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# MODELING THE MIXED EFFECTS OF OIL AND RAINFALL ON HYDROPLANING

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## ABSTRACT

Hydroplaning is a significant issue for safe driving on wet roadways, and depends on vehicle velocity, water film, and tire tread pattern. Residual oil on the roadway can also exacerbate the occurrence of hydroplaning. Most hydroplaning studies have discussed results for only the presence of water. Furthermore, computational studies modeled the pavement surface as a smooth plane, and some modeling efforts account for texture using roughness correlations. Our study presents a pavement surface model for a grooved topology and re-examines the hydroplaning problem. Computational fluid dynamics was used to model hydroplaning by incorporating the Eulerian methodology to predict the multiphase interactions between air and water. Predictions of water film thickness using the grooved surface model were compared with simulations for a smooth pavement with a roughness correction factor, published correlations, and experimental studies. The study was extended to include oil and water, whereby three distinct phases were modeled. The work sets the foundation to proceed with a three-dimensional, fluid-structure interaction model to include a tire deforming on a pavement subjected to water flow.

**KEYWORDS:** Computational fluid dynamics, Hydroplaning, Multiphase flow, Water film thickness

## 1. INTRODUCTION

Automobile accidents on wet pavement are widespread in the United States. The majority of weather-related car accidents happen on wet pavement and during rainfall [1]. Hydroplaning happens when water on the pavement accumulates in front of the tires. When the tire of a vehicle encounters more water than it can expel, the force of the fluid causes the tire to lift from the road. The water pressure acting on the tire can cause the tire to rise and slide on top of a water layer between the tire and the pavement. The effects of hydroplaning can be dangerous when a tire detaches from the pavement, and can lead to skidding, loss of steering control, and loss of vehicle traction.

Rainfall plays a substantial role in hydroplaning occurrences, and is worse when it rains after a long dry period because the accumulation of oil on roads increases the potential for skidding. Eisenberg [2] found automobile crashes significantly increased during the first rain due to the slick conditions on the road. Previous hydroplaning studies showed results with only a layer of water, assuming a smooth pavement surface [3, 4]. Few studies have examined the interaction between the water and oil, tire and road friction.

The pavement texture also can significantly influence the probability of hydroplaning as well as the loss of traction during wet conditions [5, 6]. However, little research has been conducted to computationally model grooved or textured pavement surfaces in hydroplaning studies. Thus, the motivation for the work herein is to computationally model hydroplaning using a grooved pavement surface model and compare predictions of water film thickness to a simple surface. In addition, the effects of oil interacting with water are examined.

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# 2. NUMERICAL METHODOLOGY

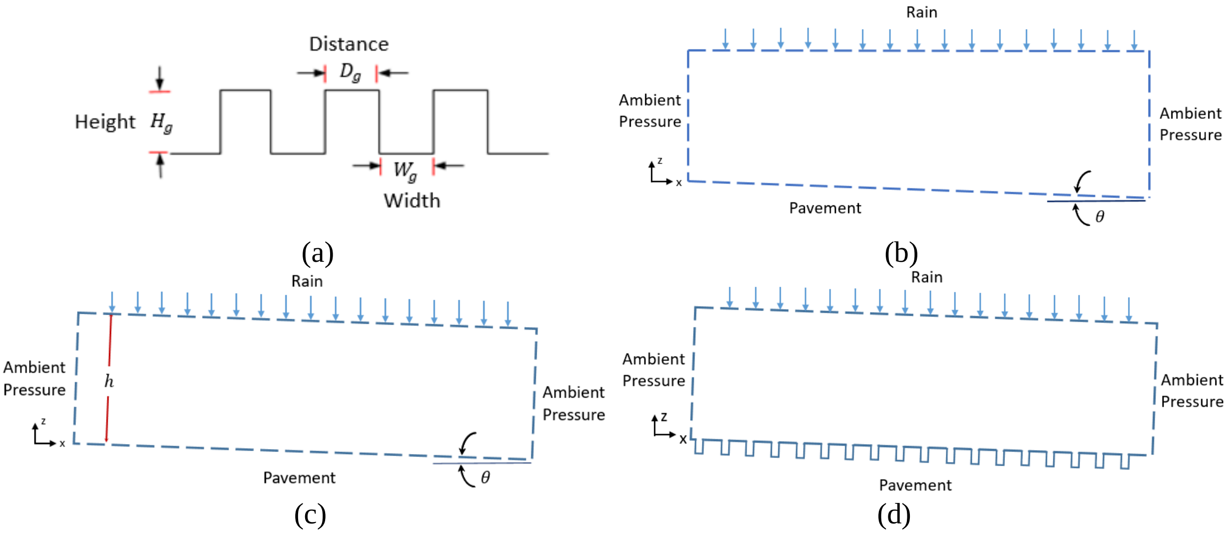
## 2.1 Pavement Surface Model

The representation of the pavement surface is critical to modeling hydroplaning because the surface roughness influences the skid resistance of a vehicle and tire-pavement friction. The pavement texture affects the water film thickness along the pavement, which in turn causes hydroplaning. Although the pavement texture has been investigated experimentally, there needs to be more in-depth investigations into computational studies that model a physical texture. Typically, a coefficient for roughness height $K_s$ is incorporated in a computational model that permits a simpler representation and eliminates the need for a complex mesh to resolve texture. The macrotexture is the texture of the larger irregularities of the pavement surface, which contributes to the drainage of water along the pavement. A mean texture depth (MTD) can be used to characterize the macrotexture and provide a measurement to quantify the water layer on a textured pavement. Thus, the thickness of the water film above the top of the surface asperities is equal to the water film thickness (WFT) plus the MTD [7]. Macrotexture was introduced to design a more accurate pavement model for the CFD analysis using a square wave form, shown in Fig. 1(a). The MTD is defined as:

$$MTD = \frac{W_g H_g}{W_g + D_g} \tag{1}$$

for groove width $W_g$, groove distance $D_g$ and groove height $H_g$. The pavement grooves were designed with $W_g = H_g = 2$ mm, and $D_g = 4$ mm, whereby MTD = 0.66 mm. Note that the typical MTD range for asphalt is between 0.31 mm and 4.05 mm [8].

The parameters in the CFD model for pavement roughness and texture depth were based on the computational work of Chen et al. [9] and the experimental results of Reed et al. [10] for a rainfall mass flow rate of 0.8 kg/s, pavement length of 10 m, and MTD = 0.66. Chen et al. [9] determined that a roughness coefficient equal to the MTD could be used with a “smooth surface” to effectively model microtexture. Fig. 1(b) shows the computational domain and boundary conditions for the simulation performed by Chen et al. [9] (assuming $h$ = 30 cm), and Fig. 1(c) is the computational domain for the smooth pavement surface used in this work. The main difference between Fig. 1(b) and (c) is the subtle change in shape of the computational domain. The domain in Fig. 1(b) is a trapezoid, whereas Fig. 1(c) is a rectangle inclined with θ = 1°. The reason for using a rectangular domain is related to the domain that models the grooved surface, shown in Fig. 1(d). After extensive attempts, meshing the grooves required orthogonal surfaces. Therefore, in order to compare predictions for a grooved surface, the smooth surface was modeled with the same rectangular domain and inclination.



(a) (b) (c) (d)

**Fig. 1** (a) Schematic of the grooved pavement, and computational domains of (b) Chen et al. (2017), (c) the smooth surface, and (d) the grooved surface

**Table 1** Mesh properties of the pavement surface model simulations

| Mesh | $\Delta x$ (mm) | Min $\Delta z$ (mm) | Max $\Delta z$ (mm) | # cells |
|---|---|---|---|---|
| Smooth surface (Coarse) | 10 | 2 | 6.1 | 8,000 |
| Smooth surface (Medium) | 5 | 1 | 3.4 | 30,000 |
| Smooth surface (Fine) | 2.5 | 0.5 | 1.7 | 120,000 |
| Grooved surface | 1 | 1 | 3.4 | 146,784 |
| Chen et al. (2017) | 6.7 | 1 | 3.4 | 39,000 |

## 2.2 CFD analysis

Simulations were conducted for hydroplaning using ANSYS Fluent with the multiphase Eulerian model for water, oil and air phases. The phases were treated as interpenetrating continua based on the volume of fluid model to resolve the fluid-fluid interfaces, and the modified implicit "high resolution interface capturing" (HRIC) was employed to capture the interface between phases. The Reynolds-Averaged Navier-Stokes (RANS) equations for conservation of mass and momentum were solved using the semi-implicit method for pressure linked equations (SIMPLE) algorithm. The quadratic upstream interpolation for convective kinematics (QUICK) scheme was used for spatial discretization. The standard $k$-ε turbulence model was included to consider the effects of flow turbulence and free surface flow. A grid resolution study was conducted to examine the predictive performance of the water film thickness. Three grids were generated with a refinement ratio of 2 and tested for the current study. The mesh properties are shown in Table 1. The grid convergence index between the medium and fine grid was less than 1% for the water film thickness predictions. Therefore, the medium mesh will be used for this study.

## 3. RESULTS AND DISCUSSION

The WFT distribution on the real pavement can be evaluated as a quasi-steady-state condition under constant rainfall. The WFT can be calculated as:

$$P = (\rho_w - \rho_a) gWFT + \rho_a gh \tag{2}$$

where, $\rho_w$ is the water density, $\rho_a$ is the air density, $P$ is the gauge pressure, and $h$ is the height of the domain. Fig. 2 compares the WFT the smooth surface (Fig. 1(c) with $K_s$ = 0.66), grooved surface (Fig. 1(d) with MTD = 0.66) and Chen et al. [9] (Fig. 1(b) with $K_s$ = 0.66). The solid line shows the WFT profile from Gallaway et al. [11] and the solid circles with error bars show data from Reed et al. [10]. The smooth surface and grooved surface simulations have very similar WFT profiles compared with Chen et al. [9] and Gallaway et al. [11]. Therefore, the top surface of the domain can be designed parallel to the pavement surface to simulate the model. Furthermore, although the grooves are a more accurate representation of pavement, the WFT predictions were very similar to those for the smooth surface with specified surface roughness, suggesting that there is no need for a complicated groove topology.

Additional simulations were conducted to consider when rain interacts with residue oil on the pavement. A layer of oil was created at the pavement surface to examine the process how oil floats on top of the water when it rains. Fig. 3 presents contours of oil volume fraction to show the process of oil rising. The domain and conditions for Fig. 3 (a) and (b) are based on Fig. 1(c) and (d), respectively, with the addition of a 1 mm layer of oil on the pavement as an initial condition. After the simulation commences, rain accumulates on the pavement and displaces the oil, as seen in Fig. 3 (a) showing oil floats to the top of the water. Fig. 3 (b) shows oil has filled the pavement grooves, but due to the slope, downstream water begins displacing the oil. The water and oil film thickness (WOFT) is also shown in Fig. 2 for the smooth surface. The WOFT was calculated using Eq. (2) and replacing the water density with the mixture density. The WOFT was a slightly thicker than WFT because there was added oil on the pavement. In summary, it was shown that adding a layer of oil on the pavement will produce the expected results when interacting with rainfall. The proposed simulation model can serve as a tool to understand how pavement grooving affects hydroplaning. The results highlight the effectiveness of pavement design in hydroplaning analysis. Furthermore, the similarity between the WFT for the smooth and grooved pavements suggests that the smooth pavement can be modeled with an appropriate roughness coefficient. Such a simplification will help with more complex simulations when considering a fluid-structure interaction model.

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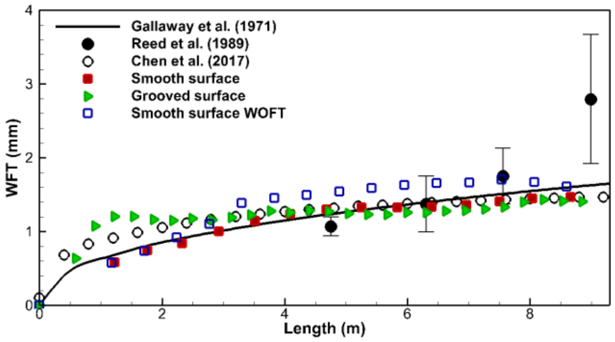
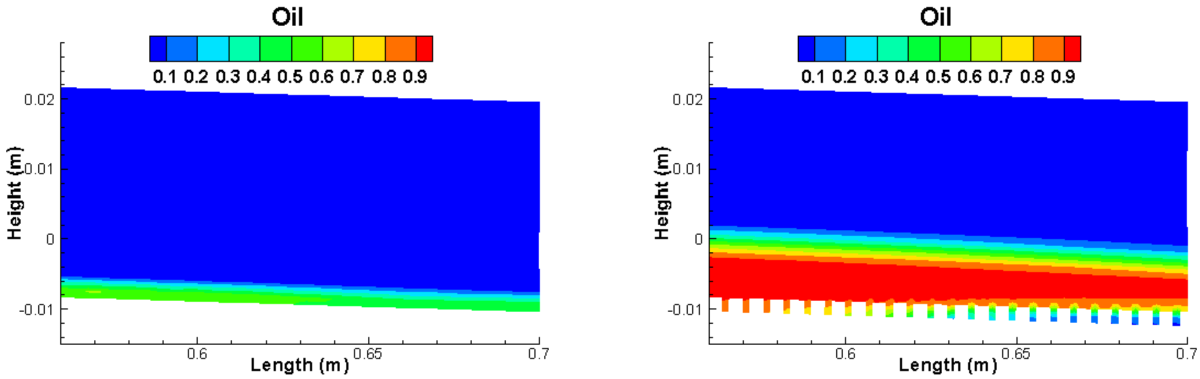


**Fig. 2** WFT for Chen et al. (2017), Gallaway et al. (1971), Reed et al. (1989) and CFD predictions for the smooth and grooved surfaces.



(a) (b)

**Fig. 3** Volume fraction of oil for smooth pavement surface: (a) initial stage; (b) intermediate stage