Multilane Highway Design Crossfall and Drainage Issues

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The safety of wet pavements has become a major concern because of the growing need to drain wide pavements. Research on the relationship between drainage design, vehicle operation, and safety, with a particular focus on crossfall and drainage characteristics of wide pavements, is reported. Following an introduction to the subject, the problem of draining wide pavements and the associated safety issues are discussed. The safety implications of longer drainage paths across four or more lanes of high-speed freeway are described in terms of the risk of loss of vehicle control due to skidding or hydroplaning. Models of skidding, hydroplaning, and water depth on pavement are reviewed. Existing practices and potential solutions for effective drainage of wide pavements are discussed. These include the appropriate crossfall design and the effective drainage at the edge of the pavement. A design methodology is advanced for (a) estimating water depth under various conditions at critical locations on highway pavements and shoulders, (b) establishing drain inlet locations, and (c) assessing whether estimated water accumulation can lead to significant loss of control from skidding and hydroplaning. An example application and sample results are discussed. Finally, conclusions on drainage design methodology and crossfall standards are presented.

Driving on a highway pavement covered by a layer of water can become unsafe. Even for a highly skilled and alert driver, especially at high speeds, it may become difficult to control the vehicle when a pavement with a layer of water fails to offer the required amount of friction or when a complete separation of tire and pavement occurs—the phenomenon of hydroplaning.

The purpose of the research described here was to investigate crossfall and other pavement surface drainage design features for large multilane freeways from the perspectives of effective drainage and road user safety.

RESEARCH FRAMEWORK

The research approach shown in Figure 1 consisted of the following steps: (a) defining wet pavement safety and drainage issues; (b) study of variables and their conceptual relationships; (c) compiling information on linkages between skid resistance, hydroplaning, and water depth on pavement; (d) compiling information on models of skid resistance, hydroplaning, water depth, and the highway–vehicle object simulation; (e) study of design practices and potential improvements; (f) development of methodology for testing drainage standards and designs; and (h) developing drainage design guidelines.

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DRAINAGE AND SAFETY ISSUES

Although research on the tire-pavement interaction has produced a wealth of information on how to improve the skid resistance properties of pavements, vehicle suspensions, brakes, and tire designs, the subject of wet pavement safety continues to be important owing to the increasing widths of pavements to be drained.

At a growing number of urban and suburban sites, because of high travel demand and the necessity to accommodate through traffic as well as collection-distribution functions within a common cross section, freeway pavements have become much wider than when freeways were mainly four lanes. Even under favorable pavement surface and tire conditions, for safety reasons wide highways must be drained effectively through appropriate crossfall and edge-of-pavement drainage designs.

Available literature indicates that poor drainage has been one of the causes for unsafe operations. In Ontario in 1991, 21.8 percent of total accidents occurred under wet pavement conditions (*1*, p. 26). Analysis of U.S. safety data reported in the literature identified wet surfaces as a probable important contributing factor to accidents, particularly at curves and downgrades (*2*).

The interactions between automobile tires and the pavement have been investigated by numerous agencies in the past for the purpose of understanding and improving safety. Lack of required skid resistance for safe driving and the onset of hydroplaning are two key phenomena that have been of special interest to researchers around the world. Horizontal forces related to tire-pavement interaction that provide traction, braking, and directional stability were investigated. Because these forces depend on the coefficient of friction between tires and the road surface, the means of maintaining a high coefficient of friction to prevent skidding accidents were emphasized. Inadequate drainage of pavement surface is recognized in the literature to be a problem area.

VARIABLES AND LINKAGES

Many factors were identified to be relevant in this research. These are pavement width, crowning considerations, cross slope, longitudinal grade, curvature, superelevation, shoulder arrangement, shoulder surface treatment, water depth, pavement surface characteristics, skid resistance, vehicle operational characteristics (i.e., safe operations and hydroplaning), and cost of drainage. The linkages between variables were defined initially in a conceptual form, based on the principles of vehicle dynamics, tire-pavement interaction, pavement characteristics, and geometric and drainage designs. As for the cost variable, only qualitative considerations could be addressed because of the scope of the study.

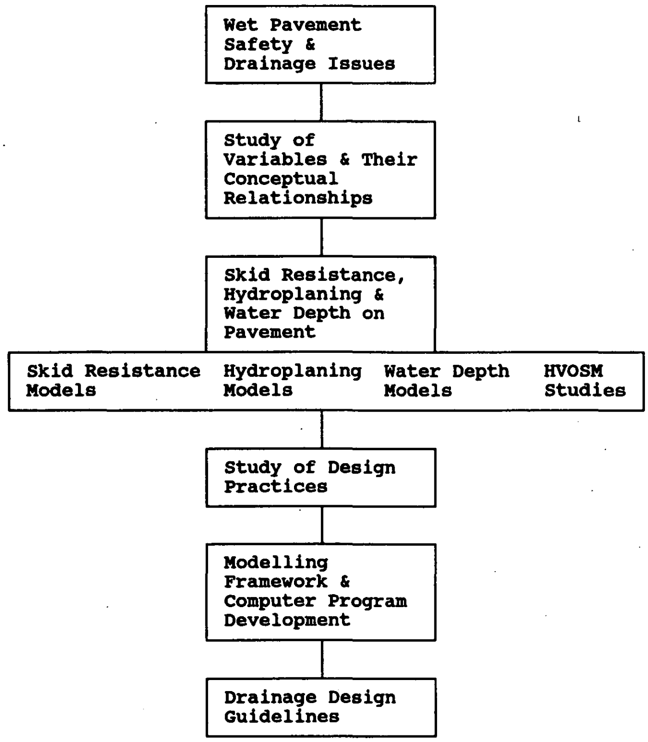

FIGURE 1 Research framework.

MODELS OF SKIDDING, HYDROPLANING, AND WATER ACCUMULATION

The skid number of a pavement is the coefficient of friction multiplied by 100. It is quantified by numerous agencies in accordance with ASTM Test Method E274 (*3*). The measurements are made by using a test vehicle, including a specified tire for pavement tests. Skidding implies a vehicle motion that results from the driver losing control of the vehicle because of the lack of required tire-pavement friction. If a vehicle is driven faster than the critical speed on wet pavement, the driver can lose control of the vehicle as a result of the onset of skidding. In the normal course of driving, even if excessive speeds are not involved, drivers may react to situations on the highway that may demand more shear force from their tires than is available from the frictional potential between the tire and road (e.g., braking and changing lanes). This may cause the vehicle to skid. Both cars and trucks can skid on wet pavements. In fact, skidding problems are amplified in the case of heavy trucks (*4*).

Safe operation of a vehicle at all speeds and under all types of vehicular movements requires that the available friction (i.e., the maximum friction force that can be generated under the conditions) must exceed friction demand. In the case of wet pavements, available friction drops with increasing speed. The opposite is the case with demand for friction on wet pavements (for directional control or performing the intended maneuvers such as braking, changing lanes, turning, or a combination of these), because it increases with speed (*3,5*). Although the advent of antilock brake systems has helped to prevent lockup of wheels in emergency braking situations, these observations clearly point to the importance of speed as a major variable in wet pavement safety.

Pavement surface properties are very important in the study of skid resistance on wet pavements. Pavement surface roughness features are divided into three scales: roughness, macrotexture, and microtexture. Roughness or unevenness of the pavement primarily affects ride comfort. Macrotexture refers to stone projections (measured by ASTM E 770 method), and microtexture is the harshness of materials (evaluated by PSV by the ASTM D 3319 method). Both macrotexture and microtexture are essential for obtaining an adequate coefficient of friction on wet pavements.

At the tire and pavement contact area, the tire deforms into a flat surface and could trap water. For preventing marked loss of skid resistance, the water trapped in this contact area must be expelled. At higher speeds, large open-flow channels potentially obtainable from the tire tread and the pavement macrotexture are needed because less time is available for expelling water.

However, despite the presence of pavement macrotexture and good tire condition, a thin water film could remain between tire and pavement unless it is expelled by harsh microtexture and a quasidry contact point between pavement and tire is established. Thus, good skid resistance under wet conditions calls for good macro- and microtextures.

Hydroplaning is the phenomenon of the separation of the tire from the road surface by a layer of water. It is recognized that on a microscopic scale all operational conditions on wet pavements may involve some degree of partial hydroplaning. On a macroscopic scale, hydroplaning occurs only if there is some significant degree of penetration of a water wedge between the tire and pavement contact area (*6*).

Three categories of hydroplaning of pneumatic-tired vehicles have been defined: viscous hydroplaning, dynamic hydroplaning, and tire tread rubber hydroplaning (*7*).

In the case of light road vehicles, the first two types are relevant to the present study. The third type of hydroplaning occurs only if heavy vehicles such as trucks or aircraft lock their wheels while moving at high speeds on wet pavements exhibiting macrotexture but little microtexture.

On pavements with little microtexture, viscous hydroplaning can occur at any speed in the presence of extremely thin films of water. It is logical to suggest that such a thin film of water remains between tire and pavement because the pavement microtexture required to break it down is absent.

Dynamic hydroplaning occurs when the amount of water encountered by the tire exceeds the combined drainage capacity of the tread pattern and the pavement macrotexture (*7*). Owing to the impact of tire surface with the stationary fluid, there is sufficient pressure to buckle the tire tread surface inward and upward from the pavement. This causes a progressive penetration (with increased speed) of the fluid film from front to rear of the footprint region of the tire (*3,6*).

Although the new designs of tires are aimed at improving the drainage capacity of the tread pattern, there is no basis to suggest that dynamic hydroplaning can be prevented.

Past research has resulted in models that can serve as guidelines for the identification of water depth and speed conditions that may lead to dynamic hydroplaning (Table 1) (*6,8*).

For the estimation of water depth on pavement under various conditions, a search was carried out for suitable empirical and theoretical models. A number of empirical models reported in the literature were examined, and one was selected for further evaluation. This empirical model of parametric form (described later in this paper) was tested against a theoretical model of water flow on pavement (*9*).

Empirical equations were developed by a number of research groups for estimating the depth of water over the pavement. These research groups were the Road Research Laboratory in the United

TABLE 1 Critical Thickness (mm) of Water Film for Dynamic Hydroplaning

Speed (km/h)	Tire Condition: Good condition	Some wear	Worn out
80	7.8	4.7	2.6
100	5.0	3.0	1.7
120	3.5	2.0	1.2
130	3.0	1.8	1.0

Source: Calculated from information reported in Reference 6, pp. 11-15.

Kingdom, Yaeger and Miller at Goodyear, and Gallaway et al. at the Texas Transportation Institute (TTI). The research work at TTI was the most comprehensive in terms of the factors studied and the amount of prototype tests and highway field studies carried out. The TTI model was widely tested at great expense in the United States and Europe.

It should be noted that the empirical equations developed by various groups cannot be compared with confidence in terms of their estimates of water depth because the variables incorporated were different. The TTI equation described later in this paper is the only model that is based on all the necessary variables.

The empirical and theoretical models were compared in a number of test cases. It is recognized that because of numerous assumptions made in the development of the theoretical model, the results of the theoretical model are approximate at best. Despite this limitation, a comparison of the results of two models was favorable. The water depth answers obtained from the empirical model were 20 to 37 percent higher than those obtained from the theoretical model. The conservative nature of the empirical model estimates is considered desirable from the perspective of developing drainage and safety strategies.

The study of safety aspects of factors that could be considered critical in terms of vehicle operation on wet pavement (i.e., those that could result in skidding) called for the use of a computer model. The Highway Vehicle Object Simulation Model (HVOSM) was used for this purpose. This model was developed initially by Cornell University and was refined by CALSPAN of Buffalo, New York, for FHWA.

HVOSM was used for testing vehicle operations for various drainage design, geometric design, and pavement characteristics. The effects of drainage design parameters were studied on turning, lane change, and a combination of these with and without braking. This model is widely used by researchers for determining operating conditions that can lead to loss of control and onset of skidding.

DESIGN PRACTICES AND SEARCH FOR IMPROVEMENTS

Existing drainage design standards used by numerous transportation agencies date back to the time when freeways were mainly four lanes with only a few six-lane sections. It has been believed by many designers that there is no comprehensive basis in current standards for establishing safe drainage designs for 8- or 10-lane divided highways. Such wide pavements could involve water flow over four or five lanes, and in the absence of well-researched drainage design guidelines, water accumulation may result in safety problems.

Even in the case of six-lane freeways, existing drainage design guidelines are not well defined and cannot be relied on to answer some design questions.

Solutions to wide pavement drainage and safety problems can be found in appropriate crossfall and superelevation design standards, the expedient removal of water at the edge of pavement, and the provision of pavements with good macrotextures as well as microtextures.

It is encouraging to note that skid correction programs are receiving increased attention in Canada, the United States, Europe, and elsewhere around the world. A literature survey indicated that a skid number of 35 is used as the critical skid index. Pavements that show a skid number below 35 are given priority for improvement. Pavements with skid numbers in the range of 35 to 45 are regarded as marginal, and those pavements with skid numbers above 45 are classified as standard (*10*).

In response to the increasing recognition of the importance of reducing accidents in wet weather, the authorities appear to be keen on the use of adequate superelevation and cross slope, particularly on long-radius curves, and of friction courses (*10,11*). Open-graded friction courses (OGFCs) improve friction during wet conditions and reduce splash and spray. However, their less than projected service lives in areas with severe winter climates is a cause for concern. Other friction courses and newer surface treatments offer appropriate texture properties.

DRAINAGE DESIGN METHODOLOGY

Capabilities

This modeling framework, implemented as a microcomputer program called RUNOFF, enables the designer to test drainage design factors in terms of water depth on the pavement, vehicle operating conditions, total amount of water to be drained, and location of drain inlets. From the knowledge of water depth and characteristics of pavement, inferences can be drawn on loss of friction, skidding, and hydroplaning. An additional feature of the model is that it can be used to estimate total water flow and drain inlet spacing.

The model calls for inputs on precipitation, roadway section features, and design decision variables. Computations are carried out for drainage path (i.e., pavement contours), drainage length and slope, and water depth. The estimation of water depth under various conditions and at critical locations on highway pavements and shoulders in conjunction with pavement characteristics enables the analyst to assess whether such accumulation can lead to significant loss of control from skidding or hydroplaning.

The methodology assists the designer in testing many what-if situations without resorting to tedious and time-consuming hand calculations. In turn, the identification of the best design becomes easier.

Model Components

There are three basic components of the model.

- Module A. This part of the model estimates water depth on the pavement.
- Module B. Here, the total quantity of water that is to be drained from a specified section of the roadway is estimated, and the user is advised on factors for drain inlet location decisions.
- Module C. This module is intended to examine the water depth answer obtained from Module A in terms of whether it falls in the satisfactory range. Also, suggestions are offered for changing design parameters or the supplemental skid resistance to be provided.

Module A

The slope of the flow path (in percent) is found from the following expression:

$$S_3 = (S^2{}_1 + S^2{}_2)^{1/2}$$

where

S_3 = slope of flow path (in percent, expressed in fractional form),
S_1 = cross slope (in percent, expressed in fractional form), and
S_2 = longitudinal grade (in percent, expressed in fractional form).

The length of flow path is found as

$$L = W(S_3/S_1)$$

where L is the length of the flow path (in m), and W is the pavement width, measured from the crown line or edge of inside shoulder (in m).

The water depth above the top of texture can be found by using the equation developed at TTI:

$$WD = (25.4)\{(0.00338)\,[(TXD/25.4)^{0.11}\,(L/0.305)^{0.43}\,(I/25.4)^{0.59}\,(S_3)^{-0.42}] - (TXD/25.4)\}$$

where

WD = average depth above top of texture (in mm) at distance L (in m) from the location where water commences to flow,
TXD = average texture depth (in mm),
L = length of flow path (in m),
I = rainfall intensity (in mm/b), and
S_3 = slope for flow path (in percent, expressed in fractional form).

The estimated WD and the results of intermediate computations are saved for use in Modules B and C.

The pavement texture (TXD) values can range widely (i.e., 0.38 to 4.19 mm). The choice of an appropriate value depends on the characteristics of the pavement, although it is recognized that there is no specific relationship between pavement type and TXD. For a given asphalt pavement type, TXD depends on the nature of the mixtures (i.e., the proportion of coarse graded versus fine graded mixtures). In the case of portland cement concrete (PCC), the texture depth depends on the method used to create macrotexture (*9*). The following guides have appeared in the literature: hot mix siliceous rock, 1.0 mm; OGFC, 1.0 to 3.0 mm; PCC, 0.51 to 1.15 mm (*6,9*). For friction courses other than the OGFC, such as dense graded mix and stone mastic pavement, 1.5 to 3.00 mm may be used. For stabilized shoulders, a TXD of more than 4 mm would be appropriate.

For specific applications of the methodology, the user may wish to use the values noted in the previous paragraph or apply the silicon putty method to estimate the TXD. Detailed descriptions of this method have been presented previously (*6,9*).

The specification of I (mm/hr) implies a duration of rainfall and storm return period (in years). For example, according to the Ministry of Transportation of Ontario (MTO) sources, an I value of 101.6 mm/hr for London, Ontario, implies a 5-min duration and a 2-year return period. An I value for crossfall design is expected to be less than the one used for storm drainage, but it can be used for checking storm inlet spacing. Crossfall design is a compromise between user safety and drainage. For instance, a storm with a 1- or 2-year frequency may be appropriate for crossfall design. On the other hand, the detailed design of the storm drainage system might require a much higher I value (e.g., a 10-year frequency). During such a severe storm, because of poor visibility, the traffic will slow to a crawl speed and, therefore, the skidding or hydroplaning concerns will not be relevant.

Module B

The quantity of water Q (m^3/hr) to be drained from the roadway section can be found by using the following methodology.

Let

Q = surface runoff (in m^3/hr),
I = precipitation rate (in mm/hr; as used in Module A),
IF = infiltration factor (percent of rainfall that is being absorbed by the pavement, expressed in fractional form), and
A = area of pavement that corresponds to the section of roadway specified in Module A (m^2).

The quantity of flow can be found as follows:

$$Q = (1 - IF) \times (I/1{,}000) \times A$$

In the case of the tangent section, the area A is given by the product of W and the length of the roadway section analyzed. For the partly superelevated section, an approximation can be made by using the approach for the tangent section. On the other hand, for the curved section, the area is taken to be a slice of a ring for which the radius of the horizontal curve is specified in Module A. The width W is also obtained from Module A.

The default value for the infiltration rate (IF) has been suggested in the literature (*12*). For highways with good sealed surface conditions (i.e., the absence of cracks or openings at joints) and on the assumption that the pores for OGFC types of pavements are clogged, a value of 0.00 may be used. The MTO drainage manual (*13*) suggests a runoff coefficient (i.e., $1 - IF$) of 0.8 to 0.95 for asphalt or concrete pavements and 0.4 to 0.6 for gravel shoulders.

This methodology is not intended for use in the development of drainage designs in terms of suggesting gutter designs (if applicable), selecting inlet grates, and establishing the locations of drain inlets, and so forth. However, it supplies the designer with preliminary information on the spacing of drain inlets.

The inlet spacing calculations take into account the amount of water to be drained, the gutter capacity, and the design spread. The design spread is the distance along the paved shoulder or roadway cross section that will be flooded. This variable in turn affects gutter capacity, the depth of flow along the gutter, and thus the capture rate of the inlet (*13*).

For wide pavements on freeways, the likely presence of a shoulder will not result in flooding of the traveled way. According to the MTO design manual, for freeways a maximum design spread of 1.5 m is allowed, provided that the gutter is at the outer edge of a paved shoulder. Also, the MTO drainage manual provides guidelines for increasing design spread under specified conditions.

From charts contained in the MTO drainage manual (*13*), for selected inlet grate, gutter grade, and design spread, a gutter flow capacity (Q_g) can be found. On the assumption that the local runoff (Q_r) to be conveyed is equal to Q_g, then the inlet spacing can be found from the following formula:

$$INL = (3.6 \times 10^6 \times Q_r)/[W \times I \times (1 - IF)]$$

where

- INL = length of roadway section to be drained (first inlet assumption) (in m),
- Q_r = runoff (set equal to Q_g) (in m³/sec),
- W = width of pavement (and shoulder if applicable) to be drained (in m),
- I = rainfall intensity (in mm/hr),
- IF = infiltration rate (expressed in fractional form), and
- $1 - IF$ = runoff coefficient.

1. In this part of the methodology, the Q (in m³/hr) calculated earlier is converted to Q (in m³/sec): Q (in m³/sec) = [Q (in m³/hr) found for the road section]/(3,600).
2. Next, the analyst is advised to compare this magnitude of water with what can be drained by the gutter at capacity and the spacing of inlets equal to a maximum of 150 m (specified by MTO). The methodology asks the user to specify Q_g. For example, for inlet grate DD-713-B, a gutter grade of 4 percent, and a design spread of 1.5 m, Chart E4.74A in the MTO drainage manual (*13*) indicates that Q_g equals 0.045 m³/sec.
3. Compare Q_g with the demand flow rate. If Q_g is greater than the demand flow rate, one inlet is required. It can be located within this section unless an adjoining road section is available. If Q_g is equal to the demand flow rate, one inlet is required within this section. If Q_g is less than the demand flow rate, more than one drain inlet is required. Inlets can be located according to the standard procedure of MTO. In all these cases, use Q_g to calculate INL. If INL is greater than 150 m, set it equal to 150 m, its maximum value specified by MTO; if not, use the calculated INL, as follows:

$$INL \text{ required} = (3.6 \times 10^6 \times Q_r)/[W \times I \times (1 - IF)]$$

The user should specify the Q_g value. If not use a default value for Q_r equal to Q_g equal to 0.045 m³/sec.

4. The user of the methodology is advised to refer to the MTO drainage manual (*13*) for developing a detailed design for pavement drainage.

Module C

1. Check the water depth against the guidelines presented in Table 2. A check should be made against the critical WD value that could result in skidding or hydroplaning. The user should be advised to check skid resistance and upgrade it if necessary.
2. The design could be modified, and the procedure could be repeated to calculate a new value for WD and check skid resistance deficiency and hydroplaning potential.
3. Following a testing of all design changes (e.g., crossfall) that could be made, the designer must explore means to enhance skid resistance. Guidelines are provided by the methodology, including the improvement of surface texture by adding a layer of OGFC or other new surface treatments, and speed control.

Example Application

Assume that a freeway pavement section (of 100 m in length) of four lanes is expected to drain toward the outside shoulder. The dimensions for the lanes and cross slopes are presented later. Information on the outside shoulder is not provided. Given that I is equal to 101.6 mm/hr and TXD is equal to 2.5 mm, find WD at the edges of the lanes (i.e., Points A, B, C, and D). The results are presented in Table 3.

Sample Calculation

Module A Find WD at Point A for TXD = 2.5 mm, $L = W$ = 3.7 m, I = 101.6 mm, $S_1 = 0.02$, $S_2 = 0$, and $S_3 = [(0.02)^2]^{1/2} = 0.02$. $WD = -0.22$ mm (i.e., below the top of pavement texture).

Module B Length of section = 100 m, width of section = 14.8 m, A = area to be drained = 1,460 m², and I = 101.6 mm/hr. For IF = 0.0, Q = 150.36 m³/hr, and for IF = 0.4, Q = 90.22 m³/hr. For demand Q = 150.36 m³/hr, Q/sec = 0.042 m³/sec. Ask the user to specify Q_g; if it is not specified, use the default value. Q_g of 0.045 > Q demand; one inlet will be sufficient:

$$INL = [(3.6 \times 10^6 \times 0.045)]/[(14.8 \times 101.6 \times (1 - 0)] = 107.7 \text{ m}$$

Since it is less than the maximum value of 150 m, use 107.7 m. If there is an adjoining section of the roadway, the drain inlet could be located there. If not, locate the inlet in this section.

Module C Compare WD with the values provided in Table 2. The results are generally acceptable, but check skid characteristics; also, repeat the design with a higher value of cross slope and attempt to reduce WD to approximately 1.0 mm if possible.

SAMPLE RESULTS

The use of the methodology described here and the HVOSM computer simulations have resulted in (a) water depth estimates on pavement and shoulder surfaces for a large number of combinations of crossfall, longitudinal slope, roadway width, pavement texture, superelevation for curved sections, and rainfall intensity; (b) water

TABLE 2 Water Depth and Assessment of Design

WD (mm)	Assessment[a]	Action Required
0-1	Acceptable	No action required
1-2	Acceptable but check skid characteristics; vehicles with worn out tires may hydroplane; potential for viscous hydroplaning	Repeat design, reduce WD if possible; if not, no action needed for friction course surfaces; check skid resistance for other surfaces and take actions such as signage, improved texture for asphalt pavement & tining for concrete pavement.
2-3	Acceptable but check skid resistance; vehicles with some tire wear may hydroplane; potential for dynamic hydroplaning	Repeat design, reduce WD if possible; if not, use signage; no other action needed for friction courses with good skid resistance; improve texture for other bituminous surfaces; improve friction for concrete pavement.
>3	Not recommended--hydroplaning potential	Repeat design, reduce WD if possible; if not, use signage & check skid resistance of all pavement types; use all feasible actions (e.g., friction courses) to improve skid resistance and reduce hydroplaning potential.

[a] Based on information contained in Table 1.

TABLE 3 Results of Sample Application

Lane	Lane 1 (Inside lane)	Lane 2	Lane 3	Lane 4 (Outside lane)
Inputs				
Width	3.7m	3.7m	3.7m	3.7m
Crossfall	2% -->	2% -->	2% -->	2% -->
Reference Point	A	B	C	D
WD (mm)	-0.22	0.55	1.14	1.61
Q (cub.m/h)				
IF=0.0	37.59	74.17	111.78	150.36
IF=0.4	22.56	44.50	67.67	90.22

depth estimates for test cases involving variable cross slopes for different parts of the roadway cross section; and (c) estimation of speed at impending skid for a large number of combinations of crossfall and superelevation, radius of curvature, rollover, longitudinal slope, pavement skid number, and relevant vehicle maneuvers (i.e., driving with and without brake action, turning, and changing lanes).

Figure 2 shows sample results in terms of water depth. In Figure 2 the longitudinal slope is assumed to be 0 percent. For reasons noted in the next section, results are almost identical even if a longitudinal slope is involved. Sample results obtained from the HVOSM applications shown in Figure 3 indicate estimates of driving speeds at impending skid. The sample results clearly show the need for adequate skid numbers and to avoid high rollover (R.O.) effects. Sample results presented in Figure 4 illustrate the influence of low skid numbers and brake action for 0 percent grade ($G = 0$ percent) and 3 percent grade.

Crossfalls for freeway pavements are presented in Table 4 for two pavement texture values and representative precipitation conditions. Also shown is the percent rollover that corresponds to crossfall and speed at impending skid for a pavement with a skid number of 40. As the footnote to Table 4 indicates, a skid number of 40 represents a marginal skid resistance. Logically, for increasing pavement width, the crossfall must be increased to limit the water depth to a specified level. As expected, higher rollover values result in decreasing speeds for safe skid-free driving. For higher rainfall intensities or a decrease in pavement texture, crossfalls must be increased to limit water depths to acceptable values, and as a consequence the increasing rollover will reduce speeds at impending skid. As shown in Table 4, an increase in *TXD* will result in effects that would be opposite those of a decrease in *TXD*.

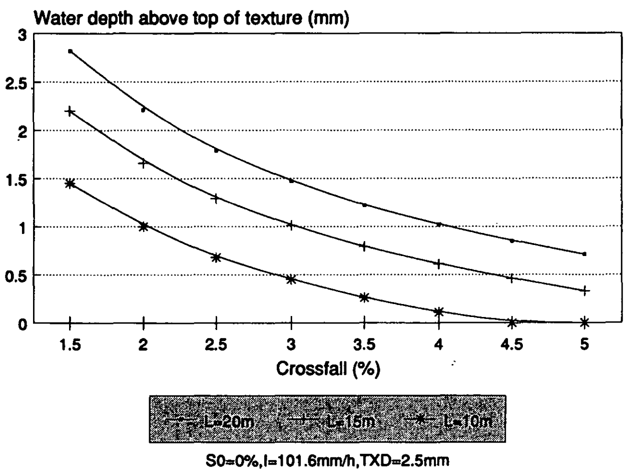

FIGURE 2 Water depth for S_2 equal to 0 percent.

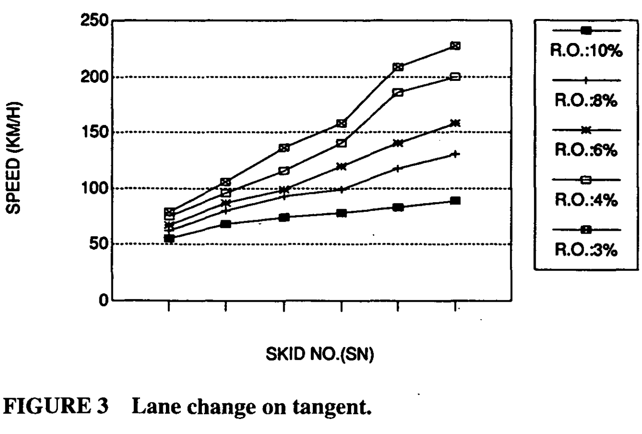

FIGURE 3 Lane change on tangent.

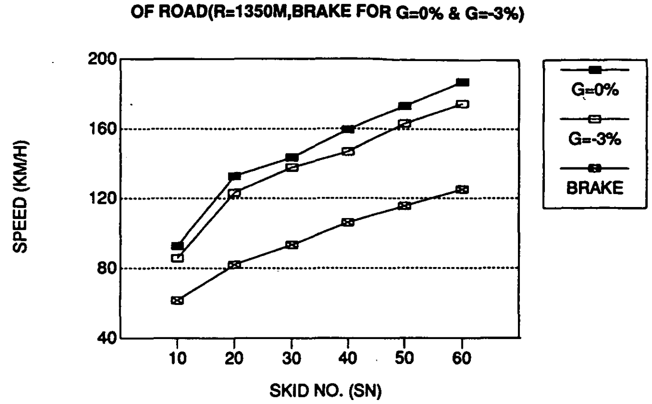

FIGURE 4 Driving on superelevated part of road (R = 1350 m, brake for G = 0 percent and G = −3 percent).

Analyses were carried out to estimate water depth and speed at impending skid for five lanes with a superelevation of 6 percent. The results shown in Table 5 indicate that without brake action the speed at impending skid is satisfactory, and even with brake action the skid-free operating speed is reasonably high.

CONCLUSIONS

Many conclusions were drawn from the results achieved in the present study (*14*). Because of space limitations only the highlights are presented here.

1. Studies of surface drainage and vehicle simulation indicate that drainage of the pavement (i.e., crossfall and superelevation as well as effective edge of pavement drainage) is a very important consideration in cross-section design. Also, the importance of reducing water thickness on pavement is stressed because it has a critical influence on the friction available at the tire-surface interface, and thus the safe operation of the vehicle.
2. Both pavement surface water depth and vehicle speed are considered critical elements for hydroplaning.
3. Better geometrics (e.g., higher radius of curvature, adherence to design superelevation rates, and use of spiral transition curves) and pavements of high-quality macrotexture and microtexture improve the safe skid-free driving speed.
4. A water layer of 1.0 to 1.5 mm can be regarded as acceptable from the vehicle operation perspective. However, design modifications are advisable for higher values. It will be necessary to have high pavement skid resistances, should the pavement be subjected to higher water depths.
5. Crossfall and pavement width are the two most important variables for reducing water depth. Although the longitudinal slope increases the length of the flow path, it also has the opposite effect on water depth because it enables faster drainage owing to an

TABLE 4 Crossfall for Freeway Pavements (I = 101.6 mm/hr)

Maximum No. of Lanes Draining in the Same Direction	Crossfall for Water Depth		Rollover & Speed at Impending Skid at SN=40[a]			
	1.5 mm (%)	1.00 mm (%)	Rollover (%)	Speed (Km/h)	Rollover (%)	Speed (Km/h)
Pavement TXD=2.5mm						
2 lanes	1.5	2.0	3	158	4.0	140
3 lanes	2.0	2.5	4	140	5.0	127
4 lanes	2.5	3.0	5	127	6.0	119
5 lanes	3.0	4.0	6	119	8.0	99
Pavement TXD=3.0mm						
2 lanes	1.0	1.5	2	175	3.0	158
3 lanes	1.5	2.0	3	158	4.0	140
4 lanes	2.0	2.5	4	140	5.0	127
5 lanes	2.5	3.0	5	127	6.0	119

Note: The range of skid numbers (SN) 35-45 is regarded "marginal". SN 35 is considered as the critical skid number.
[a] Without brake action.

TABLE 5 Evaluation of Superelevation Rate

6% Superelevation, Radius of Curvature 1350 m; Design Speed 160 km/h; 0% Longitudinal Grade

Water Depth for 5 Lanes Draining in the Same Direction	Speed At Impending Skid At SN=40	
	With Braking	Without Braking
Less than 1 mm	106 km/h	159 km/h

Note: I= 101.6 mm/h, TXD = 2.5 mm

increase in the slope of flow path. The net result of the presence of longitudinal slope is that there is only a small change (an increase) in water depth.

6. Crossfalls for freeway pavements, shown in Table 4 for representative precipitation and pavement texture conditions (e.g., 2.5 mm), suggest that values below 2 percent should be avoided for wide pavements. For a texture of 2.5 mm and a rainfall intensity of 101.6 mm/hr, up to five lanes with a crossfall of 3 percent can be drained in the same direction without exceeding a water depth of 1.5 mm. Increasing the crossfall to 4 percent would limit the water depth to 1 mm. The rollover and speed at impending skid at a skid number of 40 appear to be reasonable.

7. Wide pavements with long radii of curvature can be subjected to a high-thickness water layer unless they are designed with superelevations that match or exceed the tangent crossfall shown in Table 4. A 6 percent superelevation would be sufficient to keep the water layer at the edge of a 20-m roadway (five lanes plus a partially paved shoulder) to less than a 1-mm layer depth (Table 5).

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