Computational Analysis of Water Film Thickness During Rain Events for Assessing Hydroplaning Risk Part 1: Nearly Smooth Road Surfaces

Nuclear Science and Engineering Division

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1. Introduction

Before January 2, 1974, with 70 mph speed limits on many expressways outside of cities, hydroplaning was a factor in enough accidents to merit research and development of new federal guidelines to avoid or mitigate it. Both tire design and roadway drainage are important in hydroplaning risk. When the national 55 mph speed limit was put in place in 1974, hydroplaning accidents were greatly reduced, and the problem diminished in importance. Federal speed limits were eliminated on November 28, 1995. Since then states have been raising speed limits back to pre-1974 levels and higher. With the higher speed limits, hydroplaning accidents are once again a potentially significant problem. Highway infrastructure built in the years 1974 through 2015 was not, in general, designed and built to minimize hydroplaning hazards at current highway speeds.

Given the tight highway infrastructure budgets of recent years, the aging infrastructure, and likely ongoing budget constraints, existing problematic road conditions, where hydroplaning can be a hazard, may remain for a long time before they are fixed or replaced, and a better understanding of the factors that contribute to hydroplaning risk are needed to develop approaches to minimizing hydroplaning accidents. Hydroplaning occurs when a water film exists on the road or areas of road and vehicles are traveling at a speed that does not provide sufficient time for the tires to push the water film out of the tire path, allowing the tire to maintain contact with the road. Under these conditions, the tires ride up onto the water film, and driver control of the vehicle is lost. The water film thickness, therefore, is a key parameter in evaluating hydroplaning risk.

In the research work reported here, both two- and three-dimensional computational fluid dynamics (CFD) analysis was used to investigate modern road geometries that were not frequently encountered in the latter half of the 20th century but are much more common today. The relation of newer road geometries to the water film thickness that develops on travel lanes was a major focus of this work.

Highways with four or more lanes in each traffic direction are a primary example of new road geometries of interest in assessing hydroplaning risk. If the sides of the road with opposing traffic are separated by a median that allows for drainage, then each side of the highway may be crowned, requiring that rainwater drains across three lanes. If there is no median with drainage or the road goes through a banked curve, then drainage may be across six lanes or more. Figure 1-1 shows an example of this kind of road geometry. The road is a section of interstate 80 running through Omaha, Nebraska with 5 lanes per side, an emergency lane in the middle on each side and a wide paved shoulder. Figure 1-2 shows a center drain grate at the divider. Figure 1-4 illustrates another example, part of interstate I10 highway with a large number lanes in each direction, and Figure 1-3 shows a street view of I10 showing all lanes on the side in view sloped toward right with drain grate at road divider. These are just a few examples of the large number of very wide multilane highways that exist. Multilane roads create a large collection area for water during rain events in addition to a long drainage travel path to the side of the road. These two conditions contribute to an increased thickness of the water film that forms on these wide roads during rain events.

A significant number of modern intersections in urban and suburban areas have been designed with many lanes. These designs alleviate long backups in traffic at intersections during rush hour due to the number of cars waiting to make left and right turns. An example is shown in Figure 1-5.

There are two left turn lanes, three through lanes, and a right turn lane for each of the streets in both directions at this intersection. Currently all traffic gets through this intersection without having to wait through more than one cycle of traffic control light changes. There is no drainage at the concrete dividing median, and consequently on the sides with six turn and through lanes the road is sloped to drain water across all six lanes as shown in Figure 1-6 and Figure 1-7.

Figure 1-1: Example of Interstate highway with 5 lanes per side plus center emergency lane and wide paved shoulders on each side. Source: I80 Omaha, Nebraska, 41.222250N, -96.053220W Google Earth. Accessed: November 08, 2016

Figure 1-2: Street view of I80 Omaha with center divider and center drain grates visible in red oval. Source: I80 Omaha, Nebraska, 41.222250N, -96.053220W, Google Earth. Accessed: November 08, 2016

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Figure 1-6: 75th St. and Washington St. Naperville, IL, street level view showing six lanes on the westbound side (left) with cross slope that drains across six lanes to a curbed side with drains.

Figure 1-7: 75th St. and Washington St. Naperville, Illinois, showing drains at the side of the west bound lanes at the intersection. Source: 75th St. and Washington St. Naperville, Illinois. 41.748354N, -88.129782W, Google Earth. Accessed: November 08, 2016

2. Critical Film Thickness for Hydroplaning

Hydroplaning occurs when a rolling tire is separated from the road surface by a layer of liquid fluid [1] that leads to a loss of friction between the tire and the pavement. Hydroplaning depends on many factors, such as: water film thickness, geometry of the roadway (primarily the cross slope), and pavement roughness, as well as vehicle speed, tire tread depth, and tire inflation pressure. Over the years, multiple approaches were developed to predict the conditions necessary for hydroplaning to occur [2]. Example available relationships between the hydroplaning (critical) speed of a vehicle and tire pressure, water film depth, as well as other parameters, that can be found in literature are:

1. NASA hydroplaning equations [3], [4]
2. Hydroplaning model used in the PAVDRN computer program [5]
3. Texas DOT Hydraulic Design Manual [6] approach based on [1],
4. Florida DOT Roadway Design Drainage Manual [8], based on [2], [9].

2.1. NASA Equations

Tests performed by NASA used aircraft and automobile tires on a smooth concrete pavement. Two types of tires were tested: smooth and rib-tread tires. The average water depth in the tests was equal 7.6 mm (0.30 in) and it was assumed that it exceeded the tire tread depth. The relationship between the hydroplaning speed, v_p [km/h], and tire inflation pressure, p [kPa] was established as

$$v_p = 6.36\sqrt{p}. \quad (1)$$

Further experimental work led to a conclusion that the hydroplaning speed depends also on the dimensions of the portion of a vehicle's tire that is in contact with the road surface, i.e. tire footprint. The modified NASA equation accounting for this factor is

$$v_p = 83.35 - 27.59F_{AR} + 0.168p, \quad (2)$$

where F_{AR} is the tire footprint aspect ratio (ratio of the width of the footprint to its length).

2.2. PAVDRN Equations

PAVDRN is a computer model that determines the speed at which hydroplaning will be initiated on a highway pavement. The computations are based on equations that account for the roadway water film depth and the pavement texture, but do not consider the influence of tire inflation pressure. The underlying tests were performed at one pressure value of 165.5 kPa (24 psi) for smooth and ribbed tires.

For water film thickness, t , less than 2.4 mm, the hydroplaning speed [km/h] was predicted with the formula

$$v_p = 96.3t^{-0.259}, t < 2.4 \quad (3)$$

where t is the water film thickness given in millimeters.

For a water film thickness greater than or equal to 2.4 mm, the following formula was adopted

$$v_p = 4.94 \max\left(\frac{12.64}{t^{0.06}} + 3.507, \left(\frac{35.15}{t^{0.06}} - 7.817\right) (0.0393M_{TD})^{0.14}\right), t \geq 2.4 \quad (4)$$

where M_{TD} is the pavement macrotexture depth [mm].

2.3. Texas DOT Equations

The Texas DOT Hydraulic Design Manual recommends calculating the speed [km/h] at which hydroplaning occurs from the equation

$$v_p = S_D^{0.04} p^{0.3} (T_D + 1)^{0.06} \max \left(\frac{12.639}{t^{0.06}} + 3.507, \left(\frac{22.351}{t^{0.06}} - 4.97 \right) T_{XD}^{0.14} \right), \quad (5)$$

where $S_D = \frac{\omega_d - \omega_w}{\omega_d} 100\%$ is the spin down ratio (the spin down ratio is assumed to be equal to 10% at the initiation of hydroplaning), ω_d is the rotational velocity (rpm) of the tire on dry pavement, ω_w the rotational velocity of a wet tire at initiation of hydroplaning, T_D is the tire tread depth [mm] (the recommended minimum tire tread depth is 1.5 mm (2/32 in)), T_{XD} is the pavement texture depth (the same as M_{TD} , see section 2.2).

2.4. Florida DOT Equations

Florida DOT Roadway Design Drainage Manual recommends calculating the hydroplaning speed based a computational study by Ong and Fwa [9], [10], [11] for a standard smooth tire. The manual provides a relationship between the hydroplaning speed and tire pressure, p , as well as wheel load, W_L , as follows:

$$v_p = W_L^{0.2} p^{0.5} \left(\frac{0.82}{t^{0.06}} + 0.49 \right), \quad (6)$$

Figure 2-1 shows a comparison of the hydroplaning speed vs. water film thickness relationships according to two models: PAVDRN and TxDOT for a tire inflation pressure of 165.5 kPa (24 psi), a tire tread depth of 1.5 mm (2/32 in), and a spin down ratio of 10%. The influence of the pavement texture depth values was shown for the example of three values, TXD = 0.6 mm, 0.8 mm, and 1 mm. The equations were tested for water depth from 0.2 mm to 10 mm. The figure shows that the PAVDRN equation for hydroplaning speed with water film thickness less than 2.4 mm gives higher hydroplaning speed value than the TxDOT formula. At a film thickness 0.2 mm, the PAVDRN equation gives critical speed of 146 km/h (90.7 mph), and the TxDOT equation predicts speeds between 88.17 km/h (54.80 mph) and 95.86 km/h (59.56 mph). When the water film is thicker than 2.4 mm, both approaches give a similar result. At the highest considered water thickness, 10 mm, the calculated hydroplaning speed is approximately 71 km/h (44.12 mph). The curve based on the FDOT formula falls in between the TxDOT curves and gives similar hydroplaning speed values, when $WL=2.4$ kN.

The NASA, modified NASA, and TxDOT equations account for the influence of the tire inflation pressure on the hydroplaning speed. Figure 2-2 shows a comparison of those models for a range of pressure from 103 kPa (15 psi) to 248 kPa (36 psi) at water film thickness of 7.62 mm, as this value was used in experiments done by NASA. Also, it was assumed that the pavement texture depth was 0.8 mm; the tire tread depth was 1.5 mm; $FAR=1.36$; and the spin down ratio was 10%. The NASA equation gives a higher estimate of the critical speed compared to the other two models. The modified NASA equation is relatively close to the TxDOT prediction, which gives the lowest speeds, from 62 km/h (38.5 mph) at 103 kPa (14.9 psi) to 81 km/h (50 mph) at 248 kPa (36 psi). The FDOT formula, for $WL=2.4$ kN (0.54 Kip), gives a lower hydroplaning speed at low tire inflation pressure, and higher speed for higher pressures, than the modified NASA and TxDOT formulas. The prediction is lower than derived from the NASA equation in the considered range.

The formula used in the FDOT Drainage Manual accounts for the dependence of wheel load on hydroplaning speed. Three types of passenger car sizes were considered: compact, midsize, and large, with respective total weights: 13.3 kN (3.0 Kip), 15.6 kN (3.5 Kip), 19.5 kN (4.38 Kip). A comparison of the resulting hydroplaning speed curves, with water film thickness 7.62 mm, is shown in Figure 2-3.

Figure 2-1: Influence of water film thickness on hydroplaning speed according to PAVDRN, TxDOT, and FDOT equations; texture depths: 0.6 mm, 0.8 mm, 1 mm; tire inflation pressure 165.5 kPa (24 psi); tire tread depth 1.5mm; and spin down ratio 10% are shown.

Figure 2-2: Influence of tire inflation pressure on hydroplaning speed according to NASA, modified NASA, TxDOT, and FDOT equations. Water film thickness 7.62 mm; pavement texture depth 0.8 mm; tire tread depth 1.5 mm; $FAR=1.36$; spin down ratio 10%.

Figure 2-3: Influence of the wheel load on the hydroplaning speed according to FDOT equations at water film thickness 7.62 mm

3. Physics Modeling

The geometry of very wide roadways, i.e. multilane highways with 2, 4, and 6 or more lanes per side, is easy to model with CFD because the geometry is very simple, and in some cases even smaller, more manageable models can be built using symmetry conditions. The primary parameters are road width, cross slope, longitudinal slope, rainfall rate, and pavement surface roughness that would vary mainly due to pavement type, asphalt, or concrete. This Part 1 report focuses on nearly smooth road surfaces like concrete that can be modeled using a single region with CFD. The Part 2 report [14] focuses on the more challenging problem of modeling roughness when the roughness height exceeds computational cell thickness in the water film. Another significant geometry variation for multilane highways and roads with many lanes is whether or not the roadside is open so that water flowing down the cross slope can freely flow off the roadside or the road side is curbed with drain grates. Wide multilane roads with curbs may pose an additional risk in addition to hydroplaning. Due to the large cross street collection area under heavy rain conditions, wide roads with curbs may also have a significant water pooling hazard extending into the near curb lane. Cases with both curbs and obstructed roadsides were investigated in this study.

There are two primary ways that water may accumulate to form a hazardous pools on curbed roads: (1) Water has to drain down the road in the gutter of the curb to reach the grate locations, and therefore there is a greater possibility for accumulating at the roadside between grates than for uncurbed roads, (2) Grates are limited in their hydraulic capacity for drainage, especially ADA compliant grates. Finally, the hydraulic capacity of drain grates during heavy rains can be severely limited if there is any accumulation of debris at the grate. A basic set of cases for wide curbed roadways with curbs was investigated. Because these cases require meshing out an entire section of roadway between drain grates, with approximately 10 million computational cells or more, the number of these cases was limited.

The water film thickness varies over the cross-street slope from the high elevation (crown or center divider) to the low elevation of the roadside. Two parameters are of interest: (1) the maximum water film thickness and (2) the fraction of roadway where the water film thickness exceeds a specified value considered to be high risk for hydroplaning. Result analysis sought to identify functional relationships between these measures of water film thickness and the case parameters for a steady state condition where the rain is constant over some time.

Rain rates were adopted from the Precipitation Frequency Data Server (PFDS) [12] prepared by the National Weather Service Hydrometeorological Design Studies Center. The highest rainfall intensities in this data was for Louisiana, and therefore a set of characteristic values for this state were considered in the present study. Figure 3-1 shows the rainfall intensity vs. duration curves for 1, 10, 100, and 1000-year events. Figure 3-2 shows the rainfall intensity vs. duration curves for a 1000-year event. The values of interest are: a 1000-year event of 19.9 in/hr, with 5-minute duration; two 10-year events: 10.3 in/hr with 5-minute duration and 4.58 in/hr with duration of 30 minutes; and also a 1-year event, of 1.88 in/hr with duration of 60 minutes. In the study these values were rounded to the nearest whole number and rain intensities of 20, 10, 5, and 2 in/hr were used. Rain was assumed to be spatially and temporally uniform in the analysis. The rain period was assumed to be sufficient to establish a steady state runoff condition on the pavement.

Figure 3-1: Rainfall intensity vs. duration curves for 1, 10, 100 and 1000 year event in Louisiana. Source: [12]

Figure 3-2: Rainfall intensity vs. duration curves for a 1000 year event in Louisiana. Source: [12]

Three dimensional CFD analysis was carried out for varying road geometry configurations as detailed in the case tables below. The case tables include varying road widths, cross slopes, the presence or absence of curbs and drains, and rainfall rates.

Starting from two lanes in one direction and including four and six lane cases covers the majority of stretches of wide highways. Wide roads pose the biggest risk during high intensity rains. For lower values of cross grade and/or longitudinal grade water velocities are lower and thicker water films are expected as a result. The existence of a curb causes formation of a pool in the vicinity of the curb. The spread of the pool depends on curb height, the geometry of the road, and other factors such as drainage.

The cases for multilane highways without curbs include cross slopes from 1% to 4% and rain intensities from 2 in/hr to 10 in/hr. These cases along with major results are listed in Table 5-1. About half of these cases have cross slopes and rain intensities that are not even numbers because they were set up for comparison with the experiments of Gallaway et al. [13]. Some of these cases were run using water properties at 39 °F to check sensitivity to variation of water material properties as a function of temperature.

Very wide curbed roadsides with grate drainage are likely to have a water pooling hazard in addition to a hydroplaning hazard in heavy rains, because the curb prevents water from draining off the side of the road side, and rainwater entering the gutter must flow down the road to the nearest grate. This type of geometry is considerably more expensive to analyze than those for no curb because there is variation along the longitudinal direction of road and the domain must be lot bigger, extending, at least from midway between drains to midway over a drain, assuming symmetry boundaries at the two ends. Cases analyzed for this geometry and major results are listed in Table 5-2. A new parameter, the curb height, was included with case sets for both 4-inch

and 6-inch curbs. If water does fill up to the curb height, then the cross-street extent of the water pool next to the curb is determined geometrically by the cross slope, and the greatest width of the water pool occurs for the smallest cross slope. The risk of significant deep water in the pool extending out of the gutter depends on the hydraulic performance of the drains. Many urban and suburban areas now have wide roads with many lanes, as shown in Figure 1-6, to keep rush hour traffic moving, and the speed limits may be 40, 50, or more mph, which is in the range for hydroplaning.

An additional three simulations were done for wide roads with curbs but no drainage. With a longitudinal slope of zero and no drains, the flow conditions do not change along the road due to existence of drains, and this type of road can be represented with a simplified model of a thin strip of the road in the cross-street direction. Normally, proper drainage would be designed for roadways with curbs, so that water can drain off the surface. Nevertheless, cases of drainage inlets partially or fully blocked with debris are possible. The simulations considered in this part of the study account for the extreme situation when water can only spill over the curb. Table 5-3 lists the cases and major results for this part of the study.

Table 5-4 lists the cases and major results for curbed multilane highways and roads with longitudinal slope. The number of these cases was limited to eight because the analysis consumes a large amount of computational resources per case for the large 3-dimensional domain LES analysis. All cases used 6 inch curbs because that is the worst case for pooling spread, cross slopes included 1% and 2%, and longitudinal slopes were 2% and 4%. Rain intensities of 10 and 20 in/hr were used to analyze the hazards under heavy downpours.

4. CFD Modeling

To accurately simulate the free surface of water, the Eulerian Multiphase model combined with the Volume of Fluid (VOF) physics model was selected in the STAR-CCM+ CFD software. Cases without curbs are compared with the measurements of Gallaway et al. [13] and the Gallaway equation (13) for water film thickness. This comparison requires the inclusion of texture depth (surface roughness) even if it is very small. The k-epsilon turbulence model was used for cases without curbs in order to allow specification of a surface roughness height in the model. The Large Eddy Simulation (LES) turbulence model was used for all other cases. LES resolves large scale eddies and models small-scale turbulence. These models require many layers of cells in the vertical direction to adequately resolve velocity distribution across the fluid film boundary layer, and that requirement produces very large computational grids, especially when the cross street and longitudinal lengths of the domain are large, 48 ft for 4 lanes and a 150 ft to 300 ft length of street to include a catch basin drain. To reduce the large amount of computer resources required for these problems, symmetry conditions were used where possible to reduce the size of the computational grid.

Figure 4-1, Figure 4-2, and Figure 4-3 show sketches of the three types of roadways that were modeled along with sketches of the CFD domains used for computations. Figure 4-1 illustrates a model of a road without a curb, Figure 4-2 shows a model of a road with a curb and without

drainage in the roadway, and Figure 4-3 presents a model of a road with a curb and with drainage in the roadway.

Figure 4-1: Model of a road without a curb: (a) a sketch of a cross-section of a road, (b) a sketch of a CFD domain

Figure 4-2: Model of a road with a curb and without drainage in the roadway (a) a sketch of a cross-section of a road, (b) a sketch of a CFD domain

Figure 4-3: Model of a road with a curb and drainage in the roadway (a) a sketch of a cross-section of a road, (b) a sketch of a CFD domain

Figure 4-4: Top view of the CFD domain with dimensions for road with curb and drainage. Values of the main analysis parameters are shown. The blue arrows mark the inflow and outflow surfaces where the periodic boundary condition was used.

Assuming spatial and temporal uniformity of the rain on a very long road with constant longitudinal and cross-sectional slopes with uniform spacing of drains, a repetitive flow pattern forms between drains and the conditions become almost identical in each section of the road, except for the first and last section on a long slope. With these ideal conditions, an analysis of only one section may be done, as shown in Figure 4-4, using cyclic boundary conditions. With cyclic boundary conditions the velocity profile that develops at the exit boundary is fed back into the

domain as the inlet velocity distribution. The computations lead to fully developed flow conditions and are considered converged when the velocity profile in the interior ceases to change. In this model the volume of water entering from the upstream section of road plus the volume of rain added to the surface water film balance the volume of water leaving through the grate plus the water volume leaving at the downstream end of road section domain under steady state conditions. This condition means that the drain can handle the rain volume rate and that there is no net accumulation of water on the road.

Rainwater entering the system is modeled as a volumetric source term in the conservation of mass equation. This avoids the computationally expensive modeling of rain entering the water film from above using an additional dispersed phase multiphase model for the rain drops. Since the net effect of rain falling onto the water film is to increase the water mass flow where the rain droplets hit and join the film, modeling the addition of water mass from rain hitting the film using a mass source term in the differential equations saves a considerable amount of computer resources and run time.

5. Analysis Results and Discussion

5.1. Multilane Highways Without Curbs, Varying Cross Slope, No Longitudinal Slope, and Varying Rainfall Intensity

With no curb, the flow simply drains off the side of the road, and with no longitudinal slope, the flow path is from the crown or median to the road side with no variation along the length of the road. For these conditions, the problem becomes two dimensional in the vertical and cross street directions, and the domain was reduced to a thin strip of cross-section of a 4-lane road without a curb. Rain intensity was varied from 2 to 10 in/hr, and the cross slope was varied between 1% and 4%. The cases analyzed are listed in Table 5-1. The domain size was 0.01 m high by 0.01 m wide by 14.63 m long (48 ft), which corresponds to the width of a four-lane highway). The length in these cases corresponds to the cross-street direction. The domain was discretized with a hexahedral mesh with cell size of 6.7 mm (along the strip) by 5.0 mm (in the width direction). In vertical direction the prism layer mesher was used with the near boundary layer thickness equal to 0.3 mm which yields 50 vertical layers and a total of ~135,000 volume cells. A simulated time of one hundred seconds required 40 minutes of clock time to compute on 128 cores.

The accumulated rain running off toward the side of the road at a distance L_p from the crown where the flow rate is zero is:

$$\dot{m} = \rho R_l L_p L_n \quad (7)$$

where $\dot{m}$ is the mass flow rate of water in kg/s, ρ is water density in kg/m³, R_l is the rain intensity in m/s, and L_n is the distance normal to the flow with a patch area of $L_p L_n$ collecting rain.

Some additional relations characterizing the water film as it builds up and flows down the cross slope can be derived because the flow for these simplified cases is two dimensional with no variation in the direction along the road. Conservation of the mass of water flowing across a slice

normal to the flow direction requires that the water film thickness is related to the water mass flow rate, length along the flow path, and the velocity as follows:

$$\dot{m} = \rho v_w L_n f_w \quad \text{or} \quad f_w = \frac{\dot{m}}{\rho v_w L_n} \quad (8)$$

where f_w is the water film thickness, and v_w is the depth average water velocity. Water coming into the water film as rain increases water mass flow, $\dot{m}$, and therefore acts to increase the water film thickness. In opposition to this effect, acceleration of water in the film due to gravity, as it flows down the cross-street slope, increases the velocity, v_w , and therefore decreases the film thickness. Therefore, increasing the cross slope with the same road area collecting rain acts to lower water film thickness as gravity acts to increase film velocity on steeper slopes, as shown in Figure 5-1.

A simple relation for the depth average velocity, v_w , at distance L_p along the flow path can be obtained by substituting equation (7) into equation (8) and rearranging:

$$v_w = \frac{R_l L_p}{f_w} \quad (9)$$

From these relations, the Froude and Reynolds numbers can also be defined in terms of rain intensity, water film thickness, and distance along the flow path parameters:

$$F_r = \frac{v_w}{\sqrt{g f_w}} = \frac{R_l L_p}{f_w^{1.5} \sqrt{g}} \quad (10)$$

The hydraulic diameter, d_h , is defined by:

$$d_h = \frac{4A}{W_p} = \frac{4f_w L_n}{L_n} = 4f_w \quad (11)$$

where A is the cross-section area of the flow and W_p is the wetted perimeter. The Reynolds number is:

$$R_e = \frac{\rho v_w d_h}{\mu} = \frac{4\rho R_l L_p}{\mu} \quad (12)$$

The water velocity and hydraulic diameter are inversely and directly proportional to the water film thickness respectively, and as a consequence, the Reynolds number is independent of the film thickness and is a function of the rain intensity and length along the path only. It is not a function of cross slope because an increased velocity due to increased slope is compensated for by a decrease in hydraulic diameter.

Figure 5-1 shows water film thickness plots across the roadway at cross slopes of 1%, 2%, and 4% at a rain intensity of 5 in/hr. The position equal to zero meters corresponds to the location of the highest point on the roadway at the crown or median and the position 14.64 m (48 feet, 4 lanes) is the lowest position where the shoulder begins. Lane boundaries are marked by gridlines at 12, 24, and 36 ft. The highest water level, 2.9 mm, was obtained for the lowest cross slope of 1%. As

previously noted, larger cross slopes increase velocity in the water film, and consequently, its thickness decreases. At 4% cross slope, all 4 lanes have a water film thickness less than 2 mm. At 2% cross slope, only lane 4 next to the roadside has a water file thickness greater than 2 mm, and at 1% cross slope, the 2 lanes next to the roadside have water film thickness greater than 2 mm.

Figure 5-1: Water film thickness across the roadway without a curb at cross slopes 1%, 2%, and 4% and rainfall intensity rate 5 in/hr.

Figure 5-2: Depth average velocity and Froude number across the roadway without a curb at cross slopes 1%, 2%, and 4% at a rainfall intensity of 5 in/hr.

Figure 5-3 illustrates the influence of the rainfall intensity on the film thickness on a roadway with cross slope 2%. The water film thickness increases with rain intensity at constant cross slope. The maximum water film thickness over 4 lanes reaches 1.39 mm at 2 in/hr, 1.8 mm at 5 in/hr, and 2.36 mm at 10 in/hr. At 2 in/hr, all 4 lanes have a water film thickness less than 2 mm, at 5 in/hr, only the right lane has as water film exceeding 2 mm, and at 10 in/hr, the rightmost 2 lanes have a water film exceeding 2 mm.

Figure 5-3: Water film thickness across the roadway without a curb at cross slope 2% and rainfall intensity rates 2 in/hr, 5 in/hr, and 10 in/hr.

Figure 5-4: Depth average velocity and Froude number across the roadway without a curb at cross slope 2% and rainfall intensity rates 2 in/hr, 5 in/hr, and 10 in/hr

The Reynolds number of the water flow in the film is plotted in Figure 5-5. As previously noted from equation (12), it is independent of the cross slope, depending only on the rain intensity and linearly on the position from the crown. The Reynolds number exceeds 2000 indicating a fully turbulent flow only for the 2 rightmost lanes in the 10 in/hr case and the rightmost lane of the 5 in/hr case. For Reynolds numbers between about 500 and 2000, the flow is likely in transition, and in the k-epsilon turbulence model, the molecular and eddy viscosity are of the same order of magnitude under these conditions. Consequently, the water molecular viscosity may influence the results. Both the density and viscosity of the water are functions of temperature. The viscosity varies the most. The viscosity of water is 8.91×10^{-4} Pa-s at 25 °C (77 °F) and increases by 76% to 1.57×10^{-3} Pa-s at 4 °C (39 °F).

The CFD results from the two-dimensional geometry, can be compared with those of Gallaway et al. [13] for the smoothest surface in the experiments with mean texture depth of 0.076 mm.

Figure 5-5: Reynolds number across the roadway without a curb at cross slope any cross slope and rainfall intensity rates 2 in/hr, 5 in/hr, and 10 in/hr.

Surfaces with larger texture depths have a roughness that is too big to represent in the grid. A new method for modeling water film flow over rougher surfaces is presented and compared with experimental results in Part 2 of the technical report [14]. Gallaway et al. measured water film thickness for a variety of surfaces and then correlated the thickness with texture depth, path length, rain intensity, and cross slope in the following equation:

$$f_w = 0.00338 T_{XD}^{0.11} L_p^{0.43} R_I^{0.59} S_x^{(-0.42)} - T_{XD} \quad (13)$$

where T_{XD} is the average texture depth in inches, L_p is the drainage path length in feet, R_I is the rain intensity in inches per hour, and S_x is the cross slope. In metric units the equation is:

$$f_w = 0.1097 T_{XD}^{0.11} L_p^{0.43} R_I^{0.59} S_x^{(-0.42)} - T_{XD} \quad (14)$$

where T_{XD} is the average texture depth in meters, L_p is the drainage path length in meters, R_I is the rain intensity in meters per hour, and S_x is the cross slope.

Cases 1.6 through 1.12 in Table 5-1 were set up with the conditions of Gallaway's measured cases for the surface with 0.076 mm texture depth. The cross slopes are slightly more than 1%, 2%, and 4%, and the cases were set up to match the cross slope to 3 digits. The rain intensity is about 5 in/hr, but it varies slightly above and below that value and the given rain intensity accurate to 3 digits was used in the CFD simulations. The Gallaway et al. report [13] does not give the temperature at which the measurements were taken, and therefore CFD cases were run with water temperatures of 25 °C (77 °F) and 4 °C (39 °F) to cover a range of water material properties ranging from a probable standard temperature to a colder temperature with the highest water viscosity.

The results of these simulations are shown in Figure 5-6 giving water film thickness across four lanes. Solid lines are CFD results at 77 °F, long dashed lines are CFD results at 39 °F, and short dashed lines are calculated from the Gallaway equation (17). Experimental measurements are plotted with square markers. The color indicates the cross slope. The Gallaway et al. data stops at

24 feet because the measurements were taken across a maximum of 2 lanes. The depth measurements were done using a point gage with a vernier scale that provided direct reading to 0.2 mm (0.008 inch).

The CFD was also run for a perfectly smooth surface for the 2% cross slope case plotted with the dotted line. For that case, the water film is slightly less than but nearly the same as for a roughness of 0.15 mm indicating that including the roughness for these cases is a very minor effect. The increase in water film thickness resulting from more viscous water at 39 °F as opposed to 77 °F is clearly apparent in the figure and is about a 7% increase at 1% cross slope, a 9% increase at 2% cross slope, and an 11% increase at 4% cross slope. The CFD results slightly under predict Gallaway's measurements at 1% and 4% cross slopes, and they are very close, within the viscosity uncertainty, at the 2% cross slope. The Gallaway equation overpredicts the measurements at 1% and 2% cross slope except for the first point at 6 feet, and it is very close at 4% cross slope.

Power functions fits of the form $f_w = A L_p^n$ were fitted to the 77 °F CFD results and yielded values of exponent n ranging from 0.44 at 1% cross slope to 0.50 at 4% cross slope, very close to the Gallaway equation value of 0.43. This relationship indicates that doubling the number of lanes increases the water film thickness by at most a factor of about 1.4 over the additional lanes. For example, at 2% cross slope and 5 in/hr rain intensity, the water film is about 1.5 mm thick after draining across 2 lanes and grows to about $1.5 \times 1.4 = 2.1$ mm after draining across 4 lanes.

Figure 5-6: Water film thickness across the roadway without a curb at cross slopes 1%, 2%, and 4% and rainfall intensity rate approximately 5 in/hr showing comparison with the Gallaway equation and experimental results for a near smooth texture depth of 0.076 mm.

CFD solution results for the no curb and no longitudinal slope cases are summarized in Table 5-1 showing the maximum water film thickness, the spread of a 2 mm and greater water film thickness, the position from the crown where the Froude number transitions from less than one to greater than one, and the position where the Reynolds number transitions from less than 2000 to greater than 2000. The flow path is across four lanes that are twelve feet in width. At a rain intensity of 2 in/hr at 2% cross slope, the water film thickness is less than 2 mm across all four lanes and likely does not cause a significant hydroplaning hazard on the 4 lane per side road. At a rainfall intensity of 5 in/hr at 2% cross slope, the water film is less than 2 mm for all but the right half of the right lane next to the shoulder. This condition has some hydroplaning hazard in the rightmost lane out of four lanes traveling in the same direction. As long as slower traffic is traveling in the rightmost lane, the hydroplaning hazard appears to be small. At a rain intensity 10 in/hr on a 4% cross slope the water film is less than 2 mm thick for all but the rightmost lane out of 4, similar to the case with 5 in/hr at 2% cross slope. The hydroplaning hazard appears to be more significant for the cases with rain intensity of 10 in/hr with 1% and 2% cross slopes where a water film with thickness greater than 2 mm extends across the three and two right most lanes, respectively. One impact of wider roads with respect to the hydroplaning risk is that the hazard may be present in the rightmost lanes of multiple-lane wide roads while it is less significant on roads with one or two lanes in each direction.

Note that the Reynolds number remains less than 2000, and therefore probably laminar, over nearly all four lanes for rain intensity less than 10 in/hr. At rain intensity of 10 in/hr, the Reynolds number of the film is greater than 2000, and therefore likely turbulent, over the right two lanes out of four.

Table 5-1: Cases for Four Lane per Side Highways Without Curbs and Zero Longitudinal Slope

Case	Cross Slope [%]	Rain Intensity [in/hr]	Water Temp [°F]	WFT ≥ 2 mm spread [ft]	max WTF [mm]	Fr = 1 Position from Crown [ft]	Re = 2000 Position From Crown [ft]
1.1	1	5	77	25.2	2.92	46.2	41.4
1.2	2	2	77	0	1.40	37.0	>48
1.3	2	5	77	7.3	2.20	12.2	41.4
1.4	2	10	77	28.0	2.74	8.2	20.7
1.5	4	5	77	0	1.69	4.7	41.4
1.6	1.04	5.34	77	26.1	2.92	46.2	38.8
1.7	1.04	5.34	39	30.5	3.11	46.8	>48
1.8	2.08	4.73	77	5.3	2.14	9.9	43.8
1.9	2.08	4.73	39	14.1	2.39	19.1	>48
1.10	4.17	4.93	77	0	1.79	2.1	42.0
1.11	4.17	4.93	39	0	1.76	7.4	>48
1.12	2.08	4.73	39	13.10	2.34	18.4	>48

5.2. Multilane Highways with Curbs, Varying Cross Slope, No Longitudinal Slope, and Varying Rainfall Intensity

5.2.1. Drainage Through a Grate

An analysis of the influence of drainage on the water film thickness on roads with no longitudinal slope was performed on a set of cases listed in Table 5-2. The simulations were done with the use of a model representing half of the geometry of a roadway shown in Figure 4-4. The dimensions of the model were: 48 ft in width (covering 4 travel lanes) and 165 ft in length. The volume mesh, created with the use of directed meshing, resulted in 3 million grid cells. The near wall thickness of the prism layer was equal 0.2 mm. Large eddy simulation computations with no wall functions were performed using the free surface volume of fluid (VOF) model. Cyclic boundary conditions on upstream and downstream end surfaces were used.

Table 5-2 presents spread of water film thickness equal or greater than 2 mm and maximum water film thickness for the cases of multilane highways with curbs and drainage, varying cross slope, no longitudinal slope and varying rainfall intensity. Figure 5-7 shows the details of the computational mesh in a (a) side view of the road and curb and a (b) top view of the drain opening and curb.

Table 5-2: Cases for Multilane Highways with Curbs and Drainage and Zero Longitudinal Slope

Case	Curb height [in]	Lanes	Cross slope [%]	Rain intensity [in/hr]	WFT $\geq$ 2mm spread [ft]	WFT @ pool spread [mm] / spread [ft]	max WTF [mm]
2.1	4	2	1	20	24.0	3.5 / 24.0	77.0
2.2	4	2	2	20	16.1	2.7 / 13.0	83.0
2.3	4	2	4	20	11.7	2.7 / 7.0	91.0
2.4	4	4	1	2	3.5	- / -	34.8
2.5	4	4	1	5	38.3	2.5 / 16.6	51.8
2.6	4	4	1	10	27.6	3.0 / 24	76.0
2.7	4	4	1	20	11.0	3.7 / 30.8	100.0
2.8	4	4	2	2	38.0	1.4 / 7.2	43.7
2.9	4	4	2	5	30.0	1.8 / 10	61.3
2.10	4	4	2	10	10.0	2.8 / 13	82.7
2.11	4	4	2	20	7.0	3.7 / 14.4	100.6
2.12	4	4	4	2	34.3	~1.1 / ~5	54.0
2.13	4	4	4	5	9.4	~2.5 / ~6.8	78.5
2.14	4	4	4	10	7.0	~3.2 / ~7.4	94.0
2.15	4	4	4	20	4.4	~3.5 / ~8.4	97.3

Case	Curb height [in]	Lanes	Cross slope [%]	Rain intensity [in/hr]	WFT $\geq$ 2mm spread [ft]	WFT @ pool spread [mm] / spread [ft]	max WTF [mm]
2.16	4	6	1	2	44.0	2.3 / 14	43.6
2.17	4	6	1	5	39.0	3.1 / 20.6	66.0
2.18	4	6	1	10	28.1	4.0 / 29.9	94.5
2.19	4	6	1	20	5.3	4.6 / 46.1	145.5

(a)

(b)

Figure 5-7: Details of the computational mesh, (a) side view of the road and curb, (b) top view of the drain and curb

An initial analysis showed that using only a half of the full domain has a negligible influence on the results, but significantly decreases the computational time. Figure 5-8 shows a comparison of the water surface for a full domain and half of the domain for a case of a roadway with drainage, with no longitudinal slope, 2% cross slope, and a 4-inch high curb at rain intensity 10 inch/hr, (a) a half model, (b) a full model. Even though some differences in the water surface are noticeable, the chief features, such as the average water film thickness and the spread are in good agreement and therefore a half model was used in the subsequent simulations. The upstream and downstream boundaries are set to be symmetric. Figure 5-9 shows the average water surface in the upstream area for both models, as well as the result from a road strip model without drainage, described in chapter 5.2.2. The pool spreads almost over the whole width of the right lane, 10.2 ft,

in the models with drainage. When the drainage is not included in the model, the spread extends to the second lane, and its width reaches 16 ft.

Figure 5-8: Comparison of water surface on a roadway with drainage, with no longitudinal slope, 2% cross slope and a 4-inch high curb at rain intensity 10 inch/hr, (a) symmetry model, (b) full model. Length of computational domain in feet.

Figure 5-9: Comparison of the average film thickness in 2D model, 3D models of a roadway with drainage: half model and full model. No longitudinal slope, 2% cross slope and a 4-inch high curb at rain intensity 10 inch/hr.

Figure 5-10 shows the water surface with a contour plot of the vertical position (Position [Z]) for this case: (a) with a full range of values, and (b) when the values are cut off at 5 mm, to show the spread of the pool next to the curb. The plot in Figure 5-11 presents the water level across the roadway plotted along several lines upstream of the drain. An average curve is marked with a black dashed line.

Figure 5-10: Water surface on a 4-lane roadway with no longitudinal slope, 2% cross slope, 4-inch high curb and a drain; rainfall intensity 10 in/hr; (a) a full range of values is shown, (b) the values are cut off at 5 mm to show the spread of the pool next to the curb. Length of computational domain in feet.

Figure 5-11: Water level across the roadway plotted along several lines (location of lines shown in inset) upstream of the drain (a). Average curve is marked with a black dashed line. Plot in (b) shows zoomed section of plot (a) excluding the water pool near curb. Four-lane roadway with no longitudinal slope, 4% cross slope, 4-inch high curb and a drain. Rainfall intensity 10 in/hr.

Water film formation on two lane highways with a curb was modeled for a case of 20 in/hr rainfall intensity. Three cross-slopes were considered: 1, 2, and 4%. Figure 5-12 presents the average depth of water on the roadway surface. The pooling effect plays a significant role for this rainfall rate and geometry of the road. At 4% cross-slope more than a half of the rightmost lane is flooded, at 2% the spread reaches across the entire lane width, and at 1% the whole road is flooded fairly quickly, see the discussion on pool development rate below.

(a)

(b)

Figure 5-12: Average water level across the roadway upstream of the drain in plot (a). Plot in (b) shows zoomed section of plot (a) excluding the water pool. Two lane per side roadway with no longitudinal slope, 1%, 2% and 4% cross slope, Sx, 4-inch high curb and a drain. Rainfall intensity 20 in/hr.

The next set of figures show a comparison of the results for 4-lane roadways with 4-inch curb, varying cross-slope and rain intensities of 2, 5, and 10 in/hr. The water surface on a roadway with a curb and drainage, no longitudinal slope, and cross-slopes 1%, 2%, and 4% are shown in Figure 5-13, Figure 5-14, and Figure 5-15 respectively. Figure 5-16, Figure 5-17 and Figure 5-18 show plots of the average water level across the roadway upstream of the drain for cross-slopes 1%, 2%, and 4% respectively.

Figure 5-13: Water surface on a 4 lane roadway with a curb and drainage, with 1% cross slope, no longitudinal slope, and at rain intensity (a) 2 in/hr, (b) 5 in/hr, (c) 10 in/hr, and (d) 20 in/hr (curb overflow). The length scale of the computational domain is in feet.

Figure 5-14: Water surface on a 4 lane roadway with a curb and drainage, 2% cross slope, no longitudinal slope, and at rain intensity (a) 2 in/hr, (b) 5 in/hr, (c) 10 in/hr, and (d) 20 in/hr (curb overflow). The length scale of the computational domain is in feet.

Figure 5-15: Water surface on a 4 lane roadway with a curb and drainage, with 4% cross slope, no longitudinal slope, and at rain intensity (a) 2 in/hr, (b) 5 in/hr, (c) 10 in/hr, and (d) 20 in/hr (curb overflow). The length scale of the computational domain is in feet.

(a)

(b)

Figure 5-16: Average water level across the roadway upstream of the drain in plot (a). Plot in (b) shows zoomed section of plot (a) excluding the water pool. Four-lane roadway with no longitudinal slope, 1% cross slope, 4-inch high curb and a drain. Rainfall intensity equals 2, 5, 10, and 20 in/hr.

Figure 5-17: Average water level across the roadway upstream of the drain in plot (a). Plot in (b) shows zoomed section of plot (a) excluding the water pool. Four-lane roadway with no longitudinal slope, 2% cross slope, 4-inch high curb and a drain. Rainfall intensity equals 2, 5, 10, and 20 in/hr

Figure 5-18: Average water level across the roadway upstream of the drain in plot (a). Plot in (b) shows zoomed section of plot (a) excluding the water pool. Four-lane roadway with no longitudinal slope, 4% cross slope, 4-inch high curb and a drain. Rainfall intensity equals 2, 5, 10, and 20 in/hr.

The spread of the water pooling next to the curb depends on geometry and flow conditions. Figure 5-19 combines results for three rainfall intensity values, 2, 5, and 10 in/hr obtained from the CFD models with an open drain and for the model without drainage at 10 in/hr for roads with different cross-slopes: 1, 2, 4%. Equilibrium values of the spread are plotted. The rate of development of the spread, up to a width of two lanes, is shown in Figure 5-20 for cross-slope (a) 1% and (b) 4% at a rainfall intensity of 10 in/hr. Ten inch per hour was chosen to illustrate how quickly hazardous conditions can arise in a sudden downpour. The two curves on the plots represent the worst and the best-case scenario: when there is no drainage on the road, and when the drain is a fully open hole with no grate, and therefore these cases set an upper and lower bound for the possible flooding development time from the start of a downpour. These plots show that hazardous pooling can occur within a very short time, 5 minutes in some cases. The average water level across the

roadway on a six lane roadway with no longitudinal slope, 1% cross slope, 4-inch high curb and a drain at rainfall intensity 2, 5, 10, and 20 in/hr is plotted in Figure 5-21.

Figure 5-19: Flow spread vs. cross-slope at rain intensity 2, 5, and 10 in/hr

Figure 5-20: The development of the pooling spread in time for a case without drainage (debris clogged) and an open drain at 10 in/hr, (a) 1% cross-slope, (b) 4% cross-slope

Figure 5-21: Average water level across a 6 lane roadway plotted upstream of the drain in plot (a). Plot in (b) shows zoomed section of plot (a) excluding the water pool. The roadway has no longitudinal slope, 1% cross slope, 4-inch high curb, and a drain. Rainfall intensity of 2, 5, 10, and 20 in/hr

5.2.2. No Drainage

The test case matrix for the study of roads with curbs and no drainage is given in Table 5-3. The curb height is 4 inches. The number of lanes is four, the cross slopes were 1%, 2%, and 4%. The rainfall intensity was 10 in/hr.

An example computational domain with volume mesh used to simulate the water flow is shown in Figure 5-22. The domain geometry represents a volume of air above a strip of a roadway taken across its width with a curb and additional volume above the curb to model the runoff. A symmetry boundary condition was used on the sides of the domain. The roadway and curb surfaces were modeled as wall boundary conditions. The surface above the

curb was assigned a pressure boundary condition with pressure equal to the atmospheric pressure.

Table 5-3: Cases for Four Lane per Side Highways with Curbs, No Drainage, and Zero Longitudinal Slope

Case	Curb height [in]	Lanes	Cross slope [%]	Rain intensity [in/hr]	WFT ≥ 2 mm spread [ft]	WFT @ pool spread [mm] / spread [ft]	max WTF [mm]
3.1	4	4	1	10	39.0	2.2 / 35.3	104
3.2	4	4	2	10	27.2	2.3 / 17.3	107
3.3	4	4	4	10	7.8	2.0 / 7.4	108

Figure 5-22: Side view of the model of a roadway with a curb with details of the domain ends. The computational mesh is also shown.

Figure 5-23 shows the water film thickness across a roadway with a 4-inch high curb at cross slopes 1%, 2%, and 4%. No longitudinal slope of the road is considered. The curves are composed of two distinctive parts. Close to the median (left side), the water level is very low, the film thickness reaches only up to about 2 mm, still thick enough for hydroplaning. The flow has the same characteristics as on a road without a curb when full runoff is possible. Figure 5-23 (b) shows a comparison between the results from simulations of the flow on a road with and without a curb. The water film thickness for those two cases is very similar with the curves overlapping upslope of the pool next to the curb.

Figure 5-23: Water film thickness across a 4-lane roadway with a 4-inch high curb at cross slopes 1%, 2%, and 4% (a) full range, (b) cropped range of values on the vertical axis. Figure (b) shows results for a case with and without curb. Rain intensity 10 in/hr.

The spread of the pool close to the curb, T , increases with water depth at the curb during a rain event and it depends on the road geometry: the cross slope, S_x , and the curb height, H . The spread can be established from simple trigonometric considerations, $T = \frac{H}{S_x}$. Figure 5-24 shows a cross-section of the roadway with a water pool reaching the curb height.

Figure 5-24: Roadway cross-section with a water pool reaching the curb height

Figure 5-25: Flow spread, T , width vs. cross slope, S_x

For a 0.1 m (4 inch) high curb, the pool spread is equal to: 10 m (33 ft) at 1% slope, 5 m (16.5 ft) at 2% slope, and 2.5 m (8.3 ft) at 4% slope. The CFD computations give: 33.8 ft, 16.5 ft, and 8.2 ft, respectively. Figure 5-25 shows the relationship between the flow spread and cross slope for the considered cases as well as data points calculated from the aforementioned formula.

The change in the spread, T , in time during a rain event can be calculated from the volume of water that accumulates on the roadway in time and the geometry, with the water height being limited by the curb height, H .

$$\frac{1}{2} T H L = R_I W t L, \quad (15)$$

$$S_x = \frac{H}{T}, \quad (16)$$

$$T = \sqrt{\frac{2 R_I W t}{S_x}}, \quad (17)$$

where R_I is rainfall intensity, W is road width, L is a unit length of the road, t is time. For example, during a 5-minute rain event with rainfall intensity 2 in/hr, the spread will reach up to about half of the right lane width. The progress of the right lane flooding in time can be seen in Figure 5-26, and the change of the pool spread in time in Figure 5-27.

Figure 5-26: The progress of the right lane (36 to 48 ft) flooding in time

Figure 5-27: Change of the pool spread in time

Rapid pooling of water in the right lane can create hazardous conditions during a rain event. The time needed to flood the right lane, depends on the rain intensity, cross-slope, and number of lanes. It was calculated from the above formulas. The results were combined in column plots, for 2 in/hr in Figure 5-28, for 5 in/hr in Figure 5-29, for 10 in/hr in Figure 5-30. The time strongly depends on the accumulation area, e.g. on a 6-lane road with a 2% cross-slope, it takes only 2.9 minutes to flood the right lane during a 5 in/hr rain event, while it takes 17.3 minutes on a road with only one lane per side.

Figure 5-28: Right lane pooling time for various road widths and cross-slopes at rain intensity 2 in/hr

Figure 5-29: Right lane pooling time for various road widths and cross-slopes at rain intensity 5 in/hr

Figure 5-30: Right lane pooling time for various road widths, from 1 to 6 lanes, and varying cross-slopes at rainfall intensity 10 in/hr

5.3. Multilane Highways with Curbs. Varying Cross Slope, Longitudinal Slope, and Rainfall Intensity

In the next set of simulations, flow on roadways with cross and longitudinal slopes, a curb and fully open drainage grate was computed. High rainfall intensity rates were used in this part of the study, 10 in/hr and 20 in/hr to identify conditions resulting from more extreme rain intensities. Table 5-4 combines the case parameter values. These are the most computationally intensive runs for several reasons. Adding the longitudinal slope requires using a domain that represents a full section of the roadway, not only half of it, as in the simulations described in Chapter 5.2.1. Also, it is a challenge to obtain a fully developed flow pattern. For higher longitudinal slopes and rain intensities, there are surface waves that develop in the sheet flow, whose direction depends on the resultant slope of the roadway surface. As the flow velocity in the water film is significantly lower than in the flooded area next to the curb, it takes less time to obtain a reasonably good solution for the pool spread and average water film thickness distribution, than for the pattern of the waves. For this reason, only a few cases were run until full convergence.

Figure 5-31 presents a comparison of the average water level height across the roadway in a case of a road with 4% longitudinal and 2% cross slope at rain intensity 10 in/hr, (a) without a curb, (b) with a curb and drain. The sheet flow in both cases has similar characteristics: there are ripples forming in the direction along the road, due to the longitudinal grade, and the mean water film thickness is about the same. The influence of the curb can be seen in the form of a pool or flooded zone close to the curb that spreads out over the rightmost lane.

Figure 5-31: Water level height across the roadway for a road with and without a curb, cross slopes (a) 1% and (b) 2%, and longitudinal slope 4%, at rain intensity 10in/hr.

Table 5-4 has results for cases of four lane per side highways with curbs, drainage, and varying longitudinal slope. The results summarized in Table 5-4 show that for the high rain intensities of 10 and 20 in/hr when water is draining across four lanes, the conditions are hazardous with a water film thickness greater than 2 mm across the right three lanes. The left most lane is partially covered with a water film greater than 2 mm thick except for the two cases with a 2% cross slope and rain intensity of 10 in/hr. Further, the most of rightmost lane and in cases with 1% cross slope most of the rightmost two lanes are covered with the spread of deeper water that has accumulated from the curb.

Table 5-4: Cases for Four Lane per Side Highways with Curbs, Drainage, and Varying Longitudinal Slope

Case	Curb height [in]	Lanes	Cross slope [%]	Longitudinal slope [%]	Rain intensity [in/hr]	WFT ≥ 2mm spread [ft]	WFT @ pool spread [mm] / spread [ft]	max WFT [mm]
4.1	6	4	1	2	10	41.5	~4.5 / ~17.0	32.9
4.2	6	4	1	2	20	44.0	~5.0 / ~22.0	70.0
4.3	6	4	1	4	10	38.0	~5.0 / ~11.5	42.8
4.4	6	4	1	4	20	45.0	~6.0 / ~21.0	75.7
4.5	6	4	2	2	10	34.0	~3.3 / ~7.8	48.1
4.6	6	4	2	2	20	41.0	~4.0 / ~15.0	90.0
4.7	6	4	2	4	10	32.0	~3.5 / 7.0	44.7
4.8	6	4	2	4	20	41.0	~5.0 / 9.0	68.9

Figures from Figure 5-32 to Figure 5-35 show results for the last set of models from the test case matrix presented in Table 5-4. They combine contour plots of water surface height and plots of the water level on a plane across the roadway 100 ft upstream of the drain (as shown in Figure 5-11) on four-lane roadways with 1% and 2% cross slope, 2% and 4% longitudinal slope, 6-inch high curb and a drain at rainfall intensity 10 and 20 in/hr. The plots show the full water surface distribution across the roadway, with a noticeable pool covering the right most lanes. The spread of the pool depends on the resultant slope of the road surface and rain intensity. It decreases for higher slopes and increases for higher rain intensities. A close-up view of the plots is shown in the (b) part of the figures, which makes it possible to observe the water film thickness on the cross-planes and an average plot (in black). Results summarized in Table 5-4 show that for the high rain intensities of 10 and 20 in/hr when water is draining across four lanes, the conditions are hazardous with a water film thickness greater than 2 mm across the right three lanes. The left most lane is partially covered with a water film greater than 2 mm thick except for the two cases with a 2% cross slope and rain intensity of 10 in/hr. Further, the most of rightmost lane and in cases with 1% cross slope most of the rightmost two lanes are covered with the spread of deeper water that has accumulated from the curb.

Figure 5-32: Contour plots of water level on a four-lane roadway with (a) 1% cross slope and 2% longitudinal slope, (b) 1% cross slope and 4% longitudinal slope; 6-inch high curb and a drain. Rainfall intensity 10 in/hr. Water level across the roadway upstream of the drain for the two cases in plot (c). Plot in (d) shows zoomed section of plot (c) excluding the water pool.

Figure 5-33: Contour plots of water level on a four-lane roadway with (a) 1% cross slope and 2% longitudinal slope, (b) 1% cross slope and 4% longitudinal slope; 6-inch high curb and a drain. Rainfall intensity 20 in/hr. Water level across the roadway upstream of the drain for the two cases in plot (c). Plot in (d) shows zoomed section of plot (c) excluding the water pool.

Figure 5-34: Water level across the roadway upstream of the drain on a four-lane roadway with 2% cross slope and 2% longitudinal slope, and 2% cross slope and 4% longitudinal slope; 6-inch high curb and a drain. Rainfall intensity 10 in/hr. Plot in (a) shows the full range of water depth, and plot in (b) shows zoomed section of plot (a) excluding the water pool.

Figure 5-35: Water level across the roadway upstream of the drain on a four-lane roadway with 2% cross slope and 2% longitudinal slope, and 2% cross slope and 4% longitudinal slope; 6-inch high curb and a drain. Rainfall intensity 20 in/hr. Plot in (a) shows the full range of water depth, and plot in (b) shows zoomed section of plot (a) excluding the water pool.

6. Conclusions

A comprehensive study of the flow patterns and water film thickness on wide roads was performed with the use of computational fluid dynamics. Models of multilane roads with varying width, longitudinal, and cross-slopes were developed in the commercial software STAR-CCM+. The influence of the presence of a curb and drainage was also accounted for. The pavement surface was modeled as both smooth and rough, with the roughness height limited to 0.15 mm by the need to resolve the velocity profile within the film, limiting the cell size of the first layer of cells to less than 0.3 mm.

At the start of this research, the smooth pavement model was the only option for obtaining computational analysis results for a wide range of road geometries and conditions rapidly, and it was assumed that it would give results sufficiently accurate for engineering purposes for concrete, but possibly not for asphalt. The study analysis showed that the smooth pavement model yields reasonably accurate results for water film thickness when the roughness height is 0.15 mm or less. Roughness heights this small are not characteristic of most roadways. Three ways to include pavement roughness in the model were investigated: (1) include it as a roughness height, (2) modeling the roughness directly by meshing it out in the domain and (3) modeling the rough surface layer as a porous layer region. Part II of this reports covers the options with an extensive study using option (3), a methodology to include a porous region below the water film to model pavements with roughness height greater than 0.15 mm. The proposed modeling approaches were validated against experimental measurements found in literature. The comparison showed a good accuracy of the computational simulation results.

Two dimensional cases of rain collection and drainage across four lanes with no curbs and no longitudinal slope showed that the water film increases with approximately 0.43 to 0.5 power of the distance along the flow path. This relationship means that doubling the number of lanes increases the water film thickness by a factor of about 1.41 or slightly less over the additional lanes.

The average water film thickness shows very little backwater effect regardless of whether or not the roadside is curbed or whether and where the flow within the film exceeds a Froude number of one. This result means that if the hydroplaning hazard is low for rain draining across a two lane per side road, it remains the same for the 2 lanes next to the crown in a multilane road, which are normally higher speed lanes. On the other hand, if the rightmost lane on a 2 lane per side road has a hydroplaning hazard, then on a wider road any additional lanes have the hazard with the water film thickness increasing with approximately the square root of the distance from the crown.

The Reynolds numbers based on hydraulic diameter for these flows is relatively independent of cross slope and is between 500 and 2000 over much of the road surface on 4 lanes, a value that corresponds to a transition between laminar and turbulent flow. Under these conditions the variation of water viscosity with water temperature can be significant enough to increase water film thickness between about 7% and 11% for cross slopes of 1% and 4%, with colder water at 39 °F as opposed to 77 °F causing the increase. Designs based on water properties at 39° F would be more conservative.

For the smooth cases analyzed in this report, the CFD results match the limited measured Gallaway smooth case data well over a two-lane road. The water film thickness increases with distance across the road at about the same rate, distance to the power 0.43 to 0.5, and the Gallaway equation is close but more conservative than the CFD model results.

For roads with curbs and drainage, the water film thickness, except in the very near vicinity of the grate and any pooling created by the curb blocking runoff, the water film thickness is very close to that of the two-dimensional analysis.

The construction of many-lane curbed roads with much larger rain collection areas than single or 2 lane per side roads can lead to the rapid development of pooling next to the curb that extends

across the entire rightmost lane. At a rain intensity of 5 in/hr with water draining across 4 lanes, pooling may cover the entire rightmost lane within as little as 5 minutes at 2% cross slope and in about 11 minutes at a rain intensity of 2 in/hr.

On roads that have a cross- and longitudinal slope, the water film thickness as well the flooded section will be smaller than in the cases with zero longitudinal slope.

Future work will cover more complex geometries of roads where the grade of the pavement changes in both directions, across and along the travel lanes, with focus on the transition sections of road from straight to superelevations. As the cross-slope changes from positive to negative values, a section of the road is close to flat, more water accumulates, and the hydroplaning risk increases.

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