N	Average Number of Minutes N/9	Total Average Number of Minutes with I > Value Shown Below I	Min	Percent of Rainfall Time Greater than I (Assume Trace = 0)
0.01	0.09	113,319	12,591	0.01	18,521	100.00
0.10	0.19	24,259	2,695	0.10	5,930	32.02
0.20	0.29	13,355	1,484	0.20	3,235	17.47
0.30	0.39	5,271	586	0.30	1,751	9.45
0.40	0.49	3,311	368	0.40	1,165	6.29
0.50	0.74	3,167	352	0.50	797	4.30
0.75	0.99	1,136	126	0.75	445	2.40
1.00	1.49	1,215	135	1.00	319	1.72
1.50	1.99	689	77	1.50	184	0.99
2.00	2.99	661	73	2.00	107	0.58
3.00	3.99	198	22	3.00	34	0.18
4.00	4.99	60	7	4.00	12	0.06
5.00	5.99	25	3	5.00	5	0.03
6.00	UP	15	2	6.00	2	0.01

Metric Conversion: 1 in = 25.4 mm

Table 4. Summary of individual rainfall analyses from nine data stations in Alabama.

Rainfall Intensity Range in/h From	To	Total Number of Minutes N	Average Number of Minutes N/9	Total Average Number of Minutes with Intensity ≥ I: I	Min	Percent of Rainfall Time Greater than I (Assume Trace = 0)	(Assume Trace > 0)
0	0.009*	------	10,610	0	31,877	100	100
0.01	0.09	131,250	14,583	0.01	21,267	100	66.7
0.10	0.19	27,294	3,033	0.10	6,684	31.43	21.7
0.20	0.29	11,531	1,281	0.20	3,651	17.17	11.5
0.30	0.39	5,884	654	0.30	2,370	11.14	7.4
0.40	0.49	2,766	307	0.40	1,716	8.07	5.4
0.50	0.59	5,312	590	0.50	1,409	6.63	4.4
0.75	0.74	1,726	192	0.75	819	3.85	2.6
1.00	0.99	2,455	273	1.00	627	2.95	2.0
1.50	1.49	1,380	153	1.50	354	1.66	1.1
2.00	1.99	999	111	2.00	201	0.95	0.6
3.00	2.99	569	63	3.00	90	0.42	0.3
4.00	4.99	174	19	4.00	27	0.13	0.08
5.00	5.99	0	0	5.00	8	0.04	0.025
6.00	UP	70	8	6.00	8	0.04	0.025

*Trace Category

Metric Conversion: 1 in = 25.4 mm

Table 5. Summary of rainfall exposure time in four states.

Geographic Area	Annual Rainfall (in)	Total Time of Rainfall* (min)	Total Time of Significant** Rainfall (min)	% of Exposure Time	
				Including Trace	> 0.01 in/h
Alabama	57.3	31,877	21,267	6.1	4.1
Illinois	39.4	---	18,521	---	3.5
Central Texas	35.2	32,750	18,650	6.2	3.5
Southern Arizona Desert	<5	---	---	1***	---

*Includes Trace

**Intensities > 0.01 in/h

***Arizona Correction

Metric Conversion: 1 in = 25.4 mm

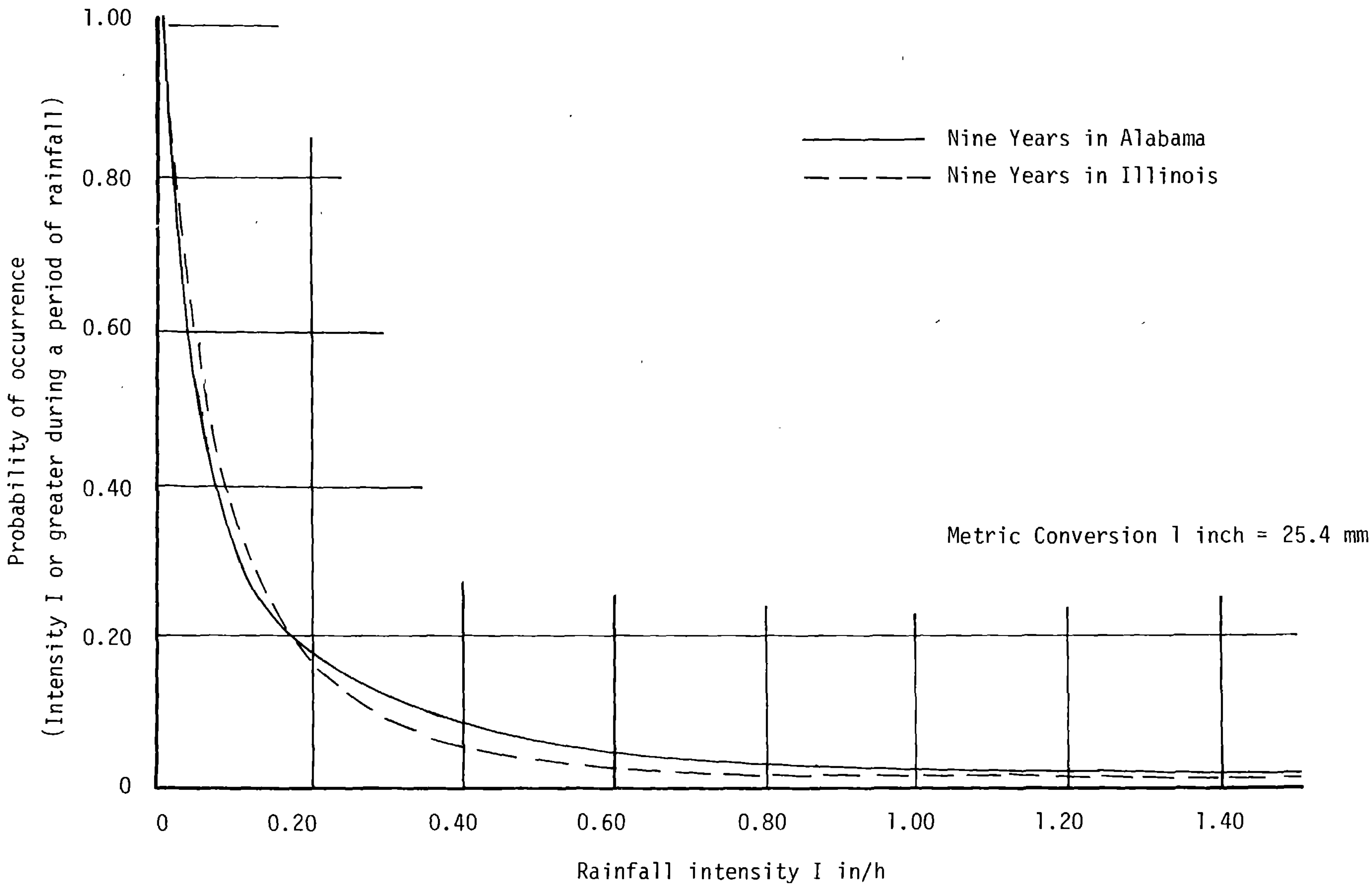


Figure 15. Probability of a given rainfall of intensity I or greater vs. rainfall intensity I.
(Trace rainfall neglected)

Table 5 summarizes the exposure percentages for four regions of the country, varying from the extremely arid climate of the southern Arizona desert to the subtropical conditions of Alabama. It should be noted that the detailed data used to arrive at the Illinois and Alabama exposure time were not used for Central Texas (15), and that the southern Arizona desert data point of approximately 1 percent exposure was adjusted upward by a 1 hour drying time for most rainfall events. The exposure time for the Arizona desert directly comparable to the Illinois and Alabama data would be less than the 1 percent presented by Burns (16). These data are plotted in Figure 16. Although four data points must not be considered definitive, they do appear to produce a reasonable trend, a curve with decreasing positive slope.

It is demonstrated that analysis of NOAA rainfall data can yield both the total exposure time and the occurrence probability of any specific intensity level. Although these two factors are highly pertinent to the determination of whether a specific pavement surface will be flooded, they do not constitute enough information to specify the exact probability of flooding. To do this it would be necessary to determine the short-term (a matter of minutes) intraevent history probability of rainfall intensities. This apparent requirement, and the possible errors resulting from neglecting it, are discussed in detail in the full report (9).

The conclusion reached, after all probable effects of rainfall pre-event histories have been considered, is that the water depth should be assumed to have reached its steady state condition for all times of exposure to a specific rainfall intensity. Based on that assumption it is now possible to conservatively estimate the probability of driving in a specific intensity rainfall or greater and/or on the water depths produced by that intensity, i.e.,

$$P_{ri} = T_w(P_i) \qquad \text{Eq. (10)}$$

where P_{ri} = the resultant probability of driving in a specific intensity rainfall or greater as designated by the subscript i;

T_w = the decimal portion of the time that rainfalls of intensity greater than 0.01 in/h (0.254 mm/h) are falling;

and P_i = the probability of an intensity equal to or greater than i occurring during any period of rainfall.

A state may determine T_w and P_i in the way presented in this chapter, or reasonable estimates can be made based on Figure 16 (to determine T_w) and Figure 15 (to determine P_i). The latter approach should be used with caution, especially in those areas of the country where rainfall patterns are atypical such as areas adjacent to mountainous regions.

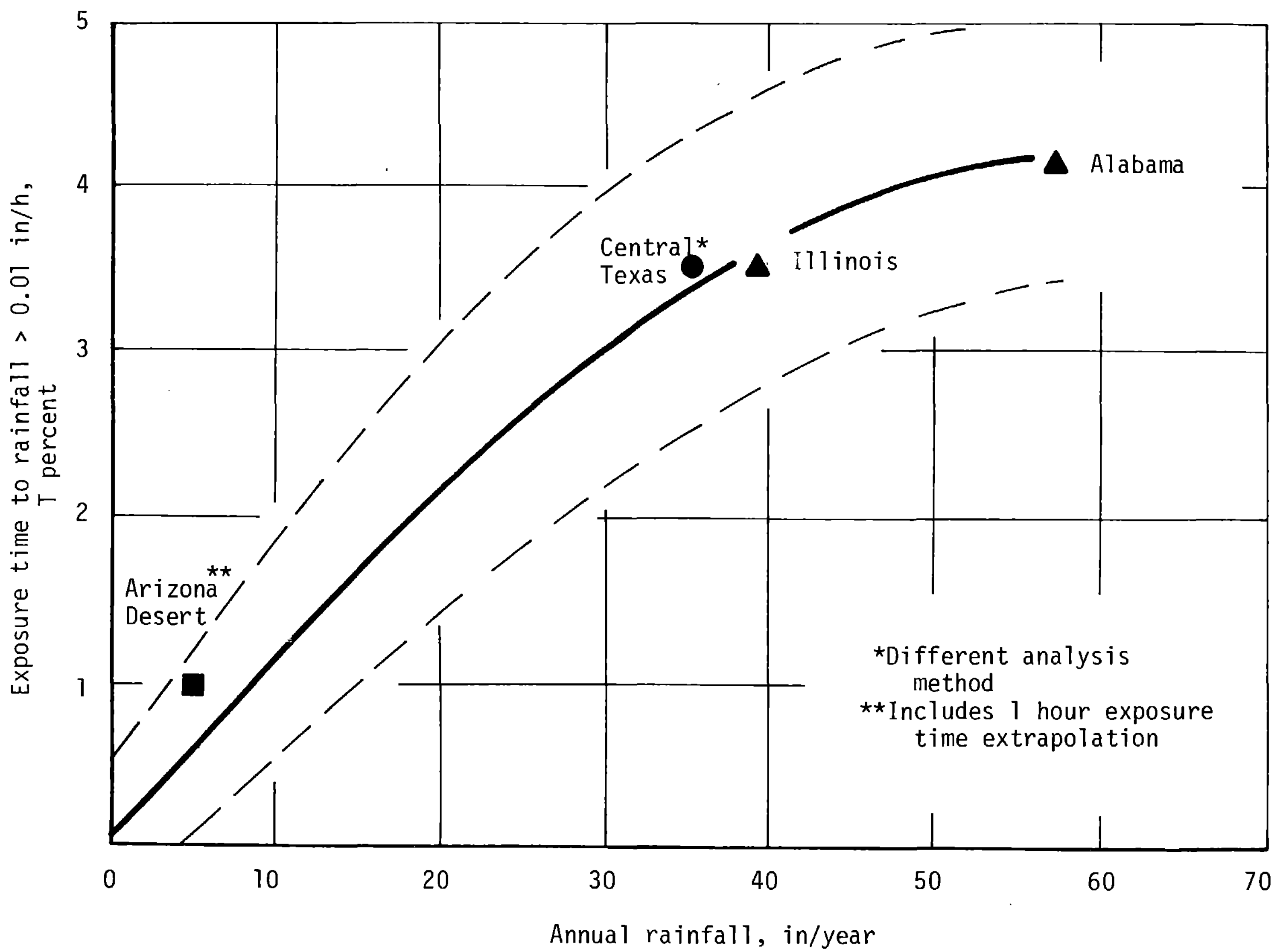


Figure 16. Determination of percent time of exposure to > 0.01 in/h rain.

Metric Conversion
1 inch = 25.4 mm

CHAPTER V

PAVEMENT DRAINAGE

Investigations of Puddle and Texture Depth

Measurements were made at 314 sites in Texas to determine (1) occurrence of significant puddling on traffic lanes and (2) amount of texture depth at the puddling areas. The location of these sites and highway category are shown in Table 6.

Test Procedures

Three types of measurements were taken to investigate puddle depths and texture depths on typical highways, Interstate, U.S. and state routes.

1. A rod and level were used to measure cross-section elevations on the pavement.
2. A 6 ft (1.83 m) steel bar and a calibrated step gauge were used to measure rut depths at these cross sections.
3. The Silicone Putty Method was employed to measure texture depths in wheel paths.

The first two measurements provided information to calculate puddle depths. The elevations were used to determine the cross slope of the pavement. Readings were taken at the centerline, edge of pavement and at an intermediate point on the traveled way. A 6 ft (1.83 m) steel bar was placed on the traveled way, and rut depths were measured by using a calibrated step gauge. The step gauge was fabricated from 17-4 PH stainless steel heat treated to H-900 condition. Previous research indicated 2.5 ft (0.76 m) for the wheel path width. This width was checked at more than 200 sites. The average width was approximately 2.5 ft (0.76 m).

Cross sections were plotted, cross slopes were determined and puddle depths were computed.

Computation methods:

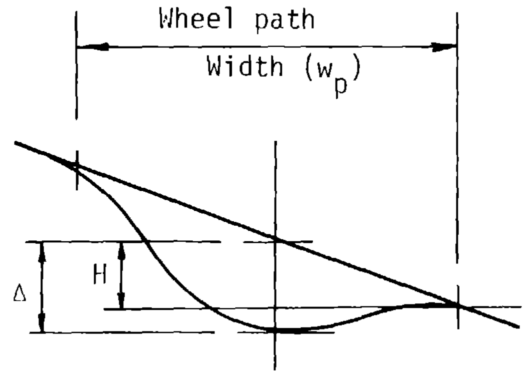
$$PD = \Delta - \frac{W_p}{2} \tan \theta \qquad \text{Eq. (11)}$$

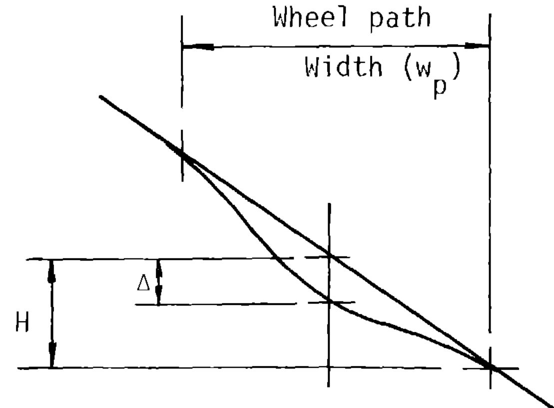
(see Figure 17)

where $\tan \theta = \frac{C}{WL}$ (see Figure 19).

Positive or negative puddle depths may exist. Positive puddle depths, as shown in Figure 17, represent measurable depths in the wheel path where puddling may occur. As shown in Figure 18, negative puddle depths indicate the slope of the road was adequate to permit water flow to the edge of the pavement.

Average texture depths were determined at each cross section by employing the equation:

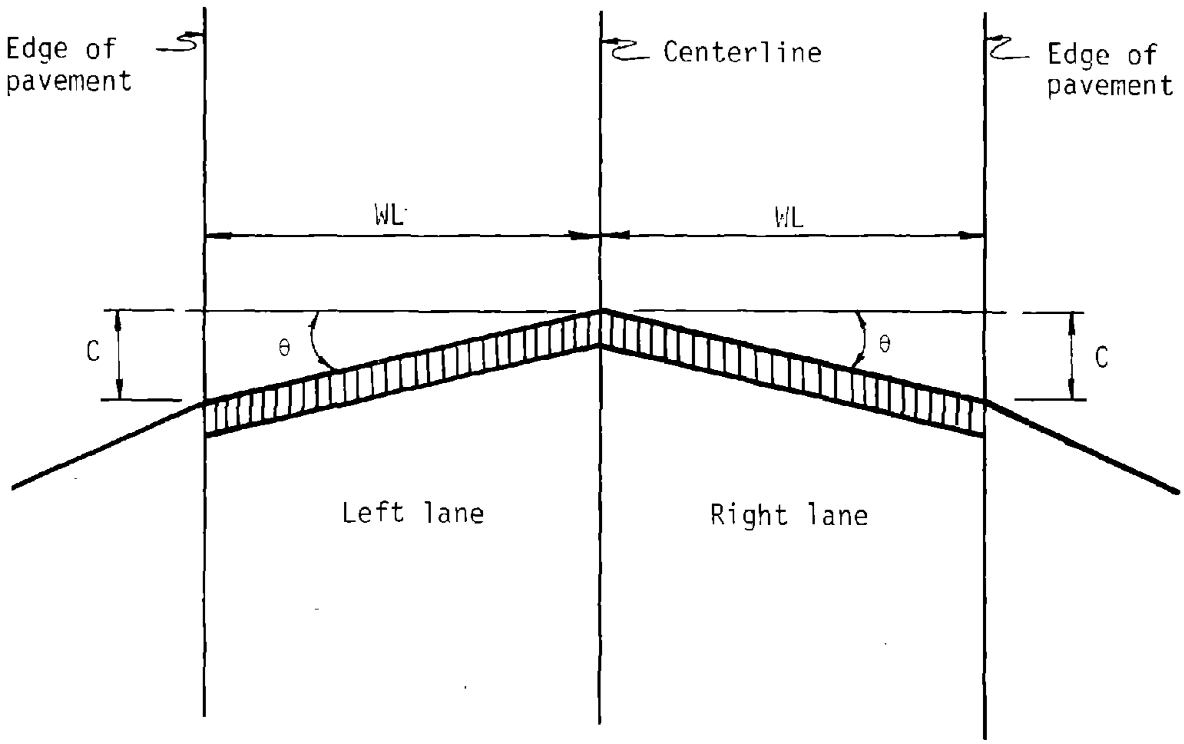




$$\text{Puddle depth} = \Delta - H$$
$$= \Delta - \frac{w_p}{2} \tan\theta \quad \text{(for } \tan\theta\text{, see Figure 19)}$$
$$= \Delta - \frac{w_p}{2} \left(\frac{C}{WL}\right) \quad \text{(for C and WL, see Figure 19)}$$

Figure 17. Positive puddle depth ($\Delta > H$)

Figure 18. Negative puddle depth ($\Delta < H$)



WL = Width of the traffic lane

C = Change in height throughout WL

PD = Puddle depth

w_p = Wheel paths = 2.5 ft (0.762 m)

Δ = Largest rut depth that existed within WL

Figure 19. Cross section of traveled way.

Table 6. Locations of test sites in Texas.

District No.	Highway Category				
	IH	US	SH	FM	Total
2		8	34	14	56
10			46		46
11		11	17		28
12			3		3
14		22			22
15	18	4	8	6	36
16		11			11
18		14	50	10	74
19		13			13
20		16	9		25
Total	18	99	167	30	314

$$TXD = \frac{1}{D_d^2} - 0.0625 \qquad \text{Eq. (12)}$$

where

D_d = Average of four diameter measurements taken on the putty

TXD = Average texture depth

Note: To measure D_d in the metric system, the putty impression device would need to be calibrated with an appropriate metric weight.

Water Depths on Multilane Highways with Different Cross Slopes

Based on experimental studies of water film depths on pavements at Texas A&M University, the following empirical expression for water film depths was determined by regression analysis (11).

$$WD = (3.38 \times 10^{-3})(TXD^{0.11})(L^{0.43})(I^{0.59})(\frac{1}{S})^{0.42} - TXD \qquad \text{Eq. (9)}$$

where

WD = Water depth above asperities in inches (mm/25.4)
TXD = Pavement texture depth in inches (mm/25.4)(putty test)
L = Length of flow in feet (m/0.305)
I = Rainfall intensity in inches per hour ($\frac{mm}{25.4}$/h)
S = Slope of drainage path.

The equation is applicable to laminar flow conditions. For laminar flow, an expression for water depth may be derived. This expression is:

$$WD = \left[\frac{3\mu IL}{\rho S}\right]^{1/3} \qquad \text{Eq. (13)}$$

where

WD = Water depth above the asperities, L
μ = Absolute viscosity of the liquid, FT/L^2
I = Rainfall intensity, L/T
L = Length of flow, L
ρ = Unit weight of liquid, F/L^3
S = Slope of drainage path.

This theoretical Equation 13 may be compared with the empirical Equation 9 and with the results shown in Table 7. See also Figure 20.

Based on the selected theoretical analysis it is apparent that the multiple cross slope pavement drains better than the single cross slope. This analysis assumes a smooth surface.

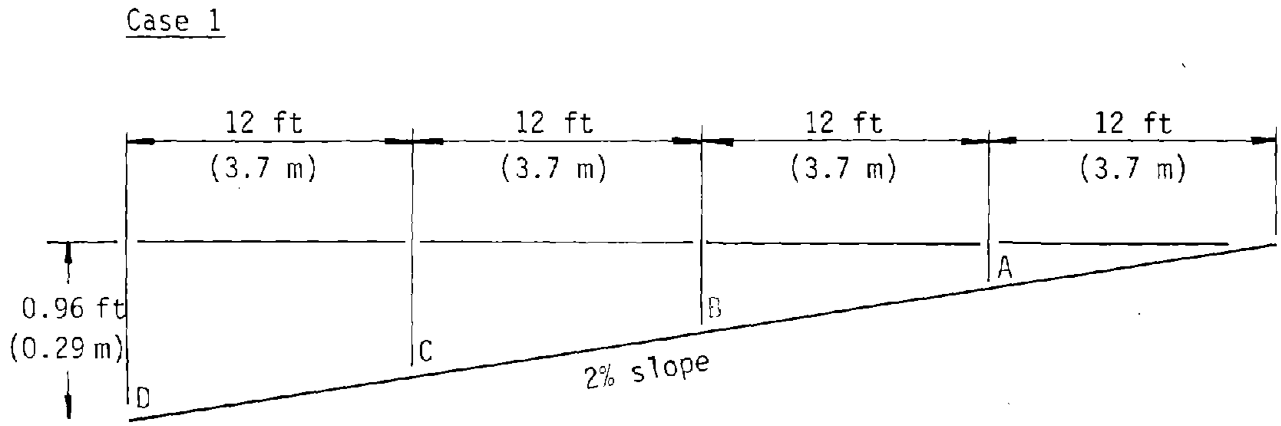
When one examines water depths from the empirical data given in Table 7 at points C and D, the measured water depth is less for the multiple cross slope pavement; however, this is not the case for points A and B. Indeed, the reverse is true.

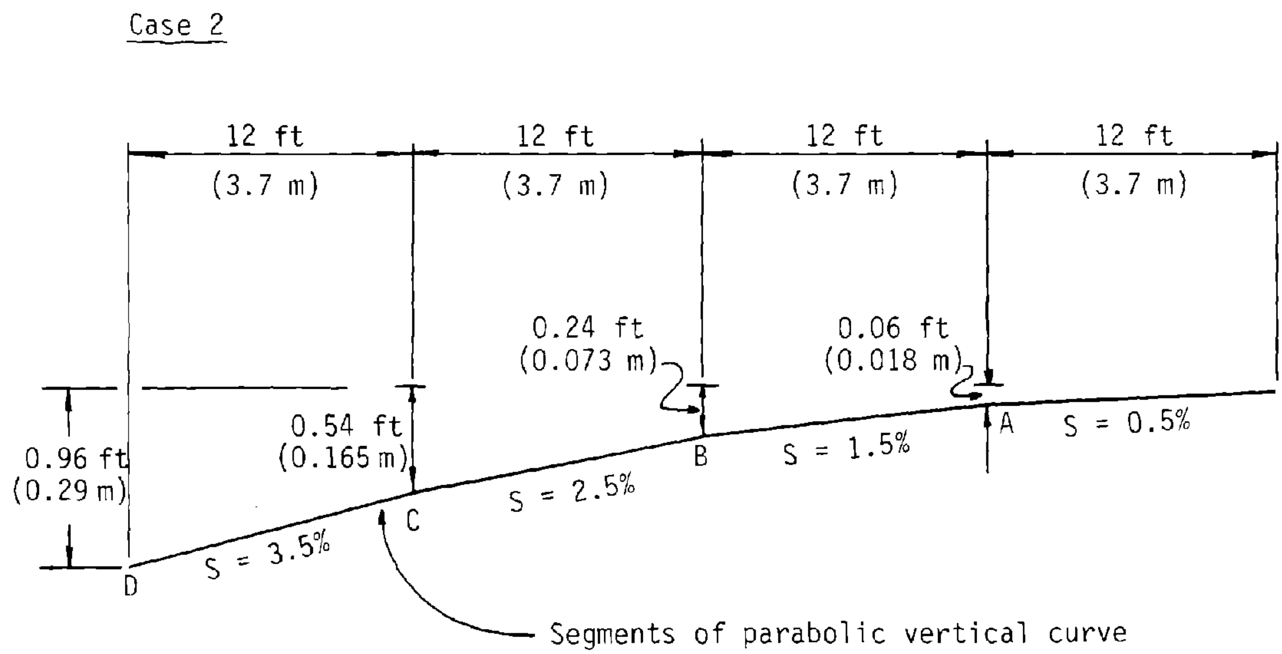
Table 7. Comparison of theoretical water depths with water depths from the empirical equation at several points along the slope.

Point **	Case 1			Case 2		
	d_t	d_B	d_T	d_t	d_B	d_T
A	0.029	0.035	0.000	0.046	0.063	0.028*
B	0.036	0.047	0.012	0.040	0.053	0.018
C	0.041	0.056	0.021	0.038	0.051	0.016
D	0.046	0.064	0.029*	0.038	0.050	0.015

*Maximum water depth
**See Figure 20 for points in question.

Note: All depths are listed in inches for d_t = theoretical depth, d_T = empirical depth with respect to top of asperities and d_B = empirical depth with respect to bottom of texture. The water depths listed are for I = 1 in/h (25.4 mm/h), water temperature = 70°F (21°C) and TXD = 0.035 in (0.9 mm).





Given:

Rainfall intensity = 1 in/h (25.4 mm/h)
Texture = 0.035 in (0.9 mm)
Water temperature = 70°F (21°C)

Figure 20. Example of comparative water depths on multilane highways with different cross slopes.

CHAPTER VI

TIRE-PAVEMENT INTERACTIONS ON OPEN-GRADED FRICTION COURSES IN SIMULATED AND NATURAL RAINFALL

Introduction

An extensive review of the literature pertaining to this specific area of study is contained in the full report. This review covers several national and international conferences which deal with tire-pavement interactions, geometrics, skid maintenance routines and design and construction of open-graded friction courses, OGFC.

This technical summary covers in brief form the research findings by the Texas Transportation Institute (TTI). The results include studies of four full-scale sections of OGFC, each designed for a different percentage of voids. A variable intensity rain simulator was substituted for natural rain. The variables studied included vehicle speed, water depth, tire type, tire inflation pressure and tire tread depth. Tests were made at different positions across the dual lane pavement, and the effect of sealing the adjoining shoulder of the outside lane on water buildup was measured.

The comparative effect of natural rain on the performance of an array of OGFC constructed under contract at four other locations in Texas was studied, and the results are presented in the form of hard data and in a series of photographs.

Field Experiments by TTI

In a total array of pavement construction and maintenance techniques, there exists a limited number of economically practical measures that may be taken to assure long lasting, high performance surfaces for medium-to-heavy traffic.

Efforts to develop new techniques to be used as partial or complete solutions to the problem have been reasonably successful. Among the several methods now in use, OGFC offer considerable promise.

Since the introduction of OGFC in the United States several years ago, a large number of states has developed mixture designs suited to their individual materials, traffic and environment. This has resulted in some cross pollenization, some of which has resulted in improved performance and some of which has caused unanticipated problems.

Theoretical mixture designs have been developed to allow control of air voids which in turn control, to a reasonable degree, the permeability of the in-place surface layer. However, the variables encountered have, in many instances, raised questions about the total drainage capability of OGFC, particularly under medium-to-heavy traffic.

Generally speaking, after about one to three million vehicle passages (applied at a rate of one million passages per year or greater), the friction, drainage, and splash and spray characteristics of OGFC stabilize. This assumes that the thickness of the layer placed is in the approximate range of 20 to 30 mm and the aggregate is nonpolishing.

Field measurements made in Texas indicate that OGFC offer a positive means to control macrotexture at a generally higher level than current dense-graded asphalt concrete designs permit. This controlled, greater macrotexture allows better drainage at the tire-pavement interface, irrespective of any internal drainage. Internal drainage in the dynamic sense is appreciably reduced after the surface layer stabilizes.

An extensive testing program was therefore initiated to assist in the classification of the performance of the OGFC. Each of the four subsections of the OGFC consists of dual lanes about 500 ft (152 m) long, and all sections are cross sloped at 1 percent toward the paved shoulder. When constructed, the voids in the four sections varied from more than 25 percent in Section 1 to about 15 percent in Section 4. Mat thickness was controlled at 1 in (25 mm).

Water on these sections was supplied by use of a rain simulator shown in Figure 21. In the operation of the rain simulator the correct rainfall intensity was controlled by pump discharge pressure and carefully monitored by actual "rainfall" measurements made under the simulator.

Since the depth of water on the test surface was a critical parameter, this was measured at designated points on the pavement with a point gage. When water depth stability was attained, testing began. The rainfall intensities investigated were in the approximate range of 0.2 to 2 in/h (5.1 to 50.8 mm/h). A typical testing situation is shown in Figure 21.

Field Test Results on OGFC

Results of about 4,000 tire-pavement interaction tests on the four pavement sections are presented in 31 graphs in the full report. This technical summary will present selected graphs from this extensive array of data which was grouped into nine categories in the full report.

Figure 22 presents the skid number versus speed for all four sections of the OGFC. Testing was performed in accordance with procedures outlined in ASTM E274. The information presented in Figure 22 was collected approximately midway in the overall test program, and check tests were made at the end of the simulated rain studies to determine whether or not significant changes as measured by ASTM E274 procedure had occurred. These check tests revealed no significant change in measurements obtained.

It is apparent from Figure 22 that all four surfaces have high skid numbers and are not very sensitive to speed.

The data presented in Figure 23 indicate a radical drop in skid number for the G-60-14 glass-belted bias-ply tire with 2/32 in (1.6 mm) tread, a positive water depth of 0.05 in (1.3 mm) and a speed of 55 mph (88 km/h). These data were gathered in Section 2 of the OGFC (voids about 25 percent).

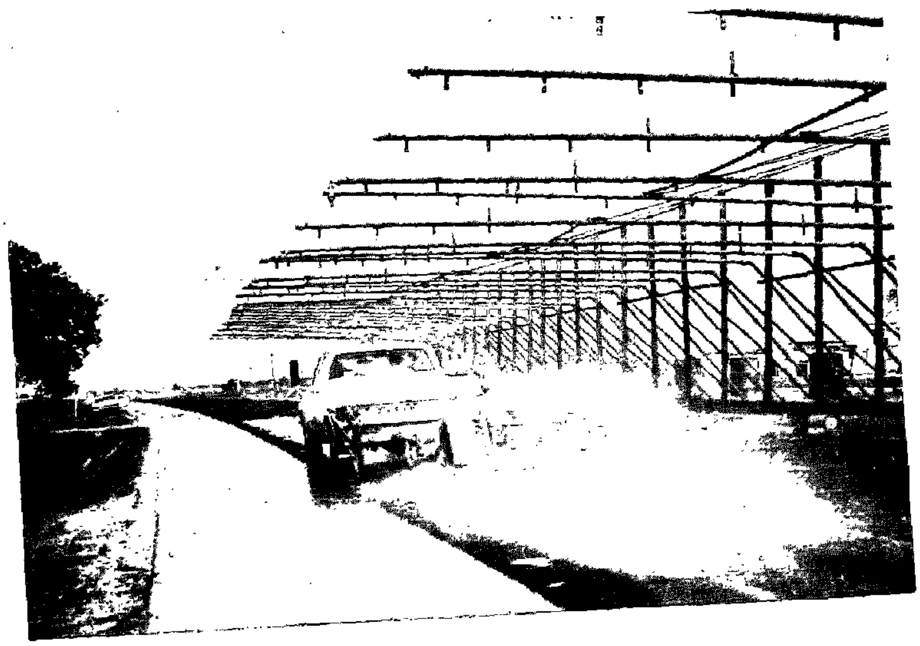


Figure 21. Testing OGFC at 40 mph (64 km/h) on SH 21 Brazos County. (Rainfall intensity about 2 in/h (51 mm/h))

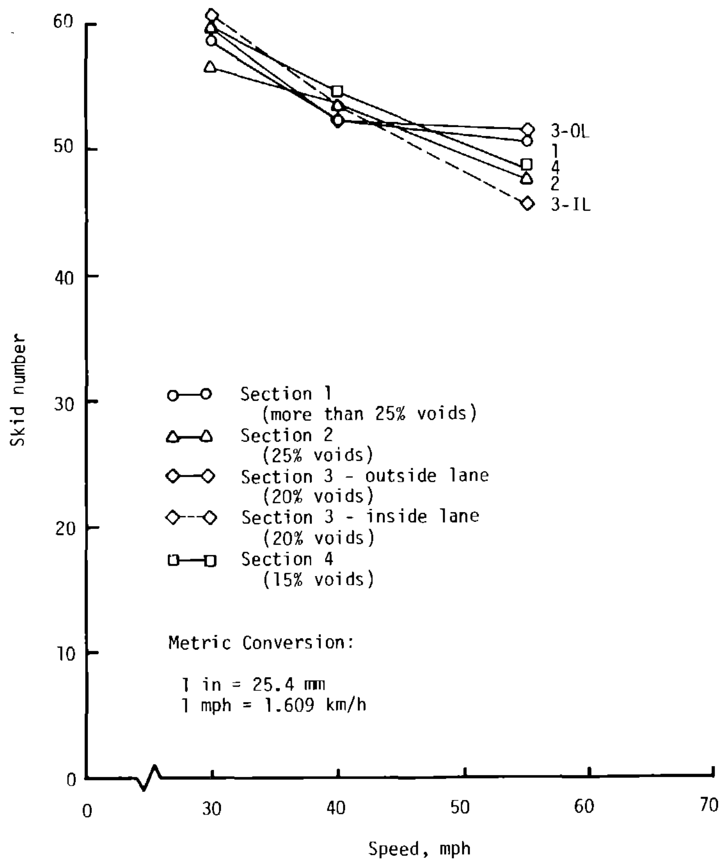


Figure 22. Skid number vs. speed from ASTM standard test method E274. ASTM standard tire E501 with 11/32 inch tread depth on all sections with internal water.

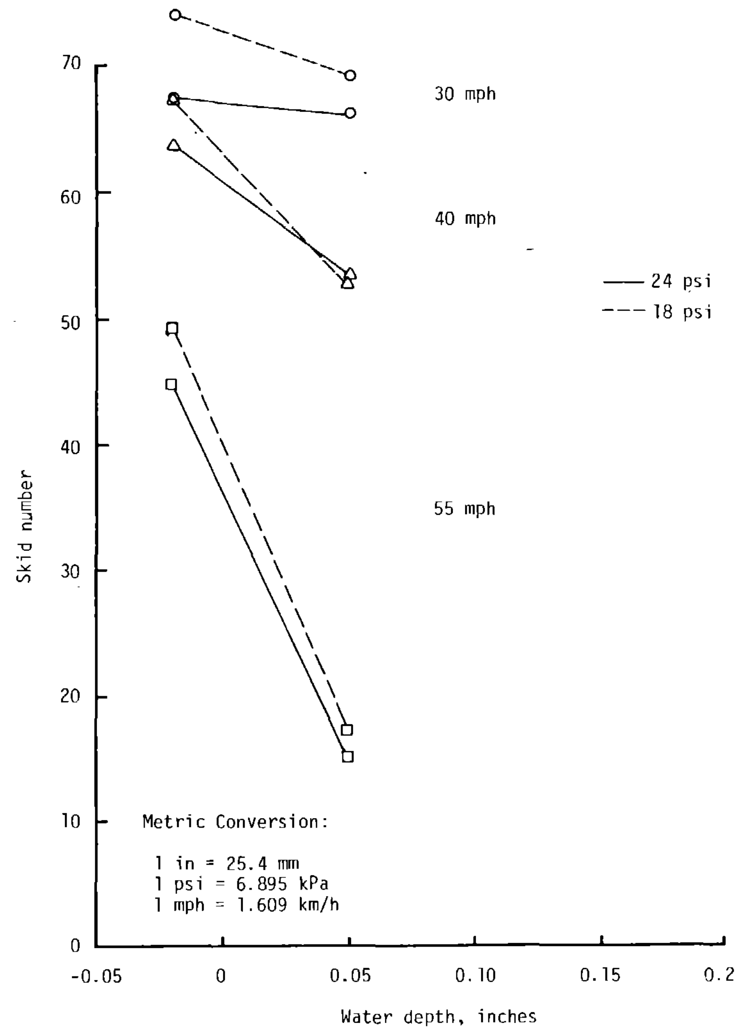


Figure 23. Skid number vs. water depth for glass-belted bias-ply wide tire (G-60-14) with 2/32 inch tread depth on Section 2 with simulated sealed shoulder, outside wheel path of outside lane.

Since the normal tire population contains among the other variables a mixture of tire tread depths, a limited series of tests was performed using two tires, one a glass-belted bias-ply (F-78-14) and the other a steel-belted radial (FR-78-14) at tread depths of 11/32 in (8.7 mm), 5/32 in (4.0 mm) and 2/32 in (1.6 mm). A tire inflation pressure of 24 psi (165 pKa) was used during these tests. The relative performance of Section 2 of the OGFC measured by these two tires of different tread depths is shown in Figure 24. Attention is directed to two indicated findings; namely, the steel-belted radial definitely delivers higher skid numbers for all tread depths, the difference being about 10 skid numbers for the 5/32 in (4.0 mm) tread depth and 55 mph (88 km/h) speed. This comparison of the effect of tread depth for the glass-belted bias-ply tire (F-78-14) is extended to include the 2/32 in (1.6 mm) tread depth in Figure 25. A marked sensitivity reduction in tread depth is evident. The tread depth is reduced from 5/32 in (4.0 mm) to 2/32 in (1.6 mm). However, it may be noted that the OGFC delivers adequate friction at 55 mph (88 km/h) and a water depth of 0.05 in (1.3 mm).

For a 12 ft (3.7 m) traffic lane the approximate center of the wheel path is 30 in (0.76 m) from the edge of the lane. This lateral position was therefore chosen as the position for wheel lockup on the various sections and lanes through the described test program. When it was observed that the skid numbers for Section 2 with the shoulder sealed were somewhat higher than measurements made earlier, an effort was made to determine whether or not there was an appreciable variation in skid number across the pavement. The results presented in Figure 26 were taken at three different points in real time with a considerable delay between the time the measurements were taken on Section 2 with and without the shoulder sealed and a very short delay between the times data on the sealed shoulder and the position across the pavement were taken.

Figures 27, 28 and 29 are plots of skid number vs. speed, not skid number vs. water depth as has been the case in past discussions. The three primary variables are rainfall intensity, vehicle speed and test section or pavement voids. This complete series of tests was performed in the outside wheel path of the outside lane in each of the sections. Similarly, this series of tests might be considered to correspond to the procedures and equipment in ASTM E274 with water depth and speed as variables. This, of course, means that for a fixed rainfall intensity of, say, 0.5 in/h (13 mm/h) the water depth increased with decreasing voids. It should be noted, however, that the effect on water depth of a given rainfall intensity is also a function of mat thickness as well as the average void content of the OGFC. In spite of small differences in mat thickness, the general trend of the data is an increase in the slope of the SN vs. speed curves and a lowering of skid numbers.

In Figures 28 and 29, skid number vs. speed data for all tires except the ASTM E501 are presented. Tire tread depth and tire inflation pressure were fixed at 2/32 in (1.6 mm) and 24 psi (165 kPa), respectively, Again, all four sections of pavement were examined for their performance characteristics during simulated rainfall. Rates in the range of about 0.2 in/h to 2 in/h (5 mm/h and 51 mm/h) were included.

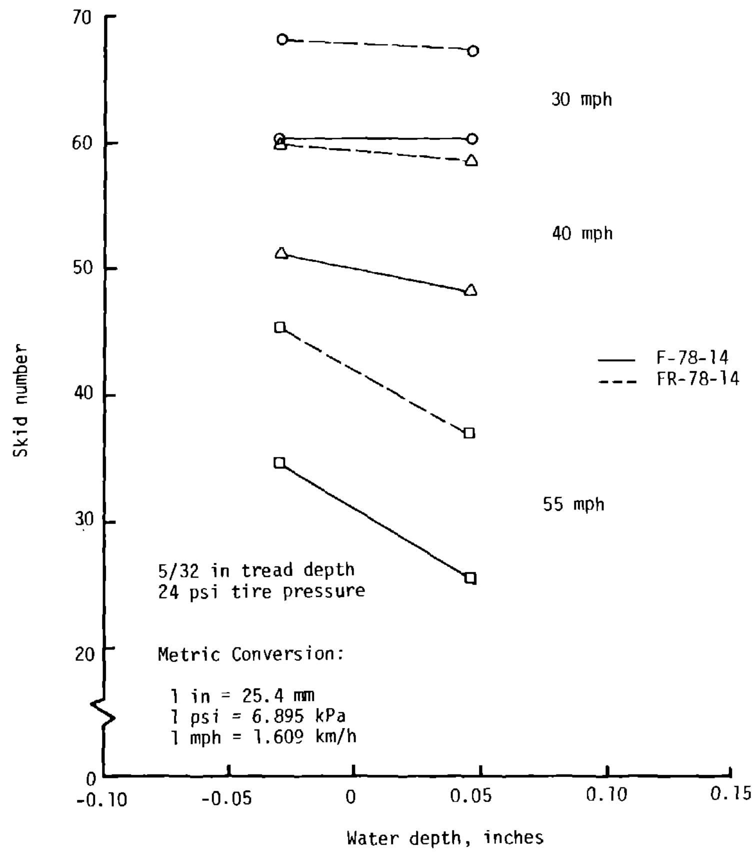


Figure 24. Skid number vs. water depth for glass-belted bias-ply tire (F-78-14) and steel-belted radial (FR-78-14) having 5/32 inch tread depth and inflated to 24 psi. Testing done on Section 2, outside wheel path of outside lane.

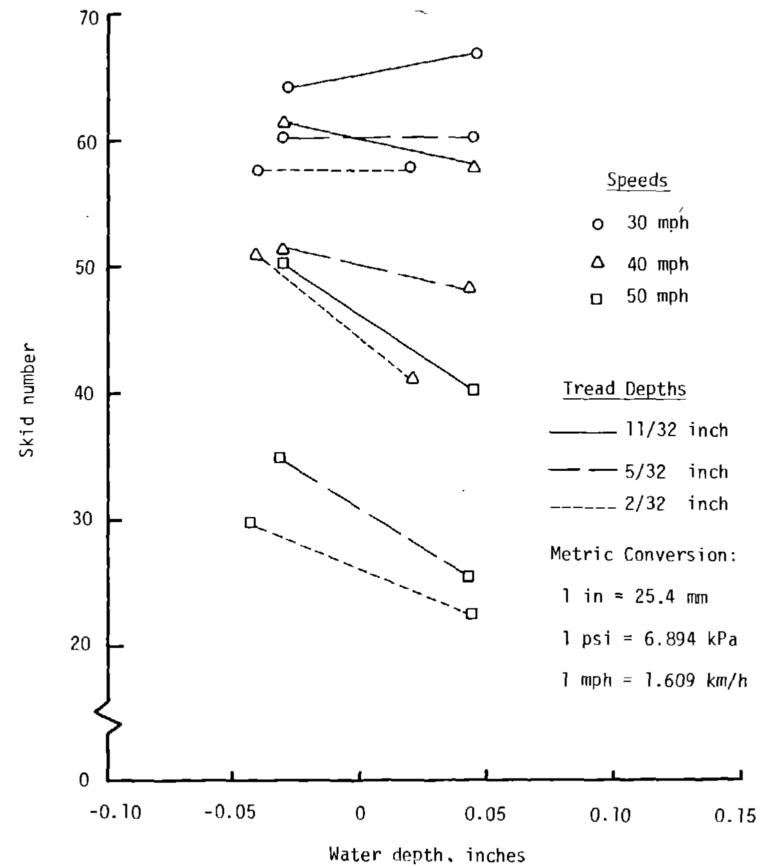


Figure 25. Skid number vs. water depth for glass-belted bias-ply tire (F-78-14) inflated to 24 psi. Testing done on Section 2, outside lane, outside wheel path.

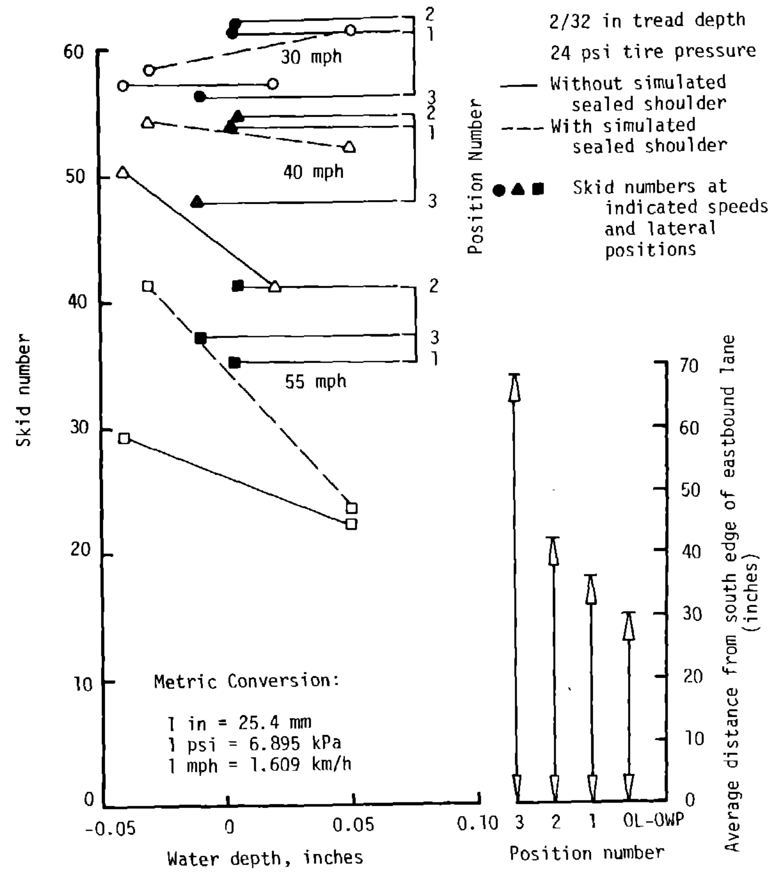


Figure 26. Skid number vs. water depth for belted bias-ply tire (F-78-14) on Section 2 at various positions across the lane.

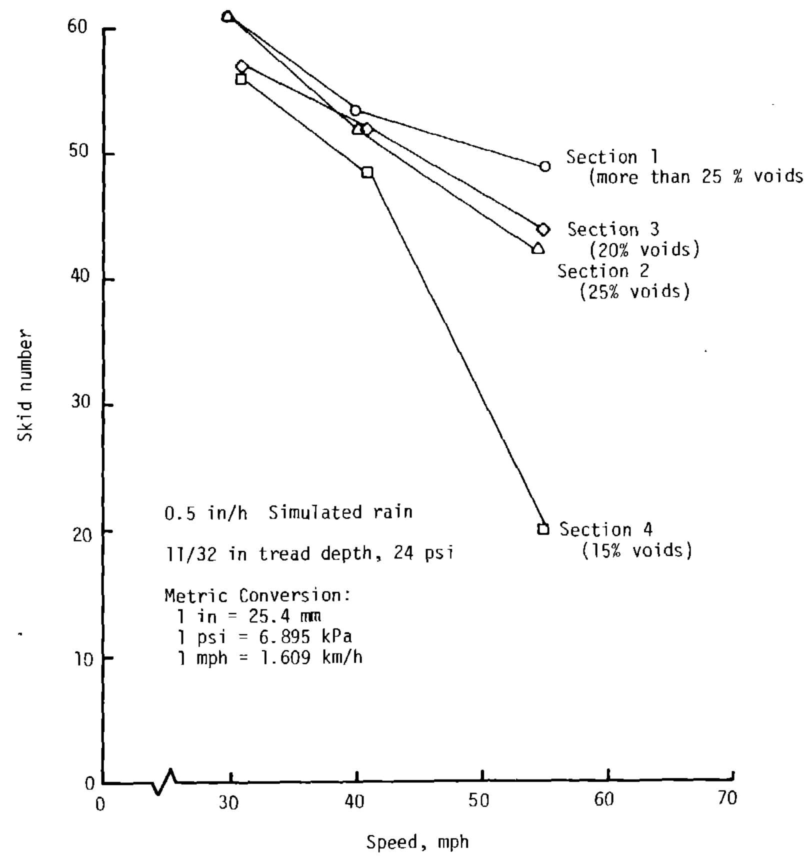


Figure 27. Skid number vs. speed for all sections, average of ASTM E501 tire only.

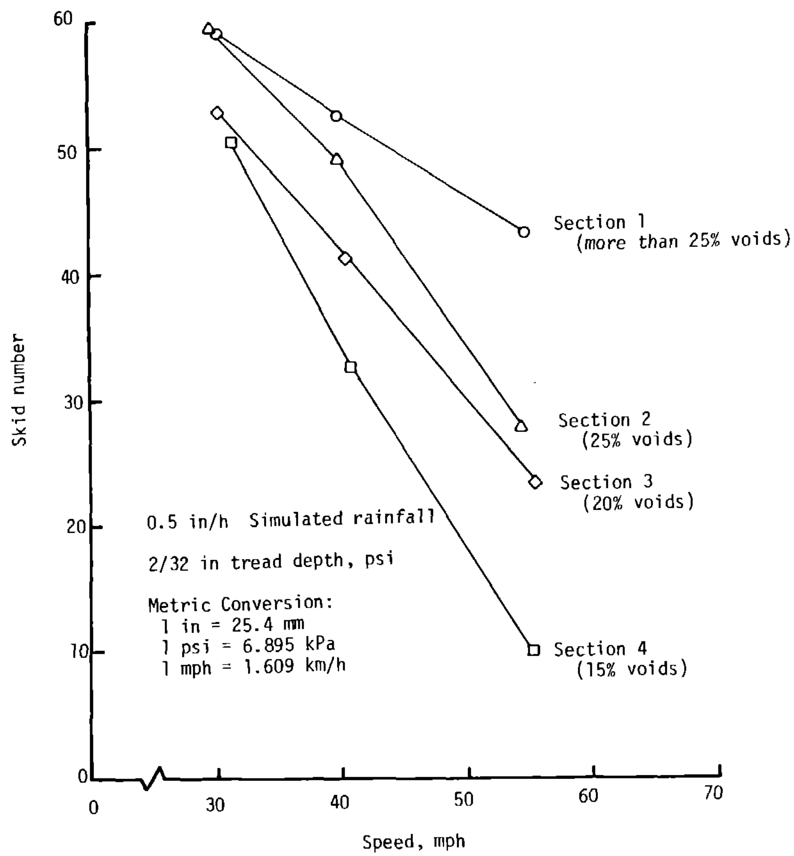


Figure 28. Skid number vs. speed for all sections, average of all tires except ASTM E501.

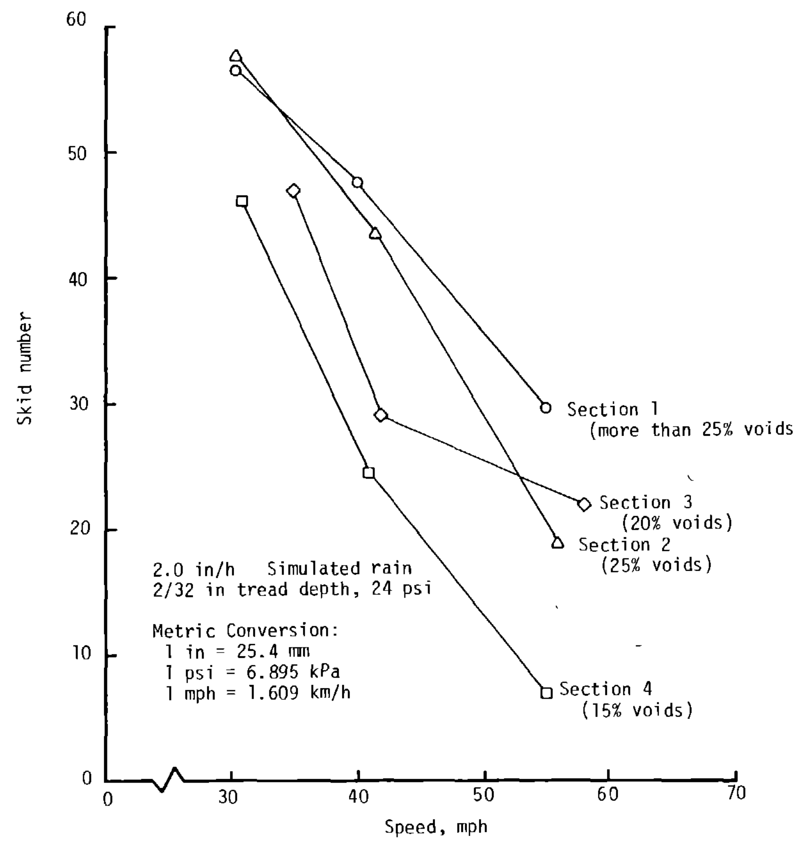


Figure 29. Skid number vs. speed for all sections, average of all tires except ASTM E501.

This overall analysis clearly indicates that the OGFC provided adequate friction in all cases except at 55 mph (88 km/h) on Section 4 where the as-constructed voids were in the range of 15 percent.

The slope of SN vs. speed curve for Section 4 is quite steep indicating a rapid approach to dynamic hydroplaning in the 55 to 60 mph (88 to 97 km/h) speed range with the associated potential dangers of this phenomenon. In a general comparison of the effect of the two rainfall intensities it is evident that the greater water depths, associated with the higher rainfall, caused a general downward, lower SN's, shift of the curves.

It should be noted that overall average macrotexture including all texture measurements made after all simulated rain testing was done was 0.107 in (2.7 mm). The range of values was from 0.084 to 0.134 in (2.1 to 3.4 mm).

A falling head water outflow meter was used to evaluate the permeability of these surfaces after all testing had been completed. These measurements indicate a reduction in permeable voids from Section 1 to Section 4 with outflow time measurements of 5.9, 8.2, 9.7 and 17.6 seconds for Sections 1, 2, 3 and 4, respectively. Voids were generally reduced 20 to 25 percent after two years of traffic.

Performance of OGFC under Natural Rainfall

The question of the comparative performance of OGFC under simulated and natural rainfall was raised during the Phase I effort. To shed some light on this question, five field sites were established in Texas to gather data on existing open-graded surfaces that have been in service for time intervals of two to five years. Traffic on these sections varies from light to very heavy.

The five selected test sites included Austin, Fort Worth, Lufkin, Beaumont and Bryan, Texas. Operators at each site were instructed to place primary emphasis on collecting data at 40 mph (64 km/h) with the full tread E501 tire in natural rain in the general intensity range of 0.01 to 0.5 in/h (0.3 to 13 mm/h) on their typical open-graded surfaces. Following this they were instructed to collect data at 55 mph (88 km/h) then change to the minimal tread tire and repeat the data collection at the two stated speeds.

Normally, the crews were available during the regular work week; also, it was difficult to estimate when a given rain shower would be at a given site. Further, a rain of uniform intensity covering an area of sufficient size to include a reasonable sized test occurred with great rarity.

Measurements made on SH 21 in Brazos County, Texas, showed a wide variation in intensity and duration within the 2200 ft (671 m) test site. Variations in intensity of 100 percent or more were not uncommon, with such variations taking place in a distance of 1000 ft (305 m) or less. These observations were most particularly true for rainfall intensities in the 0.1 to 0.5 in/h (2.5 to 13 mm/h) range. It was noted that light rain in the 0.01 to 0.1 in/h (0.3 to 2.5 mm/h) range were much more nearly uniform in intensity and usually extended over longer periods of time. The impact of this observation on the probability of wet weather accidents is important.

Given the observed facts regarding the measured variations in rainfall intensity and duration, it was considered advisable to look at recession curves for various flow lengths, particularly for open-graded friction courses.

To this end and in keeping with the work plan, a pavement surface drainage study was made utilizing a 4 by 28 ft (1.2 by 8.5 m) segment of open mixture placed 1 in (25.4 mm) thick on a double tee beam as shown in Figure 30. By using simulated rain and different cross slopes, recession curves were developed for different flow lengths. A typical plot is shown in Figure 31. It is evident that the relationship is linear after about 6 minutes.

Returning now to skid data taken during natural rainfall, Table 8 is a summary of the data collected, for the most part, over a period of eight months on SH 21 in Brazos County.

The data collection system consisted of the standard TTI locked-wheel trailer which utilized the ASTM E501 full tread tire inflated to 24 psi (165 kPa). The first column of data includes SN's obtained using the internal watering systems as per ASTM E274. These data indicate no significant difference among the four test sections.

The next six columns of data represent information collected during natural rain, the intensity of which varied from near 0 to 0.57 in/h (14.5 mm/h). An examination of these data indicates that all four sections of the OGFC performed in a highly acceptable manner as determined by procedures of ASTM E274, excepting water depth. To picture this conclusion more clearly, the more than 260 data points at SN_{40} and SN_{55} were averaged for each lane of each section at the two test speeds; and these were plotted and are shown in Figure 32. A spread in the SN_{40} of eight skid numbers (from 51 to 59) is apparent; whereas, the SN_{55} ranged from 49 to 51, a remarkably small variation. If all these data averaged for both lanes and all sections, the SN_{40} is found to be 55 and the SN_{55} is found to be 50, a drop of only five skid numbers for a speed increase of 15 mph (24 km/h).

In columns 7, 8 and 9 limited data are presented depicting skid numbers in natural rain on these same test sections wherein a G-78-15 custom belted poly-glass tire with 2/32 in (1.6 mm) tread was substituted for the full tread ASTM E501. The test speed was 40 mph (64 km/h). The skid numbers ranged from 43 to 53 with no particular pattern.

It is generally evident from the information presented that OGFC of adequate thickness and void content provide ample friction except under extreme conditions of flooding, provided the tires being used have a tread depth of about 0.2 in (5 mm) or greater.

Table 8. Performance of open-graded friction courses on SH 21 Brazos County in natural rain.

1 mph = 1.609 km/h

(Metric Conversion 1 inch = 25.4 mm)

	DATE	INTERNAL WATER	Avg. SN	DATE	RAINFALL RATE in /h	Avg. SN	DATE	RAINFALL RATE in /h	Avg. SN	DATE	RAINFALL RATE in /h	Avg. SN	DATE	RAINFALL RATE in /h	Avg. SN	DATE	RAINFALL RATE in /h	Avg. SN	DATE	RAINFALL RATE in /h	Avg. SN	DATE	RAINFALL RATE in /h	Avg. SN	DATE	RAINFALL RATE in /h	Avg. SN	DATE	RAINFALL RATE in /h	Avg. SN
Section No. 1																														
40 mph O.O.*	5/21	Int.	52	6/15	0.57	52	9/9	0.07	50	11/1	0.01	52	11/8	0.42	53	1/11	0.14	47	1/16	0.47	49	1/11	1.3	43	1/16	0.62	44	1/18	0.08	45
40 mph I.O.**	5/21	Int.	55	6/15	0.34	60	9/9	0.07	64	11/1	0.06	61	11/8	0.26	54	1/11	0.11	57	1/16	0.11	58	1/11	1.2	53						
55 mph O.O.	5/21	Int.	46	6/15	0.10	51				11/1	0.06	52	11/8	0.33	50	1/11	0.09	48	1/16	0.10	46	Goodyear Custom Belted-Polyglass								
55 mph I.O.	5/21	Int.	47	6/15	0	57				11/1	0.01	50	11/8	0.28	52	1/11	0.13	48	1/16	0.09	47	G 78 x 15 2/32-inch Tread								
Section No. 2																														
40 mph O.O.	5/21	Int.	52	6/15	0.57	60	9/9	0.07	45	11/1	0.01	56	11/8	0.42	60	1/11	0.14	53	1/16	0.47	53	1/11	1.3	55	1/16	0.62	54	1/18	0.08	53
40 mph I.O.	5/21	Int.	51	6/15	0.34	58	9/9	0.07	49	11/1	0.06	53	11/8	0.26	54	1/11	0.11	48	1/16	0.11	46	1/11	1.2	43						
55 mph O.O.	5/21	Int.	46	6/15	0.10	54				11/1	0.06	53	11/8	0.33	52	1/11	0.09	47	1/16	0.10	48	Goodyear Custom Belted-Polyglass								
55 mph I.O.	5/21	Int.	48	6/15	0	51				11/1	0.01	52	11/8	0.28	52	1/11	0.13	50	1/16	0.09	48	G 78 x 15 2/32-inch Tread								
Section No. 3																														
40 mph O.O.	5/21	Int.	53	6/15	0.57	61	9/9	0.07	50	11/1	0.01	57	11/8	0.42	58	1/11	0.14	56	1/16	0.47	54	1/11	1.3	50	1/16	0.62	50	1/18	0.08	52
40 mph I.O.	5/21	Int.	53	6/15	0.34	62	9/9	0.07	51	11/1	0.06	57	11/8	0.26	59	1/11	0.11	57	1/16	0.11	52	1/11	1.2	49						
55 mph O.O.	5/21	Int.	44	6/15	0.10	55				11/1	0.06	51	11/8	0.33	47	1/11	0.09	48	1/16	0.10	47	Goodyear Custom Belted-Polyglass								
55 mph I.O.	5/21	Int.	46	6/15	0	52				11/1	0.01	50	11/8	0.28	54	1/11	0.13	51	1/16	0.09	49	G 78 x 15 2/32-inch Tread								
Section No. 4																														
40 mph O.O.	5/21	Int.	50	6/15	0.57	59	9/9	0.07	56	11/1	0.01	60	11/8	0.42	53	1/11	0.14	53	1/16	0.47	51	1/11	1.3	51	1/16	0.62	49	1/18	0.08	53
40 mph I.O.	5/21	Int.	52	6/15	0.34	61	9/9	0.07	55	11/1	0.06	58	11/8	0.26	56	1/11	0.11	53	1/16	0.11	53	1/11	1.2	52						
55 mph O.O.	5/21	Int.	47	6/15	0.01	55				11/1	0.06	52	11/8	0.33	47	1/11	0.09	49	1/16	0.10	44	Goodyear Custom Belted-Polyglass								
55 mph I.O.	5/21	Int.	46	6/15	0	55				11/1	0.01	49	11/8	0.28	44	1/11	0.13	43	1/16	0.09	47	G 78 x 15 2/32-inch Tread								

*O.O. = outside lane, outside wheel path
**I.O. = inside lane, outside wheel path

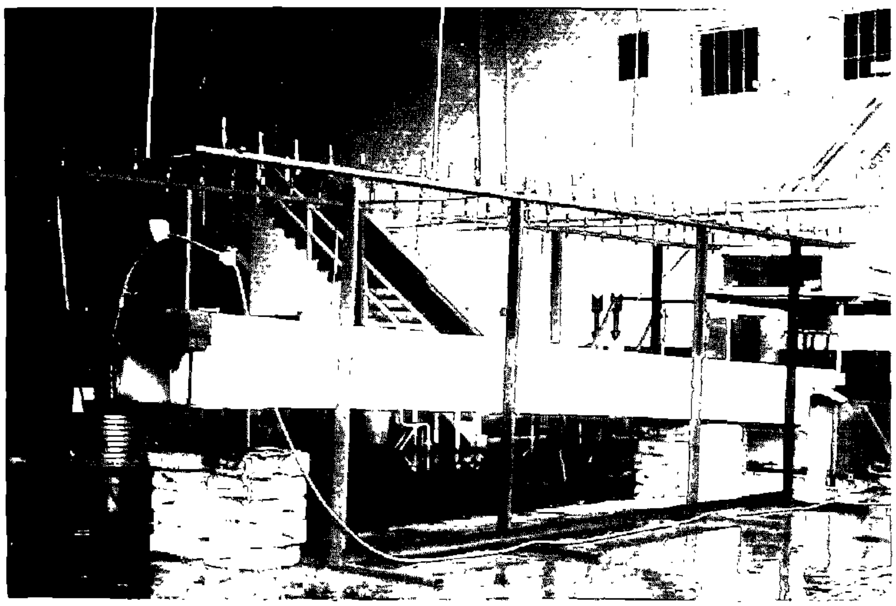


Figure 30. Model surface used to examine runoff from multilane pavements. (Note water input at left (upper) end of pavement segment and simulated rain capability on two outer lines.)

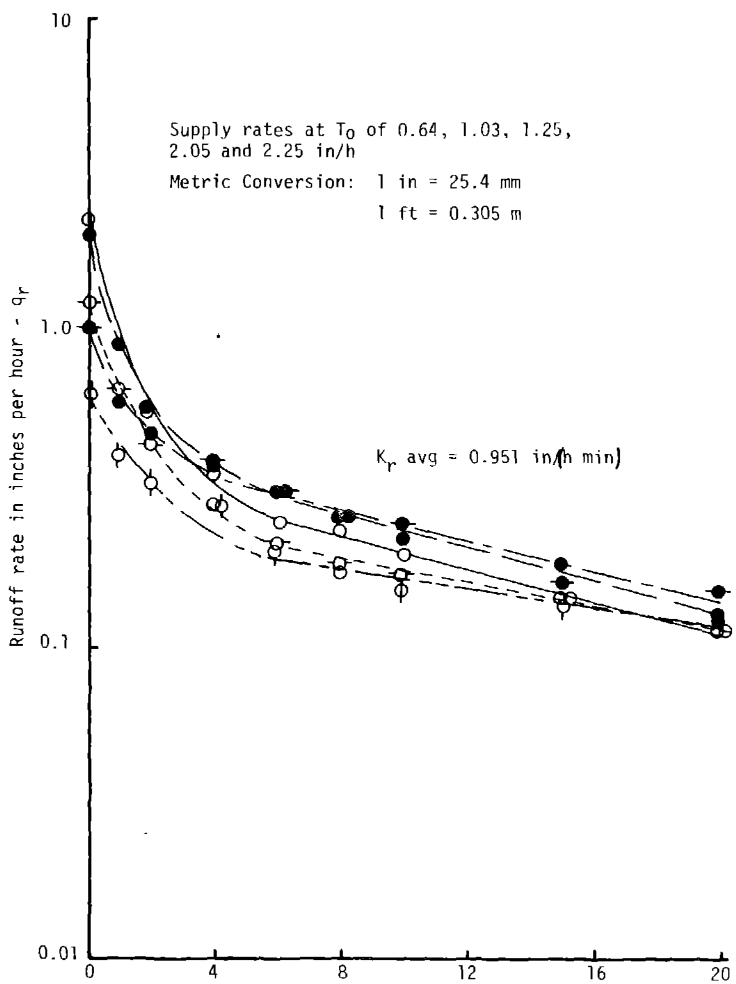


Figure 31. Recession curves 28 ft flow length, slope = 4 percent.

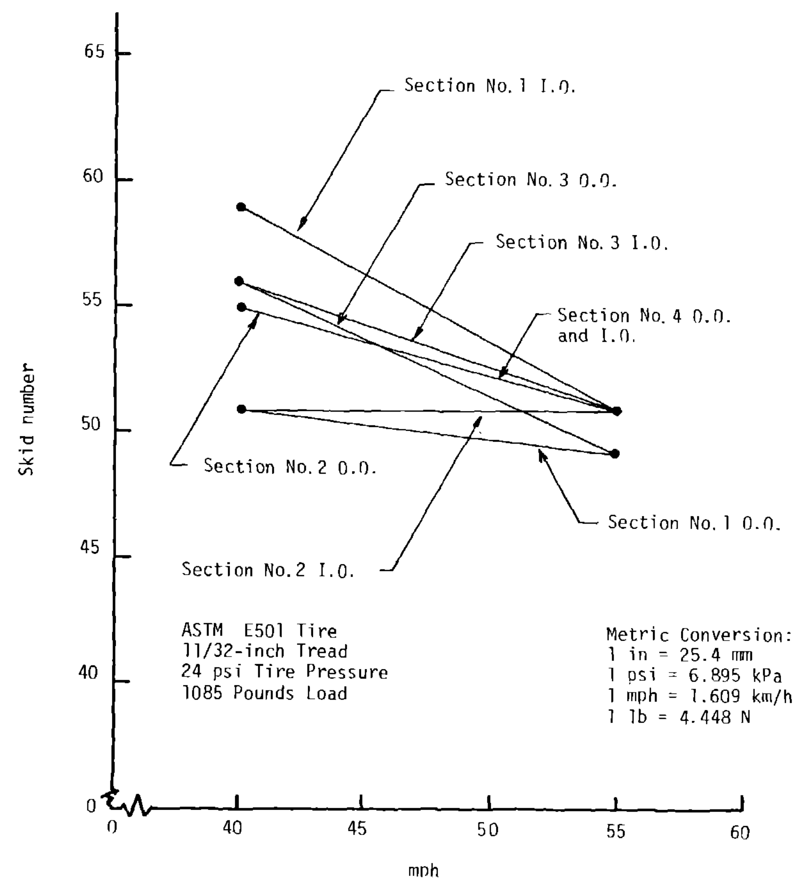


Figure 32. Average skid numbers in natural rain of various intensities on SH 21 OGFC for outside lane, outside wheel path (O.O.) and inside lane, outside wheel path (I.O.).

CHAPTER VII

PAVEMENT CROSS-SLOPE CRITERIA AS RELATED TO VEHICLE CONTROL

Introduction

Presented in this section is a synopsis of an element of the overall study which was conducted during Phase I. Reference should be made to the Phase I report for a more comprehensive presentation of the subject matter including referenced materials.

The 1965 edition of the AASHO (now AASHTO) Blue Book states, "Important characteristics of pavement surface types in relation to geometric design are the ability of a surface to retain its shape and dimensions, the ability to drain, and the effect on the driver behavior." Drainage can be improved by increasing the cross slope, but the effect of relatively steep cross slopes on driver behavior and vehicle control may be unacceptable. The Blue Book states that "cross slopes of 2 percent to 8 percent are noticeable in steering. The latter rate requires a conscious effort in steering and would increase the proneness to lateral skidding when vehicles brake on icy or wet pavements, and even on dry pavements when stops are made under emergency conditions." A survey of state practices conducted in 1972 showed that the maximum cross slope used for either flexible or rigid pavement was 2 percent. The survey included rural highways and urban freeways, but not city streets.

In the opinion of the researchers, further studies were needed and warranted to substantiate the AASHO guidelines regarding cross slopes, especially in light of recent technological advances concerning methods of studying vehicle handling. In particular, the researchers refer to the Highway-Vehicle-Object Simulation Model (HVOSM), a computer program which simulates the dynamic interaction between the automobile and the roadway. Thus, the object of this phase of the study was to conduct a preliminary investigation with HVOSM to determine the effects of cross slopes on both driver demands and vehicle control.

Research Approach and Evaluation Criteria

The HVOSM was used to simulate an automobile performing two common types of maneuvers. These were (1) travel with constant velocity along a tangent section and (2) a lane change maneuver at 60 mph (97 km/h) involving the traversal of a crown.

Certain factors, which are available through the HVOSM output, were used as indicators of the demand on both the driver and on the automobile during these maneuvers. Aligning torque on the front wheels of the automobile provided a measure of driver demands, and the required tire-pavement friction coefficient provided a measure of vehicle demands.

Aligning torques, which result from tire-pavement interaction forces, are dependent on properties of the tire, the vehicle, and the pavement.

However, it must be pointed out that in HVOSM aligning torques are simulated by means of a constant "pneumatic trail" dimension only, i.e., the aligning torque is computed by simply multiplying the side force by the constant pneumatic trail dimension (an input variable). A correction is also made for gyroscopic precession. The degree to which HVOSM simulates actual aligning torque is, therefore, subject to some question, although qualitative comparisons between the torques produced on different cross slopes can still be made.

An automobile traveling along a tangent section with a cross slope tends to turn down the slope, and front wheel torques must be applied through the steering wheel to maintain a tangent path. The aligning torque to maintain a tangent path increases as the cross slope increases.

Aligning torques on the front wheels provide an indication of what is required of the driver as he performs a given steering maneuver. The aligning torque is a moment created at the tire-pavement interface which tends to realign the wheel in the direction of motion. The relationship between aligning torques on the front wheels and the corresponding torque which must be applied at the steering wheel is dependent on a number of variables, such as type and condition of vehicle and type of power steering (if any). A review of the literature revealed very little information which identified this relationship, especially for automobiles with power steering. To gain insight into this area, the researchers performed limited static tests on two automobiles, one without power steering and one with power steering. For the auto with power steering, it appeared that the steering wheel torque was practically constant and independent of the aligning torque. The power steering unit apparently had a compensating feature which adjusted the applied steering torque as a function of the aligning torque. On the car with no power steering, steering wheel torques were found to be proportional to the aligning torques. The steering wheel torque to aligning torque ratio was found to be approximately equal to the ratio of the wheel steer angle to the steering wheel angle.

To determine the tire-pavement friction coefficient necessary to perform the simulated maneuvers. The resultant of the tire side and circumferential forces developed during the maneuver was divided by the vertical tire force. This was done for each of the four tires, and then the one requiring the largest coefficient was selected. It is assumed that friction demands on any tire which exceeds available friction constitutes an unacceptable condition.

Parameters Investigated

It was necessary to limit the number of parameters investigated in the HVOSM studies as follows:

1. All runs were made with a standard size automobile, with a set of typical tires.
2. Only one type of pavement surface was studied (as characterized by a tire-pavement friction coefficient).

3. It was assumed that the cross slope was not interrupted by geometric irregularities such as ruts or local indentation or bumps. The problems associated with the retention of pavement shape and dimension are addressed elsewhere in this report.

The parametric study consisted of 16 HVOSM simulations. Eight cross slopes were investigated, beginning at 1 percent to 8 percent in 1/8 in (3 mm) increments. For each of these eight cross slopes, two basic vehicle maneuvers were investigated. These consisted of a 60 mph (97 km/h) constant velocity path along a tangent section and a 12 ft (3.66 m) lane change maneuver at 60 mph (97 km/h) across a crown (cross slope on each side of crown equal in magnitude but in opposite directions). The maneuvers and the cross slope geometry are illustrated in Figure 33. The runs and the corresponding cross slope geometry are summarized in Table 9.

Tangent Path Results

A summary of the required aligning torques for the eight tangent path runs is shown in Table 10. As an illustration of how the aligning torque could be related to driver requirements, assume that one is driving along a tangent on a 3 percent cross slope at 60 mph (97 km/h) without power steering, and the automobile has a 25-to-1 steering wheel to steer angle ratio. If the steering wheel torque, T_{SW}, is 1/25 of the aligning torque (see Table 10), then

$$T_{SW} = \frac{1}{25}(96) = 3.84 \text{ lbf}\cdot\text{in } (0.43 \text{ Nm})$$

For an 18 in (457 mm) diameter steering wheel, the driver would have to apply a total tangential force, F_{SW}, to the steering wheel, computed as follows:

$$F_{SW} = \frac{3.84}{18.0} = 0.2 \text{ lbf } (0.89 \text{ N})$$

For a 6 percent cross slope, F_{SW} would equal 0.5 lbf (2.22 N), and for a 1 percent cross slope it would be 0.06 lbf (0.27 N); or the 6 percent cross slope would require 733 percent more "effort". The extent to which these driver "requirements" approach, or exceed, driver "limits" remains to be determined.

Also shown in Table 10 is the required friction coefficient to maintain a tangent path at 60 mph (97 km/h) for the eight cross slopes. It is interesting that in each case the rear tires demanded the greatest friction to maintain the tangent path. Also, the largest part of the demand of the rear tires is for traction, i.e., the circumferential tire force (approximately 100 lbf (445 N) per tire) necessary to maintain the 60 mph (97 km/h) speed. Since the tractional demands did not increase appreciably with cross slope, the required friction coefficient did not increase appreciably. Also shown in Table 10 is the friction coefficient needed to keep a stationary vehicle from sliding off the cross slope. The value of the coefficient in such a case is simply the cross slope in radians.

Table 9. Cross slope geometry.

Computer Run No	Cross Slope in/ft, S*	Path
1	1/8 (1%)	Tangent
2	1/4 (2%)	Tangent
3	3/8 (3%)	Tangent
4	1/2 (4%)	Tangent
5	5/8 (5%)	Tangent
6	3/4 (6%)	Tangent
7	7/8 (7%)	Tangent
8	1 (8%)	Tangent
9	1/8 (1%)	Lane Change
10	1/4 (2%)	Lane Change
11	3/8 (3%)	Lane Change
12	1/2 (4%)	Lane Change
13	5/8 (5%)	Lane Change
14	3/4 (6%)	Lane Change
15	7/8 (7%)	Lane Change
16	1 (8%)	Lane Change

*See Figure 33.

Table 10. Summary of tangent path results.

Run No	Cross Slope (in/ft)	Required Aligning Torque (lbf·in)	Required Friction Coefficient	Required Friction Coefficient for Static Equilibrium
1	1/8 (%)	25	0.092	0.010
2	1/4 (2%)	60	0.097	0.021
3	3/8 (3%)	96	0.088	0.031
4	1/2 (4%)	128	0.098	0.042
5	5/8 (5%)	164	0.110	0.052
6	3/4 (6%)	204	0.110	0.063
7	7/8 (7%)	240	0.110	0.073
8	1 (8%)	260	0.120	0.083

Metric Conversion: 1 in = 25.4 mm
1 ft = 0.305 m
1 lbf·in = 0.113 Nm

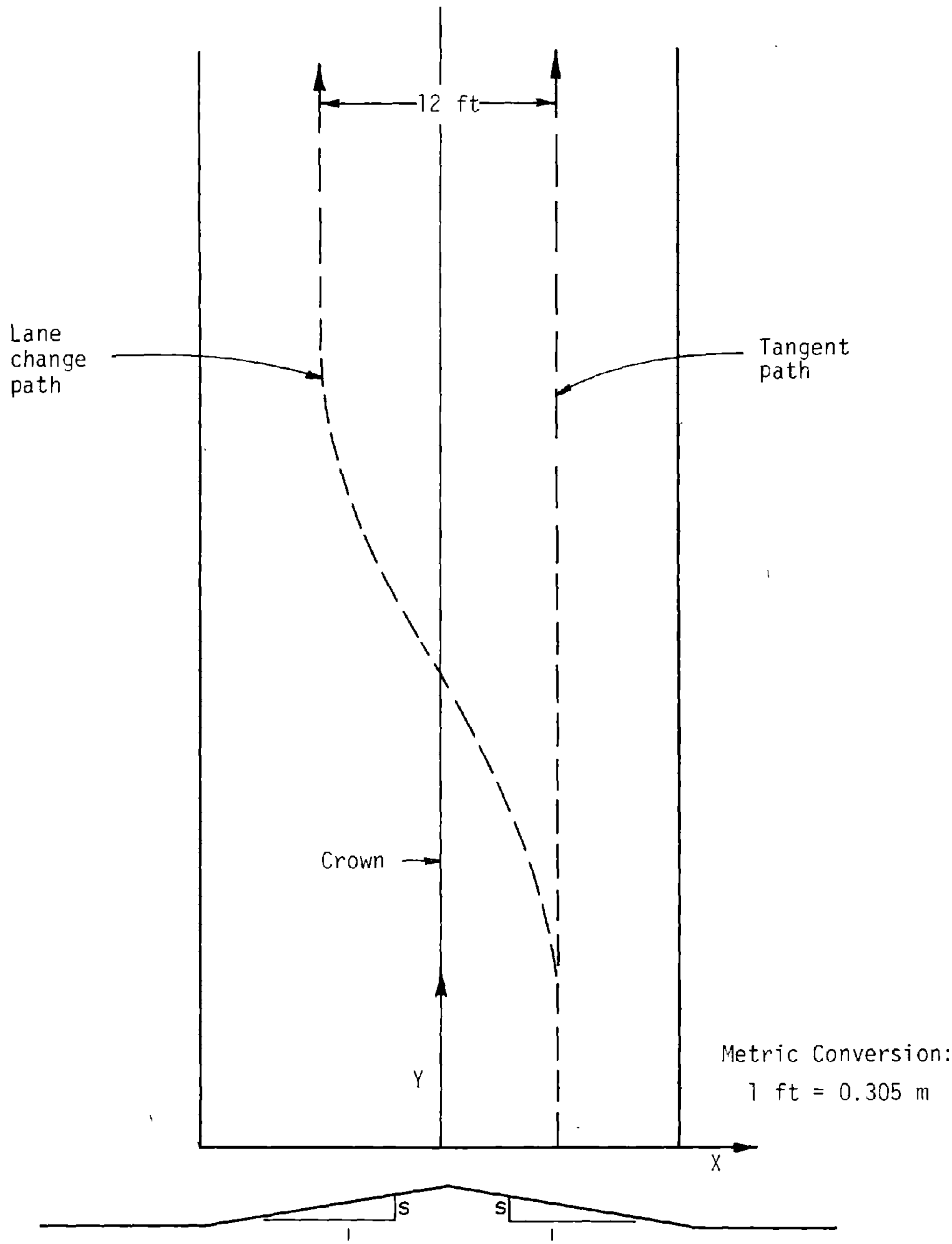


Figure 33. Maneuvers and cross slope geometry.

Information in Table 10 is shown plotted in Figure 33 . The results of these simulations indicate that increases in cross slope do not appreciably increase frictional demands of the automobile for travel along a tangent path. However, demands of the driver increase considerably as the cross slope increases.

Lane Change Results

Three quantities were evaluated for each of the lane change runs, namely, the required friction coefficient, the vehicle's path and the aligning torque. Maximum values of the required friction coefficient and the aligning torque are shown in Table 11 and are plotted in Figure 34.

In general, the maximum friction demand during the lane change appears to be proportional to the magnitude of the side slope. There are intermediate peak values of the friction demand, which occur at cross slopes of 3 percent and at 6 percent. It is not known if these cross slopes do in fact require more friction to negotiate than steeper slopes, as shown in Figure 35, or if the results for these cross slopes represent "scatter" in the HVOSM data. It should be noted that the controller routines which steer the vehicle and which apply traction for speed control continually sense deviations in the desired path and vehicle speed. However, deviations do occur which require corrections. Although attempts are made in the control routines to minimize the number and magnitude of these corrections, oscillations in the desired path and speed sometimes occur. The degree to which corrections are necessary is a function of the initial conditions of the vehicle (speed and orientation), the vehicle's characteristics, the roadway geometry and the controller algorithms themselves.

A comparison of Figures 34 and 35 shows that for a given cross slope the lane change maneuver requires a significantly greater driver effort (aligning torque) than does driving a tangent path. Vehicle demands (tire-friction coefficient) of the lane change are also considerably greater than those for the tangent path. However, with regard to driver effort, since most travel time is spent driving tangents, it seems reasonable to assume that considerably larger driver efforts would be tolerable for short periods of time, such as that needed to make the lane change. An analogous situation cannot be made with regard to friction demands. A very undesirable condition exists any time the required friction exceeds the available friction. In other words, the friction demands of the lane change maneuver must be met.

Friction demands for a constant speed tangent path appear practically independent of the magnitude of the cross slope. The largest demand comes from the rear tires due to the combined tractional force and side force requirements. However, increases in cross slope require increases in the steer angle of the front wheels which would undoubtedly increase tire wear. Studies are needed to quantify the wear as a function of cross slope.

In both the tangent path and the lane change maneuver, the vehicle remained stable and there were no indications that loss of control was

Table 11. Summary of lane change maneuvers.

Run No	Cross Slope (in/ft)	Required Aligning Torque (lbf·in)	Required Friction Coefficient
9	1/8 (1%)	475	0.16
10	1/4 (2%)	550	0.18
11	3/8 (3%)	635	0.22
12	1/2 (4%)	720	0.20
13	5/8 (5%)	840	0.25
14	3/4 (6%)	1000	0.31
15	7/8 (7%)	1300	0.28
16	1 (8%)	1440	0.34

Metric Conversion:
1 in = 25.4 mm
1 ft = 0.305 m
1 lbf·in = 0.113 Nm

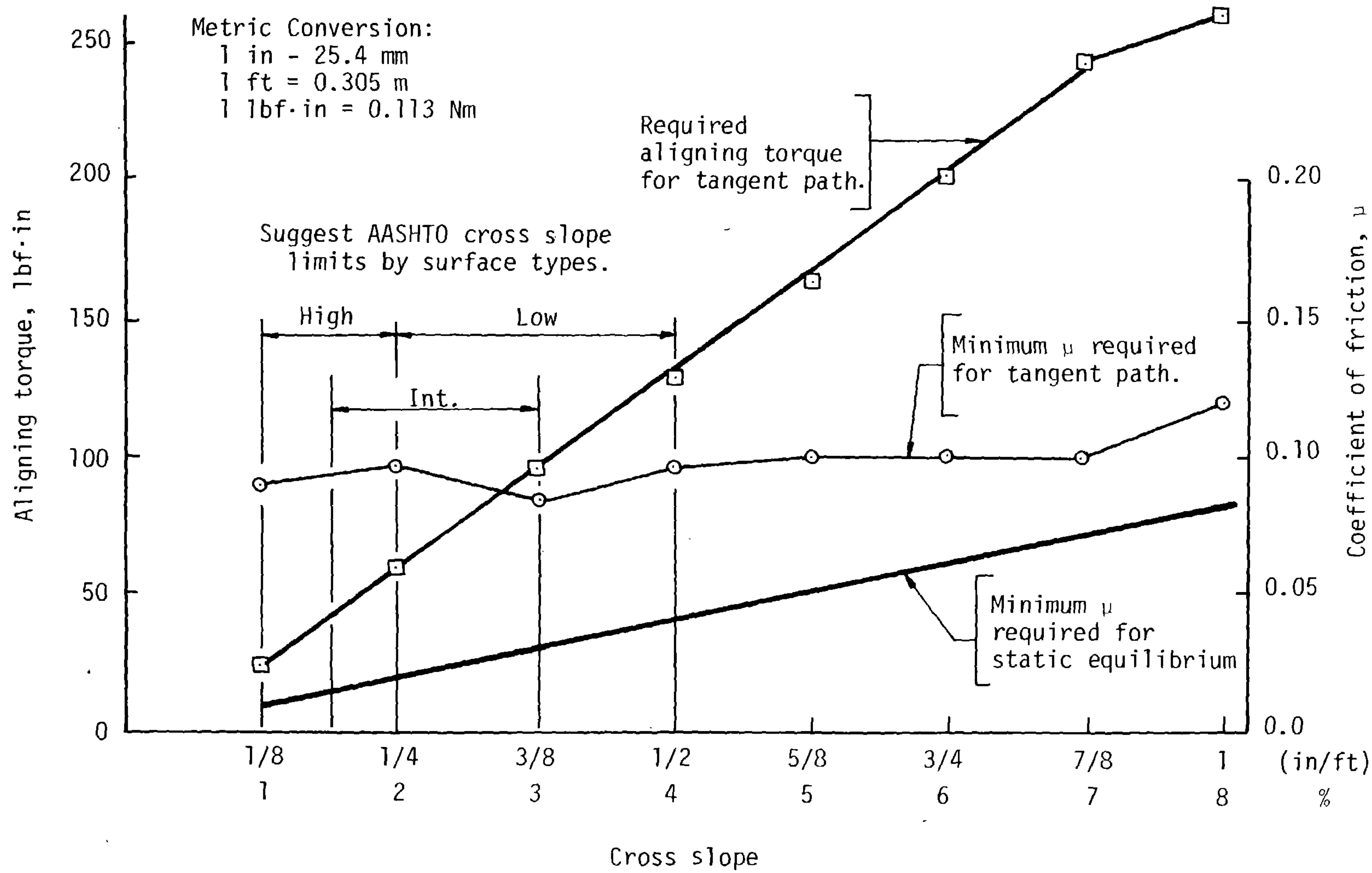


Figure 34. Tangent path results.

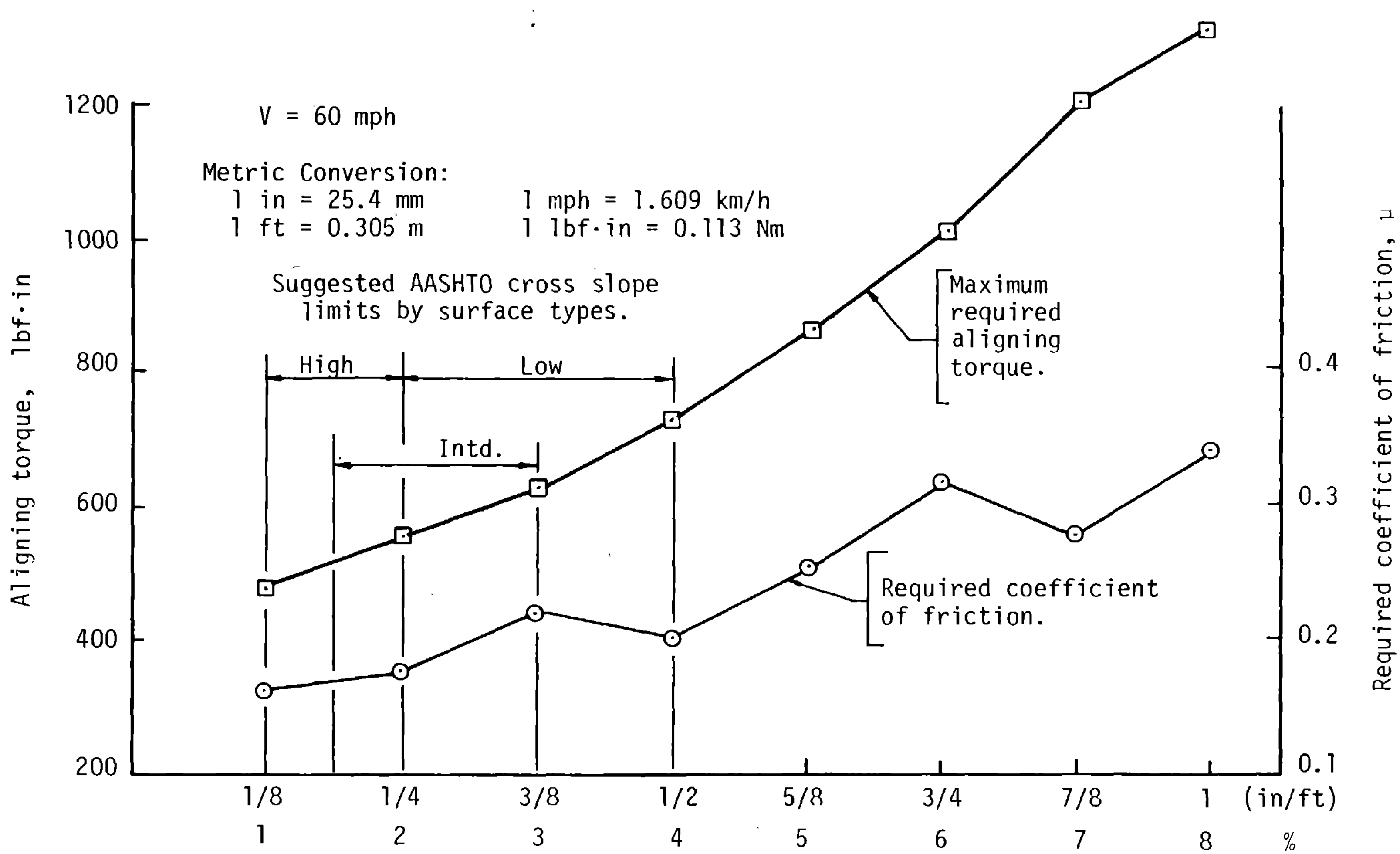


Figure 35. Aligning torque and required coefficient of friction vs. cross slope for lane change.

impending. However, for the larger cross slopes, some erratic responses occurred. As can be observed in the plotted results, the required friction and aligning torques did not reach a steady state condition for either the tangent path or the lane change (after the lane change was completed).

Conclusions

It is concluded that the HVOSM computer program can be used to quantify the effects of cross slope on both driver demands and vehicle control. However, before further investigations with the HVOSM are made, modifications are needed with regard to the vehicle controller routines. Such changes would result in a better simulation of a typical driver's response in performing various functions, such as the lane change maneuver and in maintaining a constant vehicle speed. Modifications may also be warranted to the HVOSM with regard to the simulation of aligning torques on the tires.

Tentative conclusions which can be drawn from the limited parametric study are as follows:

1. An automobile can maintain a tangent path on cross slopes up to 6 percent without significant friction demands (as measured by tire-pavement friction coefficient) or driver effort (as measured by aligning torques). For greater cross slopes, the simulation exhibits an erratic response which is probably a numerical problem related to control inputs.
2. The lane change maneuver (including crossing a crown) requires considerably larger friction demands and driver effort than does driving a tangent path. While the larger driver effort may be tolerable for the lane change (since it occurs over a relatively short period of time), the friction demands must be met, or unacceptable consequences will result.
3. Friction demands of approximately 0.10 for a constant speed tangent path appear practically independent of the magnitude of the cross slopes. The largest demand comes from the rear tires due to the combined tractional force and side force requirements. However, increases in cross slope require increases in the steer angle of the front wheels which would undoubtedly increase tire wear.
4. Required driver effort has been quantified in terms of aligning torques on the front wheels. More study is needed to (a) relate aligning torques to actual driver requirements (steering wheel torque) and (b) to determine human tolerance "limits" in terms of steering wheel torques.
5. Cross slope values up to 2 percent show no significant detrimental effects with regard to either friction demand or driver effort.

CHAPTER VIII

DESIGN CRITERIA FOR DRAINAGE OF SAG VERTICAL CURVES

Introduction

In order to examine the present practices with regard to sag vertical curve design to minimize hydroplaning, a questionnaire was sent to nine state design engineers. A summary of the significant findings of this survey is listed below:

1. No wet weather speed limits are currently in use.
2. Surface drainage is a significant design consideration in most states.
3. No special drainage considerations are given to sag vertical curves.
4. A storm recurrence interval of 8-15 years is commonly used.
5. A maximum water-film depth criterion is not currently being applied in the design process.
6. Maximum flow path length is used as a design criteria by about 20 percent of the states.
7. A 36 ft (11 m) maximum width of drainage in one direction is common.
8. Cross-slope criteria for sag vertical curves were also typical of standard criteria for tangent sections.
9. Few attempts have been made to incorporate experimental drainage features at critical drainage locations, i.e., sag vertical curves. Those states whose policy prescribes the use of storm recurrence design interval also encourage increasing the design interval for underpasses and intersection design for sag vertical curves.

Based on a review of the AASHTO standards, the input from state design engineers and engineering judgment, tentative design criteria for sag vertical curves have been prepared. These criteria are presented in Table 12, and many of the criteria are based on judgment. These must be applied and evaluated to confirm their utility in the design process.

Innovative Surface Drainage Techniques

The removal of water from the pavement surface can be accomplished in two ways: (1) over-the-surface drainage and/or (2) through-the-pavement drainage. Through-the-pavement drainage can be accomplished by drainage through an open-graded asphaltic friction course or by intercepting the water runoff through drop inlets on the surface of the pavement. These two basic concepts were incorporated into seven innovation drainage concepts which were evaluated with respect to the following criteria:

Table 12. Tentative sag vertical curve drainage design criteria based on a survey of existing practice.

Design Element	Desirable Design	Minimum Design
Maximum pavement width for one-way drainage	36 ft (11 m)	36-48 ft (11-14.6 m)
Maximum inlet spacing	50-200 ft (15-61 m)	300-500 ft (91-152 m)
Storm recurrence design interval	25 years	10 years
with crossroad intersection	25-50 years	10-25 years
with underpass structure	25-50 years	25 years
Channelized curb flow encroachment	Containing ponding on the shoulder	Containing ponding on the shoulder and half of the extreme right lane
Increase in roughness Coefficient (Manning's N) for various materials due to small gutter slopes	0.0005	0.002
Pavement cross slope for sag vertical curve section	Slight increase in cross slope	No increase in cross slope

1. Adaptability to wheel-path depression,
2. Susceptibility to ponding,
3. Susceptibility to clogging,
4. Difficulty in construction,
5. Difficulty in overlaying,
6. Expected degree of compaction,
7. Maintenance cost and
8. Difficulty in adapting to PCC pavement.

Based on this subjective analysis, the systems involving open-graded asphaltic concrete as the surface course were judged to be substantially better than drop inlet or slotted pipe drain systems. For this reason, a detailed examination of the drainage capability of the open-graded asphaltic mix was undertaken.

Open-Graded Asphaltic Mix Drainage Capacity

Based on experimentally determined values, a pavement with a 2 percent cross slope and a 0 grade shows flooding occurs on an open-graded paving mixture 1 in (25.4 mm) thick, 12 ft (3.7 m) wide, composed of a 0.3 in (7.6 mm) aggregate if the rainfall intensity is in the range of 0.3 to 0.5 in/h (8 to 13 mm/h) (11).

The drainage capacity of the permeable pavements and the water flow velocity through them has been estimated based on the data above. The resulting average velocity was 0.0078 ft/s (2.4 mm/s). Moynahan, et al., (17) reported a velocity of 0.002 ft/s (0.6 mm/s) for dense-graded aggregate. Thus, the velocity estimate appears to be of the right order of magnitude.

The thickness of the open-graded mixture needed to facilitate drainage can be estimated for a horizontal velocity of 0.0078 ft/s (2.4 mm/s). The thickness required continuously increases with drainage path length to a maximum of t' at the pavement edge as indicated in Figure 36.

Therefore

$$Q = VA = IP \qquad \text{Eq. (14)}$$

for

$V = 0.0078$ ft/s = 28 ft/h (8.54 m/h)

$A = 0.15\, t'y$

$P = Ly$

where

Q = flow quantity through the pavement units

t' = open-graded layer thickness, inches (mm/25.4)

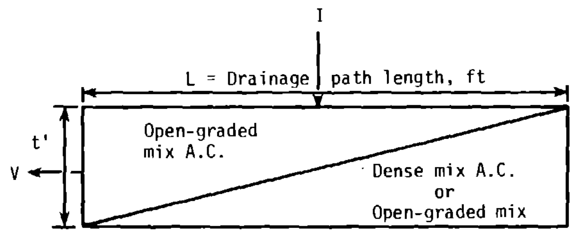


Figure 36. Thickness of open-graded pavements.

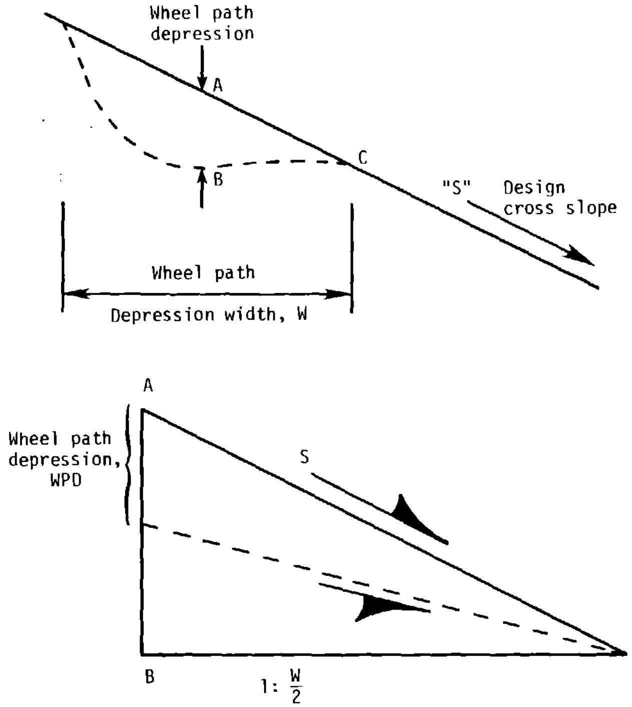


Figure 37. Basic geometry of wheel path depression.

y = longitudinal length of the pavement section in ft (m/0.305)

I = rainfall intensity, in/h ($\frac{mm}{25.4}$/h)

L = drainage path length in ft (m/0.305)

Solving Equation 14 for t', the resulting equation is

$$t' = \frac{IL}{4.21} \qquad \text{Eq. (15)}$$

Calculations from Equation 15 are shown in Table 13.

It is apparent from Table 13 that for design rainfalls exceeding about 1 in/h (25.4 mm/h) and drainage lengths exceeding 24 ft (7.3 m) the required thickness becomes excessive. Thus, open-graded mix cannot be expected to drain the pavement for typical design rainfalls. The pavement cross slope must serve this function. Open-graded pavement surfaces provide pavement macrotexture which is necessary.

Effect of Wheel Path Depression on the Critical Drainage Path Length

Drainage across the pavement can be interrupted by depressions of the pavement surface. The most common of these depressions is the wheel path depression created by material compaction and/or wear. A mathematical approach was used to evaluate the effect of wheel path depression on drainage path length.

Basic Assumptions:

1. Minimum cross slope to maintain drainage is 0.5 percent.
2. The wheel path depression is 2 ft (0.6 m) wide.

The basic geometry of the wheel path depression is presented in Figure 37. This analysis resulted in the equation:

$$WPD = (S - 0.005)\frac{W}{2} \qquad \text{Eq. (16)}$$

where WPD = wheel path depression

S = pavement cross slope

Observed wheel path depressions measured in the field revealed that the 85th percentile depression was approximately 0.3 in (7.6 mm). Using this value the maximum wheel path depression to prevent ponding can be determined. Table 14 presents the results of this analysis.

Critical Drainage Path Length

Gallaway, et al. (13) reported that water depth on the pavement can be estimated by the equation:

Table 13. Required thickness of open-graded pavement for selected rainfalls, inches (mm)

Drainage Path Length, L, feet	metres	Rainfall Intensity in/h (mm/h) 0.2 (5)	0.5 (13)	1.0 (25)	1.5 (38)	2.0 (51)
12	3.7	0.6 (15)	1.4 (36)	2.9 (74)	4.3 (109)	8.6 (218)
24	7.3	1.1 (28)	2.9 (74)	5.7 (145)	8.6 (218)	
36	11.0	1.7 (43)	4.3 (109)	8.6 (218)	12.8 (325)	
48	14.6	2.3 (58)	5.7 (145)	11.4 (290)		
60	18.3	2.9 (74)	7.1 (180)			

Required thickness excessively large (hatched area)

Table 14. Allowable wheel path depressions to provide surface drainage

Cross Slope %	Maximum Wheel Path Depression inches	millimetres
1	0.06	1.5
2	0.18	4.6
3	0.30	7.6

$$WD = 0.00338 \left[\frac{TXD^{0.11}\ L^{0.43}\ I^{0.59}}{S^{0.42}}\right] - TXD \qquad \text{Eq. (9)}$$

where

WD = water depth in inches (mm/25.4)

TXD = texture depth in inches (mm/25.4)

S = pavement cross slope

L = drainage path length (feet) (m/0.305)

I = rainfall intensity (inches/hour) ($\frac{mm}{25.4}$/h)

Solving this equation for the drainage path length, the results are

$$L = \left[\frac{(WD + TXD)S^{0.42}}{0.00338\ TXD^{0.11}\ I^{0.59}}\right]^{2.33} \qquad \text{Eq. (17)}$$

Combining the length of drainage path with the pavement grade, the grade necessary to produce water buildup on the pavement (i.e., critical drainage path length) can be determined. The relationship is presented in Equation 18.

$$g_c = \frac{S\sqrt{L^2 - W^2}}{W} \qquad \text{Eq. (18)}$$

where

g_c = critical grade

S = pavement cross slope

L = length of the drainage path in feet (m/0.305)

W = width of the pavement being drained in feet (m/0.305)

Figures 38 to 40 present these relationships in graphical form. Review of the graphs reveals that substantial water accumulation is not likely for the commonly used grades and cross slopes. While some accumulation does occur, it is not generally sufficient to produce a substantial hydroplaning problem.

Recommended Treatments for Sag Vertical Curves

The recommendations for minimizing hydroplaning in sag vertical curves are presented in Tables 15, 16 and 17.

Table 15. Recommended treatment for sag-vertical curves in new construction.

Cross Slope	PCC Pavements 2%	AC Pavements 2%
Surface Texture	High texture surface using transverse grooving of fresh concrete by metal tines. Space tines at 0.5 inches (13 mm) maximum, 0.2 inches (5 mm) maximum depth and 0.08 inches (2 mm) minimum depth.	One inch (25 mm) of open-graded AC mix or a course surface treatment (maximum size aggregate 0.5 inches (13 mm)).

Table 16. Recommended remedial treatment for sag-vertical curves subject to flooding.

Cross Slope	PCC Pavements			AC Pavements		
	Min. 1%	Max. 2%	Desirable 2%	Min. 1%	Max. 2%	Desirable 2%
Surface Treatment	Longitudinal grooving 0.1 inch (2.5 mm) grooves at 0.8 inch (20 mm) centers to a maximum depth of 0.2 inch (5 mm).			One inch (25 mm) of open-graded AC mix or a course surface treatment (maximum aggregate size of 0.4 inch (10 mm)).		
Wheel Path Depression Maintenance	Maximum wheel path depression 0.20 inch (5 mm) as measured from the normal cross slope of the pavement.			Maximum wheel path depression 0.20 inch (5 mm) as measured from the normal curve slope of the pavement.		

Table 17. Recommended remedial treatment for sag-vertical curves with curbs.

	PCC and AC Pavements
Curb	Remove
Treatment	Use slotted shoulder subdrain on a paved shoulder. Subdrain to be located a minimum of 2 ft (0.6 m) from the through-lane pavement edge, or reshape and pave shoulder to provide a drainage channel on the shoulder, and resurface with open-graded AC mix to a 2 percent effective cross slope when the cross slope is less than 1.5 percent or wheel path depressions exceed 0.2 in (5 mm). Note: Grooving may be necessary to provide sufficient pavement macrotexture.

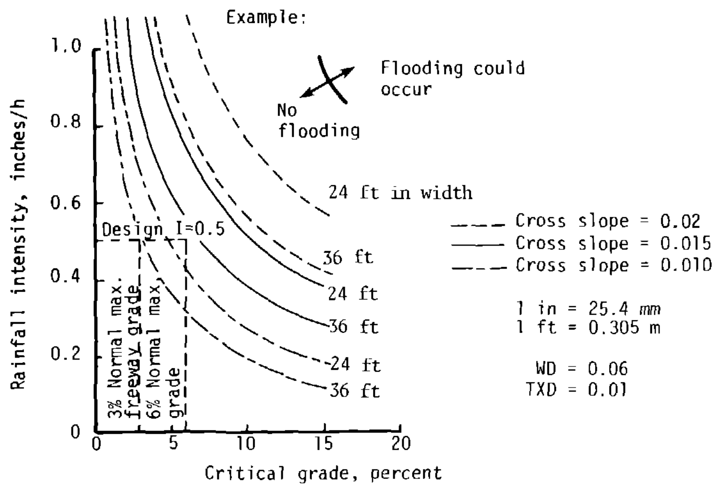


Figure 38. Rainfall intensity vs. critical grade.

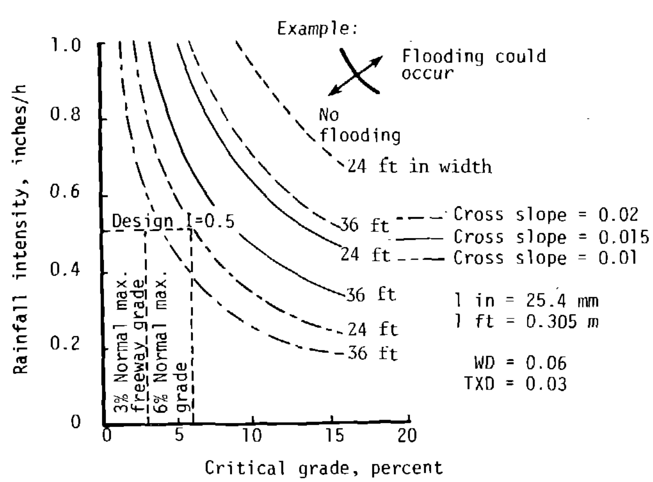


Figure 39. Rainfall intensity vs. critical grade.

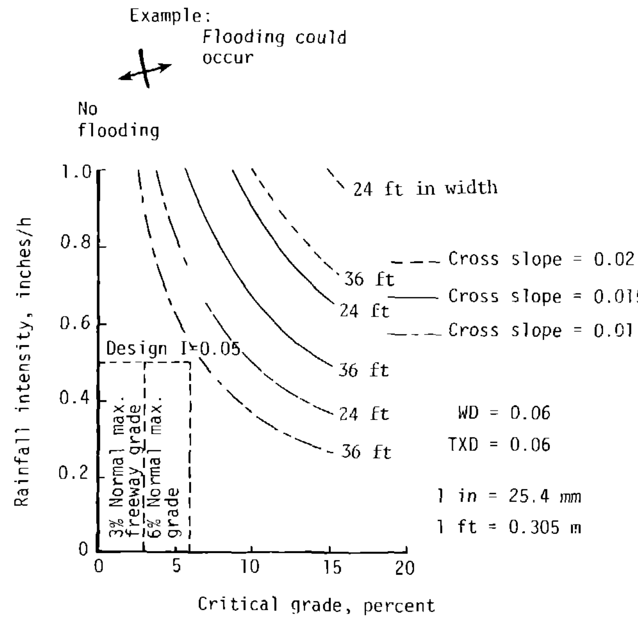


Figure 40. Rainfall intensity vs. critical grade.

Summary of Major Findings

1. Of the innovative surface drainage systems considered, those featuring a permeable surface course or a high macrotexture surface course appear to have the highest potential for reducing hydroplaning accidents.

2. Based on the observed flow rates through the open-graded mixture, the thickness required to accommodate drainage through the pavement for high intensity rainfalls is too great to be economically feasible. Excessive compaction of the overlay combined with high rainfall intensities are the primary reasons.

3. Pavement cross slope is the dominant factor in removing water from the pavement surface. A minimum cross slope of 2 percent is recommended.

4. As a guideline, a wheel path depression in excess of 0.2 in (5 mm) should be used as a criterion for resurfacing to reduce the pavement drainage problem when dense AC or PCC pavements are used.

5. The most serviceable innovative surface drainage systems are those that involve open-graded AC surface courses without a subdrain system.

6. Surface drains located parallel to the lane lines will probably not solve the drainage problem due to the wheel path depressions.

7. Transverse surface drains located on the pavement surface would probably result in a rough pavement, increase maintenance costs, and increase potential for ponding water. For these reasons, such systems are not recommended for general use.

CHAPTER IX

CRITERIA TO REDUCE HYDROPLANING

Based on the information developed in preceding chapters, a clear definition has evolved concerning the influence of different factors on the full loss of control forces (dynamic hydroplaning). It is of interest now to estimate the range and distribution of these factors on the highway. Approximate distributions of these factors are given in the full report. The approximate 50 percentile values of these obviously skewed distributions are

$$TD = 7/32 \text{ in } (5.6 \text{ mm})$$
$$P = 27 \text{ psi } (186 \text{ kPa})$$
$$TXD = 0.038 \text{ in } (0.96 \text{ mm}).$$

The lower seven percentile level of the three groups is approximately:

$$TD = 2/32 \text{ in } (1.6 \text{ mm})$$
$$P = 18 \text{ psi } (124 \text{ kPa})$$
$$TXD = 0.01 \text{ in } (0.25 \text{ mm}).$$

Two plots showing the distribution of texture depth in 1967 and in 1977 are given in Figure 41. The difference between these two plots would seem to show a remarkable (and certainly appropriate) increase in texture depths in one state over the past ten years.

Note that the plot of texture depth in terms of roadway distance is not the same as exposure rate to traffic since the more highly traveled, and thus more highly polished, roads are probably biased toward the lower texture range. Therefore the plot given is probably more optimistic than warranted in terms of actual exposure to the lower texture values. The obvious conclusion is that significant numbers of automobiles are traveling under conditions which could produce hydroplaning at speeds less than the current speed limits of 55 mph (88 km/h).

However, there is one factor that makes the situation less critical than our initial considerations would seem to indicate; that is, the comparative rarity of rainfalls intense enough to sustain significant positive water depths on the road surfaces.

The full report (9) gives the overall percentage of time that highways are exposed to rainfall of different intensities for Texas, Illinois and Alabama. The surprising conclusion from these data is that the exposures in these states are so similar. These data can also be estimated for other states and regions by use of two equations which fit Figures 15 and 16 reasonably well.

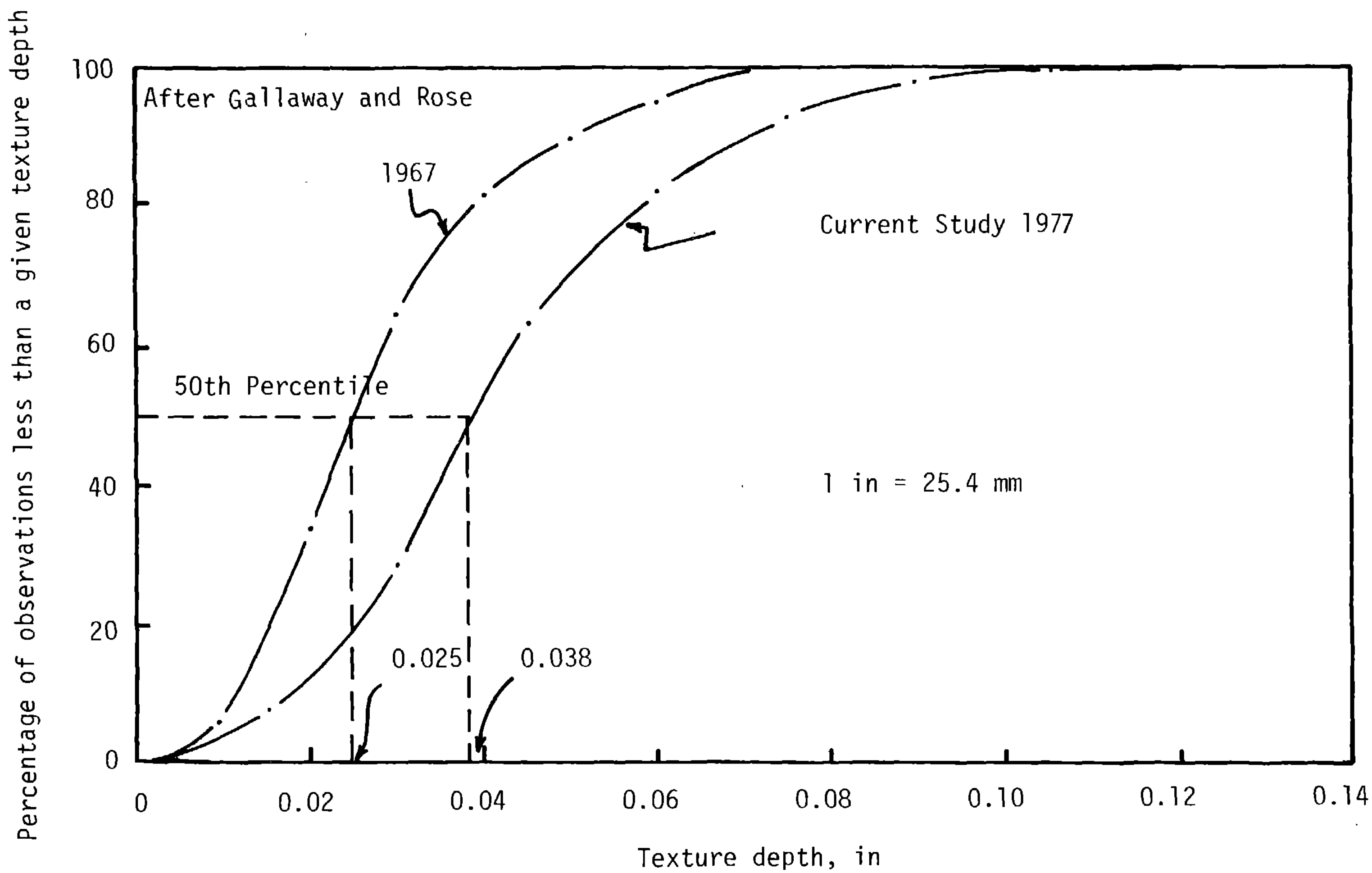


Figure 41. Approximate distribution of texture depths in one state; comparison of 1967 and 1977 data.

These equations are

$$T_w = 0.041 - \frac{(R_r - 60)^2}{87,500} \qquad \text{Eq. (19)}$$

(1 in/y = 25.4 mm/y)

where

R_r is the total annual rainfall in a specific region, r;

and

T_w is the proportion of time a region is subjected to an intensity of rainfall greater than 0.01 in/h (0.25 mm/h)

and

$$P_i = \frac{0.0324}{I_i} \qquad \text{Eq. (20)}$$

(1 in/h = 25.4 mm/h)

where

P_i is the probability of the occurrence of an intensity, I_i, during a period of rainfall.

The first produces an estimate of the proportion of time a region is subjected to rainfall equal to or greater than 0.01 in/h (0.25 mm/h) based on the total annual rainfall. The second is what appears at this stage to be a conservative estimate of the probability of observing a specific or greater intensity during a period of rainfall. These two equations can be combined to produce an estimate of the proportion of time throughout a year when a rainfall of specific or greater intensity may be expected, P_{ri}, i.e.,

$$P_{ri} = P_i \, T_w$$

or

$$P_{ri} = \frac{0.0324}{I_i} \left[0.041 - \frac{(R_r - 60)^2}{87,500} \right], \qquad \text{Eq. (21)}$$

(1 in/year = 25.4 mm/year, 1 in/h = 25.4 mm/h)

At this stage it is appropriate to discuss the selection of a "design" rainfall intensity. The purpose of a "design" intensity is twofold. First, as in the case of almost all highly variable natural phenomena, to recognize it is not practical to design for all possible events. The precedent for this position is well established in many engineering disciplines. Examples are: (1) Traffic - the design of geometrics for the 85th or in some cases the 95th percentile traffic speed; (2) Hydraulics - the design of facilities based on a 25-year flood; and (3) Structures - the design for a 20-year wind, a 50-year snowfall or a 100-year earthquake.

Second, without a "design" rainfall intensity it is impossible to "design" road surfaces to preclude hydroplaning. Through experience, relatively standard practices have emerged which have reduced the hydroplaning event to a fairly low probability; but no comprehensive "design" method has emerged to provide a real direction to the effort.

Considering ways in which "design" rainfalls could be established, two approaches are given, with obvious preference given the latter.

Approach 1

Choose a reasonable "design" rainfall intensity and ask all states to design and maintain highways in such a way that this intensity will be accommodated. For example, this choice might be based on the average 95th percentile rainfall intensity throughout the nation, a value of approximately 0.5 in/h (13 mm/h). If two states are compared, one having a great deal more rainfall than the other, and all other factors being approximately equal, each state would be required to construct and maintain the same combinations of texture, cross slope and drainage path length. This would result in the lower rainfall state achieving a significantly lower probability of hydroplaning, or a much lower cost effectiveness level for efforts to decrease hydroplaning. A more versatile approach can be formulated by the "regional equalization of probability" concept; that is, design standards which would equalize the probability of a hydroplaning event between different regions, e.g., between Nevada and Louisiana.

To do this, Table 18 illustrates the variables which must be considered to reduce the probability. Note only three of these factors -- surface texture, surface slope and drainage path length -- may be considered within the engineer's control. The other factors must be treated from the standpoint of probability as will be demonstrated in the following approach.

Approach 2

Choose a reasonable probability level of precluding hydroplaning and compute a "design" rainfall intensity for each state or geographic area to achieve that level.

As an example, consider choosing a probability level of one in one hundred thousand. This means the highway surface would be constructed and maintained in a particular area so that the probability of hydroplaning would exist one chance in one hundred thousand. Select, for the "design" tread depth, the minimum legal tire tread depth of 2/32 in (1.6 mm). (This depth or lower occurs on 7 percent of all automobiles, a probability level of 0.07.) For consistency, selecting a probability level of 0.07 for tire pressure results in a design tire pressure of approximately 18 psi (124 kPa). The probability of vehicles driving speeds necesary to achieve hydroplaning with these tire conditions is neglected on the grounds that the legal speed of 55 mph (88 km/h) should be accommodated, and this speed is certainly high enough to allow hydroplaning. At this combination of tire pressure and tread depth, very small values of water depth can cause hydroplaning.

Table 18. Variables influencing hydroplaning.

Factors Within Engineer's Control	Factors Outside Engineer's Control
Surface texture	Rainfall
Cross slope	Tire tread depths and pressures
Drainage path length	Vehicle speeds*

*Although some degree of influence may be obtained there will remain a relatively uncontrolled variation in individual vehicle speeds.

Thus, a very conservative criterion to preclude such occurrence would be the allowance of no positive water depth through management of texture, cross slope and drainage path length when the highway is subjected to the "design" rainfall intensity.

The "design" rainfall intensity may be computed as follows, based on the one in one hundred thousand choice of probability for the hydroplaning event.

$$P_e = P_t \times P_p \times P_{ri} \; . \qquad \text{Eq. (22)}$$

The probability of a specific combination of events occurring is the product of the probabilities of the individual events.*

Where

P_e = Probability of hydroplaning event (Selected in this example as 1×10^{-5})

P_t = Probability of the "design" tread depth (Selected in this example as 0.07)

P_p = Probability of the "design" tire pressure (Selected in this example as 0.07)

P_{ri} = Probability of the "design" rainfall intensity.

Then, P_{ri} may be computed as

$$P_{ri} = \frac{P_e}{P_t \times P_p} = \frac{1 \times 10^{-5}}{7 \times 10^{-2} \times 7 \times 10^{-2}}$$

$$P_{ri} = 2 \times 10^{-3} .$$

If the region we are considering has an annual rainfall, R_i, of 30 in (76.2 mm), the "design" rainfall, I_d, can be calculated from Equation 21. Thus computation shows a rainfall intensity that can be accommodated by current technology.

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*This assumes the individual factors are each randomly distributed and vary independently from each other. Since the variation is neglected, i.e., the probability of driving 55 mph (88 km/h) or greater is conservatively assumed to be one, the actual probability of hydroplaning event is even less than the amount stated here. This is considered most likely since the rainfall event at design intensity levels reduces visibility and results in many vehicles slowing down. Others slow in response to the knowledge that wet pavements make vehicle control more difficult.

$$I_i = I_d = \frac{0.0324}{P_{ri}} \left[0.041 - \frac{(R-60)^2}{87,500}\right] * \qquad \text{Eq. (21)}$$

$$I_d = \frac{0.0324}{2 \times 10^{-3}} \left[0.041 - \frac{(30-60)^2}{87,500}\right]$$

$$I_d = \frac{32.4 \times 10^{-3}}{2 \times 10^{-3}} \left[0.031\right] = 0.5 \text{ in/h } (12.7 \text{ mm}).$$

Following the same computational method, the following design rainfall intensities would be selected for regions of the country having the annual rainfalls given. See Table 19.

Although it would be more precise for each state to analyze rainfall records to develop a state or regional "design" rainfall intensity, it appears that the equations developed will provide reasonable estimates.

Once the "design" rainfall intensity is selected, information is available which will allow the prediction of water depth on the pavement as a function of surface slope, runoff length and texture. For example:

$$WD = 3.38 \times 10^{-3} [TXD^{0.11} L^{0.43} I^{0.59} S^{-0.42}] - TXD \qquad \text{Eq. (9)}$$

where

WD = the water depth above the top of the surface asperities in inches (mm/25.4)

L = runoff length in feet (m/0.305)

TXD = texture depth in inches (mm/25.4)

I = rainfall intensity in in/h (mm/25.4)

S = slope of surface in ft/ft (m/m).

Curves developed using this equation showing acceptable combinations of cross slope, drainage path length and texture depth for different rainfall intensities are given in Figures 42 through 44. They represent combinations of the critical parameters which will result in zero water depths on a road surface. Curves of this type can be used to formulate criteria to accommodate specific "design" rainfall intensities.

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*As noted in the full report (9) this equation should not be used for regions where the annual rainfall is greater than 60 in (152 cm).

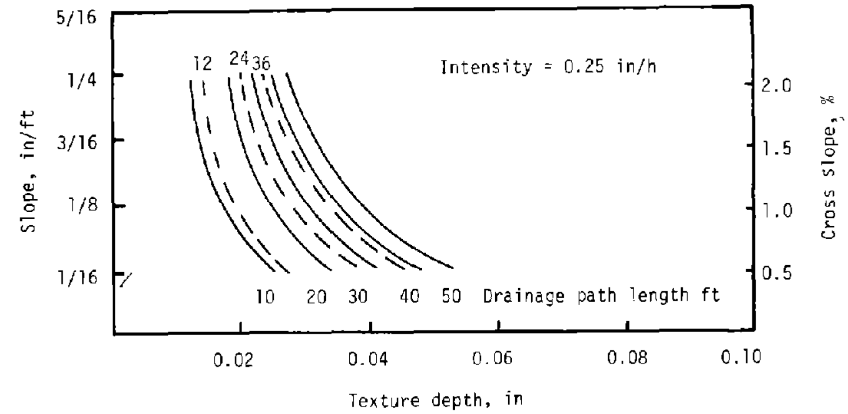

Figure 42. Curves of zero water depth for an intensity of 0.25 in/h.

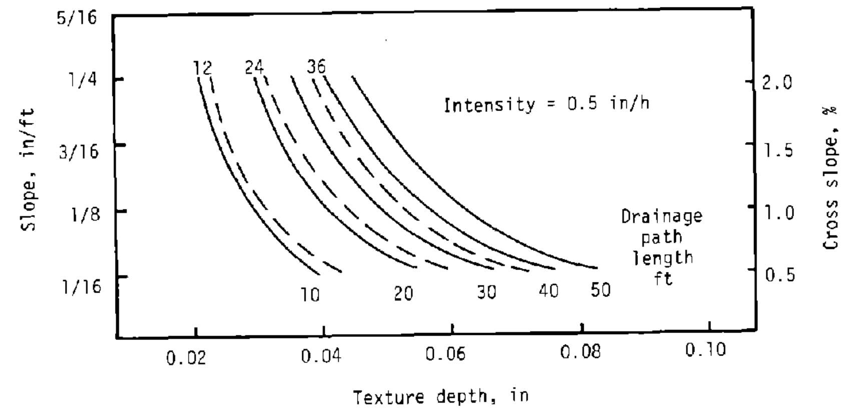

Figure 43. Curves of zero water depth for an intensity of 0.5 in/h.

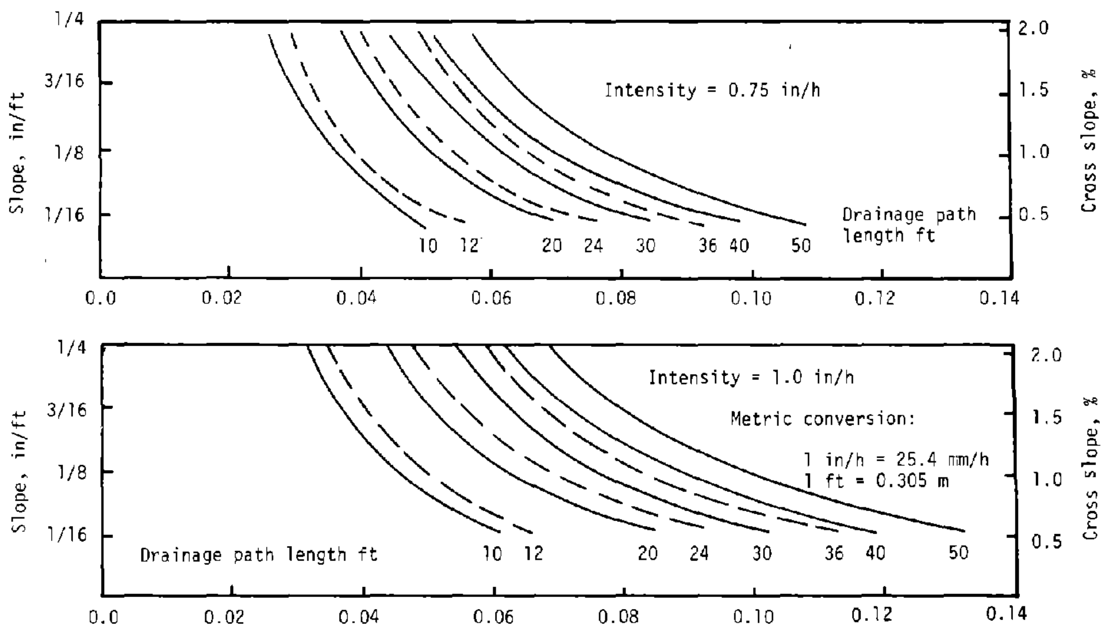

Figure 44. Curves of zero water depth for intensities of 0.75 and 1.0 in/h.

Table 19. Example design rainfall intensities.

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

Metric Conversion: 1 in = 25.4 mm

Table 20. Example allowable combination of pavement drainage parameters.

Drainage Path Lengths	Allowable Combinations of Slope and Texture		Nominal Texture Value 10^{-3} in
	percent	inches	
12	2.0	≥0.022	20
"	1.5	≥0.025	25
"	1.0	≥0.031	30
"	0.5	≥0.043	45
24	2.0	≥0.031	30
"	1.5	≥0.036	35
"	1.0	≥0.043	45
"	0.5	≥0.060	60
36	2.0	≥0.039	40
"	1.5	≥0.043	45
"	1.0	≥0.052	50
"	0.5	≥0.072	70

Metric Conversion: 1 in = 25.4 mm

For a state or region having an annual rainfall of 30 in/y (762 mm/y), criteria could take the form shown in Table 20. This is based on a rainfall intensity of 0.5 in/h (13 mm/h) as developed by "Approach 2" and on the curves shown in Figure 43.

When drainage path lengths are extended by significant longitudinal grade, it may not be practical to adhere to the zero water depth criteria. It is still practical through appropriate selection of cross slope and texture level to prevent water levels from exceeding 0.06 in (1.5 mm). This goal was explained in Chapter VIII as a somewhat more practical goal which would not allow hydroplaning to occur over a significant length of highway except where extremely poor tire conditions are allowed by a driver. Criteria can be developed for any specified "design" rainfall from these curves or from the equations used to derive them. The following criteria can be stated for a "design" rainfall intensity of 0.5 in/h (13 mm/h):

1. Where longitudinal grades do not exceed 3 percent and drainage is not over three 12-ft lanes (36 ft or 11 m)
    a. Use values of cross slope not less than 1.5 percent.
    b. Use texture levels that will not fall below about 0.04 in (1.0 mm).

2. Where longitudinal grades do not exceed 6 percent and drainage is not over three 12-ft lanes (36 ft or 11 m)
    a. Use values of cross slope not less than 2 percent.
    b. Use texture levels that will not fall below about 0.04 in (1 mm).

    or

    a. Use values of cross slope not less than 1.5 percent.
    b. Use texture levels that will not fall below 0.06 in (1.5 mm).

CHAPTER X

SUMMARY AND CONCLUSIONS

The research findings contained in full reports (9,11) of this study, relating to the pavement and geometric design criteria for minimizing hydroplaning of highway vehicles, are summarized briefly in this chapter. Several variables such as vehicle speed, pavement surface texture, cross slope, water depth, tire inflation pressure, tread depth, etc., were thoroughly investigated using full-scale field tests. Traction tests under controlled conditions included portland cement concrete pavements of different surface textures and open-graded asphalt friction courses. The torque effect of free-standing puddles was measured by continuous recording of forces on the wheels of a specially instrumented full-scale trailer. Dangerous levels of torque were measured when free-standing puddles engaged only one side of the vehicle and thus presented a greater danger potential than puddles wide enough to engage both sides.

Pavement surface water depth and vehicle speed are considered the most critical elements for hydroplaning. As such, rainfall records of three selected states (Alabama, Illinois and Texas) were carefully examined to develop the methodology to arrive at the design rainfall intensity. Once the rainfall intensity is selected, water depth can be computed for given surface slope, runoff length and texture (Eq. 9). Curves were also developed relating rainfall intensity, cross slope, drainage path and texture depth so as to produce no surface accumulation of water or zero water depth (Figs. 42 to 44). Curves of this type can be used to formulate allowable combinations of drainage parameters (Table 20).

The effects of cross slope on both driver demand and vehicle control in passing and lane change maneuvers were critically examined utilizing the Highway-Vehicle-Object Simulation Model (HVOSM). It was concluded from the model study that cross-slope values up to 2 percent showed no significant detrimental effects on friction demand or driver effort.

For given environmental conditions and pavement geometry, the water depth on the pavement surface becomes a function of the drainage capacity of the pavement. As open-graded friction courses (OGFC) offer the best currently known method of assuring adequate and controlled surface macrotexture and some internal drainage (tests on cores indicated these surfaces are not as effective as originally hypothesized with respect to drainage), additional research was conducted under controlled conditions. The variables included speed, water depth, tire pressure, tread depth, and tread design. Pavements having four percentages of internal voids (in the range of 15-25%) with essentially the same surface macrotexture of about 0.10 in (2.5 mm) and all having the same overlay thickness of 1.0 in (25mm) were tested. Performance of these surfaces was thoroughly examined in simulated rain with intensities in the range of 0.2 to 2.0 in/h (5 to 51 mm/h). It was found that even the most open surface was flooded in the outside wheel path of the outside lane (of a two-lane facility) having one percent cross slope at rainfall intensities of 0.2 to 0.4 in/h (5 to 10 mm/h).

For the mixture designs and aggregates used in these pavements, the friction developed at 55 mph (88 km/h) was completely adequate for vehicle control provided tire pressure was at or above 18 psi and the tread depth was about 0.2 in (5 mm) or more. Of course, OGFC pavements have the additional advantage of reduced splash and spray, and no surface water collects under light rainfall or heavy rain of short duration. However, data presented in Figures 18 and 19 for Section 4 indicate dangerously low skid numbers at 55 mph (88 km/h) in rainfalls of 0.5 in/h (13 mm) and 2.0 in/h (51 mm/h) and tread depths of 2/32 in (1.6 mm).

In the traction tests, OGFC pavements generally showed higher traction than asphalt slurry-seal pavements under all test conditions.

Investigation of hydroplaning conditions of portland cement concrete pavements was conducted in two parts. The first part was to determine the validity of predicted water depth for drainage lengths to 48 ft (12 m), and the other was to examine skid resistance and cornering slip on textured surfaces. An equation was developed to determine the water depth from various parameters (Eq. 9). Furthermore, it was shown that neither texture direction (longitudinal or transverse) nor texture type (brush, broom, burlap or tines) affected the resulting water depth to any significant degree.

Under both skid number measurements and cornering slip measurements on wet surfaces, transverse textures yield higher values than do longitudinal textures. However, this study did not investigate the potentially hazardous maneuver of full dynamic hydroplaning of vehicles around a horizontal curve. Experience in California indicated that longitudinal grooving was highly effective in reducing accidents at horizontal curves.

Increasing texture depth provides the greatest increase in both skid number and cornering slip values. From a construction viewpoint, texture depths of 0.06 inches (1.5 mm) can be easily constructed using properly selected tines. It must be recalled that surface texture created in plastic concrete normally decreases from wear about 30 percent in the first few months of service and then stabilizes. Therefore, one must construct a surface with about 0.06 inches (1.5 mm) of texture and expect this to be reduced to about 0.04 inches (1 mm) when it stabilizes.

Sag-vertical curves offer areas of special consideration in any accident reduction program. Innovative concepts for improving wet-weather performance of sag-vertical curves are presented in the report which include special surface drainage devices to intercept and divert surface flow and open-graded friction courses to act as sub-surface drainage devices. Tentative sag-vertical curve drainage criteria based on a survey of existing practice are given in Table 12, and the recommendations for minimizing hydroplaning at sag-vertical curves are indicated in Tables 15-17.

As a general statement the data show conclusively that a combination of two percent cross slope and a properly designed and constructed open-graded friction course coupled with appropriate geometric design furnish the driving public the best currently known device for high pavement friction during wet conditions.

CLOSURE

Through use of the equations, curves and examples given in this technical summary, a state or agency should be capable of formulating an antihydroplaning road surface design policy, a policy as conservative or as liberal as the particular entity prefers. Even without specific design policies related directly to hydroplaning, states appear to be making significant progress in achieving this goal. The precepts presented here do not require impractical goals, although these goals obviously cannot be achieved in a short period of time due to the vast area of highway surfaces in this country. However, by establishing specific design goals and working toward them continuously, the time will come when surfaces that allow hydroplaning, except in extreme rainfall or in the case of extremely substandard tire use, will no longer exist.

The implementation of these recommendations will require judgment and dedication in the execution of master maintenance and reconstruction plans over a period of years. The work presented in this study has been devoted to the future realization of this goal.

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