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Proposed Design Guidelines for Reducing Hydroplaning on New and Rehabilitated Pavements

This digest summarizes proposed design guidelines for reducing hydroplaning on new and rehabilitated pavements developed in NCHRP Project 1-29, "Improved Surface Drainage of Pavements." This digest was prepared by R. Scott Huebner, David A. Anderson, and John C. Warner of the Pennsylvania Transportation Institute. The complete project report is available as NCHRP Web Document 16 at Internet address http://www4.nas.edu/trb/crp.nsf (click on Web Documents).

SUMMARY

The intent of this document is to provide guidance for the selection and application of pavement and roadway design considerations that can be used to minimize the potential for hydroplaning. These proposed design guidelines, as presented in this document, focus on measures that can be used to reduce the potential for hydroplaning on a roadway surface. The speed at which hydroplaning occurs is a function of a number of factors. The one factor that can be controlled through pavement design is water film thickness. Other factors, such as tire pressure, tread depth, and rainfall intensity are clearly not within the control of designers but also affect hydroplaning potential. In this study, and in the PAVDRN computer program, tread depth was assumed to be 3/32 in. (2.38 mm) and tire pressure was assumed to be 24.0 psi (16.75 kPa). These values were selected because the data that were available to the authors for extending the range of the hydroplaning algorithm used in PAVDRN were also based on these assumptions. *(1)* These values are fixed within the PAVDRN program. *(2)* As a consequence, the hydroplaning speeds produced by PAVDRN and given in this report tend to be conservative.

Water film thickness on highway pavements can be controlled through the design process in four fundamental ways: controlling the geometry of the pavement to reduce the distance that the water must flow before it exits the pavement surface, increasing the surface texture depth to reduce the effective water film thickness, removing water from the pavement's surface through appurtenances located within or at the edge of the pavement surface, and providing internal drainage by using surface mixtures such as porous asphalt.

Four key areas need to be considered in order to analyze and eventually minimize the potential for hydroplaning. These areas are environmental conditions, properties of the pavement surface, geometry of the roadway surface, and the use of drainage appurtenances.

Each of these areas and its influence on the resulting hydroplaning speed of the designed section is discussed in detail later in this document.

The *environmental conditions* considered in the proposed design guidelines are rainfall intensity and water temperature. It is water temperature that determines the kinematic viscosity of the water and affects depth of flow. *Pavement surface properties* include surface characteristics such as the texture of the pavement surface and tining and grooving of portland cement concrete (PCC) surfaces. Additionally, the use of permeable pavement surfaces (porous asphalt) can dramatically reduce hydroplaning potential.

Five geometric design sections, one for each of the basic geometric configurations used in

CONTENTS

highway design, are considered in the proposed design guidelines: tangent, curve, transition, crest vertical curve, and sag vertical curve.

Finally, the use of drainage appurtenances is reviewed. Drainage appurtenances considered include longitudinal edge drains, slotted drains located between travel lanes, and transverse drains.

CHAPTER 1

OVERVIEW OF DESIGN PARAMETERS

The intent of this document is to provide guidance for the selection and application of pavement and roadway design considerations that can be used to minimize the potential for hydroplaning. The intended audience is practicing highway design engineers who work for state departments of transportation or for consulting firms. The information provided can be used in the design of new roadways or in the rehabilitation of existing roadways. The potential for hydroplaning on a road surface should be considered as part of the pavement or roadway design process when surface mixtures, drainage appurtenances, and pavement geometry are selected. The proposed design guidelines were prepared based on information obtained from National Cooperative Highway Research Program Project 1-29, "Improved Surface Drainage of Pavements." The proposed design guidelines and the examples presented in this document are based on the interactive computer program PAVDRN, which was developed as part of that project. *(2,3)*

These proposed design guidelines, as presented in this document, focus on measures that can be used to reduce the potential for hydroplaning on a roadway surface. The speed at which hydroplaning occurs is a function of a number of factors. The one factor that can be controlled through pavement design is water film thickness. Other factors, such as tire pressure, tread depth, and rainfall intensity are clearly not within the control of designers but also affect hydroplaning potential. In this study and in the PAVDRN program, tread depth was assumed to be 3/32 in. (2.38 mm) and tire pressure was assumed to be 24.0 psi (16.75 kPa). These values were selected because the data that were available to the authors for extending the range of the hydroplaning algorithm used in PAVDRN were based on these assumptions. *(1)* These values are fixed within the PAVDRN program. *(2)* As a consequence, the hydroplaning speeds produced by PAVDRN and given in this report tend to be conservative.

Water film thickness on highway pavements can be controlled through the design process in four fundamental ways:

1. Controlling the geometry of the pavement to reduce the distance that the water must flow before it exits the pavement surface;
2. Increasing the surface texture depth to reduce the effective water film thickness;
3. Removing water from the pavement's surface through appurtenances located within or at the edge of the pavement surface; and
4. Providing internal drainage by using surface mixtures such as porous asphalt.

Through the course of a typical design project, four key areas need to be considered in order to analyze and eventually minimize the potential for hydroplaning. These areas are as follows:

1. Environmental conditions,
2. Properties of the pavement surface,
3. Geometry of the roadway surface, and
4. The use of drainage appurtenances.

Each of these areas and its influence on the resulting hydroplaning speed of the designed section is discussed in detail later in this document.

The *environmental conditions* considered in the proposed design guidelines are rainfall intensity and water temperature. It is temperature that determines the kinematic viscosity of the water and affects depth of flow. The design rainfall intensity may be based on the frequency and duration of the rainfall event or on the allowable sight distance. The designer has no control over these environmental factors but should select appropriate values when determining the depth of water on the pavement surface and the resulting hydroplaning potential.

Pavement surface properties include surface characteristics, such as the texture of the pavement surface and grooving of portland cement concrete (PCC) surfaces. Additionally, the use of permeable pavement surfaces (porous asphalt) and their effect on water film thickness are discussed. In the examples in this document, a broomed PCC surface is assumed for illustrating the use of PAVDRN. Other surfaces, such as tined PCC, and various asphalt concrete surfaces, each have an associated surface texture. Surface texture determines the hydraulic roughness of the surface. Other PCC surfaces, such as tined surfaces, could have been used with an appropriate change in surface texture. Similarly, various asphalt concrete surfaces could have been used with appropriate assumptions for surface texture and the hydraulic roughness of the pavement surfaces.

Five geometric design sections, one for each of the basic geometric configurations used in highway design, are considered in the proposed design guidelines:

1. Tangent,
2. Superelevated curve,
3. Transition,
4. Crest vertical curve, and
5. Sag vertical curve.

Finally, the use of drainage appurtenances is reviewed. Drainage appurtenances considered include longitudinal edge drains, slotted drains located between travel lanes, and transverse drains. The design of these appurtenances is not addressed in the proposed design guidelines, as they are discussed elsewhere. *(4,5)*

Chapter 2 presents a series of recommendations in each of the four principal design areas: environmental conditions, pavement surface properties, pavement geometry, and appurtenances. The analyses upon which these recommendations are based are also presented. The computer model PAVDRN was used in these analyses. PAVDRN and its development are documented in the final project report and the PAVDRN user's guide. *(2,3)* Chapter 3 presents an example demonstrating an application of the PAVDRN program and the use of slotted drains to reduce the potential for hydroplaning on a pavement segment. Chapter 4 summarizes the proposed design guidelines presented in Chapter 2 and suggests possible changes to the current version of the AASHTO document *A Policy on Geometric Design of Highways and Streets. (6)*

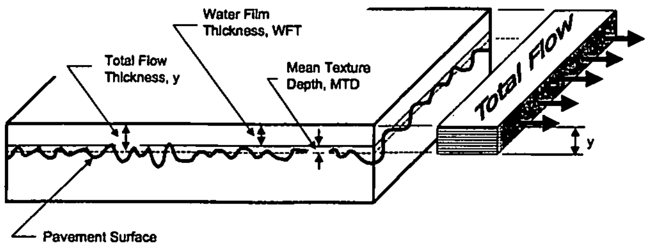


Figure 1. Definition of water film thickness, mean texture depth, and total flow.

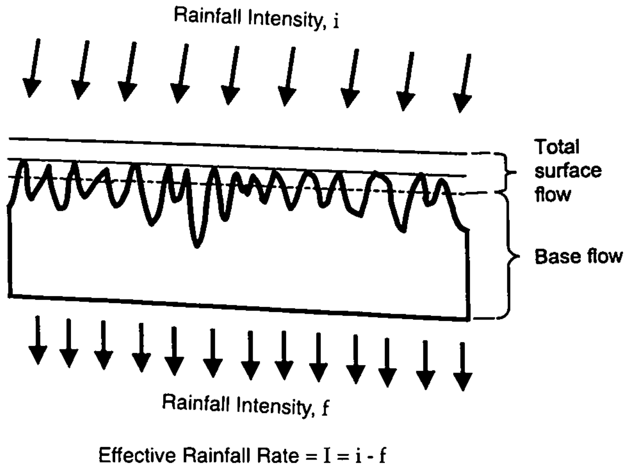


Figure 2. Definition of rainfall rates.

CHAPTER 2 DESIGN PARAMETERS THAT AFFECT HYDROPLANING

OVERVIEW OF DESIGN PARAMETERS

The potential for hydroplaning is an essential criterion for the design of new pavements and the rehabilitation of existing pavements. To address the potential for hydroplaning, certain design parameters associated with hydroplaning need to be considered. These include environmental conditions, pavement surface properties, roadway geometry, and the use of appurtenances to intercept the sheet flow of water. Each of these design parameters is used to determine the water film thickness along the longest drainage path length on the pavement surface.

Water film thickness (WFT) is defined in Figure 1 as the total thickness of the water on the pavement surface (y) minus the mean texture depth (MTD). The mean texture depth is simply the average height of the asperities on the pavement surface. The mean texture depth may be measured by profiling the pavement surface, estimated from sand patch measurements, or obtained from tables that list typical values for different pavement surfaces. *(3,7,8)* The total flow defines the water that is removed from the pavement surface; however, water flowing within the mean texture depth does not contribute to hydroplaning. Sheet flow, another term used to describe surface flow, refers to water that flows in a thin, uniform sheet over the pavement surface.

A steady-state flow condition occurs when the water film thickness is constant. This occurs somewhat after the rainfall event starts, when the rainfall rate is equal to the rate at which water is draining from the pavement. Rainfall rate, i, is defined as the rate, in terms of millimeters or inches of thickness per hour, at which water falls on the pavement. The excess or effective rainfall rate, I, is the rainfall rate minus any water that infiltrates below the mean texture depth, as shown in Figure 2. Thus:

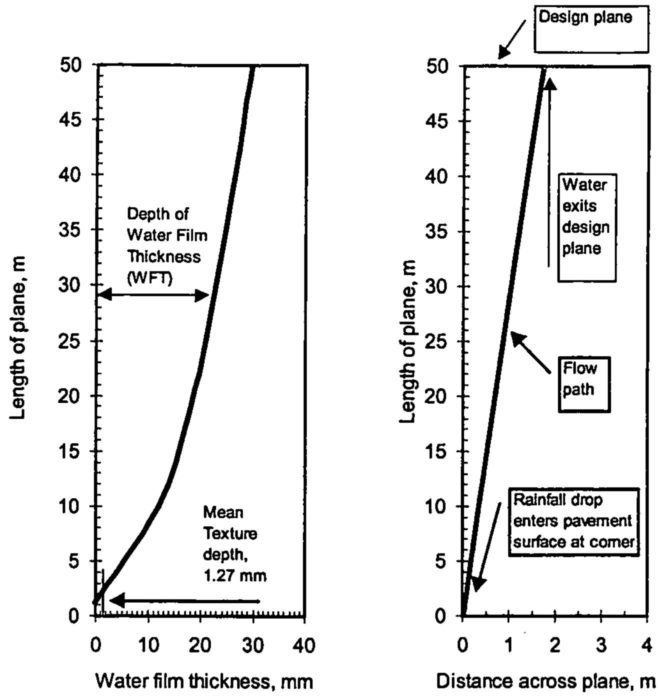
$$i = I + f \tag{1}$$

where:

- i = Rainfall intensity or rate, in./h or mm/h
- I = Excess or effective rainfall rate, in./h or mm/h
- f = Infiltration rate, in./h or mm/h

The steady-state total flow rate, from Figure 1, is calculated on the basis of the rainfall rate minus the infiltration rate.

In the design process that is based on PAVDRN, the pavement is divided into design sections that have a constant longitudinal slope. In the PAVDRN computer program these sections are referred to as planes. Flow from adjacent planes may be combined to determine the water film thickness over multiple planes (see Figure 3). Flow from one plane to a subsequent plane can be accounted for by simply



Note: The figures above show a plan view of a design plane (right) and a profile of the water film thickness (WFT) as water flows along flow path (left). Water falling on the pavement first fills the macrotexture (lower left, here 1.27 mm deep) at which point it reaches tops of the asperities of the coarse aggregate particles. At this point, the depth of the water film increases (from zero) until the water exits either an edge of the pavement plane (case here) or a drainage appurtenance.

A plane is defined as a section of pavement that has the same geometric characteristics. In the drainage model used in this study, the drainage across the pavement is modeled by linking adjacent design planes.

Figure 3. Definition of flow path and design plane.

using the flow exiting one plane as an initial flow for the subsequent plane.

For a given pavement geometry, in a steady-state condition the longest flow path length across a section produces the deepest water film thickness and, hence, the critical path for hydroplaning. Minimizing the water film thickness by shortening the flow path length, increasing the mean texture depth, and removing water from the surface pavement through appurtenances or internal drainage can each reduce the likelihood of hydroplaning. The proposed drainage guidelines presented in this document are based on PAVDRN, the interactive computer program developed as part of this study. *(2,3)* PAVDRN is based on a one-dimensional kinematic wave equation that relates the depth of sheet flow along a flow path to the rainfall rate, infiltration rate, and texture of the pavement surface. The flow path is determined from pavement geometry as the line of the resultant slope (vector product of cross slope and longitudinal slope) over the surface of the pavement. The flow path depends solely on the geometry of the pavement and is independent of environmental conditions on pavement surface properties (texture).

ENVIRONMENTAL CONSIDERATIONS

The environmental parameters of greatest concern are the rainfall intensity and the kinematic viscosity of the water. The PAVDRN model was used to examine relationships between these environmental parameters and the hydroplaning speed.

Rainfall Intensity

Effect of Rainfall Intensity on Hydroplaning Speed

The sensitivity of hydroplaning speed to rainfall intensity, as predicted by PAVDRN, is illustrated by considering a broomed PCC tangent section subjected to varying rainfall rates. The properties of the design section (or plane) used in this analysis are given in Table 1.

Rainfall intensities used in the analysis were 25 (1), 50 (2), 75 (3), 100 (4), 125 (5), and 150 (6) mm/h (in/h). The results of the analysis are shown in Figure 4. Note that the longest drainage path length in Figure 4 is 13.3 m (44 ft). This is the length of the flow path as a drop of water falls on one edge of the pavement and flows diagonally across the pavement to the other edge. Each curve in Figure 4 represents the hydroplaning speed along the drainage path length. Figure 4 shows that at any specific drainage path length, as the rainfall intensity increases, the speed at which hydroplaning occurs decreases. This response is expected. Higher rainfall intensities yield greater water film thickness values that, in turn, yield lower hydroplaning speeds. Note that in Figure 4 and in similar figures later in this document the resulting curves often show "bumps." These are the result of the merger of models used to predict Manning's n. The

TABLE 1 Tangent section properties used for rainfall intensity sensitivity analysis.

Properties of design plane	Value
Section Length	300 m
Plane Width (2 lanes)	8 m
Longitudinal Slope	0.02 m/m
Cross Slope	0.015 m/m
Computational Step Increment	1 m
Pavement Type	Broomed PCC
Mean Texture Depth	0.50 mm

Note: A plane may consist of one or more lanes. In this case the plane (a section of pavement with constant slope) is 8 m wide and 300 m long; each travel lane is 4 m wide and there are two travel lanes.

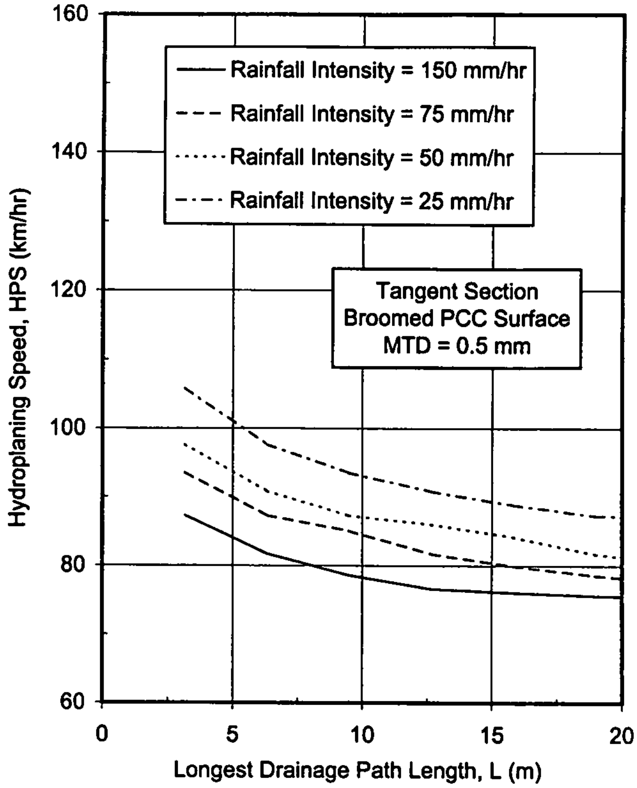


Figure 4. Sensitivity of hydroplaning speed to rainfall rate, two-lane tangent section with broomed PCC surface.

reader is referred to Equations 12, 16, and 17 in the main report. *(3)*

Figure 4 shows that the broomed PCC tangent section that was analyzed will not produce hydroplaning at speeds less than 90 km/h (56m/h) for a rainfall intensity of 25 mm/h (1 in./h) on a two-lane pavement as noted in Table 1. However, as the rainfall rate increases, concomitant increases in water film thickness cause the hydroplaning speed to decrease to speeds less than typical traffic design speeds. This illustrates the need for the user of PAVDRN to select an appropriate rainfall intensity. It should be noted that the results in Figure 4 are for a broomed PCC surface. Other surfaces would yield similar trends but different hydroplaning speeds.

Selection of Design Rainfall Intensity Based on Meteorological Considerations

Traditional hydrologic literature discusses rainfall intensity as a function of the frequency and duration of the rainfall event. The common method of reporting rainfall intensity-duration information is through the use of intensity-duration-frequency (I-D-F) curves for a given location. These curves are based on rainfall observations covering a long period of time, usually for decades or longer. This information is often used in conjunction with peak flow formulas or models for the design of hydraulic structures. *(9)*

The frequency of a rainfall event used is associated with the acceptable level of risk for hydraulic failure of the structure. Risk level is typically related to a return period. For instance, an intensity that has a 4 percent chance of being exceeded in any year has a return period of 25 years. (Note that 4 percent is equal to 1 divided by 25). Likewise, an intensity with a return period of 100 years has a 1 percent chance of being exceeded in any given year. The duration of the event is the shortest time necessary for a maximum flow to occur within the area contributing flow to the location of the structure. This period of time is usually identified as the time of concentration in the area. I-D-F curves for most urban areas of the country are available from the National Weather Service or from various agencies and departments of state governments. In summary, the key parameters for selecting a value of rainfall intensity—based on hydrologic considerations—for estimating the hydroplaning potential of a pavement surface are: (1) geographic location, (2) assumed risk level, and (3) time of concentration.

Gallaway et al. examined the relationship between rainfall intensity and probability of exceeding certain levels at several locations throughout the United States. *(10)* For instance, they found that at a location in Illinois, an intensity of 25 mm/h (1.0 in./h) occurred 1.72 percent of the time during a year, and an intensity of 50 mm/h (2.0 in./h) occurred 0.58 percent of the time. Similarly, at a location in Alabama, an intensity of 25 m/h (1.0 in./h) occurred 2.95 percent of the time during a year, and an intensity of 2.0 in./h occurred 0.95 percent of the time. They also found that in central Texas a storm with an intensity of 13 mm/h (0.5 in./h) lasts an average of 4 min; they concluded that a pavement with a mean texture depth of 1 mm (0.04 in.) and a cross slope of 2 percent would not create flow above the pavement asperities. Reed et al. selected a design rainfall intensity of 25 mm/h (1.0 in./h) as a basis for a number of analyses examining the potential for hydroplaning on road surfaces. *(11)* The selection of 25 mm/h (1.0 in./h) by Reed et al. was based on the work of Gallaway, Ivey, and others on the perception that, at a rainfall intensity of approximately 25 mm/h (1.0 in./h), drivers begin to slow down and occasionally leave the highway to wait out the storm. *(12)*

In the design of hydraulic structures such as culverts, swales, and bridges, return periods of 10, 25, 50, and 100 years are used. These return periods represent risk levels of 10, 4, 2, and 1 percent, respectively. Based on the work done by Gallaway and Ivey, an intensity of between 25 mm (1.0 in./h) and 50 mm (2.0 in./h) would represent a risk of approximately 1 to 3 percent chance of occurring. *(10)* This chance represents return periods of between 33 and 100 years, which are reasonable with respect to those commonly specified for highway projects like those in the Interstate program. However, for a given rainfall intensity, risk varies with geographic location. These proposed guidelines suggest that at a rainfall intensity above 25 mm/h (1.0 in./h), traffic slows and the risk of hydroplaning decreases.

Selection of Design Rainfall Intensity Based on Driver Visibility

A second method for selecting a design rainfall intensity is to relate the rainfall intensity to the maximum sight distance of the driver during a rainfall event. In this case, the sight distance of the driver, as limited by the rainfall event, controls the driver's speed and, in turn, the required hydroplaning speed. In other words, the required hydroplaning speed need not be any greater than the speed as limited by driver visibility. Ivey et al. identified three factors that contributed to wet-weather accidents: tire/pavement friction, visibility, and vehicle speed. *(13)* The Ivey et al. report concentrated on the latter two factors as they affect driver response. They presented a formula for estimating the maximum sight distance during a rainfall event as a function of vehicle speed and rainfall intensity:

$$S_v = \frac{2000}{i^{0.68}} \frac{40}{V_i} \tag{2}$$

where:

S_v = sight distance, ft
i = rainfall intensity, in./h
V_i = vehicle velocity, mi/h

Equation 2 can be rewritten in terms of the rainfall intensity:

$$i = \left(\frac{80,000}{S_v V_i} \right)^{1.47} \tag{3}$$

If the stopping sight distance recommended in the AASHTO publication *A Policy on Geometric Design of Highways and Streets* is used for the term S_v in Equation 2, and the design speed for the section is used for the vehicle velocity, it is possible to solve for rainfall intensity. *(6)* Table 2 was generated from Equation 3 by using the stopping distances as recommended in the AASHTO document *A Policy on Geometric Design of Highways and Streets. (6)*

A rainfall intensity was needed for the sensitivity analysis presented in this document. A value of 80 mm/h (3.1 in./h) was selected for this purpose. This value represents a maximum upper limit when considering a driver's visibility for stopping sight distance at a speed of approximately 94 km/h (59 m/h), as discussed in detail by Ivey et al. *(13)*

Kinematic Viscosity and Water Temperature

Water film thickness is affected by the viscosity of the water because the rate at which the water can drain from the pavement is related to the viscosity of the water. The kinematic viscosity is used to compute Reynold's number. Reynold's number, in turn, is used to determine Manning's n, the hydraulic resistance of the pavement surface. The effect of the viscosity of the water on hydroplaning speed was demonstrated by using PAVDRN to calculate the hydroplaning speed for the same broomed PCC tangent section that was used to demonstrate the sensitivity of hydroplaning speed to rainfall rate (Table 1). For this purpose, a range of water temperatures and a rainfall rate of 80 mm/h (3.1 in./h) was assumed. The water temperatures used in this analysis and the corresponding kinematic viscosity of water are given in Table 3.

Figure 5 displays the relationship that developed from the analysis. As the water temperature decreases, the value of the kinematic viscosity increases. This creates greater resistance to flow and causes greater water film thickness values to develop. Therefore, hydroplaning occurs at lower speeds. With this result, a conservative value for kinematic viscosity, 1.036 μm²/s (10°C), was used for all subsequent analysis in this report. The effect of temperature on the viscosity of water is significant. As shown in Figure 5, at a path length of 6 m, the hydroplaning speed increases from 87 km/h to 95 km/h when the temperature changes from 0°C to 30°C.

The value of kinematic viscosity assumed in this analysis (corresponding to 10°C) may be overly conservative, especially in warmer climates, specifically the southern United States and certain regions in the western United States. In addition, the most intense rainfall rates are usually

TABLE 2 Rainfall intensity for stopping sight distances.

Assumed Design Speed (km/h)	Stopping Distance as Given by AASHTO[6] (m)	Maximum Rainfall Intensity Given by Equation 2 (mm/h)
80	145	151
88	168	106
96	198	73
104	221	55
112	260	39

TABLE 3 Kinematic viscosity and water temperature values.

Kinematic Viscosity, ν μm²/s	Water Temperature, °C
1.785	0.0
1.518	5.0
1.306	10.0
1.139	15.0
1.003	20.0
0.893	25.0
0.800	30.0

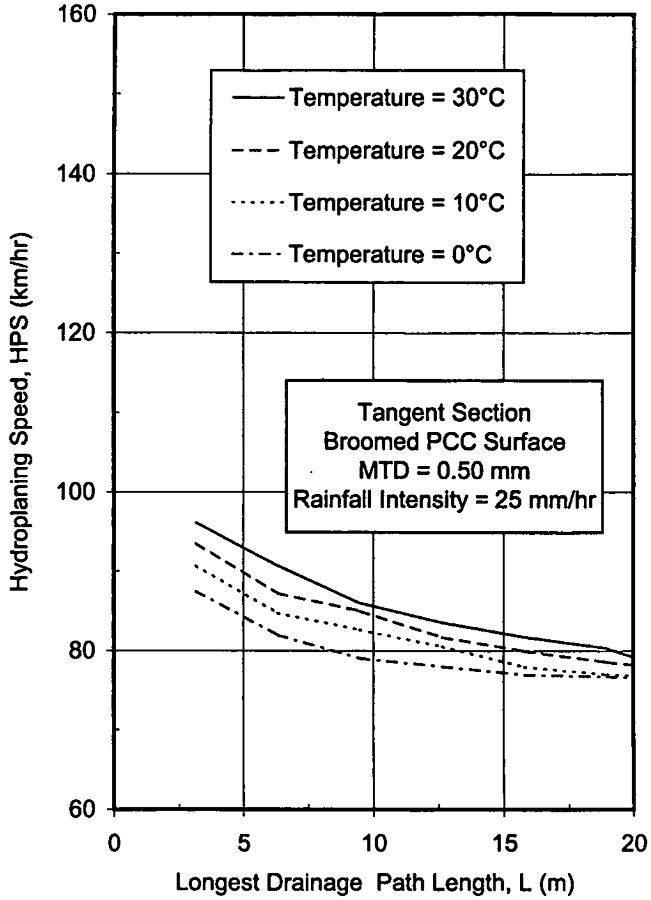


Figure 5. Sensitivity of hydroplaning speed to water temperature, two-lane tangent section with broomed PCC surface.

associated with warmer weather and typically occur during the summer months. However, it is not unusual to have intense periods of rainfall associated with (1) low pressure systems late in the fall or in the early spring and (2) significant drops in temperature during the summer, especially if considering the temperature of the rain.

Recommendations Specific to Environmental Considerations

The designer should first use Table 2 (or Equation 3) to arrive at a maximum rainfall intensity that is based on the maximum stopping distances as given in the AASHTO document *A Policy on Geometric Design of Highways and Streets. (6)* This value should be compared with rainfall information (I-D-F curves) for the location of the project, and the lower intensity should be selected for design purposes.

The authors recommend that a 100-year return period be used with the I-D-F curves. This represents a 1 percent risk or chance that the intensity will be exceeded. The 100-year return period represents a very conservative return period. Shorter design periods may be used at the option of the designer.

A kinematic viscosity corresponding to a water temperature of 10°C (50°F) is recommended for most design purposes. This is a conservative value; in warmer climates, higher water temperatures may be justified at the option of the designer. PAVDRN allows the user to select the water temperature.

PAVEMENT SURFACE PROPERTIES

The physical properties of a pavement surface contribute to the effectiveness of the pavement in reducing hydroplaning potential. These surface properties include

1. Mean texture depth as affected by mixture design for dense-graded asphalt concrete and surface finish for portland cement concrete,
2. Internal drainage as generated by the permeability of porous asphalt concrete, and
3. Drainage as generated by the grooving for portland cement concrete.

The mean texture depth (MTD) of a pavement section, as defined in Figure 1, is characterized by the average relative height of the pavement aspirates. The MTD can be measured using the volumetric method, ASTM E 965, "Standard Method for Measuring Surface Macrotexture Depth Using a Volumetric Technique," or ASTM E 1845-96, "Standard Practice for Calculating Mean Profile Depth." *(7,8)* ASTM E 965 is often referred to as the sand patch method. The sand patch method should be used with caution on porous asphalt because the sand may fill internal voids, giving a misleading estimate of the surface texture. *(3)* If a measured value for mean texture depth is not available, as is often the case during the design process, values from Table 4 may be used as a general guideline. Table 4 shows ranges of typical mean texture depths for various types of pavements. *(3,14)* Reference 14 contains photographs and mean texture depths for a wide variety of pavement surfaces. It should be noted however that actual values will depend on maximum aggregate size, mixture gradation, and pavement wear.

TABLE 4 Recommended ranges in mean texture depths for different pavement types.

Pavement type	Mean Texture Depth	
	(mm)	(in.)
PCC Broomed, Burlap drag	0.50 – 1.0	0.02 – 0.04
PCC Tined	0.50 – 2.0	0.02 – 0.08
Dense Graded Asphalt (DGAC)	0.50 – 2.0	0.02 – 0.08
Porous Asphalt (OGAC)	1.0 – 4.0	0.04 – 0.16
Surface Dressing (Treatment)	1.0 – 3.0	0.04 – 0.12

Conventional Pavement Surfaces

A higher MTD value results in a lower water film thickness value for a given flow depth. The smaller the water film thickness, the greater the speed at which hydroplaning will occur. In order to illustrate the importance of MTD, PAVDRN was used to predict hydroplaning speeds on several different pavement surfaces with varying mean texture depths. The results are shown in Figures 6 and 7 for dense-graded asphalt concrete (DGAC) and portland cement concrete surfaces. It should be pointed out that the curves in Figures 6 and 7 are independent of pavement geometry. However, the length and position of the flow path on the pavement surface will vary with pavement geometry as well as with pavement width and the location of drainage appurtenances. The curves in Figures 6 and 7 were generated assuming steady-state conditions, a rainfall rate of 80 mm/h (3.1in./h) and a water temperature of 10°C (50°F).

Figures 6 and 7 demonstrate the importance of surface texture in reducing the potential for hydroplaning. A coarse-graded asphalt concrete with exposed coarse aggregate particles may have a surface texture as high as 2.0 mm (0.08 in.), whereas a fine-graded mixture with a large sand content may have a surface texture of 0.50 mm (0.02 in.). With a drainage path of 8 m (26 ft), hydroplaning speed for these surfaces, according to the results of the PAVDRN program as shown in Figure 6, would be 120 (75) and 100 (62) km/h (mi/h), respectively. Similar results are shown for PCC surfaces in Figure 7. At 8 m (26 ft) along the flow path, the PAVDRN model predicts that for a tined surface the hydroplaning speed would be well over 100 km/h, (62 mi/h; for a worn surface or a surface without any texturing, the hydroplaning speed would be well under 100 km/h (62 mi/h). For both OGAC and PCC surfaces, mean texture depth has a very important effect on HPS. In many instances, surface texture alone may be sufficient for controlling hydroplaning speed. This is especially true as long as the surface texture (MTD) is not lost as the pavement is trafficked.

Porous asphalt surfaces are particularly effective in terms of reducing hydroplaning speed, and their use is highly recommended in those instances where durability issues are not of concern. *(3)* Here, porous asphalt includes conventional open-graded friction course as well as the more open mixtures used in parts of Europe. Figure 8 shows the effect of MTD on the hydroplaning speed of porous asphalt pavement sections. A comparison of the hydroplaning speeds in Figure 8 with those in Figures 6 and 7 shows the dramatic increase in hydroplaning speed that porous asphalt offers when contrasted with PCC or DGAC.

Full-scale skid testing conducted as part of this study indicated that the texture offered by porous asphalt is more significant in reducing hydroplaning than the internal drainage these mixtures offer. In the field trials conducted as part of this study, the onset of hydroplaning for porous asphalt

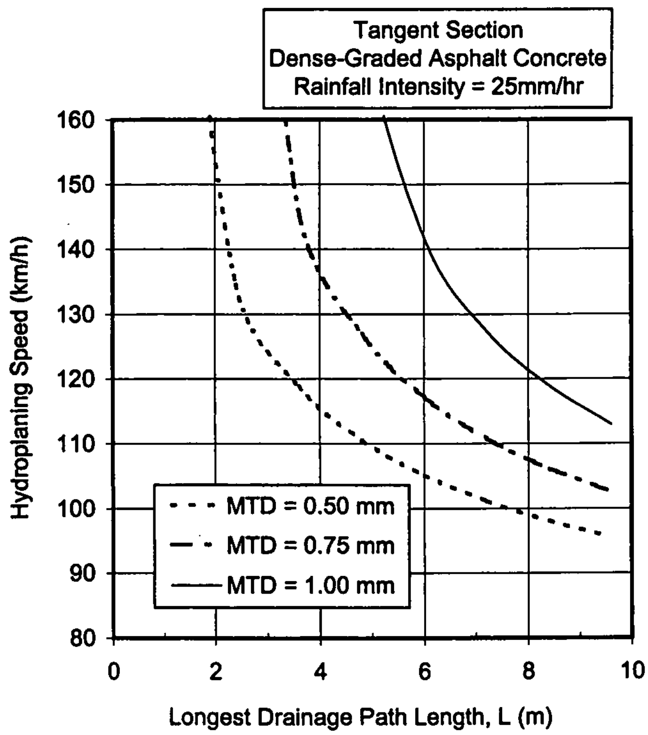


Figure 6. Effect of MTD on HPS for dense-graded asphalt concrete, two-lane tangent section.

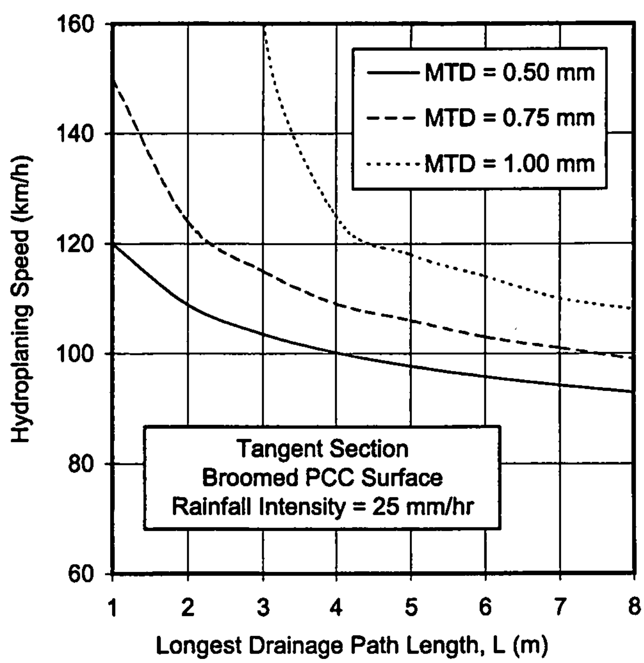


Figure 7. Effect of MTD on HPS for portland cement concrete, two-lane tangent section.

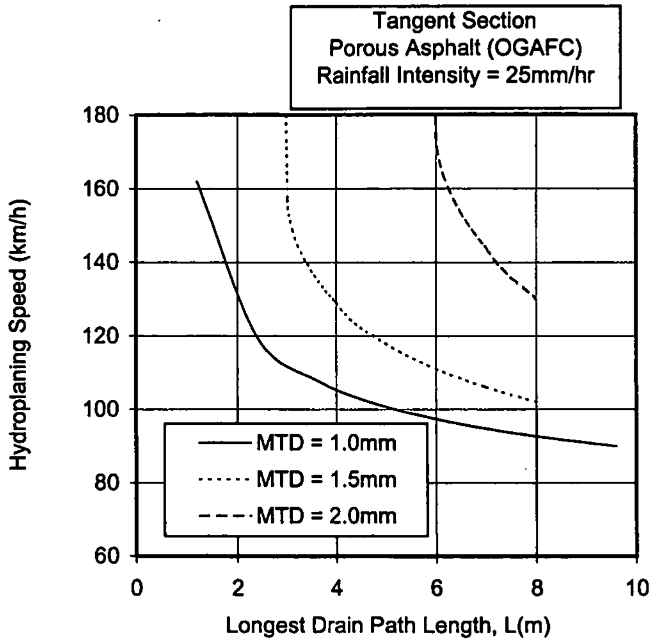


Figure 8. Effect of MTD on HPS for open-graded asphalt concrete, two-lane tangent section.

mixtures was determined by the water film thickness. The effect of the coarse texture offered by porous asphalt was simply to decrease the water film thickness for a given total surface flow. *(3)* No benefit was demonstrated for the internal drainage. Given this preliminary finding, other surfaces that enhance this MTD should be equally effective in reducing the potential for hydroplaning. Surfaces such as split mastic asphalt and a variety of micro-surfacing mixtures offer increased MTD when compared to dense-graded asphalt concrete.

The advantages and disadvantages of porous asphalt surfaces are discussed in detail in the main report for this study. *(3)* While used successfully by many agencies, not all agencies have been successful in the use of porous asphalt surfaces, and they should be used with due consideration to their advantages and disadvantages. *(3)*

Consideration of Internal Drainage

Drainage through permeable pavements has been incorporated into the code for the PAVDRN model by using the permeability of the porous asphalt surface mixture to represent the vertical flow capacity of the mixture under saturated conditions. This constitutes a conservative estimate of the conductivity of these surfaces but is not unreasonable considering the hydraulic gradients that can be expected on a pavement section. For the purposes of determining the hydroplaning potential, the depth of water remaining on the surface after the infiltration is the key parameter. Thus, in the PAVDRN program an effective rainfall intensity is calculated using Equation 3, but substituting the coefficient of permeability for the infiltration rate. Equation 3 becomes:

$$i = I + f \tag{4}$$

where:
- i = design rainfall intensity, in./h or mm/h
- I = effective rainfall intensity, in./h or mm/h
- f = coefficient of permeability, in./h or mm/h

PAVDRN allows the user to select the coefficient of permeability, f. A procedure for measuring the permeability of asphalt concrete cores is described in the main report for this study. *(3)* Measurements made in that study gave coefficients of permeability that ranged from 20 to 40 mm/s. Isenring et al. reported values of 0.75 to 3.5 mm/s for open-graded asphalt mixtures. *(15)* The default values used in PAVDRN are taken from Isenring because they are conservative (lower than those measured during this study). The user of PAVDRN has the option of overriding the default values. It should be noted that the coefficient is not the same coefficient that is obtained with the conventional outflow meter. *(16)*

Grooving of PCC Surfaces

The grooving of PCC pavements can be used to reduce the water film thickness that develops during rainfall. These grooves act as small channels that can conduct the surface water from the pavement surface as long as the grooves are contiguous with an appropriate drainage path. The grooves also act as reservoirs at the start of the rainfall event. Splash and spray caused by passing traffic are likely to purge the grooves with each vehicle pass, thereby extending the usefulness of the grooves as reservoirs. Figure 9 shows the results of applying PAVDRN to a grooved pavement with different grooving configurations, but otherwise as described in Table 1.

During full-scale skid testing conducted as part of this project, the grooves were found to be ineffective in reducing the water film thickness once the water filled the grooves. At this point the hydroplaning speed was determined by the water film thickness, with the surface of the pavement as the datum for calculating water film thickness. In spite of this finding, field experience demonstrates that the grooving of PCC pavements is still effective. For example, the response to a questionnaire that was compiled as part of this project indicated that approximately half of the agencies reported the use of grooving on multilane, high-speed highways. The dimensions of longitudinal grooves ranged from 17.8 mm (0.70 in.) wide by 3.18 mm (0.125 in.) deep, and the transverse grooving is 0.762 mm (0.030 in.) wide by 4.76 mm (0.188 in.) deep. Various agencies reported using grooving in areas with accident problems *(3)*.

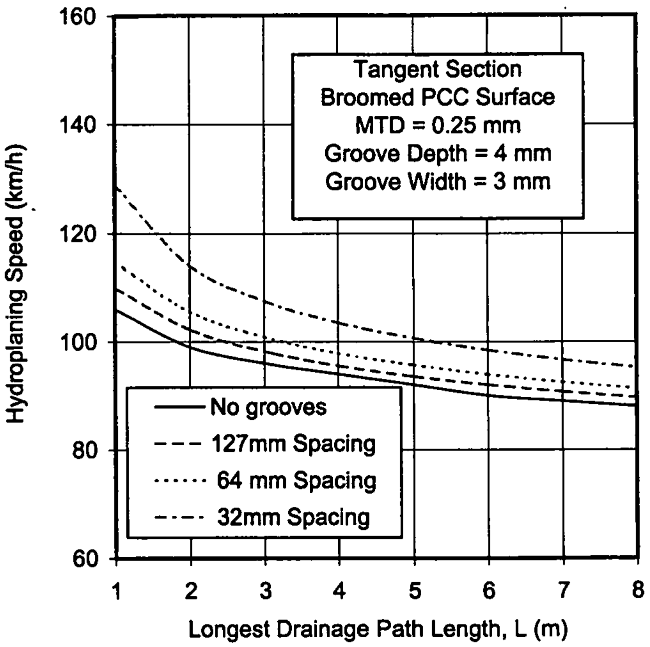


Figure 9. Effect of MTD on HPS for grooved PCC section, two-lane tangent section

Recommendations Specific to Pavement Surface Properties

The texture of the pavement surface, as reflected in the mean texture depth (MTD), is a very important parameter in determining the water film thickness and hydroplaning potential of a pavement surface. In the absence of measured values, the mean texture depth values from the range of values presented in Table 4 can be used when analyzing the potential for hydroplaning using PAVDRN.

Porous asphalt is a highly effective surface for reducing the water film thickness and minimizing the potential for hydroplaning; for this reason, porous asphalt should definitely be considered as an alternative pavement material when designing a pavement. The main benefit of porous asphalt is the large mean texture depth that it offers. Porous asphalt has the additional benefit of typically having higher mean texture depths than other pavement materials (see Table 4). Porous asphalt should be chosen as a pavement surface only when durability issues specific to porous asphalt are also considered. Other asphalt surfaces, such as split mastics, may also offer enhanced levels of mean texture depth, but they were not investigated as part of this project.

Grooving PCC pavements can reduce the depth of surface water film thickness that develops during rainfall by serving as a reservoir and acting as drainage channels. Once the water overflows the grooves, the grooves have little effect on the mean texture depth. Grooved pavements have been effective in practice and should be considered as part of an overlay strategy. Grooving is most effective for this purpose if the direction of the grooves is coincident with the slope of the pavement.

GEOMETRY OF THE ROADWAY SURFACE

The following five basic geometric configurations or sections were examined in this study:

1. Tangent,
2. Superelevated curve,
3. Transition,
4. Crest vertical curve, and
5. Sag vertical curve.

Each of these geometric sections was analyzed using the PAVDRN model to determine the sensitivity of water film thickness and hydroplaning speed to the geometric characteristics of the respective sections. The results and recommendations are discussed in this section. A portland cement surface with the properties described in Table 5 was used for all the analyses in this section. Design speed for the analyses was 85 km/h (53 mi/h).

Tangent Sections

Analysis and Discussion of Tangent Sections

In order to illustrate the sensitivity of water film thickness and hydroplaning speed to the geometry of a tangent section, the PAVDRN model was applied to a PCC surface with the geometric characteristics described in Table 5. Multiple runs of the PAVDRN program were performed with various combinations of longitudinal slope and cross slope, as indicated in Table 5. The results of the analysis are shown in graphical form in Figures 10 and 11. The figures

TABLE 5 Geometric and texture properties used to analyze tangent section.

Property	Value
Section Length	300 m
Plane Width (2 lanes)	8 m
Longitudinal Slope (Grade)	Varies from 0.00 to 0.10 m/m[a]
Cross Slope	Varies from 0.01 to 0.10 m/m[a]
Computational Step Increment	1 m
Pavement Type	Broomed PCC
Mean Texture Depth	0.50 mm

[a]Longitudinal slope and cross-slope are constant over section but were allowed to vary in analysis over range given in table. The values used in the analysis exceed those recommended in the AASHTO publication *A Policy on Geometric Design of Highways and Streets*. They were used for comparison purposes only. *(6)*

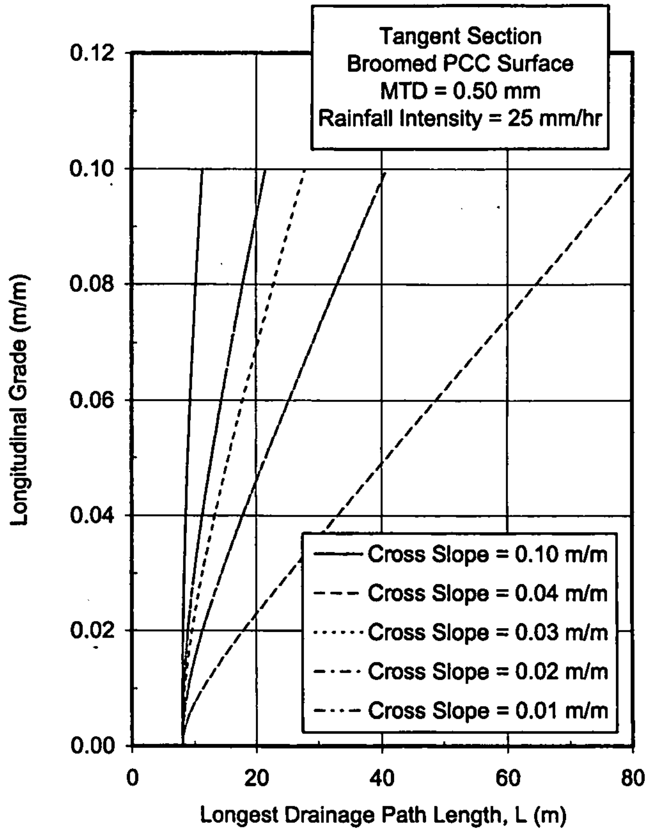


Figure 10. Longest drainage path length versus cross slope for different longitudinal grades, two-lane tangent section with broomed PCC surface.

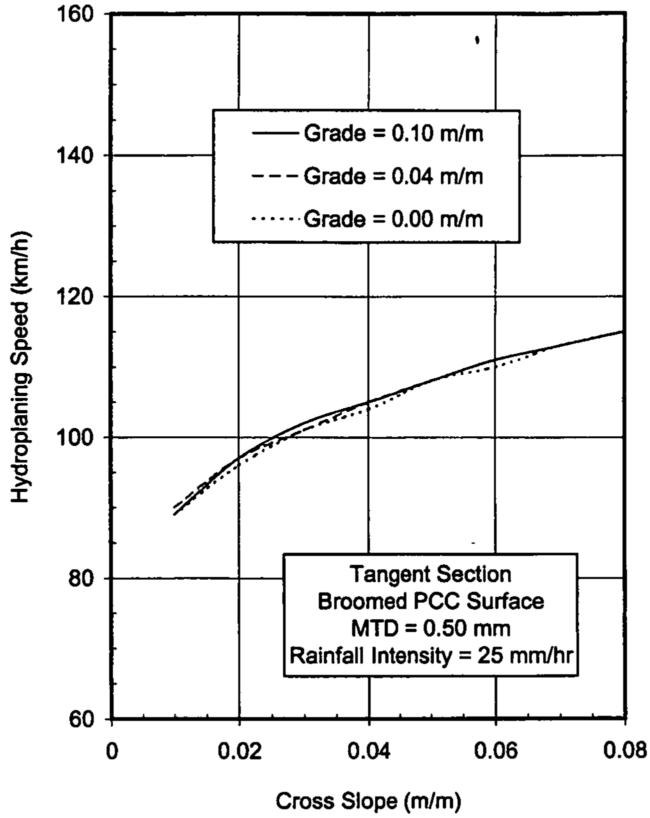


Figure 11. Hydroplaning speed versus cross slope for different longitudinal grades, two-lane tangent section with broomed PCC surface.

show that longitudinal grade has little influence on water film thickness and hydroplaning speed, but that cross slope is significant. The minimum recommended cross slopes that were developed from the results are shown in Table 6. Note that for high-speed traffic (100 km/h) (62 mi/h) the minimum recommended cross slope is in excess of that recommended in the AASHTO publication *A Policy on Geometric Design of Highways and Streets (6)*. These values apply to a broomed concrete surface, which represents a very conservative surface in terms of mean texture depth. These values will differ for other pavement types.

Table 6 shows that at a design speed of 100 km/h (64mi/h), the required cross slope to prevent hydroplaning is practically a constant value at 0.085 m/m (0.85 ft/ft). This cross slope has been underlined because it is at the borderline of values recommended in the AASHTO document. Therefore, depending on agency practice, it may be necessary to employ other design techniques, such as intercepting flow using drainage grates or increasing texture depths or using pervious asphalt, in order to minimize the hydroplaning potential of this roadway section.

TABLE 6 Minimum recommended cross slopes for analyzed tangent section; broomed PCC surface.

	Recommended Cross Slopes (m/m)		
Grade (m/m)	**Low Volume (70 km/h)**	**Intermediate Volume (85 km/h)**	**High Volume (100 km/h)**
0.00	0.015	0.020	<u>0.085</u>
0.01	0.015	0.020	<u>0.085</u>
0.02	0.015	0.020	<u>0.085</u>
0.03	0.015	0.020	<u>0.085</u>
0.04	0.015	0.020	<u>0.085</u>
0.06	0.015	0.020	<u>0.080</u>
0.08	0.015	0.025	<u>0.080</u>
0.10	0.015	0.025	<u>0.080</u>

Note: Underlined values exceed values recommended in the AASHTO publication *A Policy on Geometric Design of Highways and Streets. (6)*

Recommendations Specific to Tangent Sections

Based on the section that was analyzed, which has a very low mean texture depth, longitudinal slope has little effect on the water film thickness and hydroplaning speed. For tangent sections, other strategies such as maximizing cross slope, optimizing the mean texture depth, or using appurtenances may be necessary to control water film thickness and hydroplaning speed.

Curve Sections

Analysis and Discussion Specific to Circular Curve Sections

In order to illustrate the sensitivity of water film thickness and hydroplaning speed to the geometry of a curve section, the PAVDRN model was applied to a PCC surface with the geometric characteristics described in Table 7. Multiple runs of the PAVDRN program were performed with various combinations of longitudinal slope and cross slope, as indicated in Table 7. The PAVDRN program is based on the assumption that the slope is constant along the centerline of the section in the direction of travel. Therefore, the flow path is linear. The results of the analysis appear in graphical form in Figures 12 and 13, which show that longitudinal grade has little influence on water film thickness and hydroplaning speed, but cross slope is significant. The minimum recommended cross slopes that were developed from the results are shown in Table 8. Note that for high-speed traffic (100 km/h) the minimum recom-

TABLE 7 Geometric and texture properties used to curve section.

Property	Value
Plane Width (2 lanes)	8 m
Longitudinal Slope or Grade	Varies from 0.0 to 0.10 m/m[a]
Superelevation	Varies from 0.0 to 0.10 m/m[a]
Radius of Curve	300 m
Computational Step Increment	1 m
Pavement Type	Broomed PCC
Mean Texture Depth	0.050 mm

[a]Longitudinal slope and cross slope are constant over section but were allowed to vary in analysis over range given in table. The values used in the analysis exceed those recommended in the AASHTO publication *A Policy on Geometric Design of Highways and Streets*. They were used for comparison purposes only. *(6)*

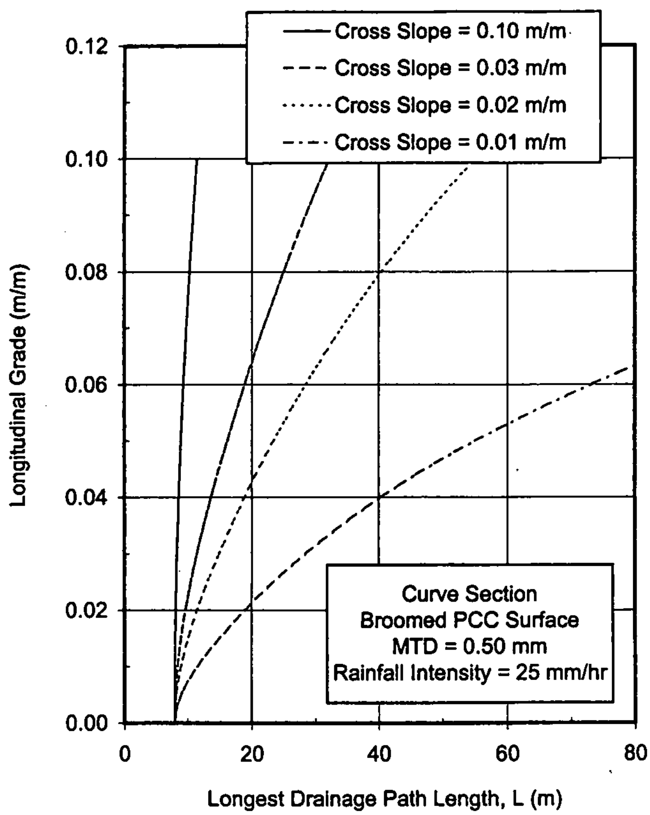


Figure 12. Longest drainage path length versus cross slope for different longitudinal grades, two-lane curve section with broomed PCC surface.

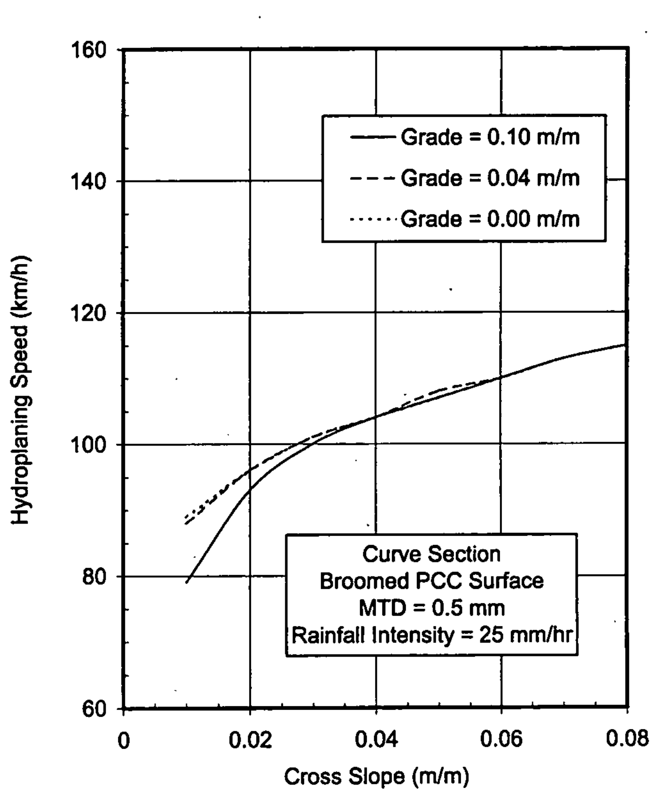


Figure 13. Hydroplaning speed versus cross slope for different longitudinal grades, two-lane curve section with broomed PCC surface.

TABLE 8 **Minimum recommended cross slopes for analyzed curve section; broomed PCC surface.**

	Recommended Cross Slopes (m/m)		
Grade (m/m)	**Low Speed (70 km/h)**	**Intermediate Speed (85 km/h)**	**High Speed (100 km/h)**
0.00	0.015	0.020	<u>0.080</u>
0.01	0.015	0.020	<u>0.080</u>
0.02	0.015	0.020	<u>0.080</u>
0.03	0.015	0.020	<u>0.080</u>
0.04	0.015	0.030	<u>0.080</u>
0.06	0.015	0.030	<u>0.090</u>
0.08	0.015	0.030	<u>0.090</u>
0.10	0.015	0.030	<u>0.090</u>

Note: Underlined values exceed recommended values given in the AASHTO publication *A Policy on Geometric Design of Highways and Streets. (6)*

mended cross slope is in excess of that recommended in the AASHTO publication *A Policy on Geometric Design of Highways and Streets. (6)* These values apply to a broomed concrete surface that represents a very conservative surface in terms of mean texture depth. These values will differ for other pavement types.

As can be seen from Table 8, at a design speed of 100 km/h (64m/h), the required cross slope to prevent hydroplaning (underlined values ranging from 0.080 to 0.090) is at the borderline of those recommended in the AASHTO publication *A Policy on Geometric Design of Highways and Streets. (6)* Therefore, it may be necessary to employ other design techniques, such as intercepting flow using drainage grates, increasing texture depths, or using pervious asphalt, in order to minimize the hydroplaning potential of this roadway section.

Recommendations Specific to Circular Curve Sections

Based on the section that was analyzed, which has a very low mean texture depth, longitudinal slope has little effect on the water film thickness and hydroplaning speed. For curved sections, other strategies such as optimizing the mean texture depth or using appurtenances may be necessary to control water film thickness and hydroplaning speed.

Transition Sections

Analysis and Discussion Specific to Transition Sections

A transition section represents a section that is in transition from a tangent section to a curve section. Assumptions used in the PAVDRN analysis for this section are (1) a constant transition from the transverse slope on the tangent section to a superelevated slope at the start of the curve, and (2) the tangent section at the start of the transition having a constant transverse slope across its entire width. (Note: The runout length is the length of the pavement section [not flow path length]. The runout length is the distance between the tangent and curve section.)

In order to illustrate the sensitivity of water film thickness and hydroplaning speed to the geometry of a transition section, the PAVDRN model was applied to a PCC surface (as defined in Table 1) with the geometric characteristics described in Table 9. Multiple runs of the PAVDRN program were performed with various combinations of longitudinal slope and cross slope as indicated in Table 9. The results of the analysis are shown in graphical form in Figures 14 and 15. The figures show that both longitudinal grade and cross slope influence water film thickness and hydroplaning speed.

The minimum recommended cross slopes that were developed from the results are shown in Tables 10 and 11. Note that for high speed traffic (100 km/hr) the minimum recommended cross slope is in excess of that recommended in the AASHTO publication *A Policy on Geometric Design of Highways and Street. (6)* These values apply to a broomed concrete surface which represents a very conservative surface in terms of mean texture depth. These values will differ for other pavement types.

Recommendations Specific to Transition Sections

The transition section is a geometrically complex section with respect to determining the drainage flow path and the resulting water film thickness. The worst case of hydroplaning on transition sections occurs when the tangent-end of the section has a mild cross slope adverse to the curve-end of the transition. This situation causes water to flow over longer lengths on the pavement section because slopes at one point in the section are nearly zero. This results in

TABLE 9 **Geometric and texture properties used to analyze transition section.**

Property	**Value**
Section Length	Varies from 10 to 250 m
Width of Plane in Curve (2 lanes)	8 m
Width of Plane in Transition	8 m
Superelevation of Curve	Varies from 0.01 to 0.10 m/m
Tangent Cross Slope	Varies from –0.10 to 0.10 m/m
Tangent Longitudinal Slope	0.02 m/m
Computational Step Increment	1 m
Pavement Type	Broomed PCC
Mean Texture Depth	0.50 mm

[(a)]Longitudinal slope and cross slope are constant over section but were allowed to vary in analysis over range given in table. The values used in the analysis exceed those recommended in the AASHTO publication *A Policy on Geometric Design of Highways and Streets*. They were used for comparison purposes only. *(6)*

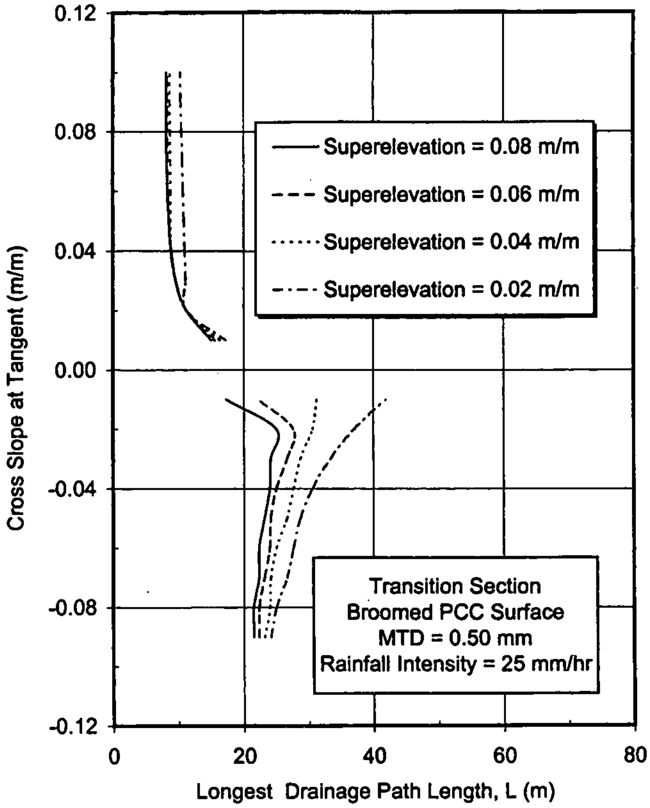


Figure 14. Longest drainage path length versus cross slope for different longitudinal grades, two-lane transition section with broomed PCC surface.

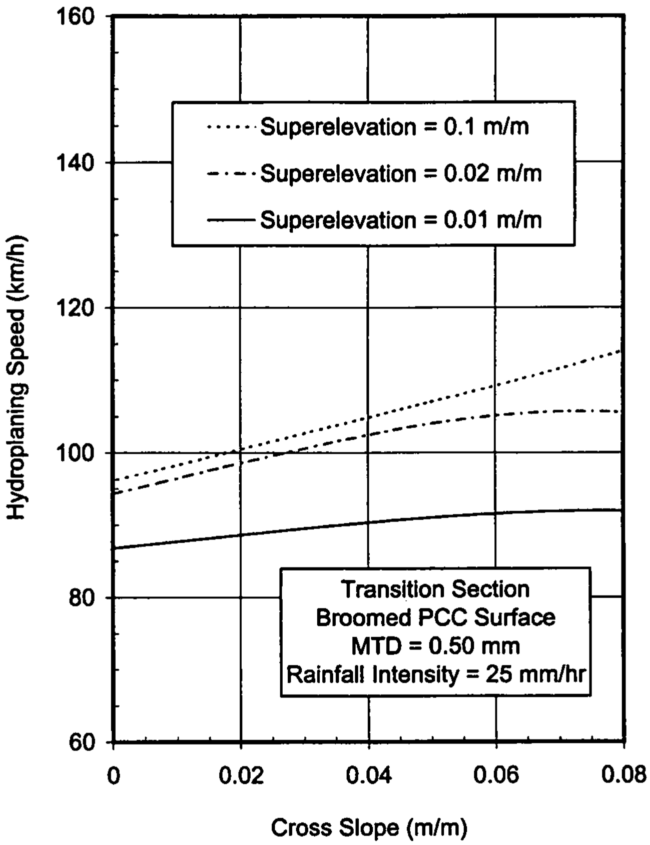


Figure 15. Hydroplaning speed versus cross slope for different longitudinal grades, two-lane transition section with broomed PCC surface.

greater water film thickness and lower hydroplaning speeds. If considering only hydroplaning potential, the runout length should be less than 30 m (98 ft) to prevent hydroplaning on high-volume sections (100 km/h design speed). Because a transition of this length is impractical, other measures besides cross slope and runout length need to be used to control hydroplaning on transition sections.

Crest Vertical Curve Section

Analysis and Discussion Specific to Crest Vertical Curve Sections

A crest vertical section is defined by a vertical point of curvature (VPC) and a vertical point of tangency (VPT). For a crest vertical curve, the longitudinal grade at the VPC is positive and the longitudinal grade at the VPT is either negative or positive. As with the transition section, the grade or longitudinal slope of the crest vertical curve varies along the length of the pavement. The PAVDRN algorithm uses a piecewise process in increments specified by the user along the length of the section to calculate the vector sum of the effective grade and cross slope. This establishes the direction of flow and thus the flow path length for the increment. The greatest length occurs on the section with the steepest grade, either the initial roadway (tangent) or the final roadway (tangent). The increments proceed from the highest elevation toward the lowest elevation at the VPC or the VPT, whichever has the greatest grade, until the edge or end of the pavement is encountered.

In order to illustrate the sensitivity of water film thickness and hydroplaning speed to the geometry of a crest vertical section, the PAVDRN model was applied to a PCC surface (as defined in Table 1) with the geometric characteristics described in Table 10 and an assumed vehicle speed of 85 km/h (53 m/h). Multiple runs of the PAVDRN program were performed with various combinations of longitudinal slope, and cross slope as indicated in Table 10. The results of the analysis are shown in graphical form in Figures 16 and 17. The relationships between the geometrical parameters and water film thickness and hydroplaning speed are again complex, as shown in Figures 16 and 17. However, both longitudinal and transverse slope are significant in

TABLE 10 Geometric and texture properties used to analyze crest vertical section.

Property	Value
Section Length	300 m
Plane Width (2 lanes)	8 m
Cross Slope	Varies from 0.005 to 0.10 m/m[(a)]
Grade at PC	Varies from 0.01 to 0.10 m/m[(a)]
Elevation of PT from PC	-30 m
Flow Direction	Toward PC Side
Mean Texture Depth	0.50 mm
Pavement Type	Broomed PCC
Computational Step Increment	1 m

[(a)]Longitudinal slope and cross slope are constant over section but were allowed to vary in analysis over range given in table. The values used in the analysis exceed those recommended in the AASHTO publication *A Policy on Geometric Design of Highways and Streets*. They were used for comparison purposes only. *(6)*

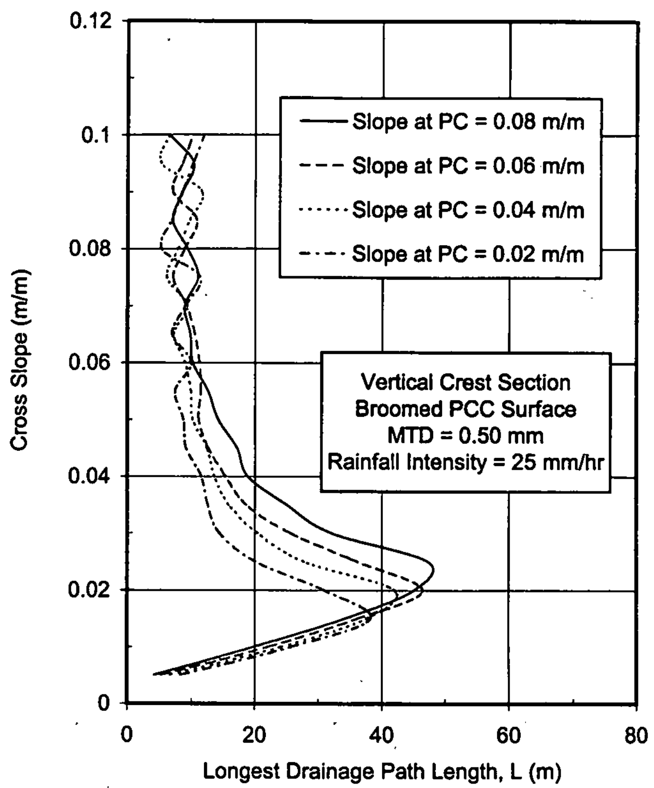


Figure 16. Longest drainage path length versus cross slope for different longitudinal grades, two-lane crest vertical section with broomed PCC surface.

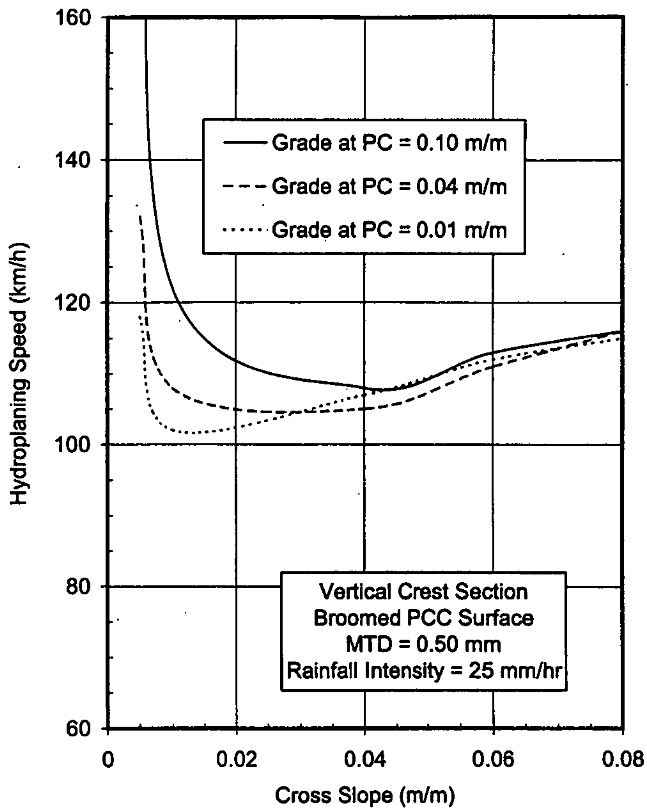


Figure 17. Hydroplaning speed versus cross slope for different longitudinal grades, two-lane crest vertical section with broomed PCC surface.

TABLE 11 Minimum recommended cross slopes for analyzed crest vertical section; broomed PCC surface.

P. C. Grade (m/m)	Minimum Cross Slope (m/m)
0.01	0.015
0.02	0.020
0.03	0.020
0.04	0.020
0.06	0.025
0.08	0.025
0.10	0.025

terms of affecting water film thickness and hydroplaning speed.

The minimum recommended cross slopes that were developed from the results are shown in Table 11. In this case, the minimum recommended cross slopes are well within the values recommended in the AASHTO publication *A Policy on Geometric Design of Highways and Streets. (6)* Once again, these values apply to a broomed concrete surface, which represents a very conservative surface in terms of mean texture depth. These values will differ for other pavement types.

It should be noted that Table 11 applies only to PCC pavements and has been developed for a curve of a given length and elevation difference between VPC and VPT. An analysis using PAVDRN should be made for designs using other pavement materials and geometric properties.

Recommendations Specific to Crest Vertical Sections

The results for the section that was analyzed indicate that for crest vertical curves, the selection of proper cross slope can provide sufficient control of water film thickness and hydroplaning speed. Because the section that was analyzed represents a conservative section in terms of mean texture depth, the results are likely to apply to other pavement types as well.

Sag Vertical Curve Section

Analysis and Discussion Specific to Sag Vertical Curve Sections

A sag vertical curve section is defined by a point of vertical curvature and a point of tangency, where the longitudinal grade at the VPC is negative and the longitudinal grade at the VPT is either negative or positive. The grade or longitudinal slope of the sag vertical curve varies along the length of the pavement. The algorithm used in PAVDRN uses a piecewise process in increments, as specified by the user along the length of the section to calculate the vector sum of the effective grade and cross slope. This establishes the direction of flow and thus the flow path length for that increment. The greatest length occurs on the section with the steepest grade, either the initial roadway (tangent) or the final roadway (tangent). The increments proceed from the highest elevation at the point of vertical curvature or the point of vertical tangency, whichever has the greatest grade, toward the low point of the sag until the edge of the pavement or the low point is encountered.

In order to illustrate the sensitivity of water film thickness and hydroplaning speed to the geometry of a sag vertical section, the PAVDRN model was applied to a PCC surface with the geometric characteristics described in Table 12. Multiple runs of the PAVDRN program were performed with various combinations of longitudinal slope and cross slope as indicated in Table 13. The results of the analysis are shown in graphical form in Figures 18 and 19. The figures show that longitudinal grade has little influence on water film thickness and hydroplaning speed, but that cross slope is significant.

TABLE 12 Geometric and texture properties used for sag vertical section.

Property	Value
Section Length	300 m
Width of Plane (2 lanes)	8 m
Cross Slope	Varies from 0.005 to 0.10 m/m[(a)]
Grade at PC	Varies from 0.01 to 0.10 m/m[(a)]
Grade at PT	0.02 m/m
Elevation of difference between PT and PC	-30 m
Flow Direction	Toward PC side
Pavement Type	Broomed PCC
Mean Texture Depth	0.50 m
Computational Step Increment	1 m

[(a)]Longitudinal slope and cross slope are constant over section but were allowed to vary in analysis over range given in table. The values used in the analysis exceed those recommended in the AASHTO publication *A Policy on Geometric Design of Highways and Streets*. They were used for comparison purposes only. *(6)*

TABLE 13 Minimum recommended cross slopes for analyzed sag vertical section; broomed PCC surface.

P. C. Grade (m/m)	Minimum Cross Slope (m/m)
0.01	0.030
0.02	0.030
0.03	0.030
0.04	0.030
0.06	0.030
0.08	0.035
0.10	0.035

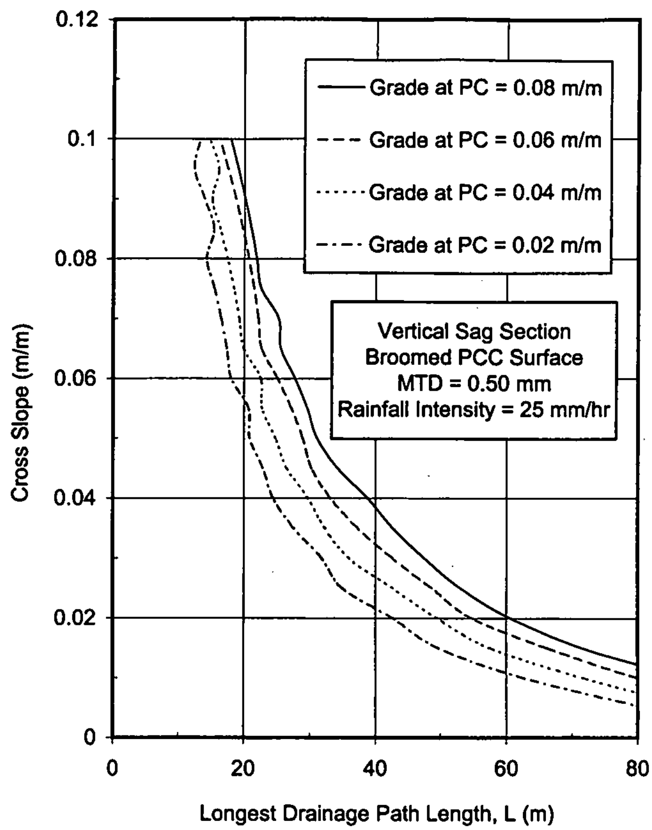


Figure 18. Longest drainage path length versus cross slope for different longitudinal grades, two-lane sag vertical section with broomed PCC surface.

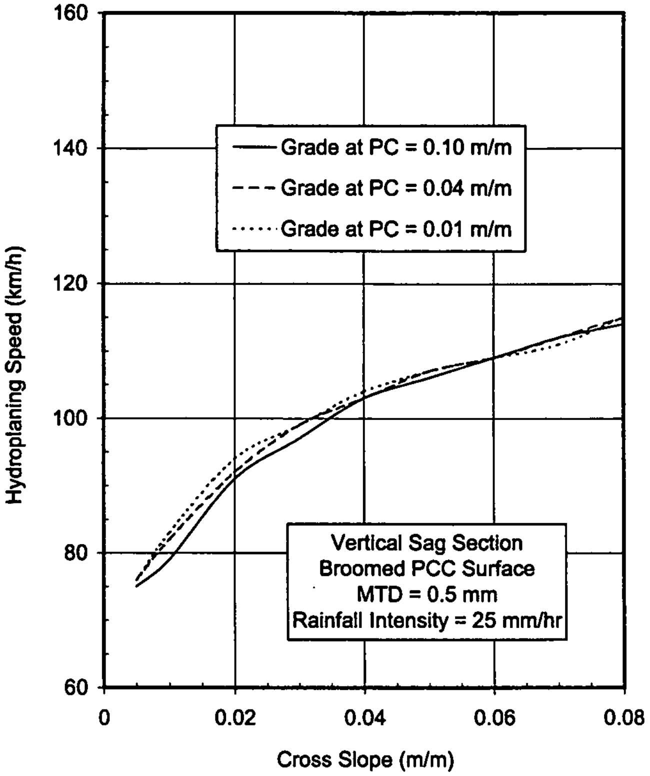


Figure 19. Hydroplaning speed versus cross slope for different longitudinal grades, two-lane sag vertical section with broomed PCC surface.

The minimum recommended cross slopes that were developed from the results are shown in Table 13. In this case the minimum recommended slopes are all within the values recommended in the AASHTO publication *A Policy on Geometric Design of Highways and Streets.(6)* The values are, however, larger than those used by many agencies; therefore, alternate surfaces or other strategies for reducing water film thickness may be warranted for this section.

Recommendations Specific to Sag Vertical Curve Sections

The results for the section that was analyzed indicate that for sag vertical curves the selection of proper cross slope can provide sufficient control of water film thickness and hydroplaning speed. Because the section that was analyzed represents a conservative section in terms of mean texture depth, the results are likely to apply to other pavement types as well.

APPURTENANCES

Analysis and Discussion of Appurtenances

Drainage appurtenances can also be used to reduce the hydroplaning potential of a roadway surface by ensuring that there is proper drainage at the edge of the roadway and by providing drainage within the roadway itself. Drainage appurtenances used for these purposes include inlet structures such as grated inlets and slotted drains. Comprehensive analyses of inlet structures, including interception capacity and spacing recommendations, have been performed in many studies, such as the one by Johnson and Chang. *(4)* Recommended policy for the use of these structures is given in the *AASHTO Policy on Geometric Design of Highways and Streets, Highway Drainage Guideline.* (*5,6*) However, these studies and the AASHTO policy only consider the use of appurtenances along the outer edge of the traveled way.

The proposed guidelines as presented in this document assume that proper drainage is present at the edge of the pavement such that water that flows to the edge is removed without ponding. This may be accomplished with proper curbs and gutters, proper shoulder design, or drop inlet structures. In 1993 a questionnaire was sent to various transportation agencies as part of NCHRP Project 1-29, "Improved Surface Drainage of Pavements." There was general agreement among the agencies responding as to the methods for removing surface water from the pavement surface. The typical procedure employed by transportation design agencies is to allow the water on multilane, high-speed highways to flow freely over the pavement surface and the shoulder to a drainage swale, or to channel the water with a curb or gutter to an inlet. Depending on the geometry of the roadway section, the appurtenances to collect the surface water runoff usually are placed on the outer edge of the travel lane or in the median section. Seven agencies reported using slotted drains along the outer edge of the travel lane. One state reported using this method at a distance of 0.8 m (30 in.) from the edge of the pavement. Several state highway agencies were considering using longitudinal slotted drains to drain curbed medians. Four states reported using longitudinal slotted drains between traffic lanes.

The selection and spacing of curb opening inlets is usually in accordance with highway design guidelines such as the *AASHTO Policy on Geometric Design of Highways and Streets, Highway Drainage Guidelines; Drainage of Highway Pavements: HEC-12*; or individual agency standards. *(4,5,6)* To aid in the selection of inlets and drains, companies that manufacture these devices have produced computer programs and design guides for their specific products. At least one manufacturer has developed a computer program that allows the user to analyze grates with water flowing in the gutter and grates in a sump condition. The user must input various parameters such as street geometric configurations, the particular inlet type, and plugging factor. The program will determine the depth of flow at the curb, the spread of the flow, and the amount of flow captured by the grate. The procedure also can be used for grates that are submerged in a ponded condition.

The increased use of slotted drains within the traveled way is a very promising technique for reducing the potential for hydroplaning on multilane roadways. A slotted drain is essentially a section of pipe cut along the longitudinal axis with transverse bars spaced to form slots. Many configurations and sizes of slotted drains exist. An example is shown in Figure 20. Slotted drains are produced by a number of manufacturers that produce drainage products. Each of these manufacturers provides detailed descriptions of its drainage products and their structural and hydraulic performance characteristics. The overall goal of these proposed guidelines is to recommend methods to reduce the water film thickness values within the traveled section of the roadway. Therefore, the main purpose of this section is to discuss the use of appurtenances within the traveled section of the roadway.

Telephone conversations with representatives of the two agencies that use slotted drains installed in the traffic lanes indicated that the drains were placed in a transverse direction (i.e., perpendicular to the direction of travel on the pavement). Neither agency had experienced problems with the slotted grates and snow removal operations or clogging. One state reported using a concrete slurry backfill to ensure structural soundness of the slotted drain placed across the width of the pavement. From a hydraulic standpoint, slotted drains offer considerable promise for reducing water film thickness by reducing the drainage path. This is true for slotted drains placed either transverse to traffic or parallel to traffic between travel lanes. A typical slotted drain is shown in Figure 20, and examples of drain placement are shown in Figure 21. In each case in Figure 21, the effect of the slotted drain is to reduce the longest drainage path on the roadway section. This reduces the maximum water film thickness and the resulting potential for hydroplaning.

In the authors' opinion, more use should be made of transverse and longitudinal slotted drains. Issues concerning plugging need to be considered, although several agencies report using them at the edge of the pavement and report that plugging is not a problem. Another issue is the potential structural problem that these drains may cause. Support must be adequate so that traffic loads do not damage the drains or cause settlement.

Figure 22 shows a device used in France to drain porous asphalt pavements. It works the same way as the slotted drains shown in Figure 22. *(17)* This device can be placed either longitudinally or transversely within the surface layer.

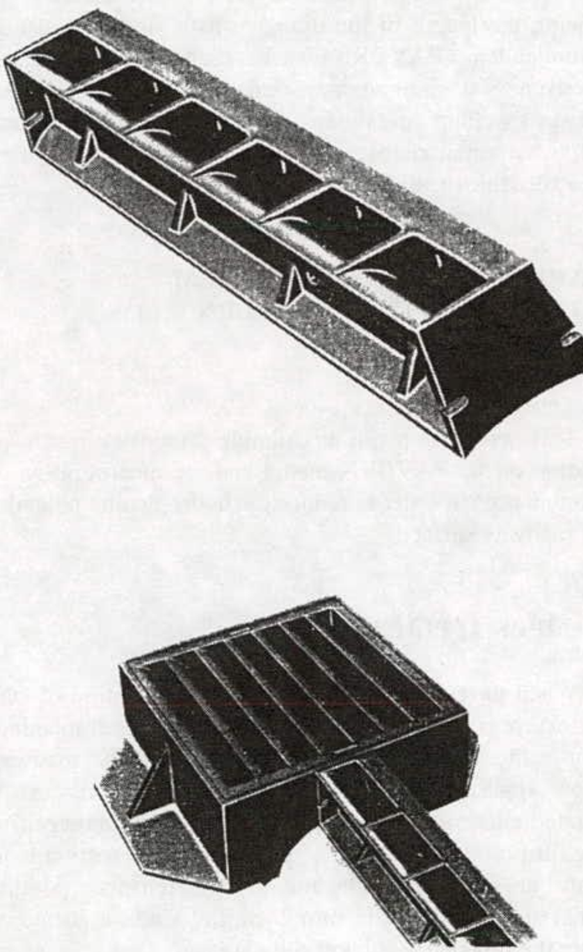


Figure 20. Examples of different types of slotted drains.

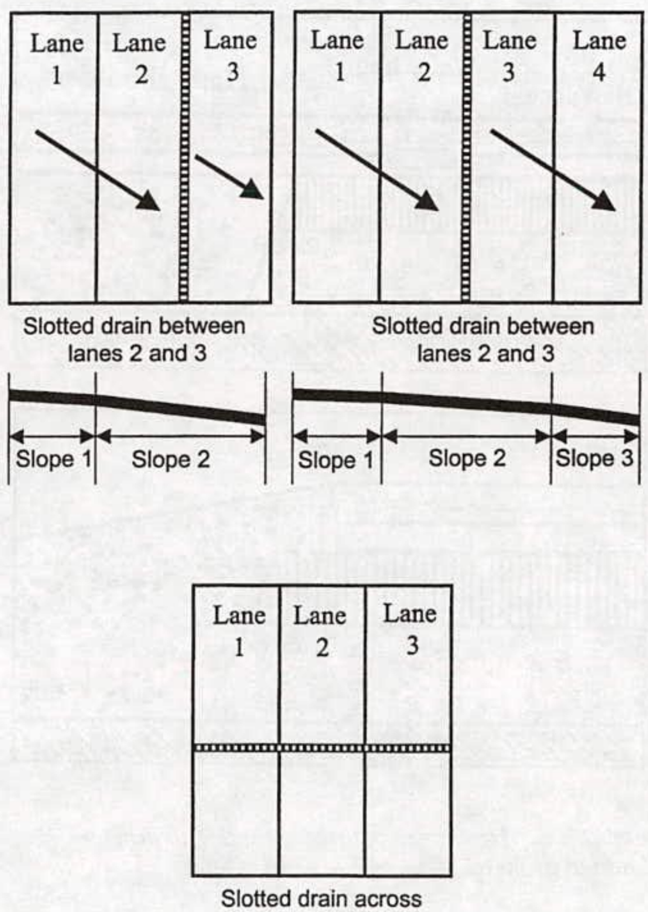


Figure 21. Recommended placement of slotted drains.

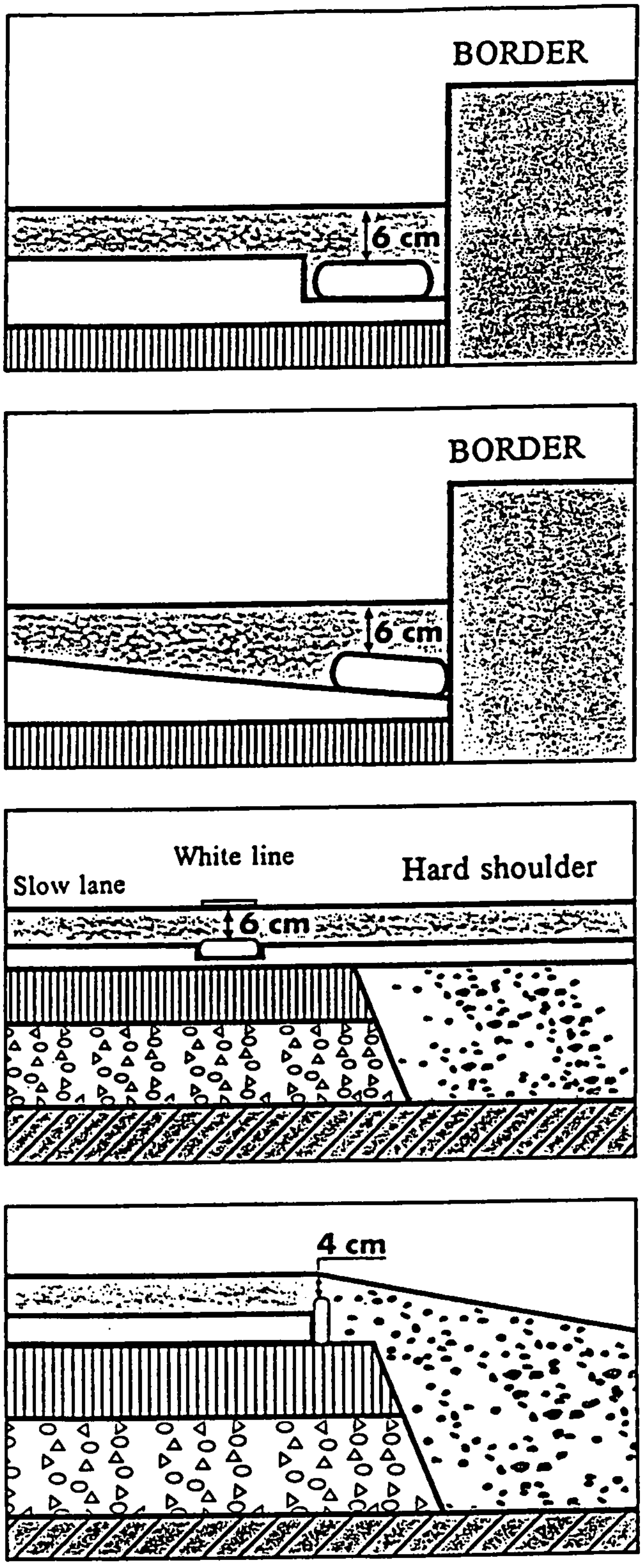


Figure 22. Drainage appurtenance used to provide internal drainage in porous asphalt.

This drain, a geocomposite core wrapped with a polyester geotextile, is furnished in coils that are 54 m (180 ft) in length and 16 mm (0.63 in.) by 60 mm (2.4 in.) in cross-section.

Regardless of the type of appurtenance used, the water film thickness should be determined with the use of the PAVDRN program or another similar tool or procedure. The flow rate over appurtenances can be designed and placed to capture the flow at critical locations along the pavement. An example of this procedure, including a longitudinal slotted drain, is given in Chapter 3.

Recommendations Specific to Appurtenances

Slotted drains installed between or across traveled lanes offer considerable promise in terms of reducing water film thickness and hydroplaning potential. While slotted drains have been used in this manner only on a limited basis, roadway engineers are encouraged to use them on a trial basis. Due consideration should be given to potential plugging and structural problems and any driver handling problems that might occur as a result of traveling over the appurtenances.

Experience in France indicates that drainage fixtures placed within porous asphalt layers also are effective in reducing the length of the drainage path, and their use is recommended. PAVDRN can be used to determine the effectiveness of drainage appurtenances placed within the roadway by comparing the length of drainage path with and without the appurtenances and then computing the resulting water film thickness and hydroplaning speed.

CHAPTER 3 EXAMPLE PROBLEM ILLUSTRATING USE OF PAVDRN

INTRODUCTION

This section contains an example demonstrating an application of the PAVDRN model and the incorporation of appurtenances in order to reduce the hydroplaning potential on a roadway surface.

EXAMPLE APPLICATION

When pavement geometry or the optimization of surface texture is not sufficient to protect against hydroplaning, appurtenances may be considered as part of the roadway design. Appurtenances include drainage inlet structures such as grated inlets and slotted drains and internal drainage fixtures for porous asphalt. The purpose of this section is to present an example of the use of appurtenances (slotted drains) to minimize water film thickness depths at locations within the traveled section of the roadway.

The anticipated resultant water film thickness values on the pavement should be determined first. PAVDRN can be used for this purpose. Once the water film thickness is known, an appropriate method for the removal of the surface water can be selected. In particular, a specific type of drainage inlet structure needs to be identified. Because this example involves the use of a structure within the travel lanes, appurtenances such as curb opening inlets can be eliminated from further consideration. An open drainage channel cannot be used because it would introduce localized irregularity in the pavement surface. Inlet structures such as small, rectangular grated inlets would not be effective because they require channelized flow to or across the structure in order to intercept flow. Slotted drains are the only appurtenances that can be used to intercept flow within the traveled way.

Consider the installation of a slotted drain placed in the lanes of travel for the removal of surface water as shown in Figure 23. Specifically, this example examines a tangent section that is three lanes wide; all lanes are sloped in the same direction, toward the shoulder, as shown in Figure 23. PAVDRN was used to determine the resultant water film thicknesses. The data that were used for the analysis are listed in Table 14.

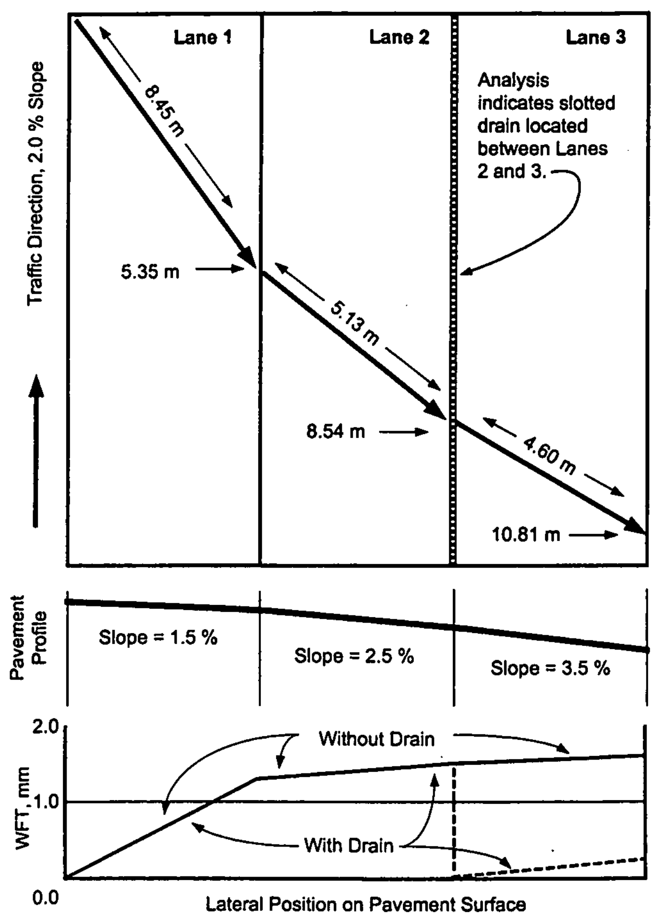


Figure 23. Pavement profile and location of slotted drains in example application of PAVDRN.

TABLE 14 Geometric and texture properties used for tangent section in example application of PAVDRN.

Property	Value
No. of Planes (3 lanes)	3
Section Length	300 m
Longitudinal Slope	0.02 m/m
Width of Each Plane	4 m
Pavement Type	PCC
Mean Texture Depth	0.50 mm
Cross Slope of Plane 1	0.015 m/m
Cross Slope of Plane 2	0.025 m/m
Cross Slope of Plane 3	0.035 m/m
Pavement Surface	Broomed PCC
Mean Texture Depth	0.50 mm

A rainfall intensity of 80 mm/h was used,and a kinematic water viscosity of 1.306 x 10^{-6} m^2/s (water temperature = 10°C) was chosen for the analysis. A summary of the output of the model is show in Table 16.

The results in Table 15 show the value of the water film thickness at the end of the longest drainage path length across each section of the pavement. At the end of the first plane, the model predicted that the flow length of water across the innermost lane will be 6.66 m and the hydroplaning speed at that point will be 90 km/h. For a facility design speed of 90 km/h, this equals the speed at which hydroplaning is predicted to occur. However, as the drainage length increases across the second and third lanes of travel, the water film thickness increases to a point where the predicted hydroplaning speed on the third, outermost lane of travel is substantially below the design speed of the facility. In other words, if vehicles travel at the posted speed limit (90 km/h), hydroplaning is likely to occur.

A solution to this problem is to install a longitudinal slotted drain between the second and third lanes of travel, in the direction of travel. This drain would intercept the flow from the second lane, reduce the water film thickness at the end of the second lane, and reduce the water film thickness across the entire third lane of travel. This would reduce the hydroplaning potential of the entire roadway system so that

TABLE 15 Output for example application of PAVDRN; tangent section with broomed PCC surface.

End of Plane	Drainage Length (m)	Water Film Thickness (mm)	Flow/ Width ($m^3/s/m$)	Hydroplaning Speed (km/h)
1	6.66	1.3	0.00013	90
2	11.79	1.5	0.00023	88
3	16.39	1.6	0.00032	86

the design speed of 90 km/h could be maintained by vehicles without the threat of hydroplaning.

A typical slotted drain inlet structure was used for this example. The flow at the end of the second plane needs to be captured by the analysis. If a slotted vane is selected and placed between the second and third lanes, the grate will capture 0.000516 m^3/s per meter of length of the slotted drain inlet. This value was obtained using a chart provided by the manufacturer to obtain a grate inlet coefficient, K, of 39 and a depth of flow equal to 1.5 mm from Table 15. These values were used in Equation 5 to determine the capacity of the grate:

$$Q = K\,D^{5/3} \tag{5}$$

where:

Q = flow rate, cfs/ft
D = depth of flow, ft

Converting to SI units, the flow rate is 0.000516 $m^3/s/m$.

At this location in the pavement, the flow is only 0.00023 $m^3/s/m$ (Table 15). Therefore, the total flow will be captured. This grate should be installed for the entire length of the pavement section and will reduce the hydroplaning potential to meet the desired design speed of the facility.

In summary, a drainage system can be designed so that appurtenances are placed at critical locations in the pavement to capture flow and remove it from the pavement. This design example was presented in order to provide the reader with a specific application of the recommended procedure. Each grate inlet has its own capacity and should be analyzed for both weir flow and orifice flow, selecting the lower capacity of the inlet grate. Additionally, the specific grate manufacturer should be aware of the design intent in order to obtain information about the structural integrity of the grate systems and their suitability for the proposed application.

CHAPTER 4 SUMMARY AND RECOMMENDATIONS

The following sections summarize recommended changes to the AASHTO publication *A Policy on Geometric Design of Highways and Streets* and in general to geometric design practices for highway pavements. *(3)* They result from the analyses presented previously.

- As the design speed for pavement section approaches 100 km/h, the designer should consider at least one of the three following methods to increase the speed at which hydroplaning is expected to occur:

  1. Use alternative finishing techniques, such as grooving and tining, and mix designs to increase the effective mean texture depths on PCC pavement surfaces.
  2. Use drainage appurtenances, such as slotted drains, between lanes to reduce water film thickness on the pavement surface.
  3. Use alternative pavement materials, such as porous asphalt, to reduce water film thickness.

- Similar results will be found for asphalt concrete pavements, except that mean texture depths of new pavements are generally higher than those for PCC pavements and thus expected hydroplaning speeds will be higher.
- With respect to pavement geometry, cross slope should be maximized wherever possible. The AASHTO publication *A Policy on Geometric Design of Highways and Streets* should be reviewed to determine if some of the recommended cross slopes can be extended to higher values as long as driver safety is not compromised.
- The transition section is a geometrically complex section with respect to determining the longest drainage path length. The designer would be well served by using a tool such as PAVDRN to analyze flow for a given design and making necessary corrections to reduce the likelihood of hydroplaning.

In general, shorting the runout or runoff length reduces water film thickness and the potential for hydroplaning. Changing this design parameter must take into account driver control and comfort.

With respect to appurtenances:

- It is recommended that slotted drainage inlet structures be considered in the design of all roadway geometric sections as an alternative for reducing water film thickness values.
- PAVDRN or a similar tool should be used to determine the water film thickness at the location of the proposed drainage structure or appurtenance.

REFERENCES

1. Agrawal, S. K., and Henry, J. J., "Experimental Investigation of the Transient Aspect of Hydroplaning." *Transportation Research Record 788*. TRB, The National Research Council, Washington, DC (1980).
2. Huebner, R. S. PAVDRN, Computer Program with User's Guide. Produced for NCHRP Project 1-29 "Improved Surface Drainage of Pavements." TRB, National Research Council, Washington, DC (June 1998).
3. Anderson, D., Huebner, R. S., Reed, J., Warner, J., and Henry, J. J. "Improved Surface Drainage of Pavements." Final Report produced for National Cooperative High-

way Research Program. TRB, National Research Council, Washington, DC (June 1998).

4. Johnson, F. L. and Chang, F. F. M., "Drainage of Highway Pavements," *Highway Engineering Circular Number 1*, FHWA-TS-84-202. Federal Highway Administration, U.S. Department of Transportation, Washington, DC (1984).
5. *AASHTO Highway Drainage Guidelines*. American Association of State Highway and Transportation Officials, Washington, DC (1992) 250 pp.
6. *AASHTO A Policy on Geometric Design of Highways and Streets*. American Association of State Highway and Transportation Officials, Washington, DC (1994), 1087 pp.
7. "Standard Method for Measuring Surface Macrotexture Depth Using a Volumetric Technique." ASTM E965, American Society of Testing and Materials, West Conshohocken, PA.
8. "Standard Practice for Calculating Mean Profile Depth." ASTM E845-96, American Society of Testing and Materials, West Conshohocken, PA.
9. Bedient, P. B. and Huber, W. C., *Hydrology and Flood Plain Analysis*, 2nd edition. Addison-Wesley, Reading, MA (1992).
10. Gallaway, B. M., Schiller, R. B., and Rose, J. G., "The Effects of Rainfall Intensity, Pavement Cross Slope, Surface Texture, and Drainage Length on Pavement Water Depths." *Federal Highway Administration Report No. 138-5*. FHWA, U.S. Department of Transportation, Washington, DC (1971).
11. Reed, J. R., Kibler, D. F., Huebner, R. S., and Marks, G. W., "Prediction of Hydroplaning Potential from Runoff Characteristics of Highway Pavements." *FHWA/RD-84/044*, The Pennsylvania Transportation Institute (1985), 157 pp.
12. Gallaway, B. M., Ivey, D. L., Hayes, G. G., Ledbetter, W. G., Olson, R. M., Woods, D. L., and Schiller, R. B., "Pavement and Geometric Design Criteria for Minimizing Hydroplaning." *Report No. RD-79-31*, FHWA, U. S. Department of Transportation, Washington, DC (1979).
13. Ivey, D. L., and Lehtipuu, Eero K., "Rainfall and Visibility - The View from Behind the Wheel." Research Report 135-3, Texas Transportation Institute (August 1974).
14. *International PIARC Experiment to Compare and Harmonize Texture and Skid Resistance Measurements*, AIPCR/PIARC, Paris, France, ISBN 01.04.B (1995).
15. Isenring, T., Koster, H., and Scazziga, I., "Experiences With Porous Asphalt in Switzerland." In *Transportation Research Record 1265*. TRB, National Research Council, Washington, DC (1990), pp. 41–53.
16. Lewis, A. E., Chase, S. B., and Lee, K. W., "Correlation of Pavement Surface Texture to Hydraulic Roughness." In *Transportation Research Record 1471*. TRB, National Research Council, Washington, DC (1994), pp. 10–17.
17. Johnson, F. L., and Chang, F. M., "Drainage of Highway Pavements." *Report TS-84-202*. FHWA, U.S. Department of Transportation, Washington, DC (March 1984), 136 pp.
18. Surchamp, A., "Collecteur pour enrobés drainants sur périphérique parisien" ("Collector for Porous Asphalt on the Paris Ring Road"), *Route Actualité* No. 41 (1995).

GLOSSARY

Asperities—The tops of aggregate particles that are exposed on the surface of the pavement.

Base flow—Flow that occurs on the surface of the pavement but below the top of the surface asperities. To account for the volume of the asperities, for calculation purposes, base flow is considered to occur below the MTD or MPD.

Coefficient of permeability—A coefficient of proportionality that relates flow per unit volume to the hydraulic gradient causing the flow, k, mm/h (in./h).

Computational step—The distance along a drainage path at which water film thickness and hydroplaning speed are calculated.

Drainage appurtenance—In the context of the proposed design guidelines, any device located either on the surface of the pavement or within the pavement and used to remove sheet flow.

Effective rainfall intensity—The rainfall, in terms of thickness per hour, that falls in the pavement surface, minus any water that infiltrates the pavement and drains from within the pavement in either a lateral or vertical direction, I, mm/h (in./h).

Excess rainfall rate—See effective rainfall intensity.

Flow path—The path that a drop of water traces as it drains from the pavement surface.

Full-scale skid testing—In this report, full scale skid testing conducted in accordance with ASTM E 524-88 "Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire."

Grooved pavements—Portland cement concrete pavements containing grooves cut with a saw.

Hydroplaning speed—The speed at which hydroplaning is initiated, km/h (mi/h).

Hydroplaning—A condition resulting from a film of water on the pavement surface that causes the friction between the tire and pavement to decrease to a point where the driver can no longer control the vehicle.

Hydroplaning potential—The speed at which hydroplaning is initiated.

Infiltration rate—The rate, in terms of depth per unit time, that water penetrates into and is removed from the surface of a pavement, f, mm/h (in./h).

Kinematic wave—A mathematical technique used to determine flow parameters such as depth and velocity based on the assumption that the friction slope is equal to the slope of the plane or channel.

Kinematic viscosity—Coefficient that defines rate of flow for a liquid, ν, $\mu m^2/s$.

Longest drainage path length—For a given section of pavement, the longest distance on that section that a drop of water must flow in order to exit the pavement.

Manning's n—An empirical coefficient that quantifies the hydraulic roughness of a surface where hydraulic roughness implies resistance to flow.

Mean profile depth —The average of the texture depth where the texture depth is measured by ASTM E 1845, "Standard Practice for Calculating Mean Profile Depth," mm (in.).

Mean texture depth—The average of the texture depth where the texture depth is measured by ASTM E 965, "Standard Method for Measuring Surface Macrotexture Depth Using Volumetric Technique," mm (in.).

Outflow meter—A device that is placed on the pavement surface and water is allowed to flow through the gap created between the base of the device and the pavement surface.

PAVDRN—A computer program used to determine the longest drainage path length on a pavement section and the water film thickness and hydroplaning speed at points along that path.

Plane—A continuous section of pavement with constant cross-slope.

Porous asphalt—Asphalt concrete designed to allow water to flow internally within the mix. In this report porous asphalt includes open-graded friction courses (OGAFC) and the more open porous asphalt as used in Europe.

Flow rate—Rate at which water flows into a drainage appurtenance, Q, m^3/s (ft^3/s).

Rainfall event—A period of time when rainfall occurs with a measurable intensity.

Rainfall intensity—The rate at which rainfall encounters a surface in units of depth per unit time, i, mm/h (in./h).

Rainfall rate—See rainfall intensity.

Return period—A means of relating relative risk. The return period, reported in years, is equal to the inverse of the probability that an event will be exceeded, e.g., a one hundred-year rainfall has a 1 percent chance of being exceeded in any year (1/0.01=100).

Reynold's Number—A dimensionless variable used to determine if flow is laminar or turbulent.

Runout Length—The length of a transition section from a tangent section to a curve section of pavement measured along the centerline of the pavement.

Sand patch—A test used to determine mean texture depth, ASTM E 965, "Standard Method for Measuring Surface Macrotexture Depth Using Volumetric Technique."

Section—A geometrically uniform length of pavement, e.g., curve section or tangent section.

Sheet flow—Water that flows in a thin, uniform sheet over a pavement surface.

Sight distance—The distance that a driver can see. In this report, sight distance may be given by pavement geometry or by reduced visibility that occurs during a rainfall event. S_v, m (ft).

Slotted drain—A storm water inlet drain that is characterized by a long and narrow opening referred to as a slot.

Steady-state flow—A condition where depth and velocity is not changing at a point with respect to time. This occurs when flow into a control volume equals flow out of the control volume.

Surface texture—See mean texture depth or mean profile depth.

Time of concentration—The time it takes for flow to travel some specified distance on the surface of the pavement, min.

Vehicle velocity—Speed of vehicle as used in calculation of sight distance during a rainfall event, V_i, km/h (mi/h).

Volumetric method—A test used to determine mean texture depth, ASTM E 965, "Standard Method for Measuring Surface Macrotexture Depth Using Volumetric Technique."

TERMS AND ACRONYMS

ν — Kinematic viscosity, $\mu m^2/s$.

D — Depth of flow approaching a grate inlet, mm (in.).

DGAC — Dense-graded asphalt concrete, conventional hot-mix asphalt concrete.

f — Infiltration rate, mm/h (in./h).

HPS — Hydroplaning speed.

I — Effective rainfall intensity, mm/h (in./h).

I — Rainfall intensity – the rate at which rainfall encounters a surface in units of depth per unit time, i, mm/h (in./h).

I–D–F — Intensity–duration–frequency.

k — Coefficient of permeability (porous asphalt mixtures), mm/h (in./h).

K — Grate inlet coefficient.

L — Longest drainage path length, m (ft).

MPD — Mean profile depth, mm (in.).

MTD — Mean texture depth, mm (in.).

n — (Manning's n) an empirical coefficient that quantifies the hydraulic roughness of a surface.

OGAFC — Open-graded asphalt concrete.

PAVDRN — A computer program used to determine the longest drainage path length on a pavement section and the water film thickness and hydroplaning speed at points along that path.

PC — Point of curvature.

PCC — Portland cement concrete.

PT — Point of tangency.

PVC — Point of vertical curvature.

PVT — Point of vertical tangency.

Q — Rate at which water flows into a drainage appurtenance, m^3/s (ft^3/s).

R — Reynold's number.

S_v — Sight distance, m (ft).

V_i — Vehicle velocity, km/h (mi/h).

WFT — Water film thickness measured as the thickness of the water film above the top of the pavement asperities.

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