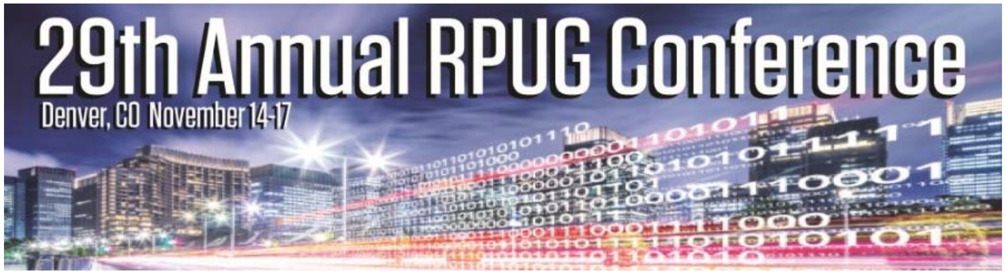
Center for Sustainable Transportation Infrastructure



VirginiaTech
Invent the Future

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

http://auto.howstuffworks.com/car-driving-safety/accidents-hazardous-conditions/hydroplaning.htm

Gerardo W. Flintsch

29th RPUG Conference
Marriott Denver West, Golden, CO
November 14 to 17, 2017

Vehicle Terrain Performance Laboratory (VTPL)
Computational Research for Energy Systems & Transport (CREST) Laboratory
Center for Tire Research (CenTire)
Center for Sustainable Transp. Infrastructure (CSTI)
VirginiaTech Transportation Institute

Contents

Center for
Sustainable
Transportation
Infrastructure

Center for Sustainable Transportation Infrastructure

Research Team Acknowledgement

NCHRP 15-55 Program Officer

Gerardo Flintsch (VTTI) - PI
Road/Vehicle Interaction & Surface Properties

John Ferris (ME)
Vehicle Dynamics & Surface Characterization

David Kibler (VT/Consultant)
Hydraulics & Hydrology

Saied Taheri (ME)
Tire Dynamics & Tire/Pavement Interaction

Alejandra Medina (VTTI)
Driver Behavior & Safety Analysis

Edgar de Leon (VTTI)
Surface Characterization & Mitigation Strategies

David Hargreaves (NTEC)
Hydraulics & CFD

Francine Battaglia (ME)
Computational Fluid Dynamics (CFD) Modeling

Tony Parry (NTEC)
Road/Vehicle Interaction & Guidance Development

Samer Katicha (VTTI)
Data Analysis & Modeling

Kevin McGhee (VCTIR)
Surface Properties & Guidance Development

Lu Chen (ME/CREST)

Yong Suk Kang (ME/VTPL)

Ashkan Nazari (ME/CenTire)

Lijie Tang (CEE/VTTI)

Kenneth Velez (CEE/VTTI)

Center for Sustainable Transportation Infrastructure

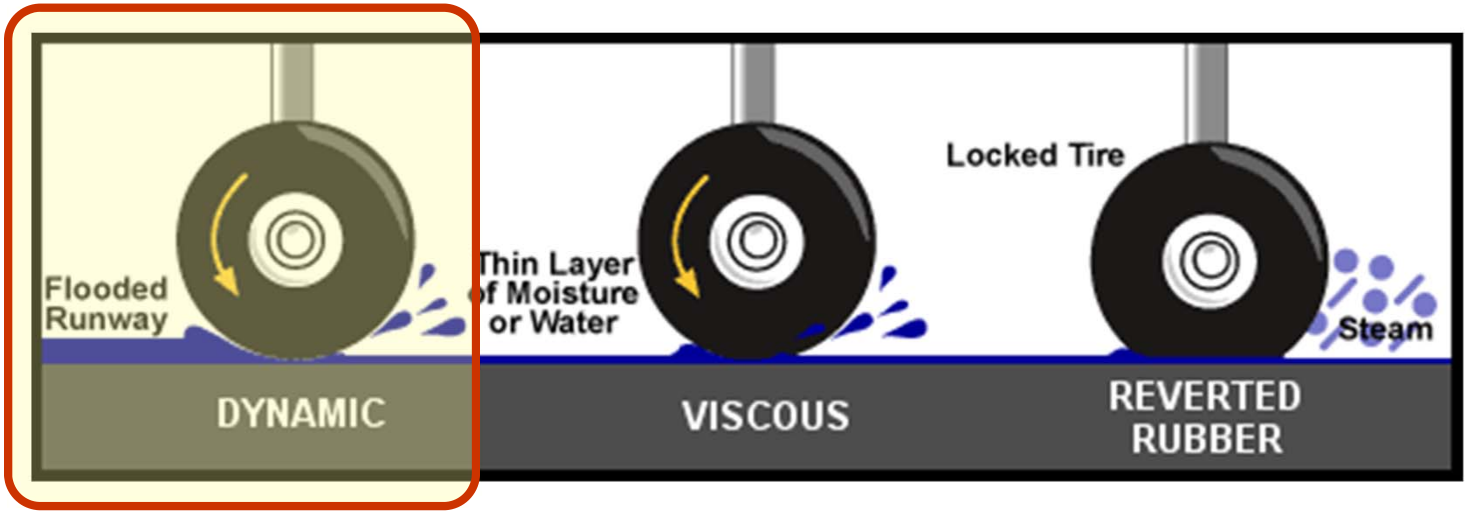
VirginiaTech Transportation Institute

Center for Sustainable Transportation Infrastructure

Background

Advancing Transportation Through Innovation

Dynamic Hydroplaning



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

Center for Sustainable Transportation Infrastructure

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:

$$v_p = 26.04 WFT^{-0.259}$$

✓ 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).

VirginiaTech Transportation Institute

Center for Sustainable Transportation Infrastructure

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.

Center for Sustainable Transportation Infrastructure

VirginiaTech Transportation Institute

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.

Center for
Sustainable
Transportation
Infrastructure

NCHRP 15-55 Objective (Cont.)

✓ Two Supporting products:

– A ***Hydroplaning Risk Assessment Tool***

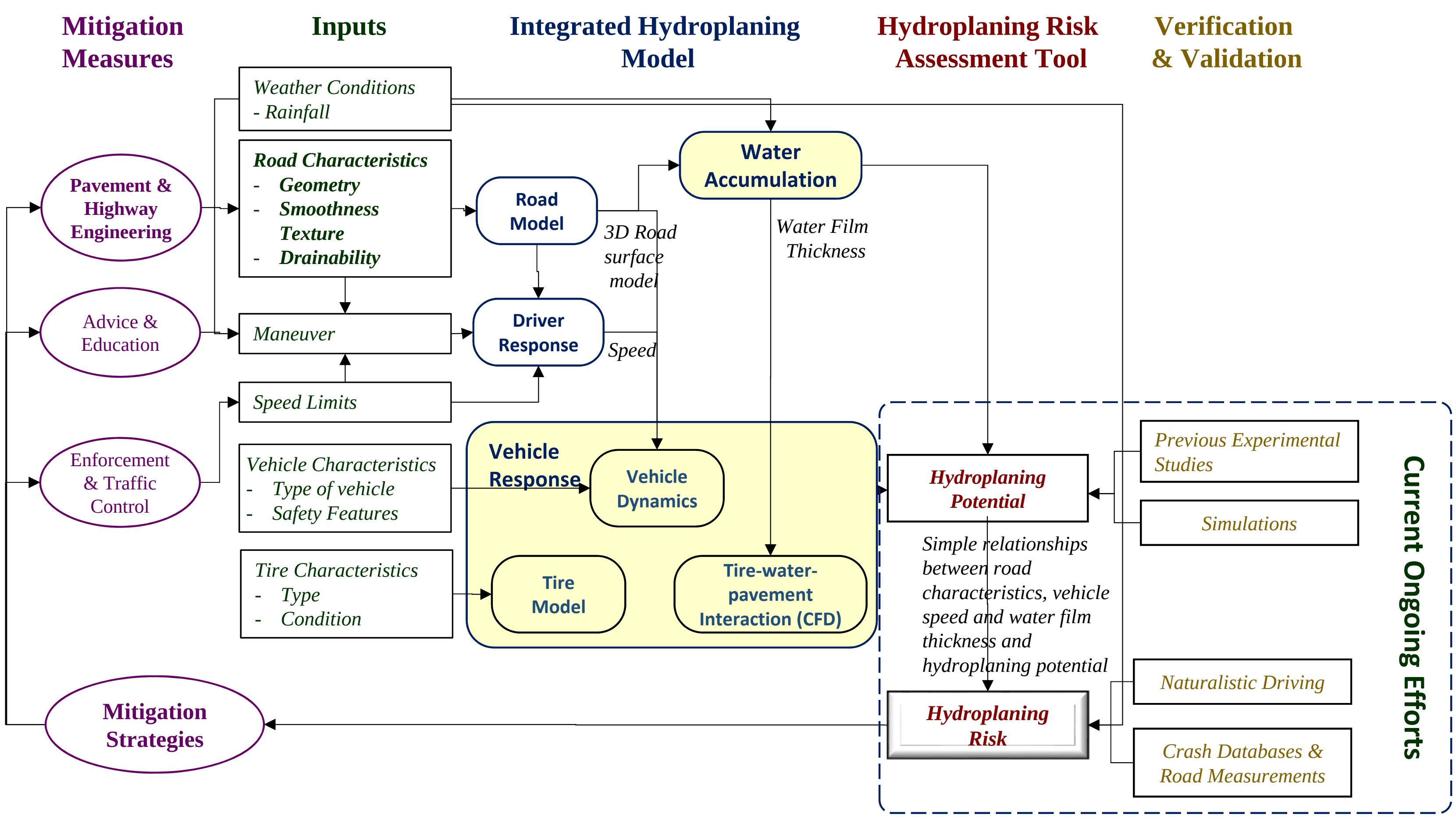
- To provide highway engineers with practical and simple means for assessing the impact of roadway geometric features on the accumulation of water on the pavement and determining the hydroplaning potential for existing or new roads.

– An ***Integrated Hydroplaning Model***

- Intermediate product, generated mainly for the development of the simpler, more practical assessment tool.

Center for
Sustainable
Transportation
Infrastructure

Research Approach Overview



Water Film Model

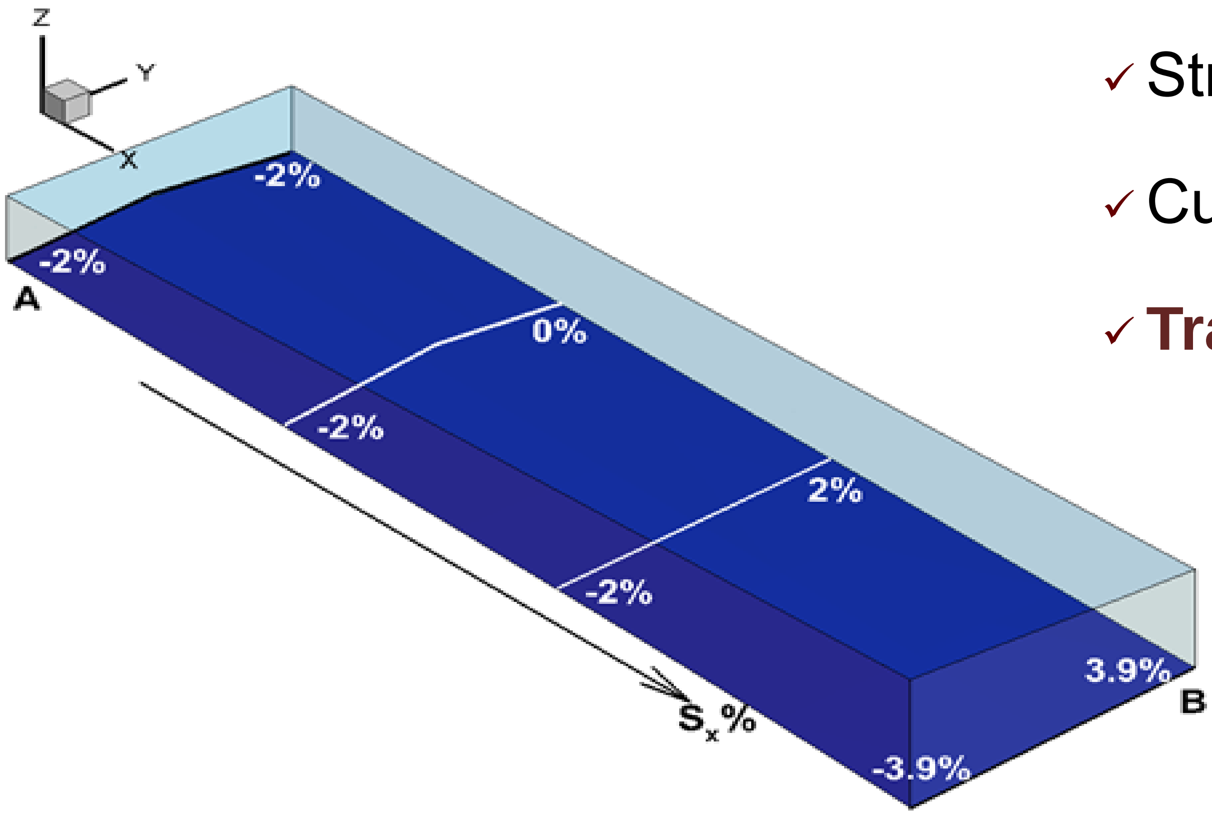
Water Flow Models

Models	Input	Description	Functions
TXDOT (1971)	Cross slope Macrotexture Rain intensity	1D empirical equations	$d = 3.38 \times 10^{-3} (\frac{1}{T})^{-0.11} L^{0.43} I^{0.59} (\frac{1}{S})^{0.42} - T$
PAVDRN (1997)	Cross slope Draining length Pavement Permeability Rain intensity	1D wave equations based on kinematic approximation conservation of mass and momentum	$WFT = (\frac{n \times L \times I}{36.1 \times S_x^{0.5}}) - MTD$
TXDOT (2008)	Cross slope Draining length Longitudinal slope Rain intensity	2D wave equations based on Navier-Stokes equation	$\frac{\partial H}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} - r = 0$ $\frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q_x^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{q_x q_y}{h}\right) + gh\left(\frac{\partial h}{\partial x} + S_{fx} - S_{ex}\right) = 0$ $\frac{\partial q_y}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q_y^2}{h}\right) + \frac{\partial}{\partial x}\left(\frac{q_x q_y}{h}\right) + gh\left(\frac{\partial h}{\partial y} + S_{fy} - S_{ey}\right) = 0$
NCHRP 15-55	Cross slope Draining length Longitudinal slope Macrotexture Pavement characteristics Rain intensity	3D full Navier-Stokes equations	$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_x)}{\partial x} + \frac{\partial(\rho u_y)}{\partial y} + \frac{\partial(\rho u_z)}{\partial z} = 0$ $\frac{\partial(\rho u_x)}{\partial t} + \frac{\partial(\rho u_x^2)}{\partial x} + \frac{\partial(\rho u_x u_y)}{\partial y} + \frac{\partial(\rho u_x u_z)}{\partial z} + \frac{\partial P}{\partial x} + \rho g_x = \frac{\partial \overline{\overline{\tau}}_{xx}}{\partial x} + \frac{\partial \overline{\overline{\tau}}_{xy}}{\partial y} + \frac{\partial \overline{\overline{\tau}}_{xz}}{\partial z}$ $\frac{\partial(\rho u_y)}{\partial t} + \frac{\partial(\rho u_x u_y)}{\partial x} + \frac{\partial(\rho u_y^2)}{\partial y} + \frac{\partial(\rho u_y u_z)}{\partial z} + \frac{\partial P}{\partial y} + \rho g_y = \frac{\partial \overline{\overline{\tau}}_{xy}}{\partial x} + \frac{\partial \overline{\overline{\tau}}_{yy}}{\partial y} + \frac{\partial \overline{\overline{\tau}}_{yz}}{\partial z}$ $\frac{\partial(\rho u_z)}{\partial t} + \frac{\partial(\rho u_x u_z)}{\partial x} + \frac{\partial(\rho u_y u_z)}{\partial y} + \frac{\partial(\rho u_z^2)}{\partial z} + \frac{\partial P}{\partial z} + \rho g_z = \frac{\partial \overline{\tau}_{xz}}{\partial x} + \frac{\partial \overline{\overline{\tau}}_{yz}}{\partial y} + \frac{\partial \overline{\tau}_{zz}}{\partial z}$

Center for
Sustainable
Transportation
Infrastructure

Center for Sustainable Transportation Infrastructure

Water Film Thickness Modeling



- ✓ Straight Alignment
- ✓ Curves
- ✓ **Transitions**

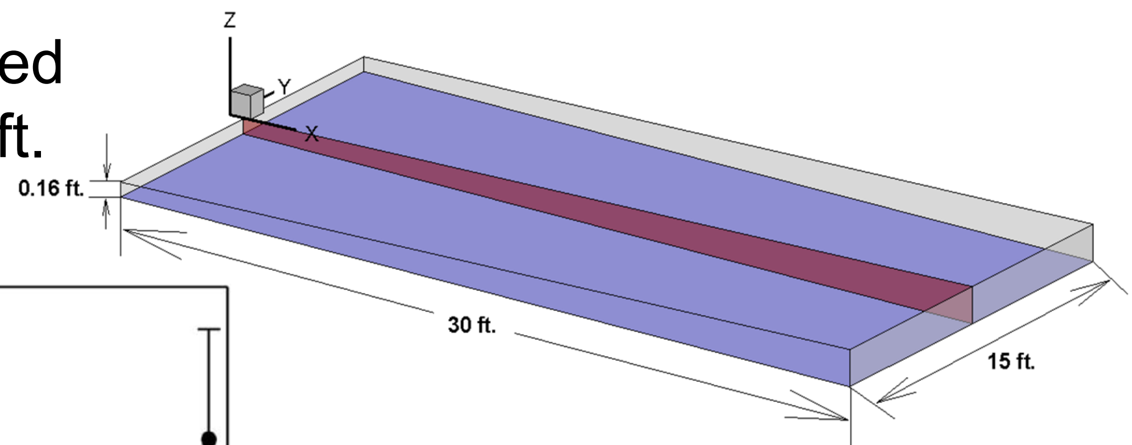
Advancing Transportation Through Innovation

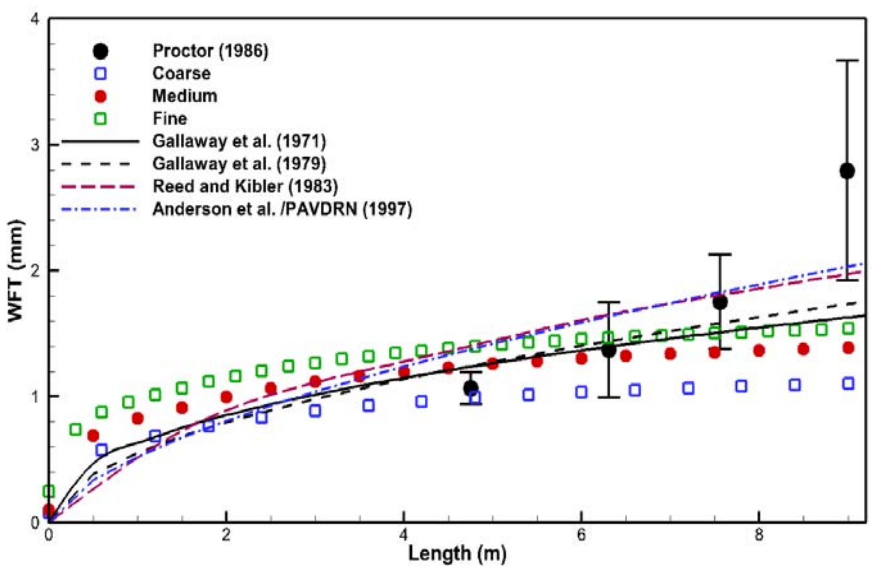
VirginiaTech Transportation Institute

Center for Sustainable Transportation Infrastructure

Mesh Definition and Initial Verification Work

- ✓ Proctor (1986) measured WFT on a 30-ft. by 15-ft.





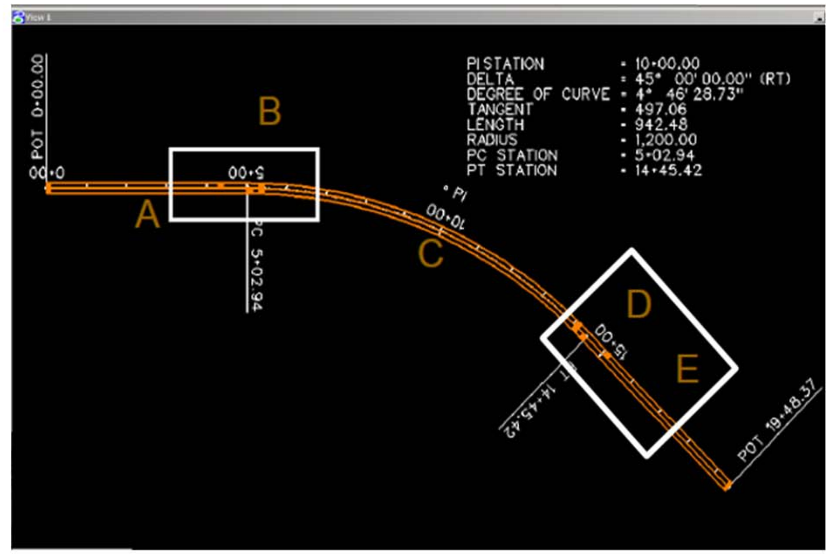
Advancing Transportation Through Innovation

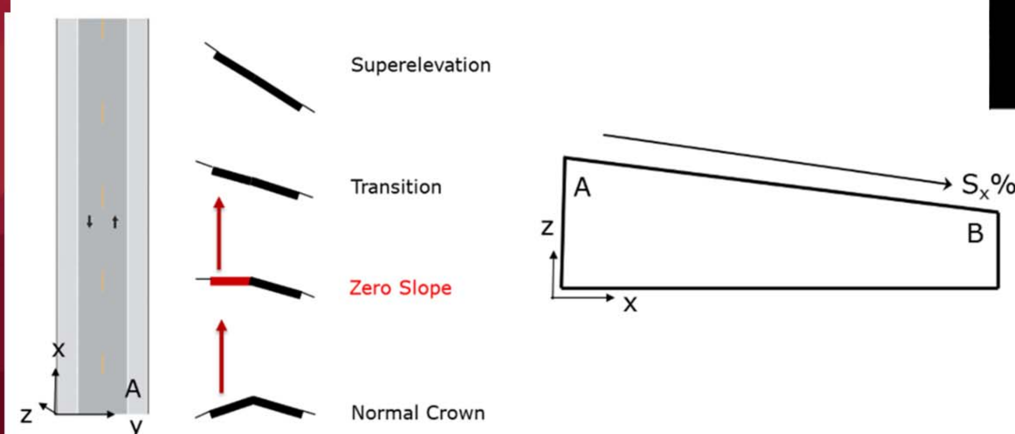
VirginiaTech Transportation Institute

Center for Sustainable Transportation Infrastructure

Water Film Thickness Sensitivity Analysis

✓ Modeled Transitions



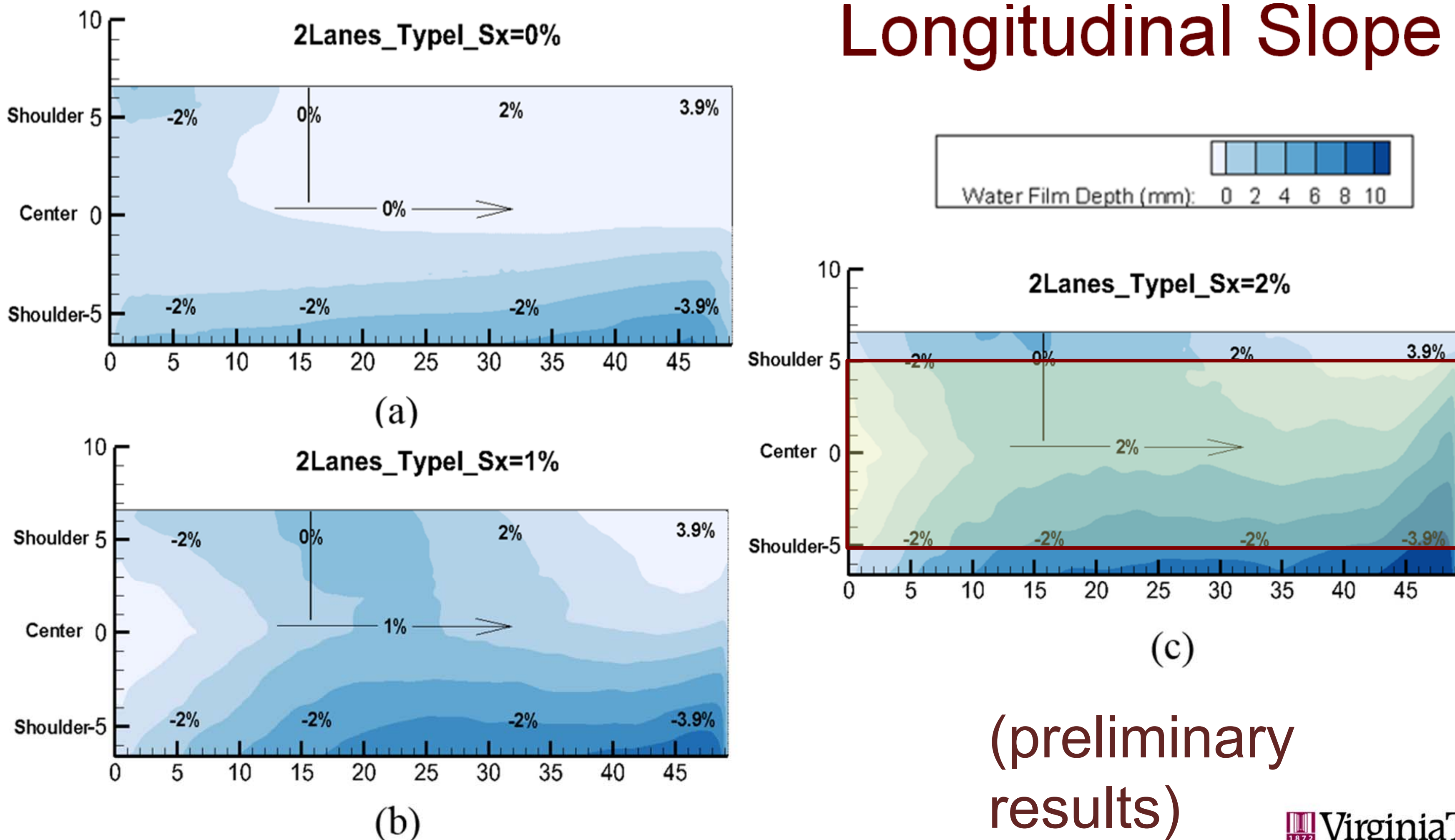


(a) (b)

VirginiaTech Transportation Institute

Center for Sustainable Transportation Infrastructure

Longitudinal Slope



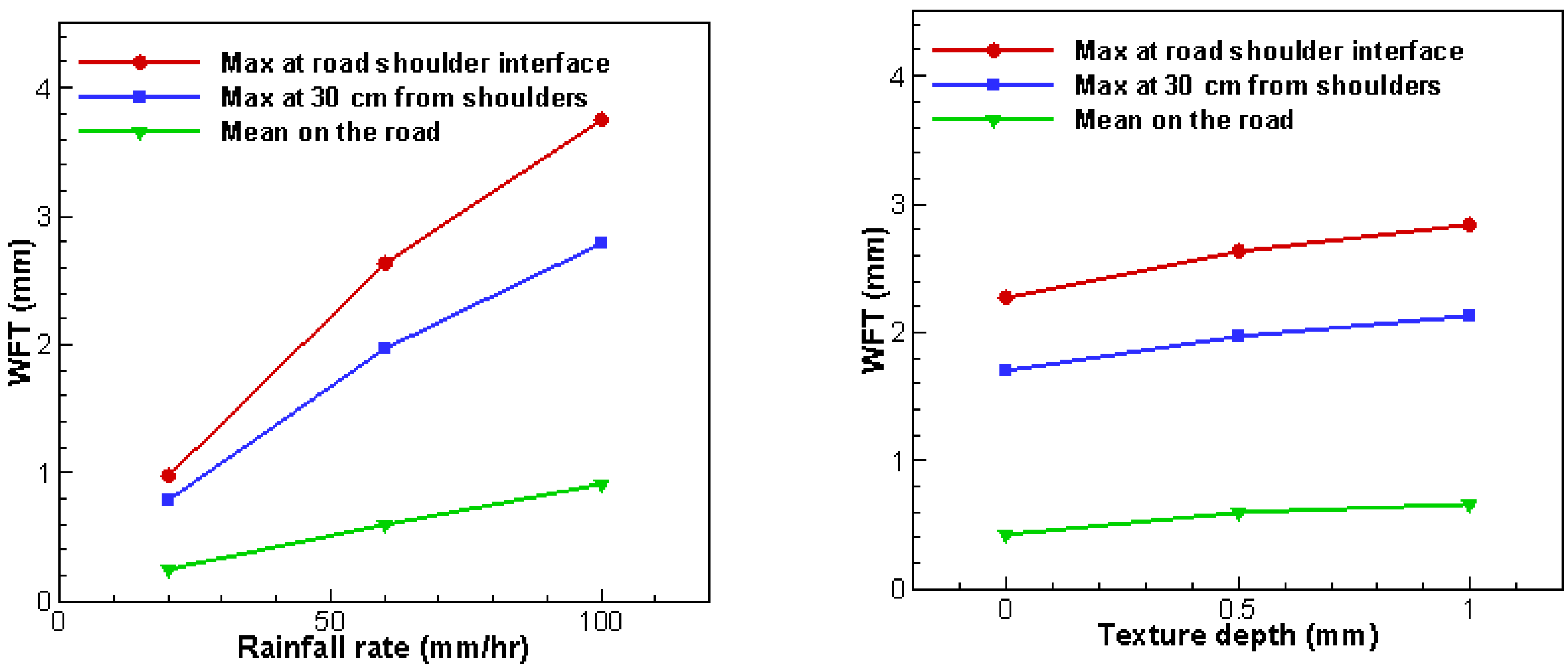
(preliminary results)

Advancing Transportation Through Innovation

VirginiaTech Transportation Institute

Center for Sustainable Transportation Infrastructure

Example of Preliminary Results



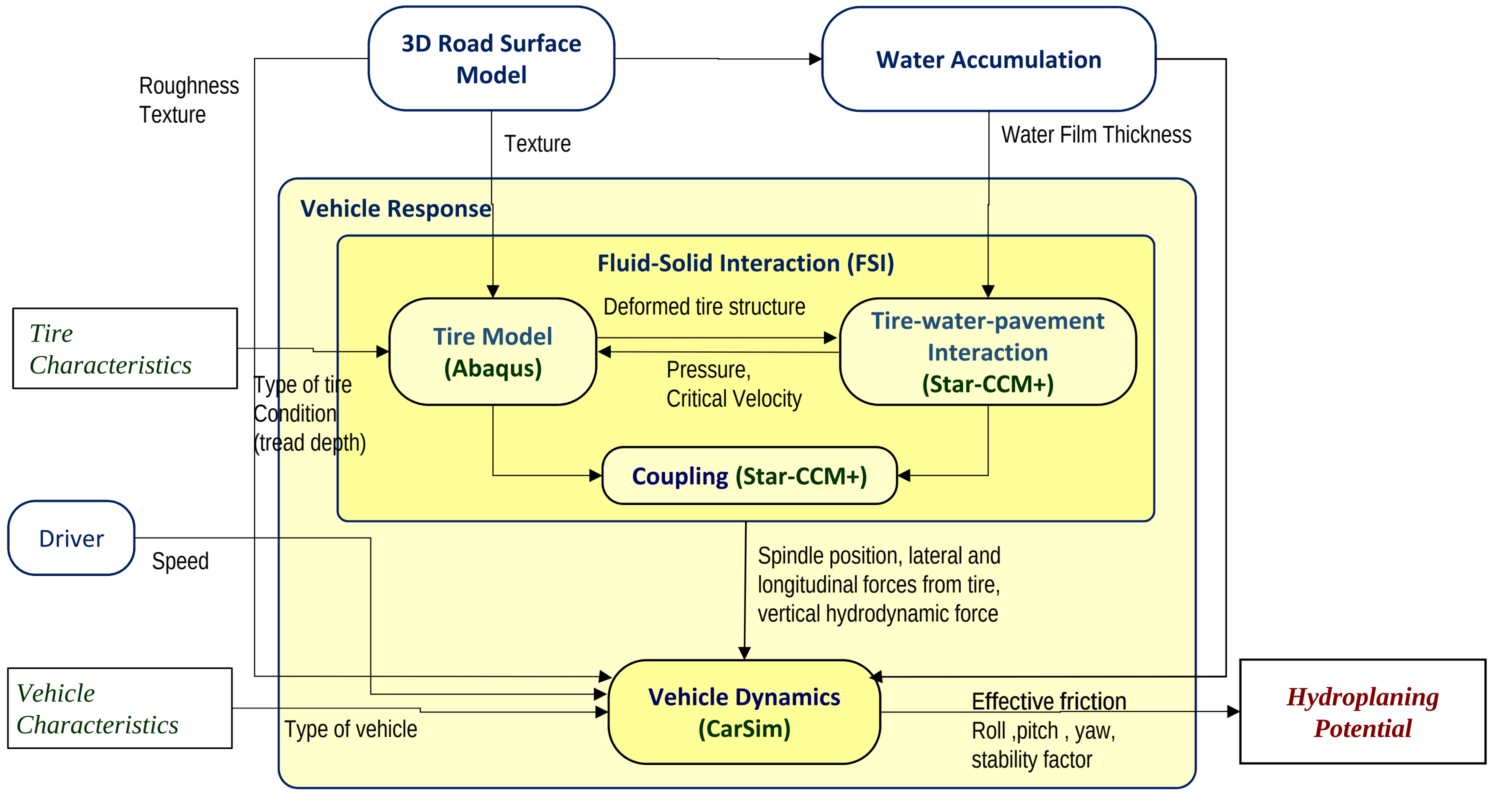
Advancing Transportation Through Innovation

VirginiaTech Transportation Institute

Vehicle Handling Model

Center for Sustainable Transportation Infrastructure

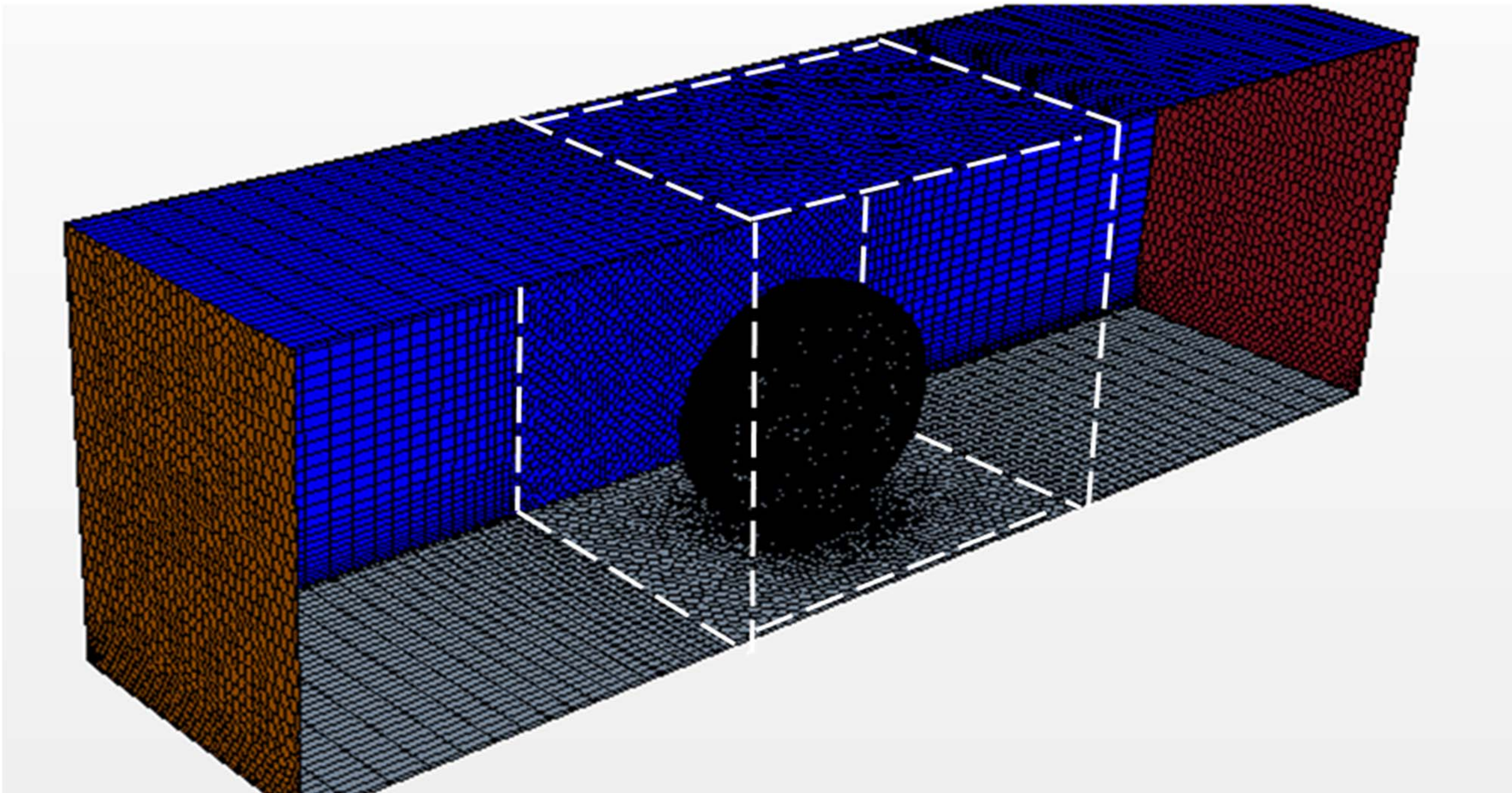
Vehicle Model



VirginiaTech Transportation Institute

Center for Sustainable Transportation Infrastructure

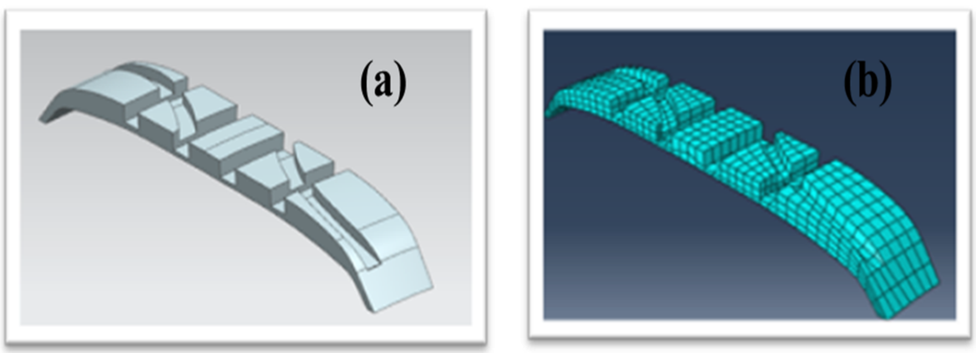
FSI Model Domain

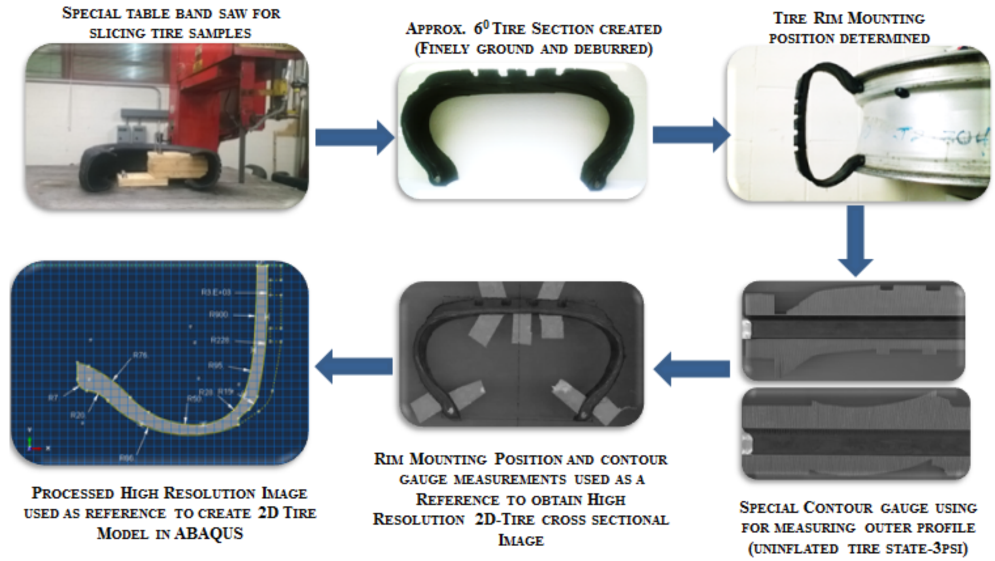


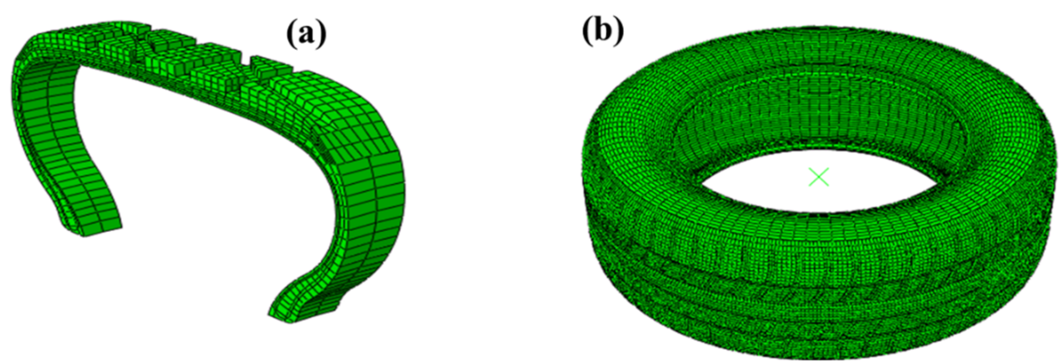
Advancing Transportation Through Innovation

Center for Sustainable Transportation Infrastructure

Tire Model



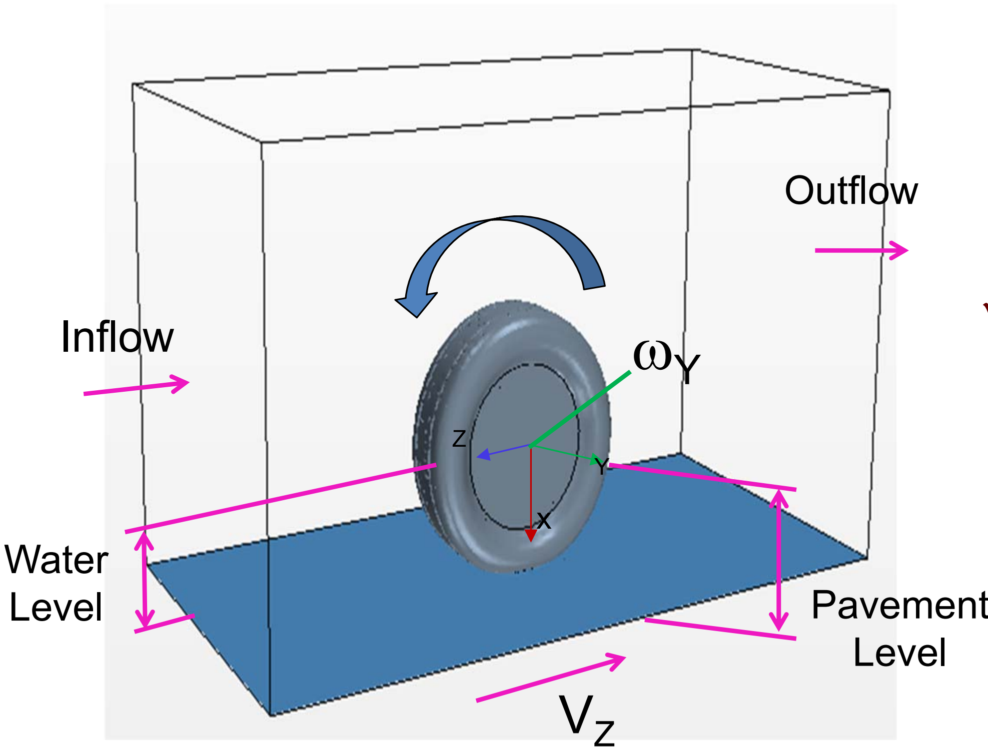




Advancing Transportation Through Innovation

Center for Sustainable Transportation Infrastructure

FSI Model Setup



✓ Models setup in Star-CCM+
- Implicit Unsteady ($\Delta t = 5\times10^{-4}$ s)
- Eulerian Multiphase (air, water)
- SST K-Omega turbulence model
- VOF waves (water film)

X – toward pavement;
Y – cross stream direction;
Z – car travel direction.

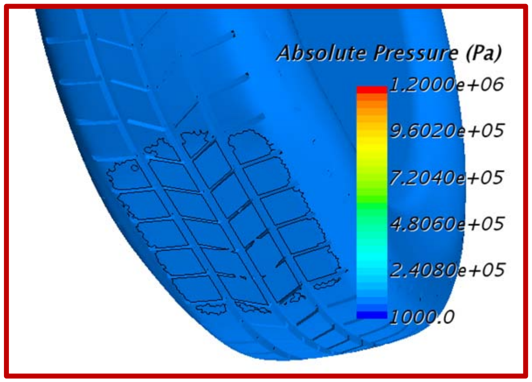
◆ Initial Boundary conditions:

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

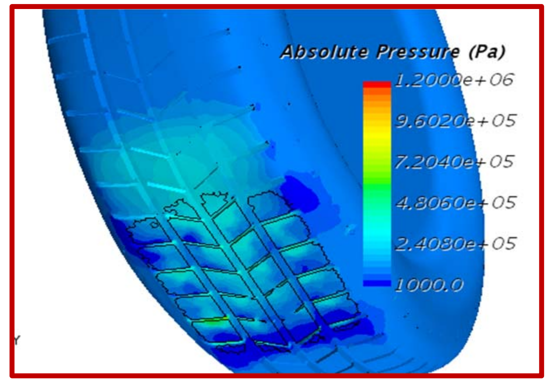
Center for Sustainable Transportation Infrastructure

Effects of water film (preliminary results)

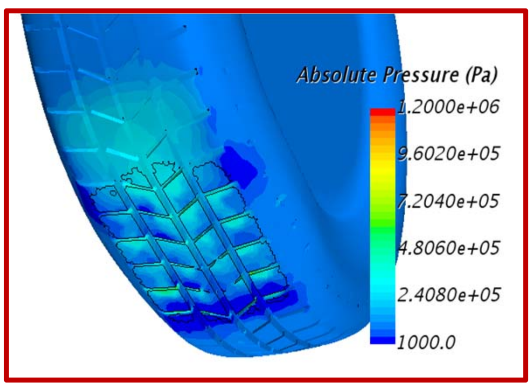
Water 0 mm



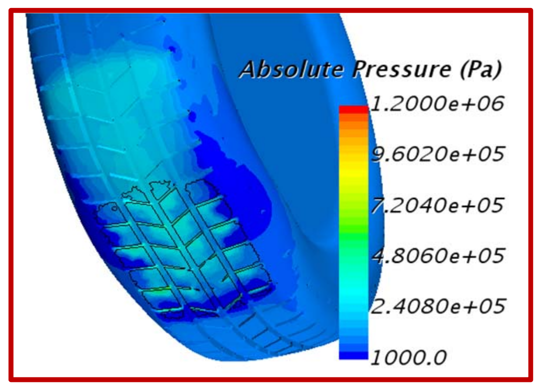
Water 5 mm



Water 8 mm



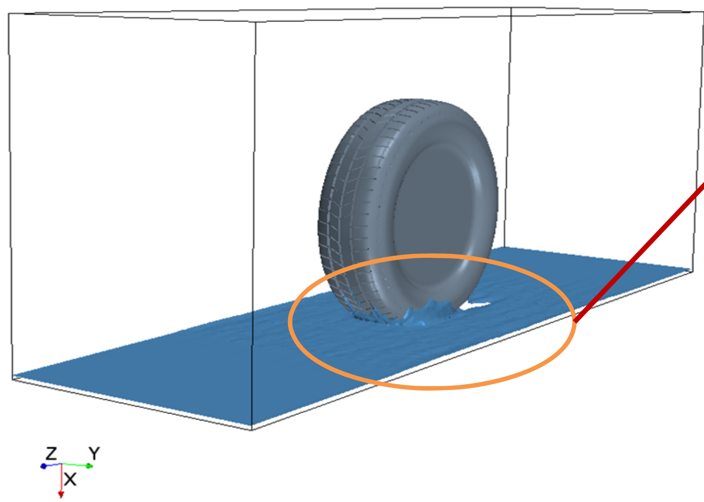
Water 30 mm

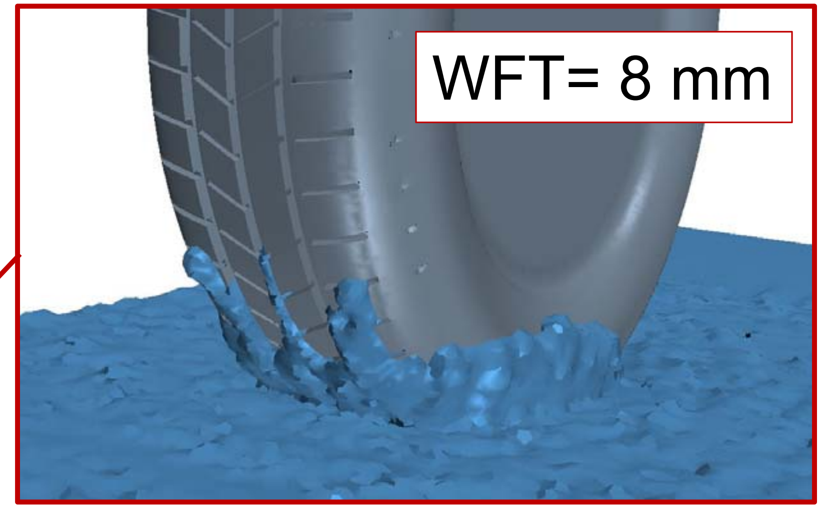


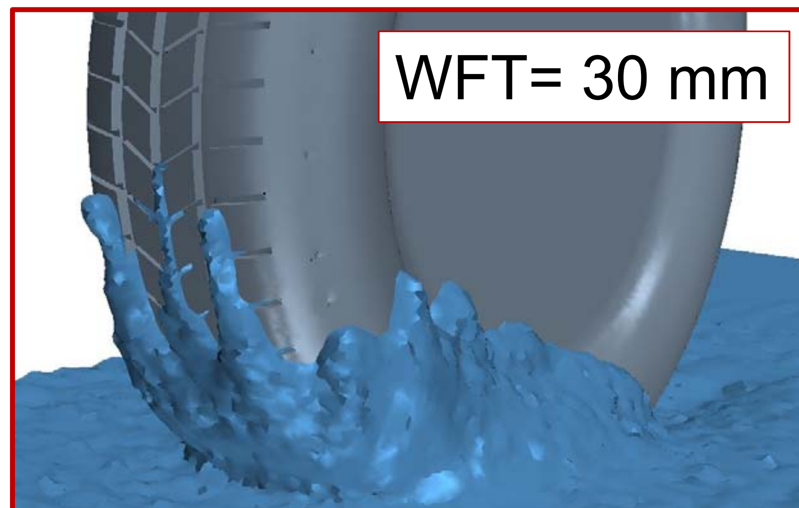
VirginiaTech Transportation Institute

Center for Sustainable Transportation Infrastructure

Water splash





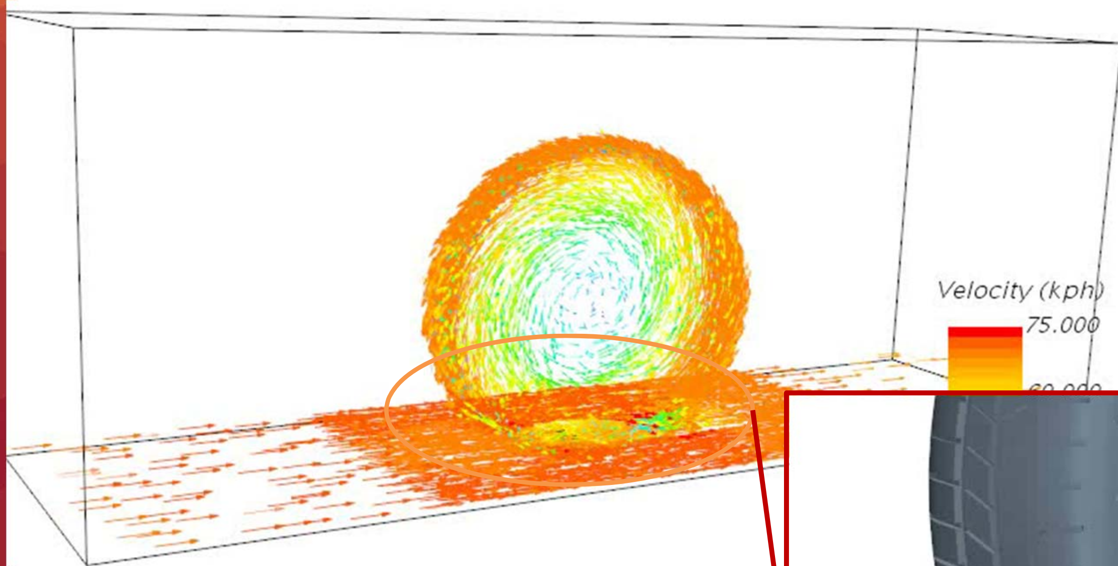


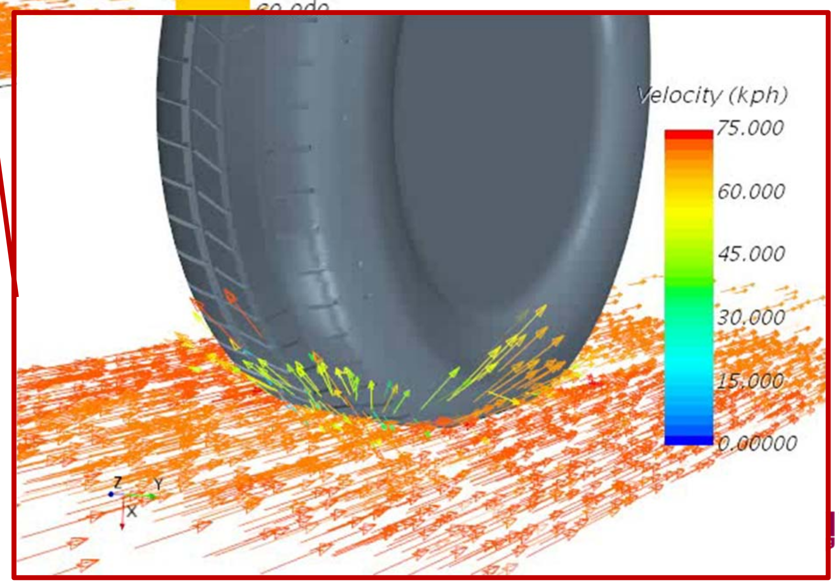
Tech
Transportation Institute

Center for Sustainable Transportation Infrastructure

Velocity Vectors

WFT= 8 mm

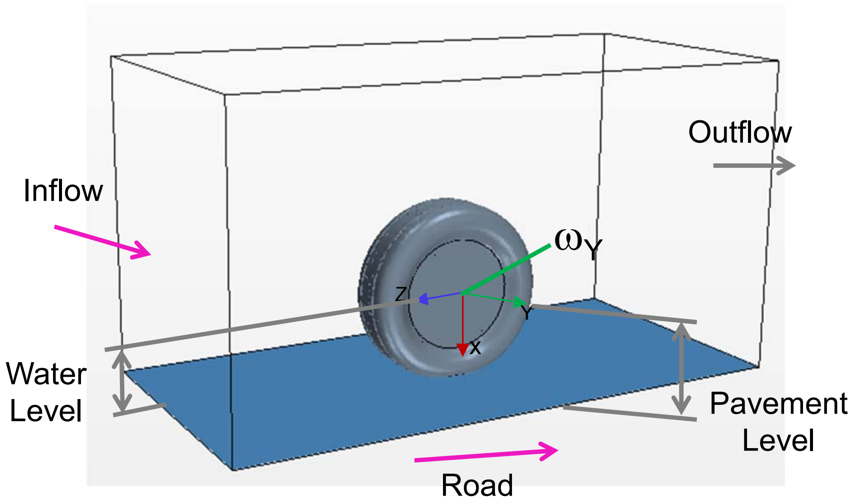


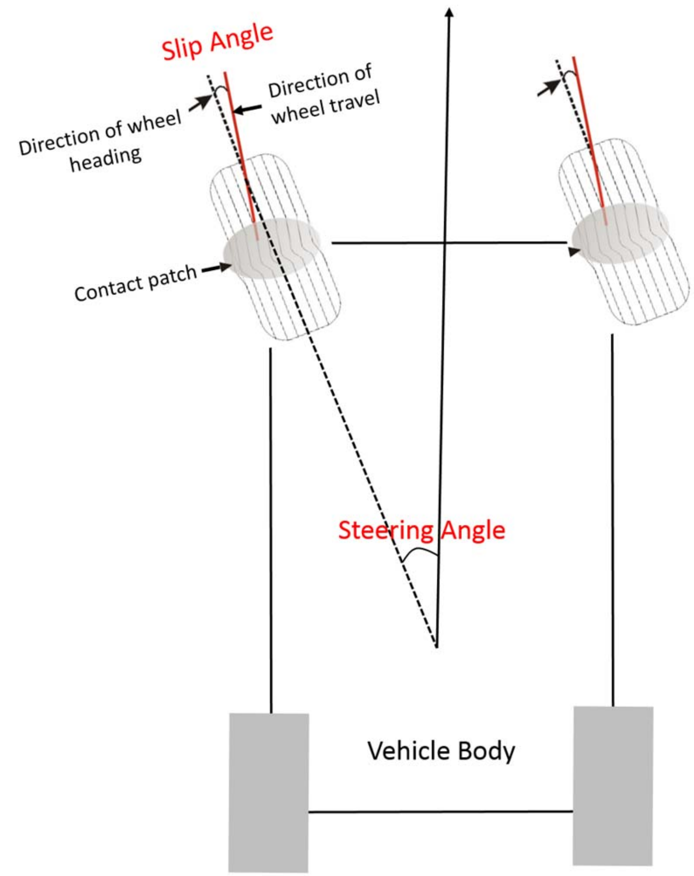


VirginiaTech
Transportation Institute

Center for Sustainable Transportation Infrastructure

FSI model with slip angle 2º

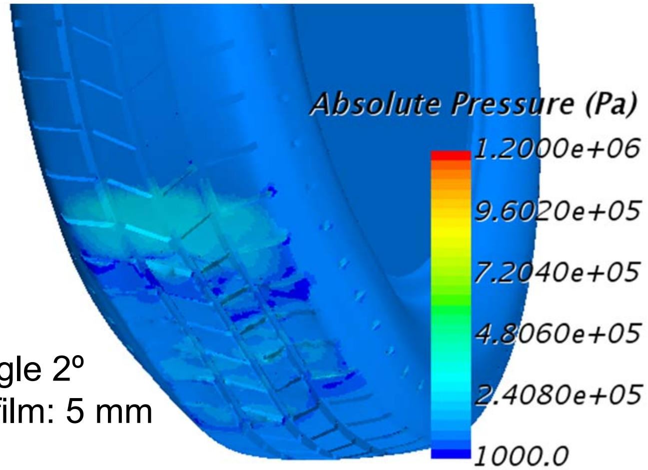




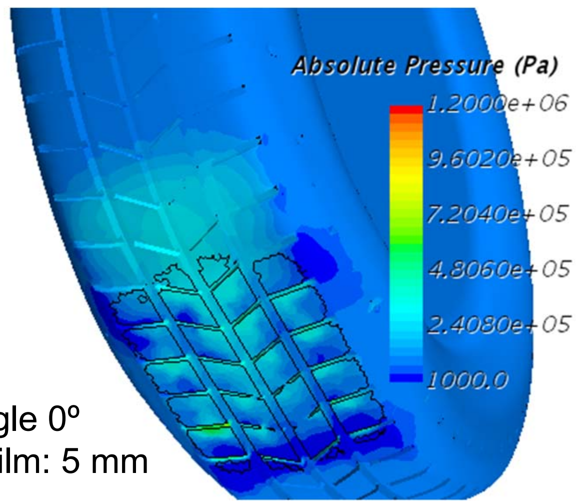
- Operating conditions:
  - Water film velocity: [0.0, -0.6239262, -17.867] m/s
  - Inflow velocity [0.0, -0.6239262, -17.867] m/s
  - Pavement: [0.0, -0.6239262, -17.867] m/s
  - Side and top surfaces: Free-slip wall
  - Tire: Local rotation rate, ω_Y=61.19 rad/s

Center for Sustainable Transportation Infrastructure

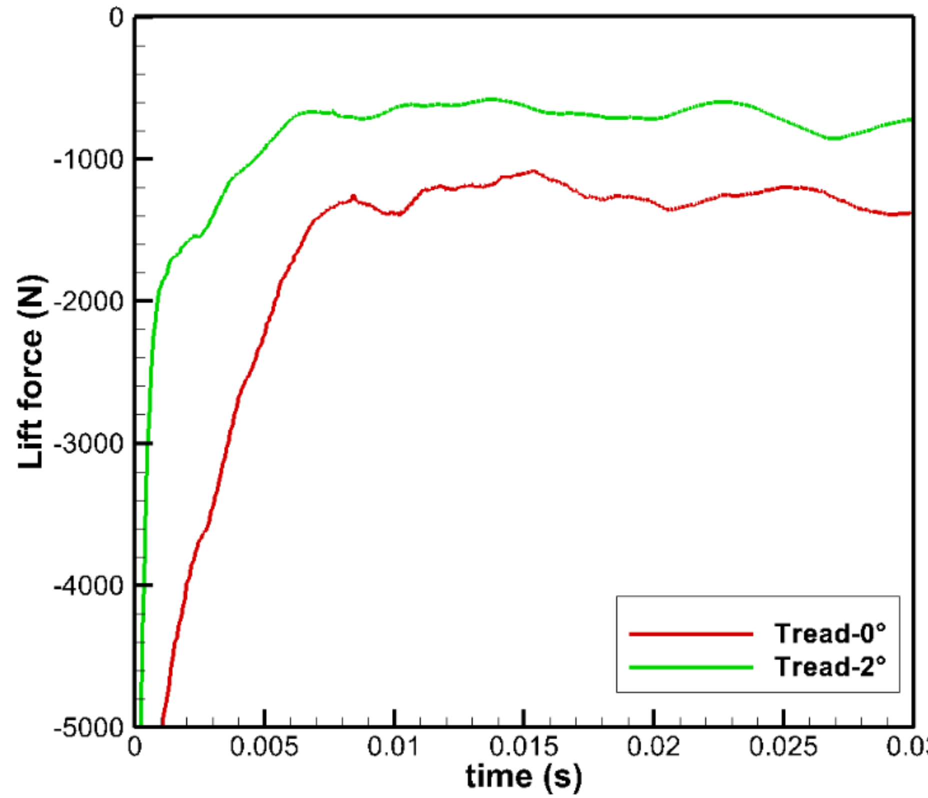
Pressure: effects of slip angle



Slip angle 2º
Water film: 5 mm

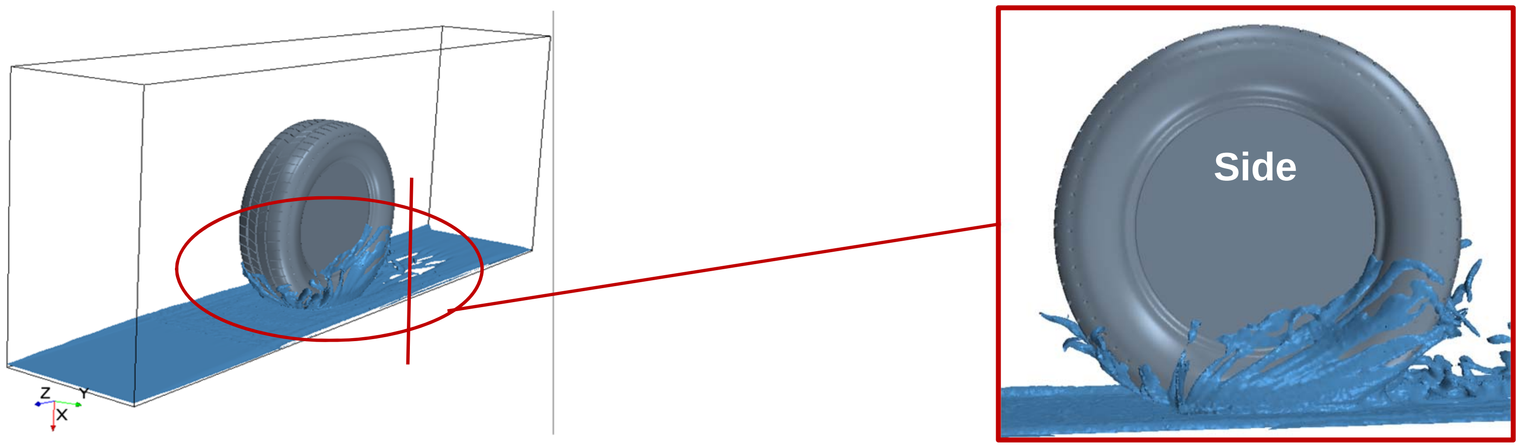


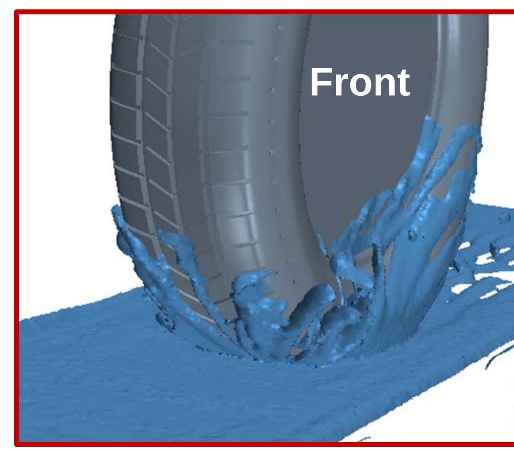
Slip angle 0º
Water film: 5 mm



VirginiaTech Transportation Institute

Effect on contact patch and water splashing



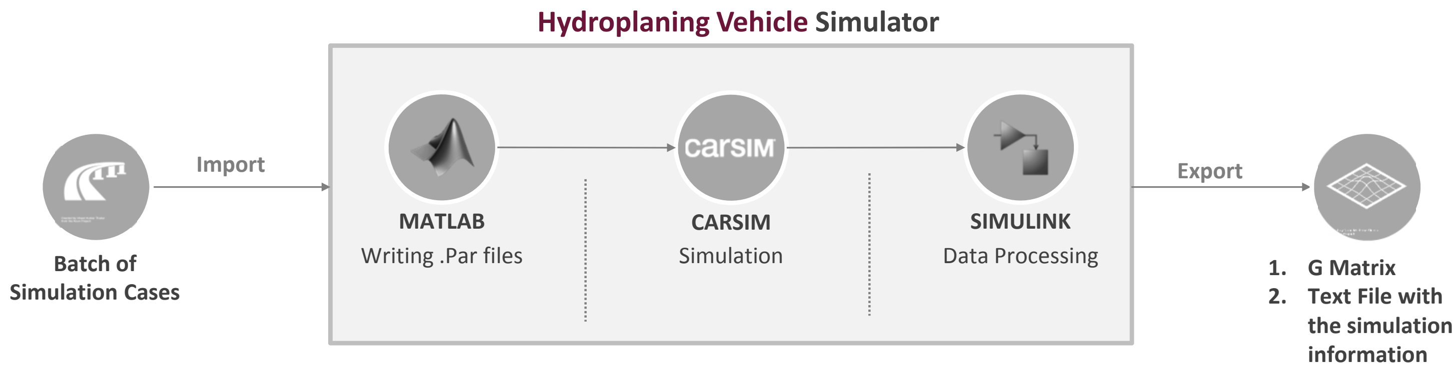


Center for Sustainable Transportation Infrastructure

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)



VirginiaTech Transportation Institute

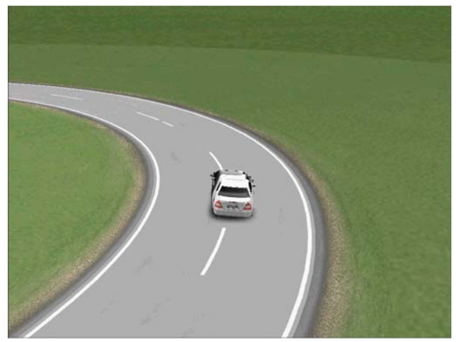
Center for Sustainable Transportation Infrastructure

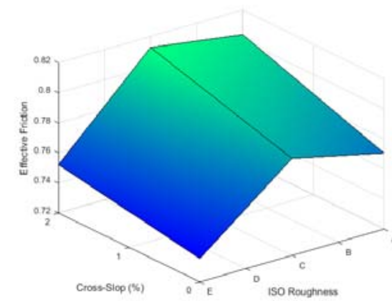
Hydroplaning Vehicle Simulator & G Value

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

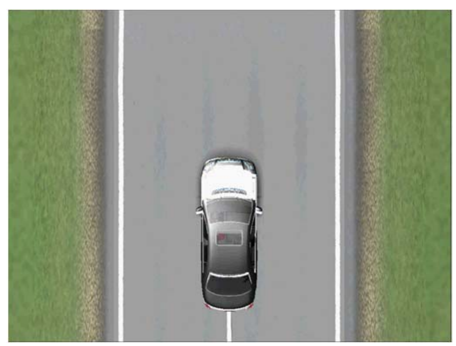
Vehicle	Maneuver	Grade	Cross-slope	Roughness	WFT	Tire
Vehicle cornering						
Hatchback	0mph to Max. mph	0%	0%	ISO A	Dry	Bald
Sedan			2%	ISO C	2mm	Min tread depth
SUV				IOS E	5mm	
					10mm	
Vehicle braking						
Hatchback	Braking test	0%	0%	ISO A	Dry	Bald
Sedan		2%		ISO C	2mm	Min tread depth
SUV		6%		ISO E	5mm	
					10mm	

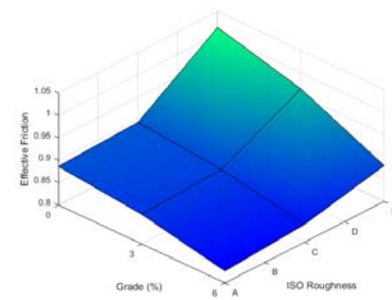
Vehicle Cornering Simulation





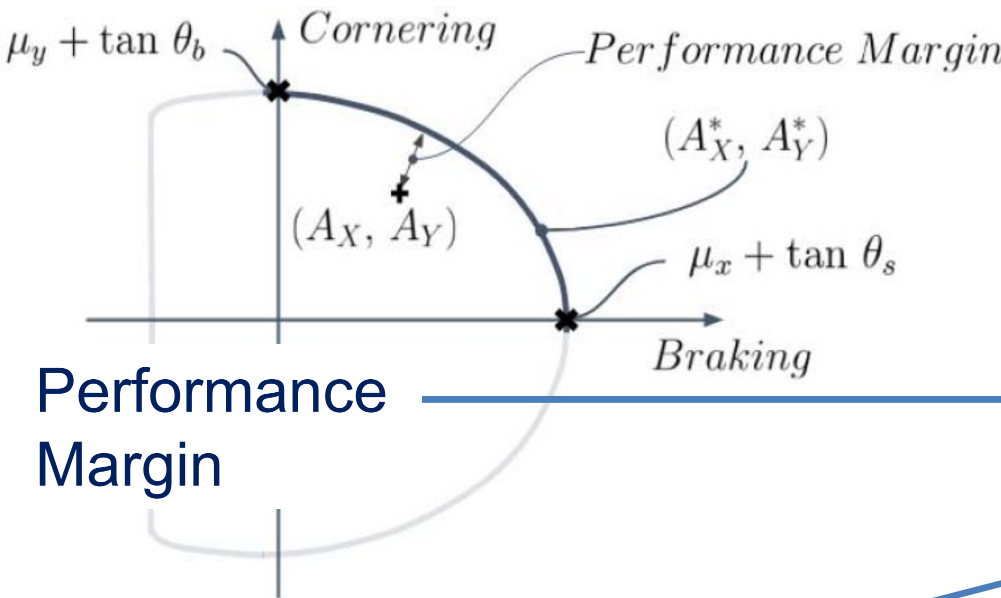
Vehicle Braking Simulation



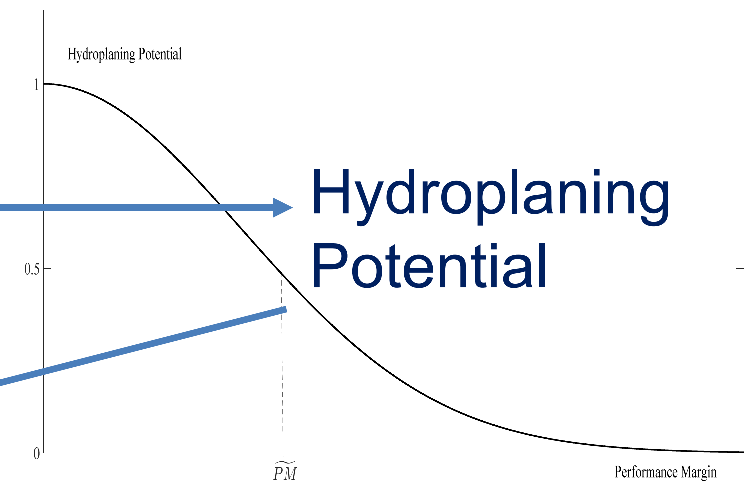


Center for Sustainable Transportation Infrastructure

Proposed Approach



Performance Margin → Hydroplaning Potential



Hydroplaning Risk

$$P\,(H \mid R) = \sum_i \sum_j P\,(H \mid R\,V_i\,W_i)\,P\,(V_i \mid R)\,P\,(W_j \mid R)$$

Advancing Transportation Through Innovation

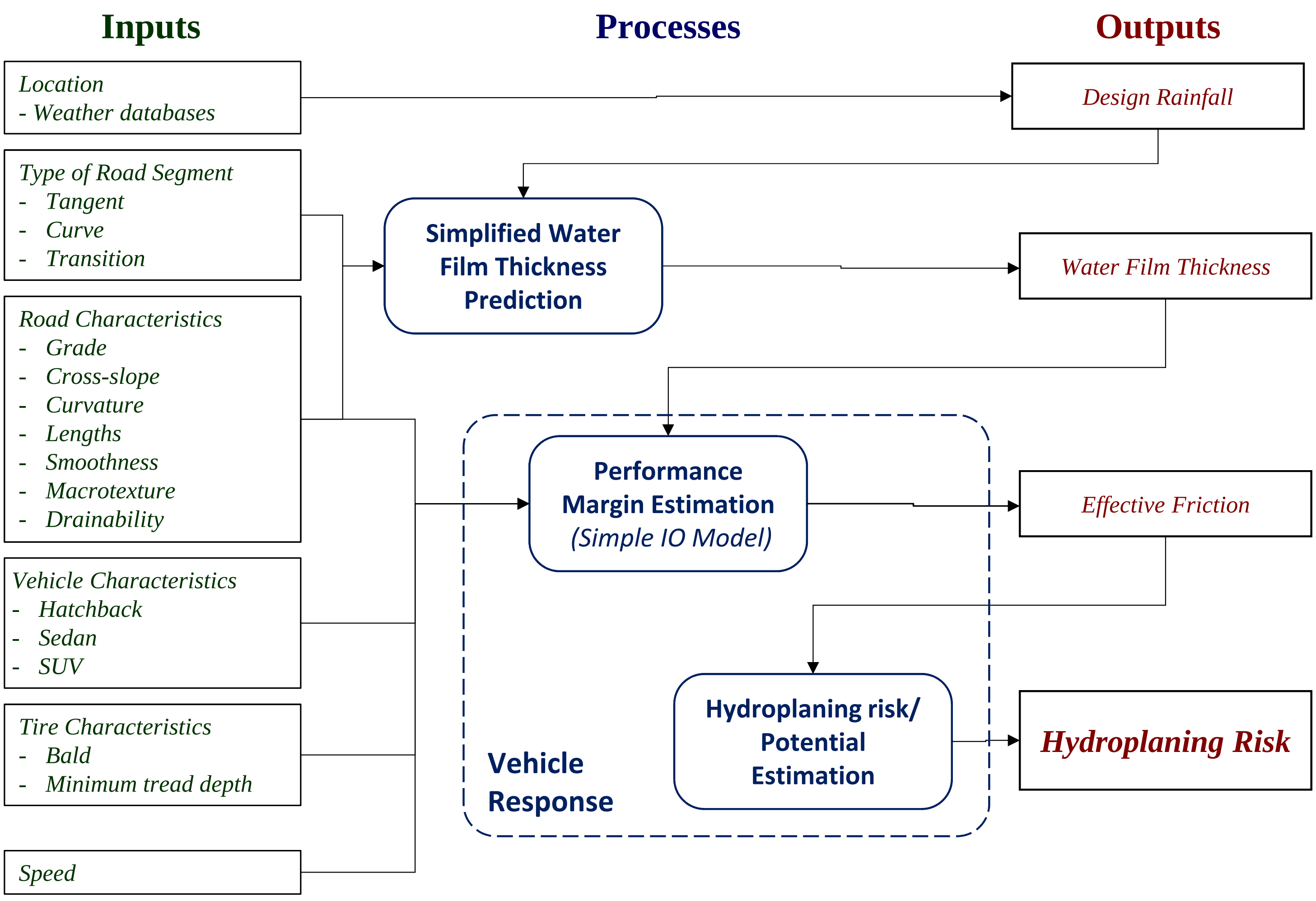
VirginiaTech Transportation Institute

Center for Sustainable Transportation Infrastructure

Expected Products

Center for Sustainable Transportation Infrastructure

Proposed Hydroplaning Risk Assessment Tool Format



VirginiaTech Transportation Institute

Center for Sustainable Transportation Infrastructure

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

Advancing Transportation Through Innovation

VirginiaTech Transportation Institute

Center for Sustainable Transportation Infrastructure

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

Advancing Transportation Through Innovation

VirginiaTech Transportation Institute

Concluding Remarks

Center for Sustainable Transportation Infrastructure

Concluding Remarks

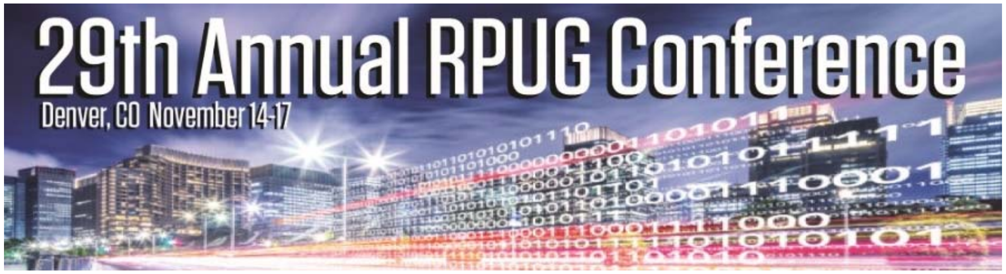
- ✓ **Ongoing work**
  - All results may change
- ✓ **Some significant advances**
  - Water film thickness prediction
  - Hydroplaning definition & assessment approach

- ✓ Main product:
  - **Guide to predict and mitigate hydroplaning on roadways**
- ✓ Secondary products
  - Hydroplaning Assessment tool (practitioners)
  - "Integrated" Hydroplaning Model (researchers)

Advancing Transportation Through Innovation

VirginiaTech Transportation Institute

Center for Sustainable Transportation Infrastructure



Virginia Tech
Invent the Future

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

http://auto.howstuffworks.com/car-driving-safety/accidents-hazardous-conditions/hydroplaning.htm

Gerardo W. Flintsch

29th RPUG Conference
Marriott Denver West, Golden, CO
November 14 to 17, 2017

Vehicle Terrain Performance Laboratory (VTPL) | *Computational Research for Energy Systems & Transport (CREST) Laboratory* | *Center for Tire Research (CenTire)* | *Center for Sustainable Transp. Infrastructure (CSTI)* | Virginia Tech Transportation Institute