Transportation Pooled Fund Program TPF-5(446) Quarterly Progress Report

Quarter 3, July -September 2020

prepared by
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October 2020

TRANSPORTATION POOLED FUND PROGRAM
QUARTERLY PROGRESS REPORT

Lead Agency (FHWA or State DOT): _FHWA_______________________________________

INSTRUCTIONS:
Project Managers and/or research project investigators should complete a quarterly progress report for each calendar quarter during which the projects are active. Please provide a project schedule status of the research activities tied to each task that is defined in the proposal; a percentage completion of each task; a concise discussion (2 or 3 sentences) of the current status, including accomplishments and problems encountered, if any. List all tasks, even if no work was done during this period.

Transportation Pooled Fund Program Project # *(i.e, SPR-2(XXX), SPR-3(XXX) or TPF-5(XXX)* *TPF-5(446)*		**Transportation Pooled Fund Program - Report Period:** ☐Quarter 1 (January 1 – March 31) ☐Quarter 2 (April 1 – June 30) ☑Quarter 3 (July 1 – September 30) ☐Quarter 4 (October 1 – December 31)
Project Title: **High Performance Computational Fluid Dynamics (CFD) Modeling Services for Highway Hydraulics**		
Name of Project Manager(s): *Kornel Kerenyi*	**Phone Number:** *(202) 493-3142*	**E-Mail** *kornel.kerenyi@fhwa.dot.gov*
Lead Agency Project ID:	**Other Project ID (i.e., contract #):**	**Project Start Date:**
Original Project End Date:	**Current Project End Date:**	**Number of Extensions:**

Project schedule status:

☑ On schedule ☐ On revised schedule ☐ Ahead of schedule ☐ Behind schedule

Overall Project Statistics:

Total Project Budget	Total Cost to Date for Project	Percentage of Work Completed to Date

Quarterly Project Statistics:

Total Project Expenses and Percentage This Quarter	Total Amount of Funds Expended This Quarter	Total Percentage of Time Used to Date

Project Description:

The Federal Highway Administration established an Inter-Agency Agreement (IAA) with the Department of Energy's (DOE) Argonne National Laboratory (ANL) Transportation Analysis Research Computing Center (TRACC) to get access and support for High Performance Computational Fluid Dynamics (CFD) modeling for highway hydraulics research conducted at the Turner-Fairbank Highway Research Center (TFHRC) Hydraulics Laboratory. TRACC was established in October 2006 to serve as a high-performance computing center for use by U.S. Department of Transportation (USDOT) research teams, including those from Argonne and their university partners. The objective of this cooperative project is to:

- Provide research and analysis for a variety of highway hydraulics projects managed or coordinated by State DOTs.
- Provide and maintain a high-performance Computational Fluid Dynamics (CFD) computing environment for application to highway hydraulics infrastructure and related projects.
- Support and seek to broaden the use of CFD among State Department of Transportation employees.

The work includes:

- Computational Mechanics Research on a Variety of Projects: The TRACC scientific staff in the computational mechanics focus area will perform research, analysis, and parametric computations as required for projects managed or coordinated by State DOTs.
- Computational Mechanics Research Support: The TRACC support team consisting of highly qualified engineers in the CFD focus areas will provide guidance to users of CFD software on an as needed or periodic basis determined by the State DOTs.
- Computing Support: The TRACC team will use the TRACC clusters for work done on projects; The TRACC system administrator will maintain the clusters and work closely with the Argonne system administrator's community; The TRACC system administrator will also install the latest versions of the OpenFOAM [1] and STAR-CCM+ [2] CFD software and other software that may be required for accomplishing projects.

Progress this Quarter:

(includes meetings, work plan status, contract status, significant progress, etc.)

1: Computational Mechanics Research on a Variety of Projects

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

Hydroplaning occurs when a rolling tire is separated from the road surface by a layer of liquid fluid [3] 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. Many modern roadways have many lanes in each direction increasing the water collection area and the drainage path during rain events, and consequently also increasing the water film thickness in the outer lanes. Thicker water film combined with higher speed limits on modern highways have increased hydroplaning risk. This project used computational fluid dynamics to analyze the water film buildup on roadways with varying geometry parameters and rain intensity. The geometry parameters included number of lanes, presence, and absence of curbs with and without drainage through catch basins, varying cross slope, and varying longitudinal slope.

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 to model the flow of a water film with air above. Cases without curbs are compared with the measurements of Gallaway et al. [3] and the Gallaway equation (1) 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.

Gallaway et al. [3] 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:

$$f_w = 0.00338\, T_{XD}^{0.11}\, L_p^{0.43} R_I^{0.59}\, S_x^{(-0.42)} - T_{XD} \qquad (1)$$

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.

When there is no curb and no longitudinal slope, drainage across the road can be modeled using a thin strip over the cross slope from the crown to the shoulder. A diagram of the CFD domain is shown in Figure 1 with the boundary conditions in the cross street and vertical directions. Symmetry conditions are applied on the sides of the strip.

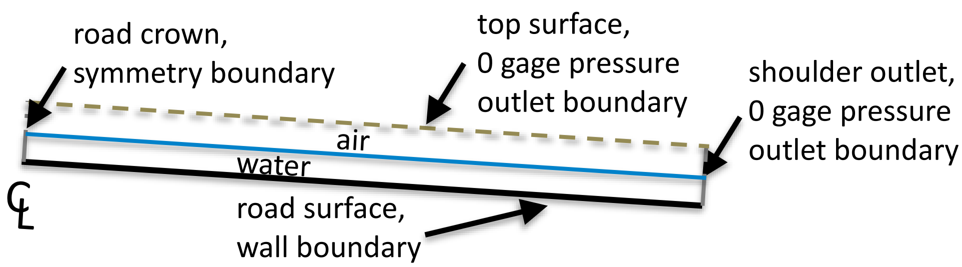

Figure 1. Diagram of computational domain with boundary conditions for thin strip of road from crown to shoulder.

The CFD results of the cases plotted in Figure 2 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 that 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. Gallaway's data did not give the temperature at which the measurements were taken, and consequently the 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. In Figure 2, 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 (1). Experimental measurements are plotted with square markers. The color indicates the cross slope. The Gallaway 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 and plotted with the dotted line. For that case, the water film thickness 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 x 1.4 = 2.1 mm after draining across 4 lanes.

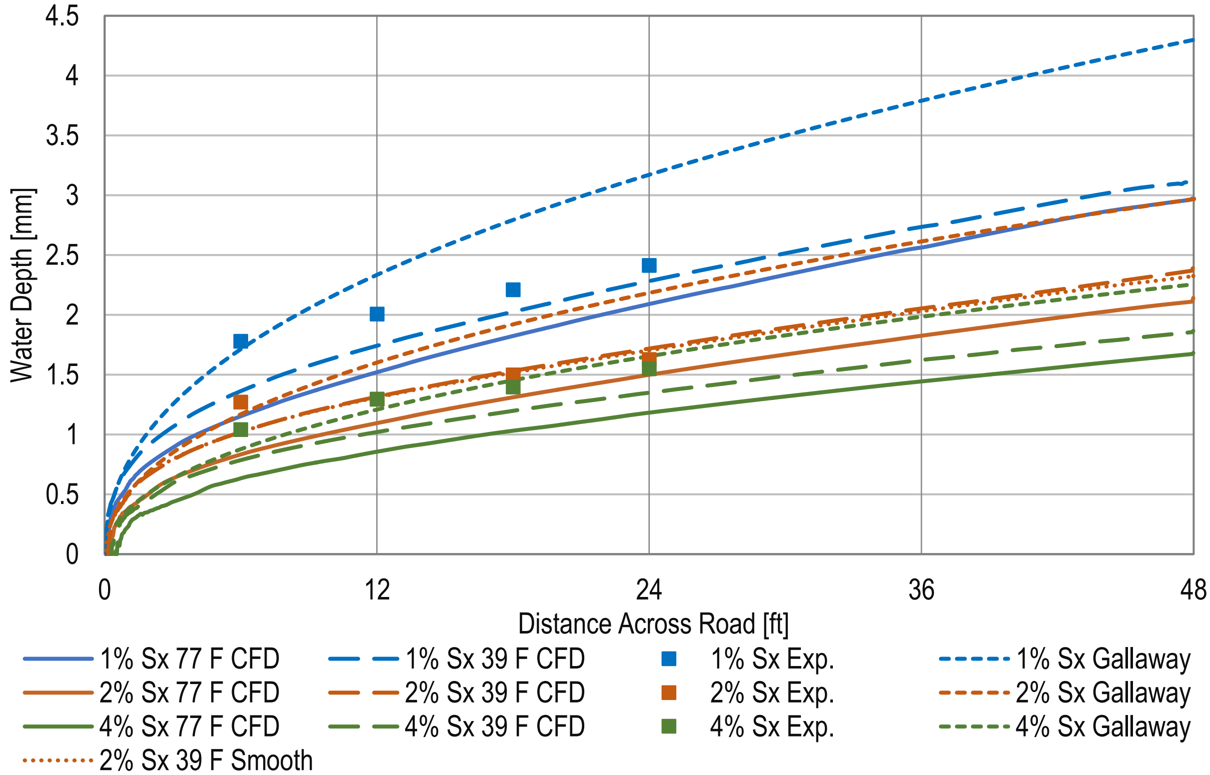

Figure 2. Water film thickness across the roadway without a curb at cross slopes 1%, 2%, and 4% and rainfall intensity rate approximately 5 in/hr showing comparison with the Gallaway equation and experimental results for a near smooth texture depth of 0.076 mm.

Figure 3 shows the model CFD domain viewed from above for 3D calculations of a section of road 330 ft long by 48 ft wide (4 lanes) with a drain in the middle. To save computational resources, cases with zero longitudinal slope run on a half domain that assumed a symmetry plane in the middle.

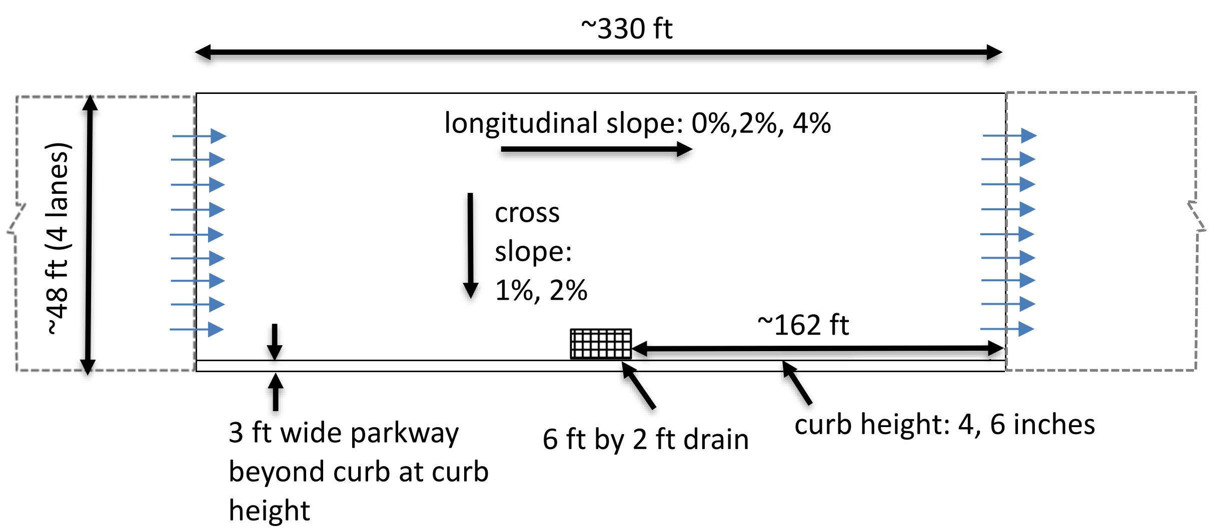

Figure 3. Top view of the CFD domain with dimensions for road with curb and drainage. Values of the main analysis parameters are shown. The blue arrows mark the inflow and outflow surfaces where the periodic boundary condition was used.

Figure 4 shows and example of water film thickness color plotted on a section of curbed roadway with a 2% cross slope at rain intensities of 2, 5, 10, and 20 in/hr. The drain is on the lower right. The water pools at the curb with a spread that covers the rightmost lane at a rain intensity of 2 in/hr with spread increasing slightly with rain intensity. The red zone is the pooled area with water depth greater than 6 mm. Water enters the system over the entire area as rain via a source term in the differential equations and generally flows down to the pooled zone and then from left to right into the drain.

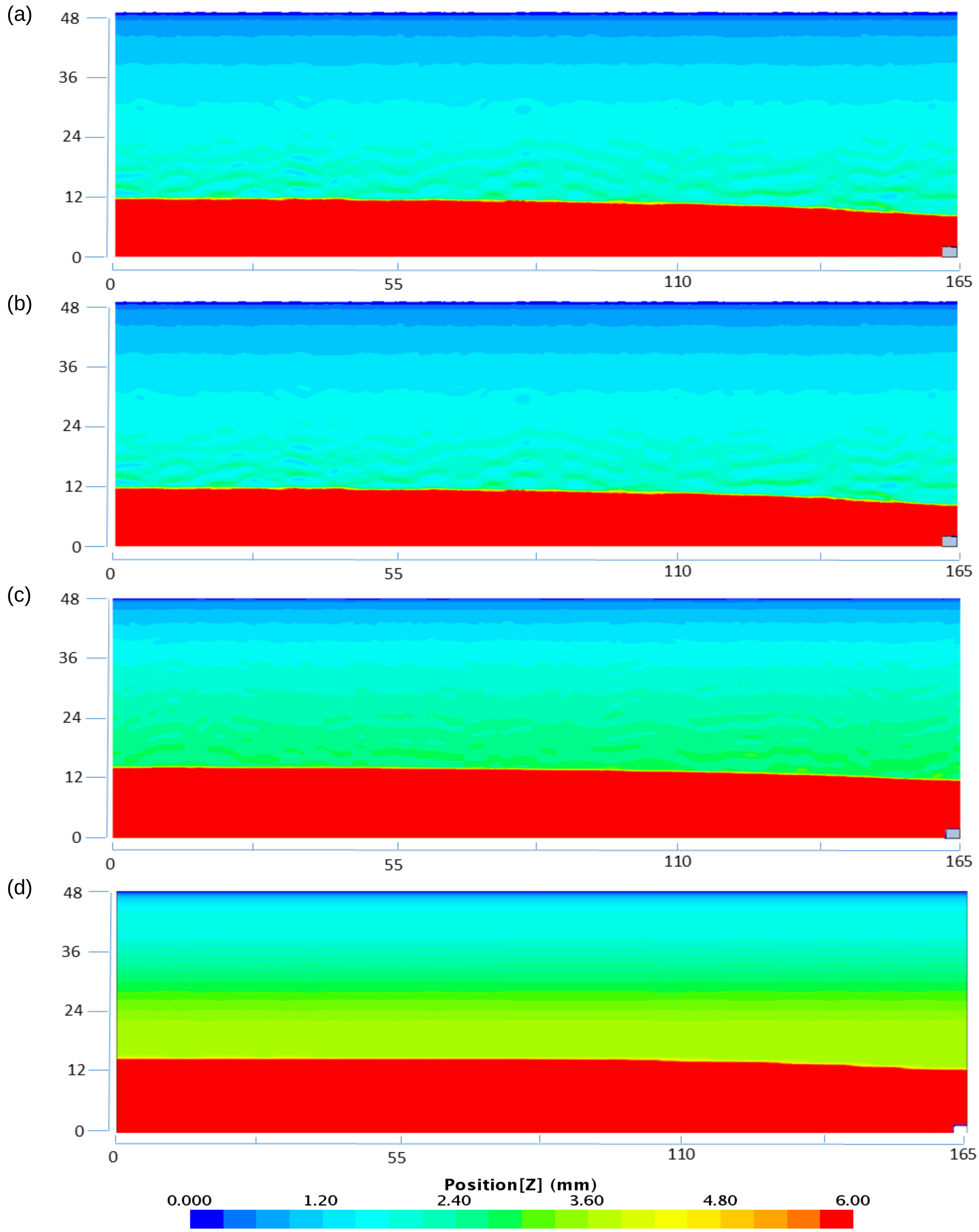

Figure 4. Water surface on a 4 lane roadway with a curb and drainage, 2% cross slope, no longitudinal slope, and at rain intensity (a) 2 in/hr, (b) 5 in/hr, (c) 10 in/hr, and (d) 20 in/hr (curb overflow). The length scale of the computational domain is in feet.

The pooling in heavy rains in the lane next to the curb creates a hazard in addition to the hydroplaning hazard. As seen in Figure 4, the pool covers nearly all of the rightmost lane for all of the rain intensities. Figure 5 shows plots of the pooling spread as a function of time from the start of a downpour for a case where the drain is blocked with debris in blue and a case where the drain is open in green on road sections with 1% and 4 % cross slopes and a rain intensity of 10 in/hr. The results indicate that during a heavy downpour the pooling hazard can develop within about 5 minutes. Figure 6 shows a diagram of a cross section of the street showing the geometry of the pooling in the rightmost lane with much thinner water film from crown on the left to the pool.

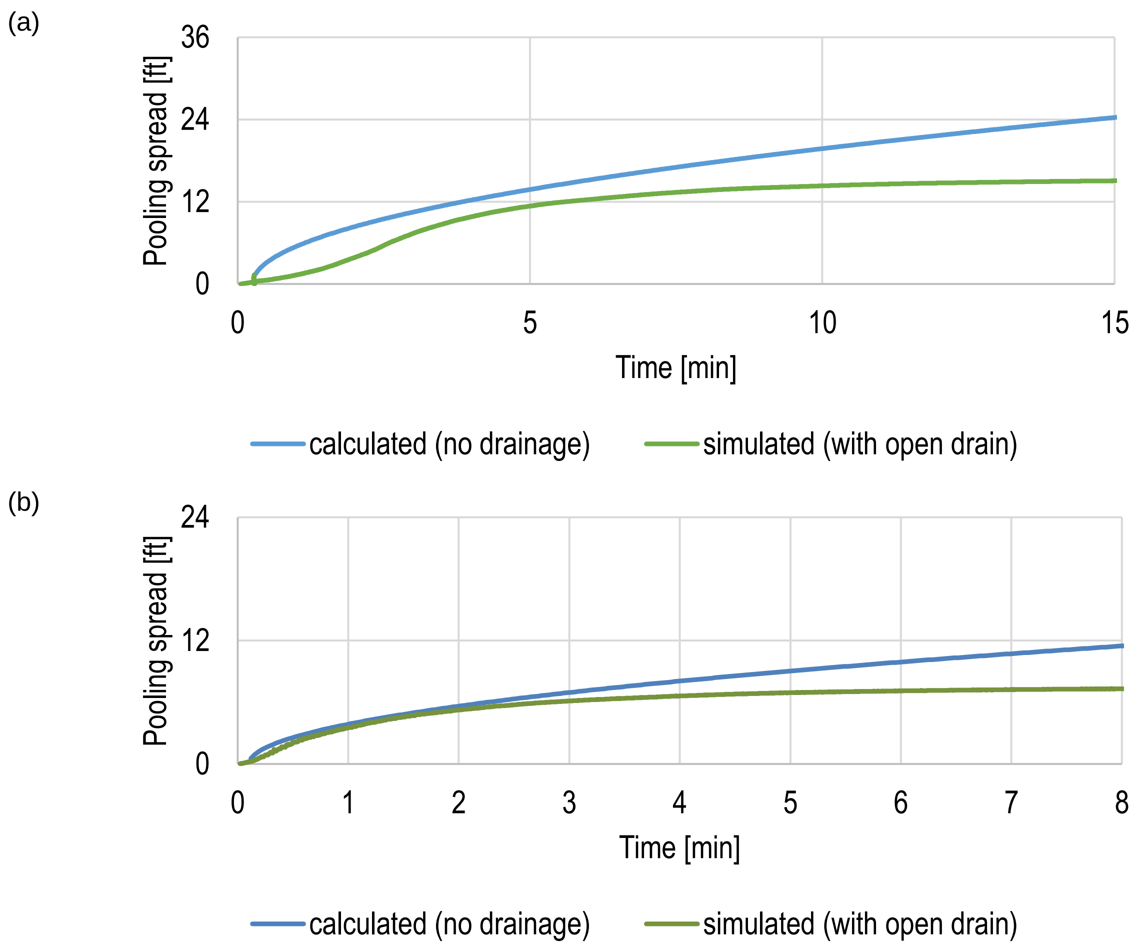

Figure 5. The development of the pooling spread in time for a case without drainage (debris clogged) and an open drain at 10 in/hr, (a) 1% cross-slope, (b) 4% cross-slope

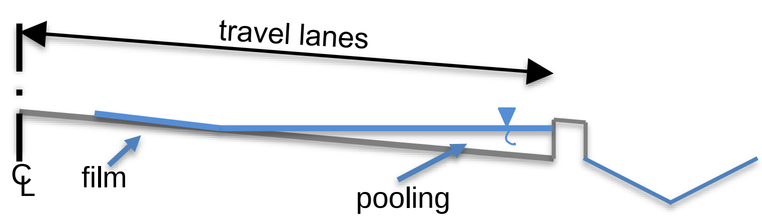

Figure 6. Diagram showing pool that forms at the curb when drainage is not fast enough.

Figure 7 compares water film thickness from the crown at zero distance across a road with and without a curb and the existence of a pool in cases with a curb. For the most part, the downstream presence of the pool does not affect the growth of the water film.

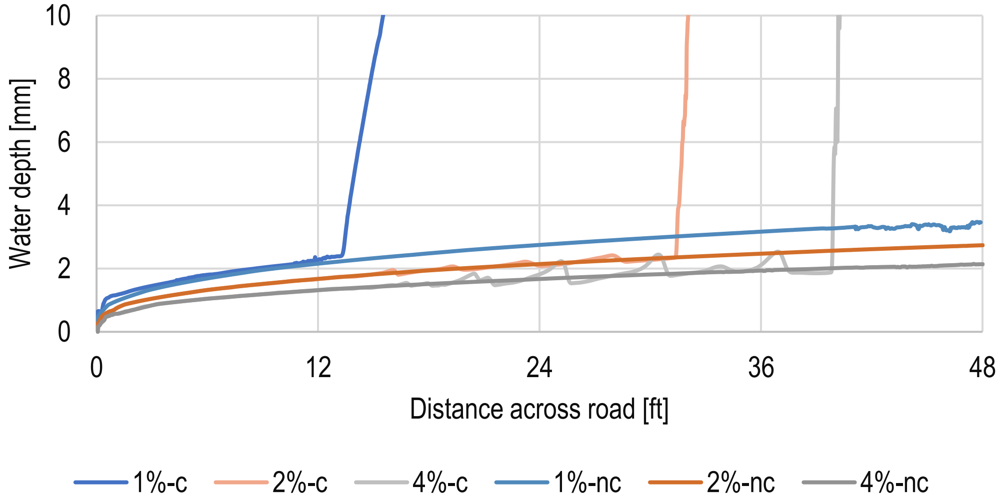

Figure 7. Water film thickness across a 4-lane roadway with a 4-inch high curb at cross slopes 1%, 2%, and 4%. Rain intensity 10 in/hr. The 'c' is legend is with a curb and 'nc' denotes no curb.

1.2: Conclusions

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.

Expanded details, case sets, and results and discussion can be found in [4].

[1] www.openfoam.org
[2] https://www.plm.automation.siemens.com/global/en/products/simcenter/STAR-CCM.html
[3] Gallaway B., Schiller R., Rose J., The Effects of Rainfall Intensity, Pavement Cross Slope, Surface Texture, and Drainage Length on Pavement Water Depths, Texas Transportation Institute Research Report 138-5, 1971.
[4] Sitek M., Lottes S.A., and Sinha N., Computational Analysis of Water Film Thickness During Rain Events for Assessing Hydroplaning Risk Part 1: Nearly Smooth Road Surfaces, Technical Report ANL-20/36, Argonne National Laboratory, July 2020.

2: Computational Mechanics Research Support

Argonne Transportation Research and Analysis Computing Center (TRACC) computational mechanics staff ran nationwide videoconferences every other Thursday that were open to state Department of Transportation staff and university researchers supported by the Federal Highway Administration or state DOTs. The videoconferences provide a venue to discuss approaches and issues related to hydraulics modeling projects. Topics during this reporting period included, but were not limited to:

- new methodologies of scour modeling,
- approaches to modeling and mitigating hydroplaning risk,
- hydraulic analysis of catch basins.

3: Computing Support

Routine cluster maintenance including software and hardware upgrades, security patching against cyber threats, and development of custom tools to increase users' productivity. Currently working on upgrading the TRACC clusters to support the latest scientific and engineering software utilizing industry's best practice guidelines in Open-Source software and virtualization.

Anticipated work next quarter:

1: Computational Mechanics Research on a Variety of Projects

- development of a new methodology for riverbed scour,
- hydraulic analysis of a catch basins,
- analysis of water film thickness on pavements

2: Computational Mechanics Research Support

This work will continue.

Task 3: Computing Support

This work will continue.

Circumstance affecting project or budget:

(Please describe any challenges encountered or anticipated that might affect the completion of the project within the time, and fiscal constraints set forth in the agreement, along with recommended solutions to those problems).

None.