Guidance to Predict and Mitigate Dynamic Hydroplaning on Roadways - Project Update

Gerardo W. Flintsch

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Contents

✓ Background
✓ Water Film Thickness Model
✓ Vehicle Handling Model
✓ Expected Outcomes
✓ Concluding Remarks
Background
Dynamic Hydroplaning

https://www.faasafety.gov/gslac/ALC/course_content.aspx?cID=34&sID=171&preview=true
Hydroplaning Models - Hydroplaning Speed Prediction

**NASA:**
\[ v_p = 51.80 - 17.15(FAR) + 0.72p \]
\[ v_p = 7.95\sqrt{p(FAR)^{-1}} \]

**TXDOT:**
\[ v_p = SD^{0.04} p^{0.3}(TD + 1)^{0.06} A \]
\[ A = \max \left(3.507 + \frac{10.409}{WFT^{0.06}}, \left[ \frac{28.952}{WFT^{0.06}} - 7.817 \right] T^{0.14} \right) \]

**PAVDRN:**
\[ v_p = 26.04WFT^{-0.259} \]

**USF:**
\[ v_p = WL^{0.2} p^{0.5} \left( \frac{0.82}{WFT^{0.06}} + 0.49 \right) \]

\( v_p = \) vehicle speed (km/h); 
\( p = \) tire pressure (kPa); 
\( FAR = \) tire footprint aspect ratio; 
\( WL = \) wheel load (N); 
\( WFT = \) water film thickness (mm).
NCHRP 15-55 Objective

- To develop a comprehensive hydroplaning risk assessment tool that can be used by transportation agencies to help reduce the potential of hydroplaning.
  - Treating hydroplaning as a multidisciplinary and multi-scale problem
  - Solutions for areas with a high potential of hydroplaning based on a fundamental and meaningful understanding of the problem.
NCHRP 15-55 Objective (Cont.)

✓ Final Product: *Guidance and tools to predict and mitigate hydroplaning on roadways*

- Applicable to all types of roadways
- Site-specific factors such as geometric design, etc.
- Appropriate for new construction, reconstruction, and maintenance/retrofit projects.
NCHRP 15-55 Objective (Cont.)

✓ Two Supporting products:

- A **Hydroplaning Risk Assessment Tool**
  • To provide highway engineers with practical and simple means for assessing the impact of roadway geometric features on the accumulation of water on the pavement and determining the hydroplaning potential for existing or new roads.

- An **Integrated Hydroplaning Model**
  • Intermediate product, generated mainly for the development of the simpler, more practical assessment tool.
Research Approach Overview

Mitigation Measures
- Pavement & Highway Engineering
- Advice & Education
- Enforcement & Traffic Control
- Mitigation Strategies

Inputs
- Weather Conditions
  - Rainfall
- Road Characteristics
  - Geometry
  - Smoothness
  - Texture
  - Drainability
- Maneuver
- Speed Limits
- Vehicle Characteristics
  - Type of vehicle
  - Safety Features
- Tire Characteristics
  - Type
  - Condition

Integrated Hydroplaning Model
- Road Model
- Driver Response
- 3D Road Surface Model
- Water Accumulation
- Water Film Thickness
- Speed

Hydroplaning Risk Assessment Tool
- Vehicle Dynamics
- Tire Model
- Tire-water-pavement Interaction (CFD)

Verification & Validation
- Previous Experimental Studies
- Simulations
- Naturalistic Driving
- Crash Databases & Road Measurements

Hydroplaning Risk
- Simple relationships between road characteristics, vehicle speed and water film thickness and hydroplaning potential

Current Ongoing Efforts
Water Film Model
<table>
<thead>
<tr>
<th>Models</th>
<th>Input</th>
<th>Description</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>TXDOT</td>
<td>Cross slope</td>
<td>1D empirical equations</td>
<td>[ d = 3.38 \times 10^{-3} \left( \frac{1}{T} \right)^{0.11} L^{0.43} I^{0.59} \left( \frac{1}{S} \right)^{0.42} - T ]</td>
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<tr>
<td>(1971)</td>
<td>Macrotexture</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Rain intensity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAVDRTN</td>
<td>Cross slope</td>
<td>1D wave equations based on kinematic approximation</td>
<td>[ WFT = \left( \frac{n \times L \times I}{36.1 \times S_x^{0.5}} \right) - MTD ]</td>
</tr>
<tr>
<td>(1997)</td>
<td>Draining length</td>
<td>conservation of mass and momentum</td>
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<tr>
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<td>Pavement Permeability</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Rain intensity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TXDOT</td>
<td>Cross slope</td>
<td>2D wave equations based on Navier-Stokes equation</td>
<td>[ \frac{\partial H}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} - r = 0 ]</td>
</tr>
<tr>
<td>(2008)</td>
<td>Draining length</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Longitudinal slope</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rain intensity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NCHRP</td>
<td>Cross slope</td>
<td>3D full Navier-Stokes equations</td>
<td>[ \frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_x)}{\partial x} + \frac{\partial (\rho u_y)}{\partial y} + \frac{\partial (\rho u_z)}{\partial z} = 0 ]</td>
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<tr>
<td>15-55</td>
<td>Draining length</td>
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<td></td>
<td>Longitudinal slope</td>
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<tr>
<td></td>
<td>Macrotexture Pavement characteristics</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rain intensity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Water Film Thickness Modeling

- Straight Alignment
- Curves
- Transitions
Mesh Definition and Initial Verification Work

✓ Proctor (1986) measured WFT on a 30-ft. by 15-ft.
Water Film Thickness Sensitivity Analysis

✓ Modeled Transitions
Longitudinal Slope

(a) 2Lanes_Type1_Sx=0%

(b) 2Lanes_Type1_Sx=1%

(c) 2Lanes_Type1_Sx=2% (preliminary results)
Example of Preliminary Results

![Graph 1](image1)

- Max at road shoulder interface
- Max at 30 cm from shoulders
- Mean on the road

![Graph 2](image2)

- Max at road shoulder interface
- Max at 30 cm from shoulders
- Mean on the road

Rainfall rate (mm/hr)

Texture depth (mm)
Vehicle Handling Model
Vehicle Model

- **3D Road Surface Model**
  - Roughness
  - Texture

- **Water Accumulation**
  - Texture
  - Water Film Thickness

- **Vehicle Response**
  - **Fluid-Solid Interaction (FSI)**
    - Tire Model (Abaqus)
      - Deformed tire structure
      - Pressure, Critical Velocity
  - **Tire-water-pavement Interaction (Star-CCM+)**
    - Tire-water-pavement Interaction (Star-CCM+)
    - Tyre-, water-, pavement-Interaction (Star-CCM+)
    - Spindle position, lateral and longitudinal forces from tire, vertical hydrodynamic force
  - **Coupling (Star-CCM+)**
  - **Vehicle Dynamics (CarSim)**
    - Effective friction
    - Roll, pitch, yaw, stability factor
  - **Hydroplaning Potential**

- **Driver**
  - Speed

- **Vehicle Characteristics**
  - Type of vehicle
  - Type of tire
  - Condition (tread depth)

- **Tire Characteristics**
  - Texture
  - Type of tire
  - Condition (tread depth)
FSI Model Domain
Tire Model

1. Special table band saw for slicing tire samples
2. Approx. 6" tire section created (finely ground and deburred)
3. Rim mounting position determined
4. Processed high resolution image used as reference to create 2D tire model in ABAQUS
5. Rim mounting position and contour gauge measurements used as a reference to obtain high resolution 2D tire cross sectional image
6. Special contour gauge used for measuring outer profile (uninflated tire state-3psi)
FSI Model Setup

✓ Models setup in Star-CCM+
  - Implicit Unsteady (Δt= 5×10^-4 s)
  - Eulerian Multiphase (air, water)
  - SST K-Omega turbulence model
  - VOF waves (water film)

Initial Boundary conditions:

- Inflow (water and air): Velocity inlet, \( V_z = -40 \text{ kph} \); VOF wave
- Outflow (water and air): Atmospheric pressure
- Pavement: Non-slip wall, \( V_z = -40 \text{ kph} \)
- Side and top surfaces: Free-slip wall
- Tire: Non-slip wall, Local rotation rate, \( \omega_y = 61.19 \text{ rad/s} \)

X – toward pavement;
Y – cross stream direction;
Z – car travel direction.
Effects of water film (preliminary results)

Water 0 mm

Water 5 mm

Water 8 mm

Water 30 mm
Water splash

WFT = 8 mm

WFT = 30 mm
Velocity Vectors

WFT = 8 mm
FSI model with slip angle 2°

Operating conditions:
- Water film velocity: \([0.0, -0.6239262, -17.867]\) m/s
- Inflow velocity \([0.0, -0.6239262, -17.867]\) m/s
- Pavement: \([0.0, -0.6239262, -17.867]\) m/s
- Side and top surfaces: Free-slip wall
- Tire: Local rotation rate, \(\omega_Y=61.19\) rad/s
Pressure: effects of slip angle

Slip angle 2°
Water film: 5 mm

Slip angle 0°
Water film: 5 mm
Effect on contact patch and water splashing
Vehicle Dynamic Simulation (preliminary)

Hydroplaning Vehicle Simulator

Hydroplaning Vehicle Simulator allows the user to do a batch simulation by changing the CarSim simulation factors (vehicle type, road characteristic, maneuver, and tire models) automatically by writing CarSim own code file (.par file)
Hydroplaning Vehicle Simulator & G Value

Table 3. Initial combinations of factors considered for the vehicle simulations.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Maneuver</th>
<th>Grade</th>
<th>Cross-slope</th>
<th>Roughness</th>
<th>WFT</th>
<th>Tire</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle cornering</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hatchback</td>
<td>0% to Max. mph</td>
<td>0%</td>
<td>ISO A</td>
<td>Dry</td>
<td>Bald</td>
<td></td>
</tr>
<tr>
<td>Sedan</td>
<td>2%</td>
<td>2%</td>
<td>ISO C</td>
<td>2mm</td>
<td>Min tread depth</td>
<td></td>
</tr>
<tr>
<td>SUV</td>
<td></td>
<td></td>
<td>IOS E</td>
<td>5mm</td>
<td></td>
<td>10mm</td>
</tr>
<tr>
<td><strong>Vehicle braking</strong></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Hatchback</td>
<td>0%</td>
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<tr>
<td>SUV</td>
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<td>6%</td>
<td>ISO E</td>
<td>5mm</td>
<td></td>
<td>10mm</td>
</tr>
</tbody>
</table>

Vehicle Cornering Simulation

Vehicle Braking Simulation
Proposed Approach

\[
P(H \mid R) = \sum_i \sum_j P(H \mid RV_i W_i) P(V_i \mid R) P(W_j \mid R)
\]
Expected Products
Proposed Hydroplaning Risk Assessment Tool Format

**Inputs**
- Location
  - Weather databases
- Type of Road Segment
  - Tangent
  - Curve
  - Transition
- Road Characteristics
  - Grade
  - Cross-slope
  - Curvature
  - Lengths
  - Smoothness
  - Macrotexture
  - Drainability
- Vehicle Characteristics
  - Hatchback
  - Sedan
  - SUV
- Tire Characteristics
  - Bald
  - Minimum tread depth
- Speed

**Processes**
- Simplified Water Film Thickness Prediction
- Performance Margin Estimation (Simple IO Model)
- Vehicle Response
- Hydroplaning risk/Potential Estimation

**Outputs**
- Design Rainfall
- Water Film Thickness
- Effective Friction
- Hydroplaning Risk
Guide for Predicting and Mitigating Hydroplaning on Roadways (Preliminary Outline)

Executive Summary

Introduction

✓ Background
✓ Objectives
✓ Scope and Organization

Understanding Hydroplaning

✓ Definitions
✓ Accumulation of Water on the Pavement
  – Basic hydraulic and hydrologic principles
  – Road surface properties
  – Predicting rainfall
✓ Vehicle Response to Driver Behavior and Road Conditions
  – Driver behavior
  – Vehicle and tire dynamics
  – Fluid dynamics at the tire-pavement interface
✓ Integrated Hydroplaning Model
Guide for Predicting and Mitigating Hydroplaning on Roadways (Preliminary Outline) (cont.)

Assessment of Hydroplaning Risk

✓ Hydroplaning Risk Assessment Tool
  – Tool development
  – Applications
✓ Evaluation of Pavement Surface Properties
  – Assessment technologies
  – Examples
✓ Precipitation Estimations
  – Using available climatic data
  – Examples
✓ Prediction of Hydroplaning Risk

Hydroplaning Mitigation Strategies

✓ New Roadways
  – Virtual audits
✓ Existing Roadways
  – Road Surface Improvements
  – Operational Strategies
  – Outreach and Education
✓ Case Studies

Implementation Recommendations

Appendices
Concluding Remarks
Concluding Remarks

✓ Ongoing work
  – All results may change

✓ Some significant advances
  – Water film thickness prediction
  – Hydroplaning definition & assessment approach

✓ Main product:
  – Guide to predict and mitigate hydroplaning on roadways

✓ Secondary products
  – Hydroplaning Assessment tool (practitioners)
  – “Integrated” Hydroplaning Model (researchers)
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