Splash, Spray and Hydroplaning 101
Gerardo Flintsch, Virginia Tech
Contents

1. Introduction
2. Water accumulation on the pavement
3. Splash and Spray
4. Hydroplaning
5. Final Thoughts
1. Introduction
Road Evolution

1st Generation ⇒ Track

2nd Generation ⇒ Paved road

3rd Generation ⇒ Smooth road (comfort)

4th Generation ⇒ Highway (safe & efficient)

5th Generation ⇒ Smart, Sustainable and Resilient roads & highways

Adapted from the FEHRL Concept for

FOREVER OPEN ROAD
Redefining Road Transport for the 21st Century

Virginia Smart Road (1999)

Paving Pennsylvania Avenue (1870’s)


http://www.romeacrosseurope.com/?p=5417#sthash.0cge6wg.dpbo
What is the function of the Road?

What does the use want/expect?

- Mobility
- Access
- Safety
- Comfort
- Fast & Reliable Travel
- Energy Efficient
- Low pollution / Low noise
- Renewable  ...

Level of Service (Performance)

→ Focus on the User

Economic Development
Social Equity
Environmental Protection
Sustainable Infrastructure

Focus on the User
Vehicle (Tire) / Road (Pavement) Interaction

- Smoothness – Ride Quality
- Friction - Safety
- Hydroplaning
- Fuel Consumption
- Rolling Resistance
- Noise
- Tire Wear
- Splash and Spray
- Environment Pollution

Optimization
Pavement Texture – PIARC Classification and Impact on Pavement Vehicle Interaction

Key

- Good
- Bad

PIARC Classification

- Microtexture
- Macrotecture
- Megatecture
- Uneveness

Spatial frequency

- 20k 10k
- 2k 1k
- 200 100
- 20 10
- 2 1
- 0.2 0.1

Wavelength

- 5µm 10µm
- 50µm 100µm
- 0.5mm 1mm
- 5mm 10mm
- 0.5m 1m
- 5 m 10 m

Influence

- Wet Weather Friction
- Dry Weather Friction
- Splash and Spray
- Tire Wear
- Vehicle Wear
- In-Vehicle Noise
- Rolling Noise
- Hydroplaning
- Ride Quality
- Rolling Resistance
Tire/Pavement Interface – Three Zone Concept

1. Macrotexture
2. Microtexture
3. Dry Contact

Example of the Effect of Texture on Crash Rate
2. Water Accumulation
Measuring/Predicting Water Film Thickness

✓ Lab Measurements

✓ Field Measurements

✓ Modeling

Examples of Water Accumulation Models

Table 1. Overview of previous and current models.

<table>
<thead>
<tr>
<th>Models</th>
<th>Input</th>
<th>Description</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>TXDOT (1971)</td>
<td>Cross slope Macrotexuture Rain intensity</td>
<td>1D empirical equations</td>
<td>$d = 3.38 \times 10^{-3} \left( \frac{1}{T} \right)^{0.11} L^{0.43} T^{0.59} \left( \frac{1}{S} \right)^{0.42} - T$</td>
</tr>
<tr>
<td>PAVDNRN (1997)</td>
<td>Cross slope Draining length Pavement Permeability Rain intensity</td>
<td>1D wave equations based on kinematic approximation conservation of mass and momentum</td>
<td>$WFT = \left( \frac{n \times L \times I}{36.1 \times S_x^{0.5}} \right) - MTD$</td>
</tr>
<tr>
<td>TXDOT (2008)</td>
<td>Cross slope Draining length Longitudinal slope Rain intensity</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></td>
<td></td>
<td></td>
<td>$\frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q_x^2}{\rho} \right) + \frac{\partial}{\partial y} \left( \frac{q_x q_y}{\rho} \right) + gh \left( \frac{\partial h}{\partial x} \right) + S_{fx} - S_{ex} = 0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\frac{\partial q_y}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q_x q_y}{\rho} \right) + \frac{\partial}{\partial y} \left( \frac{q_y^2}{\rho} \right) + gh \left( \frac{\partial h}{\partial y} \right) + S_{fy} - S_{ey} = 0$</td>
</tr>
<tr>
<td>NCHRP 15-55</td>
<td>Cross slope Draining length Longitudinal slope Macrotexuture Pavement characteristics Rain intensity</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>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\frac{\partial (\rho u_x)}{\partial t} + \frac{\partial (\rho u_x)^2}{\partial x} + \frac{\partial (\rho u_x u_y)}{\partial y} + \frac{\partial (\rho u_x u_z)}{\partial z} + \frac{\partial P}{\partial x} = \frac{\partial \tau_{x}^{xx}}{\partial x} + \frac{\partial \tau_{x}^{xy}}{\partial y} + \frac{\partial \tau_{x}^{xz}}{\partial z}$</td>
</tr>
<tr>
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<td>$\frac{\partial (\rho u_y)}{\partial t} + \frac{\partial (\rho u_y)^2}{\partial y} + \frac{\partial (\rho u_x u_y)}{\partial x} + \frac{\partial (\rho u_y u_z)}{\partial z} + \frac{\partial P}{\partial y} = \frac{\partial \tau_{y}^{xy}}{\partial x} + \frac{\partial \tau_{y}^{yy}}{\partial y} + \frac{\partial \tau_{y}^{yz}}{\partial z}$</td>
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<tr>
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<td>$\frac{\partial (\rho u_z)}{\partial t} + \frac{\partial (\rho u_z)^2}{\partial z} + \frac{\partial (\rho u_x u_z)}{\partial x} + \frac{\partial (\rho u_y u_z)}{\partial y} + \frac{\partial P}{\partial z} = \frac{\partial \tau_{z}^{xz}}{\partial x} + \frac{\partial \tau_{z}^{yz}}{\partial y} + \frac{\partial \tau_{z}^{zz}}{\partial z}$</td>
</tr>
</tbody>
</table>
Splash–Spray Assessment Tool Development Program Water Film Thickness Model

1. Lab Work

<table>
<thead>
<tr>
<th>Material</th>
<th>Texture (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone Mastic Asphalt</td>
<td>0.549</td>
</tr>
<tr>
<td>Asphaltic Concrete</td>
<td>0.633</td>
</tr>
<tr>
<td>Porous Asphalt</td>
<td>1.644</td>
</tr>
<tr>
<td>Tined Concrete</td>
<td>1.011</td>
</tr>
<tr>
<td>Smooth Concrete</td>
<td>0.208</td>
</tr>
<tr>
<td>Perspex</td>
<td>0.001</td>
</tr>
</tbody>
</table>

2. Generic Formula

\[ d = k T^w (LI)^y S^z \]

- \( d \) = Water depth (m)
- \( T \) = texture (mm)
- \( L \) = drainage length (m)
- \( I \) = rainfall intensity (m/h)
- \( S \) = slope
- \( w, x, y, z, w, k \) = regression coefficients
- (k incorporates Manning’s coefficient)

3. Calibrated Formula

\[ d = 6 \times 10^{-4} T^{0.09} (LI)^{0.6} S^{-0.33} \]
NCHRP 15-55 3D Water Accumulation Model

Validation work with Reed at al. (1989) and 1-D correlations.

(a) Base case with 20 mm/h
(b) Case 2 with 60 mm/h
(c) Case 3 with 100 mm/h

WFT distribution on pavement with different rainfall rate
NCHRP 15-55 Hydroplaning Risk Assessment Tool
Simplified Water Model

- Modified Gallaway Equation
- Gaussian Kernel Smoothing

Step 1

Step 2

Streamlines

Water Distribution

WFT (mm) = 1.67
Recent FHWA / USDoE / Argonne Reports

Figure 5-5: Water depth on a rough pavement, (a) close to the median, (b) close to the shoulder. Rainfall intensity 5 in/hr, slope 2%.

Figure 5-12: 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 overflows). The length scale of the computational domain is in feet.

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

Nuclear Science and Engineering Division
3. Splash and Spray
Splash & Spray

✓ Splash: “the mechanical action of a vehicle’s tire forcing water out of its path. Splash is generally defined as water drops greater than 1.0 mm (0.04 inches) in diameter, which follow a ballistic path away from the tire.”

✓ Spray: being formed “when water droplets, generally less than 0.5 mm (0.02 inches) in diameter and suspended in the air, are formed after water has impacted a smooth surface and been atomized.”
Factors affecting Splash and Spray

✓ Surface Geometry
  ▪ Gradient
  ▪ Cross-slope
  ▪ Number and with of the lanes
✓ Pavement Macrotexture
✓ Surface Type
  ▪ Permeable vs non-permeable
✓ Location or Rain Intensity
  ▪ Intensity
  ▪ Rain duration
✓ Tire
  ▪ Width
  ▪ Tread grooved proportion
  ▪ Tread depth
✓ Speed
Exposure Model

- Builds on CalTrans project (Huang et al. 2008) which updated the California Wet Percentage Time tables.
  - Wet hours (for different thicknesses)
  - Wet exposure = percentage time

User Impact

- Test under to a range of different controlled conditions
- Measure of splash and spray: **Occlusion Factor**
- Correlates with user responses (subjective ratings of obstruction, concentration, and risk and lower ratings for confidence and control)

**Occlusion Factor** = ratio of the mean luminance of the black squares to the mean luminance of the white squares
Occlusion Factor - Correlation with User Perceptions

Mean Risk Rating by Mean Occlusion Factor

Mean Confidence Rating by Mean Occlusion Factor

$R^2 = 0.7786$

$R^2 = 0.7777$
Splash and Spray Model

CDF Simulation
→ Capillary Adhesion + Tread Pickups
  + Bow wave
  + Side Wave
→ Combined
→ Used results to build the model
Splash–Spray Assessment Tool Development Program Products

1. Splash and Spray Assessment Tool Development Program Final Report


www.fhwa.dot.gov/pavement/pub_details.cfm?id=964
Spreadsheet Tool

Pavement surface cross slope

Longitudinal grade

Calculated drainage path

Precipitation

Spray Density

Splash & Spray Density under 0.68 inch/hour rain

Level of Nuisance
1 2 3 4 5
0.68-inch/h rainfall (10-hour level) non-porous pavement

Example

Splash & Spray Density under 0.68 inch/hour rain

1-inch/h rainfall (4-hour level) non-porous pavement

Splash & Spray Density under 1.0 inch/hour rain
Case Study (cont.)

1-inch/h rainfall (4-hour level) porous pavement
4. Hydroplaning

Hydroplaning

Traditional Hydroplaning Models: Hydroplaning Speed Prediction

✓ NASA:

\[ v_p = 51.80 - 17.15(FAR) + 0.72p \]

\[ v_p = 7.95\sqrt{p(FAR)^{-1}} \]

✓ TXDOT:

\[ v_p = SD^{0.04} p^{0.3}(TD + 1)^{0.06} A \]

\[ A = \max \left( 3.507 + \frac{10.409}{WFT^{0.06}}, \frac{28.952}{WFT^{0.06} - 7.817} \right)^{0.14} \]

✓ PAVDRN:

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

✓ USF:

\[ v_p = WL^{0.2} p^{0.5} \left( \frac{0.82}{WFT^{0.06}} + 0.49 \right) \]
Factors affecting Hydroplaning

- Roadway and Pavement
  - Pavement micro- and macrotexture
  - Cross-slope (including superelevation)
  - Longitudinal grade
  - Pavement width (number of lanes)
  - Roadway curvature
  - Rut depth
  - Depressions

- Environmental conditions
  - Rainfall intensity
  - Rainfall duration
  - Temperature

- Driver behavior
  - Speed
  - Acceleration or baking
  - Steering maneuver

- Vehicle conditions
  - Vehicle type
  - Vehicle (or axle) weight
  - Tire tread wear (tread depth)
  - Tire pressure
  - Tire tread design
Florida DOT Hydroplaning Tool (cont.)

Pavement Inputs

Deterministic Analysis

Longitudinal Grade (%) 3
Surface Type Open Graded Friction Course
Permeability (in/hr) 0

Hydroplaning Tool

WFT & HPS Model Selection

<table>
<thead>
<tr>
<th>WFT Model</th>
<th>Hydroplaning Speed Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PAVDRN</td>
</tr>
<tr>
<td>Gallaway</td>
<td>Y</td>
</tr>
<tr>
<td>UK RRL</td>
<td></td>
</tr>
<tr>
<td>NZ Mod.</td>
<td></td>
</tr>
<tr>
<td>PAVDRN</td>
<td></td>
</tr>
</tbody>
</table>

Water Film Thickness (WFT) Table (Units: in.)

<table>
<thead>
<tr>
<th>Plane Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Shoulder</td>
<td>Lane 1</td>
<td>Lane 2</td>
<td>Buffer</td>
<td>Lane 3</td>
<td>Lane 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal Grade (%)</td>
<td>Gallaway</td>
<td>-0.002</td>
<td>0.026</td>
<td>0.048</td>
<td>0.054</td>
<td>0.060</td>
<td>0.068</td>
<td></td>
</tr>
<tr>
<td>Surface Type</td>
<td>UK RRL</td>
<td>-0.003</td>
<td>0.024</td>
<td>0.045</td>
<td>0.051</td>
<td>0.060</td>
<td>0.068</td>
<td></td>
</tr>
<tr>
<td>Permeability (in/hr)</td>
<td>NZ Mod.</td>
<td>-0.010</td>
<td>0.010</td>
<td>0.025</td>
<td>0.029</td>
<td>0.031</td>
<td>0.035</td>
<td></td>
</tr>
<tr>
<td>Width (ft.)</td>
<td>PAVDRN</td>
<td>-0.013</td>
<td>0.000</td>
<td>0.008</td>
<td>0.011</td>
<td>0.012</td>
<td>0.014</td>
<td></td>
</tr>
</tbody>
</table>

Hydroplaning Speed (HPS) Table (Units: mph)

<table>
<thead>
<tr>
<th>Plane Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Shoulder</td>
<td>Lane 1</td>
<td>Lane 2</td>
<td>Buffer</td>
<td>Lane 3</td>
<td>Lane 4</td>
<td>Gore</td>
<td>Ramp</td>
</tr>
<tr>
<td>A Parameter</td>
<td>Gallaway</td>
<td>0.00</td>
<td>19.34</td>
<td>18.45</td>
<td>18.27</td>
<td>18.11</td>
<td>17.96</td>
<td>17.76</td>
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<td>WFT</td>
<td>UK RRL</td>
<td>0.00</td>
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<td>18.54</td>
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<td></td>
<td>NZ Mod.</td>
<td>0.00</td>
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<td>19.17</td>
<td>19.07</td>
<td>18.91</td>
<td>18.67</td>
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<tr>
<td></td>
<td>PAVDRN</td>
<td>0.00</td>
<td>21.04</td>
<td>20.65</td>
<td>20.50</td>
<td>20.27</td>
<td>19.69</td>
<td>19.45</td>
</tr>
</tbody>
</table>

Hydroplaning Speed

PAVDRN HPS using Gallaway WFT
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.
Research Approach Overview

**Mitigation Measures**

- Pavement & Highway Engineering
- Enforcement & Traffic Control
- Mitigation Strategies

**Inputs**

- Weather
  - Rainfall
- Road Characteristics
  - Geometry
  - Smoothness
  - Texture
  - Drainability
- Maneuver
- Speed
- Tire Characteristics
  - Condition
- Vehicle Characteristics
  - Type of vehicle
- Agency Criteria
  - PM Threshold

**Integrated Hydroplaning Model**

- 3-D Water Model
- Road Model
- Water Accumulation
- Vehicle Response Model
- Tire Model
- Tire-water-pavement Interaction
- Vehicle Dynamics

**Hydroplaning Risk Assessment Tool**

- Simplified Hydroplaning Risk Assessment Tool
  - Simple relationships between road characteristics, vehicle speed and water film thickness and Performance Margin

**Hydroplaning Potential**

- Water Film Thickness
- Performance Margin

**Road Assessment**

- Hydroplaning Risk Assessment Tool
Hydroplaning Definition

✓ Based on vehicle handling capabilities
  ▪ Performance margin
    (available fiction) dry
  ▪ Required friction
  ▪ Available fiction wet

✓ Performance Margin

\[
\frac{(A_{brk}^* - \tan(\theta_s))^2}{\mu_X^2} + \frac{(A_Y^* - \tan(\theta_b))^2}{\mu_Y^2} = 1
\]
Hydroplaning Potential and Risk

- Not implemented in the tool

- Hydroplaning potential
  \[ H_P = P(\frac{H}{V S W}) = \left( 1 + \left( \frac{PM}{\alpha} \right)^{-4\alpha\beta} \right)^{-1} \]

- Hydroplaning risk
  \[ H_R = P(\frac{H}{S}) = \sum_V \sum_W P(\frac{H}{V W S})(P P(W) P(W/S)) \]
Integrated Hydroplaning Model

Vehicle Response

Fluid-Solid Interaction (FSI)
- Deformed tire structure
- Tire Model (Abaqus)

Tire-water-pavement Interaction (Star-CCM+)
- Pressure, Critical Velocity

Coupling (Star-CCM+)
- Spindle position, lateral and longitudinal forces from tire, vertical hydrodynamic force

Vehicle Dynamics (CarSim)
- Type of vehicle

Vehicle Characteristics
- Type of tire
- Condition (tread depth)
- Speed

Driver
- Speed

Roughness Texture
- Texture

Water Accumulation
- Water Film Thickness

3D Road Surface Model
- Texture

Inflow
- Pavement Level

Outflow
- Pavement Level

V
- V

Wavy
- Wavy

Water Level
Volume fraction of the water flowing in the tire pattern groove with 5-mm WFT at 40 mph.
Vehicle Dynamics Model - Performance Margin

Simple Input-Output Model
- Create Simple Input-Output Model
  - INPUT: Vehicle, Road, Tire, WFT
  - OUTPUT: Effective Friction
- Simple IO Model
- GUI

Simple Risk/Potential Model
- Method to Estimate Hydroplaning Risk/Potential
  - INPUT: Effective $\mu$, G Values
  - OUTPUT: Risk/Potential
- Risk/Potential Model
- G Values

Hydroplaning Vehicle Simulator
- MATLAB
- CARSIM
- SIMULINK

\[
\frac{(A_{brk}^* - \tan(\theta_s))^2}{\mu^2_X} + \frac{(A_Y^* - \tan(\theta_b))^2}{\mu^2_Y} = 1
\]

GUI

Hydroplaning Risk/Potential

Performance Margin

$\mu_y + \tan \theta_b$

Cornering

$A_{brk}, A_Y$

Braking

$\mu_x + \tan \theta_s$
Hydroplaning Risk Assessment Tool

**Inputs**
- Location
  - Weather databases
- Road Surface
  - Grid
- Road Characteristics
  - Grade
  - Cross-slope
  - Curvature
  - Smoothness
  - Macrotexture
- Vehicle Characteristics
  - Hatchback
  - Sedan
  - SUV
- Tire Characteristics
  - Bald
  - New
- Operating Conditions
  - Speed
  - Breaking
- Agency Criteria
  - PM Threshold

**Processes**
- Hydroplaning Risk Assessment Tool
  - Simplified Water Film Thickness Prediction
  - Performance Degradation Estimation

**Outputs**
- Design Rainfall
- Maximum Water Film Thickness
- Performance Margin
- Hydroplaning Potential
  (based on agency-defined criteria)
NCHRP 15-55 Tool – beta version

1. Select a file containing a prepared coarse grid for the alignment
2. Add the main surface characteristics and road geometric characteristics
3. Select the design speed and braking deceleration, design vehicle, and tire condition (or approve the default).
Performance Margin Calculation

Step 3

Performance Margin = 0.149

PM (%) = 20

P = 0.15
Example – Effect of Macrotexture

\[
\text{MPD} = 0.5 \text{ mm}; \quad \text{WFT} = 1.57 \text{ mm}; \quad \text{PM}_{136\text{km/h}} = 0.098
\]

\[
\text{MPD} = 1.8 \text{ mm}; \quad \text{WFT} = 0.58 \text{ mm}; \quad \text{PM}_{136\text{km/h}} = 0.122
\]
5. Final Thoughts
Final Thoughts

- There are many pavement-vehicle interactions that impact driving safety and comfort.
- The accumulation on water on the pavement impact the vehicle performance and safety and the comfort of drivers.
- Splash and Spray and Hydroplaning are two interactions that are difficult to measure directly.
- However they can be modeled and the presentation presented a couple of simple tools to predict them.
- These tools can be used to identify roadway sections in need for interventions and the potential impact of various treatments.
Splash, Spray and Hydroplaning 101
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