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QUANTIFYING HYDROPLANING RISK: A MONTE CARLO SIMULATION APPROACH FOR ENHANCING ROADWAY SAFETY IN TEXAS

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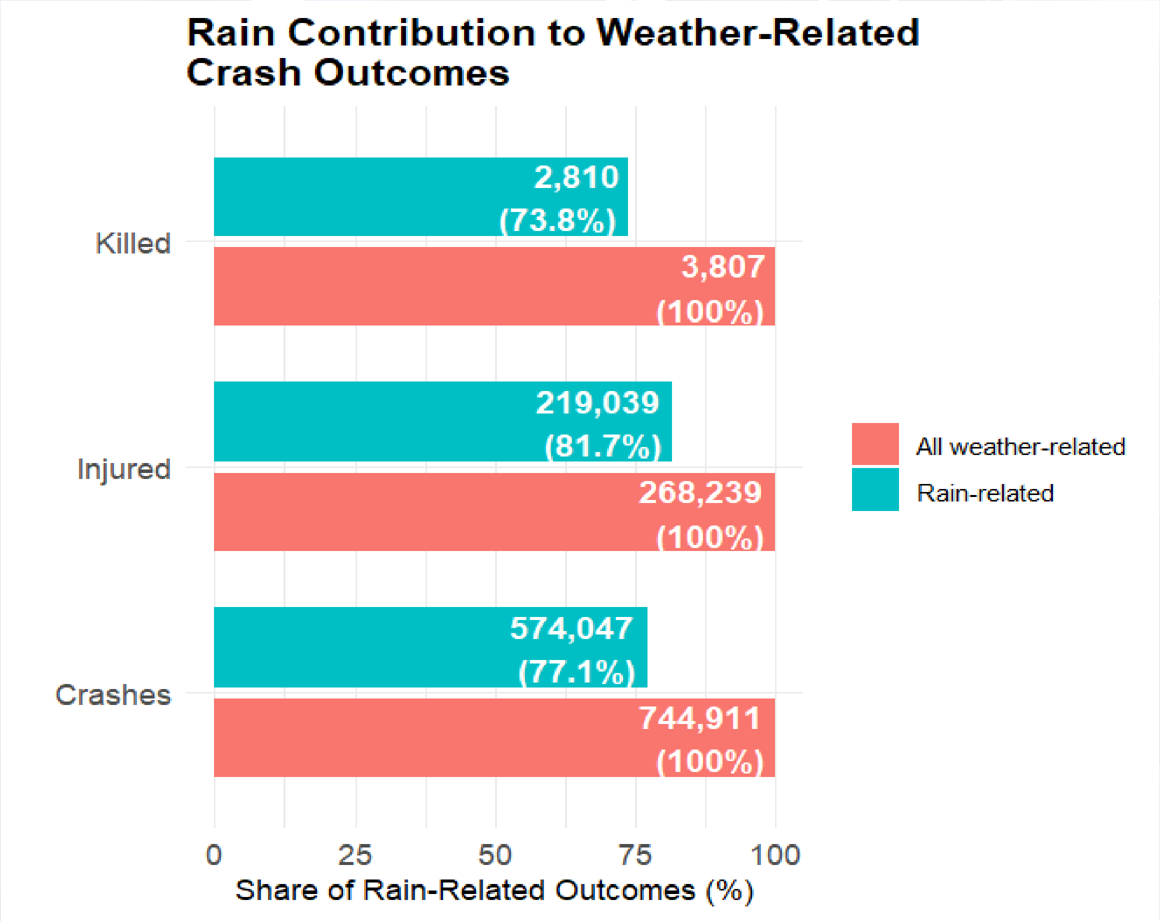
PRESENTATION OUTLINE

- BACKGROUND
- PROBLEM STATEMENT
- RESEARCH OBJECTIVE
- LITERATURE REVIEW
- METHODOLOGY
- RESULTS
- KEY FINDINGS

BACKGROUND

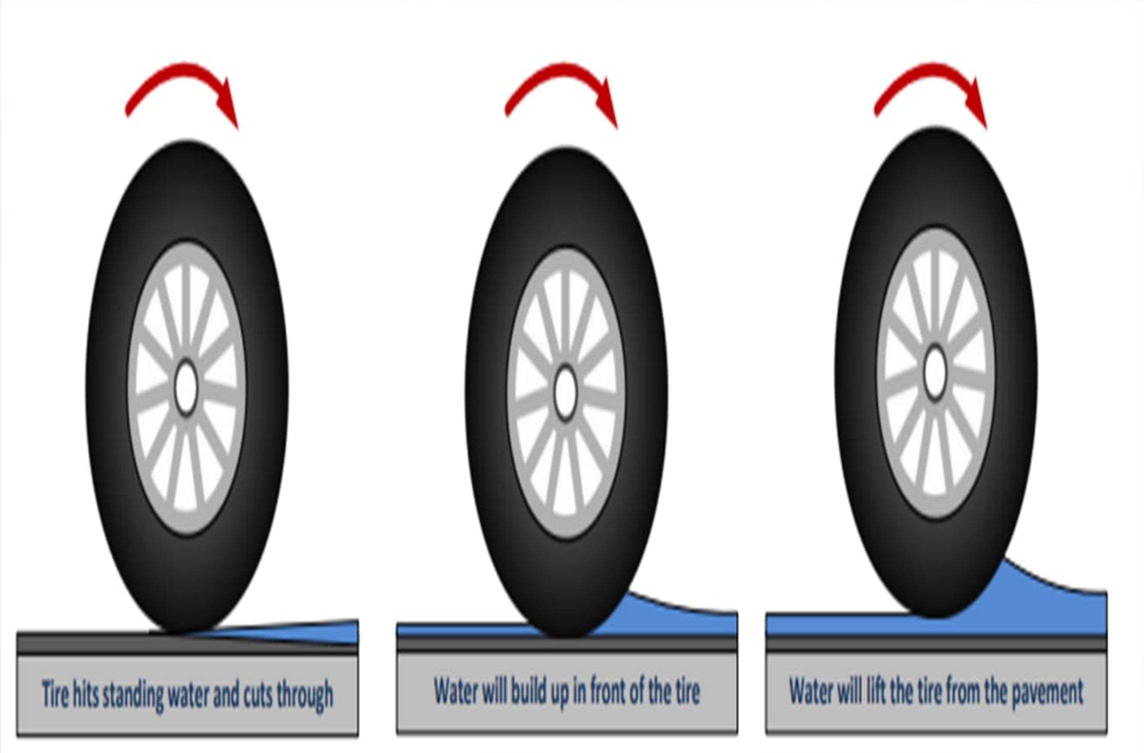
- According to National Highway Traffic Safety Administration (NHTSA) data analysis
  Total weather crashes~744,000 / year
  Rain-related crashes~574,000 / year
  Rain fatalities~2,800 / year
- Hydroplaning is one of the rain driven crashes.
- Texas ranks in the top two states of the US for total annual frequency of hydroplaning high- risk events (Salvi & Kumar, 2022)



Weather related crash statistics (5-year averages, 2019-2023) (Source: FHWA)

WHAT IS HYDROPLANING?

- Occurs when a layer of water builds between the vehicle's tires and the road surface.
- Tire separation from pavement surface
- Consequences: loss of traction, preventing the vehicle from responding to steering, braking, or accelerating.



Representation of hydroplaning (Source: Lee & Ayyala, 2020)

PROBLEM STATEMENT

Variability in parameters contributing to hydroplaning

- Rainfall intensity fluctuates.
- Pavement geometry and texture vary spatially.
- Vehicle tire characteristics are not uniform.

Deterministic approach

- Assumes fixed input values for all variables
- Does not account for variability/uncertainty in real world conditions.
- Results in limited accuracy and reliability in risk assessment.

The need for probability - provides a robust, quantifiable safety metric

RESEARCH OBJECTIVES

1. To develop a probabilistic framework through Monte Carlo simulation (MCS) to compute the probability of hydroplaning by incorporating parameter variability.
2. To utilize Gallaway's equation as the core prediction model within the MCS framework.
3. To integrate high-res data and create a methodology for processing lidar roadway geometry and stochastic rainfall data.

LITERATURE REVIEW

TYPES OF HYDROPLANING

Horne (1968) classified hydroplaning into three distinct categories:

Dynamic hydroplaning
- High speed
- High water film thickness (WFT)

Viscous hydroplaning
- Thin film, smooth surface
- Low speed

Reverted rubber hydroplaning
- Locked wheels, heat generation
- Mostly encountered by aircraft/ trucks

DYNAMIC HYDROPLANING FOCUS

Why this focus?

Dynamic hydroplaning is the most common safety concern for passenger cars traveling at highway speeds during typical heavy rainfall events (Ivey & Mounce, 1984; Spitzhüttl et al., 2020)

LITERATURE REVIEW

FACTORS AFFECTING HYDROPLANING

- Roadway factors: Pavement texture, Cross slope, Grade, Pavement width, Rutting
- Environmental factors: Rainfall intensity, Rainfall duration
- Vehicle factors: Tire pressure, Tread depth, Vehicle type

LITERATURE REVIEW

WATER FILM THICKNESS (WFT) MODELS

Model (Author, Year)	Water Film Thickness Equation	Key Notes / Limitations
British RRL Model (Watkins et al., 1963; Ross et al., 1968)	WFT (in) = $0.005\ (L_f * I)^{0.47}\ S_f^{-0.20}$ Where L_f = Drainage length (ft) I= Rainfall intensity (in/hr) S_f = Slope of flow path (ft/ft)	• Developed using extremely coarse-textured pavements • Limited applicability to modern U.S. highways. • Doesn't include pavement texture
Gallaway WFT Model (Gallaway et al., 1971)	WFT (in) = $[3.38 * 10^{-3}\ (MTD)^{0.11}(L_f)^{0.43}(I)^{0.59}(S_f)^{-0.42}] - MTD$ Where MTD = Mean Texture Depth (in) L_f = Drainage length (ft) I= Rainfall intensity (in/hr) S_f = Slope of flow path (ft/ft)	• Empirical model
PAVDRN WFT Model (Anderson et al., 1998)	WFT (in) = $[\frac{n * L_{f} * I}{36.1 * Sf^{0.5}}]^{0.6} - MTD$ Where n= Manning's roughness coefficient L_f = drainage length (in) I= rainfall rate (in/hr) – infiltrate rate of pavement (in/hr) S_f = Slope of flow path (mm/mm)	• Semi-empirical model based on kinematic wave theory • Sensitive to Manning's roughness coefficient

LITERATURE REVIEW

Hydroplaning speed (HPS) Models

Model (Author, Year)	Hydroplaning Speed Equation	Key Limitations
NASA Model (Horne et al., 1963, 1986)	$HPS = 6.36\sqrt{P_t}$ $HPS = 51.80 - 17.15\,(FAR) + 0.72\,P_t$ Where, HPS= Hydroplaning speed (mph) FAR= Tire footprint Aspect Ratio ($\frac{tread\ width}{length}$) P_t= Tire inflation pressure (psi)	• Does not explicitly include water film thickness • Pavement texture effects neglected
Gallaway Model (Gallaway, 1979)	HPS = $SD^{0.04}P_t^{0.3}(TD+1)^{0.06}A_T$ Where, A_T is the greater of: A_{T1}= $\frac{10.409}{\text{WFT\^{}0.06}}$ + 3.507 or A_{T2}=$\left[\frac{28.952}{WFT^{0.06}} - 7.817\right]MTD^{0.14}$ Where: HPS = Vehicle speed while hydroplaning (mph) SD = Spindown (percent) P_t = Tire Pressure (psi) TD = Tire Tread Depth (1/32 inch) WFT = Water film thickness (inch) MTD = Mean Texture Depth (inch)	• Empirical curve-fitting model

LITERATURE REVIEW

HYDROPLANING SPEED (HPS) MODELS

Model (Author, Year)	Hydroplaning Speed Equation / Concept	Key Limitations
PAVDRN Model (Anderson et al., 1998)	For WFT < 2.4 mm (0.094 in): $HPS = 26.04 * WFT^{-0.259}$ Where, HPS = Hydroplaning Speed (mph) WFT = Water Film Thickness (inch) For WFT ≥ 2.4 mm (0.094 in): This model is frequently paired with the Gallaway WFT equation in practice. $HPS = 3.09 * A_T$ Where A_T is the previously defined parameter in Gallaway's equation for HPS.	• Simplified form of Gallaway model • Considers only WFT and MTD • Does not include any vehicle parameters
Numerical FE–CFD Model (Fwa & Ong, 2008)	Hydroplaning occurs when fluid uplift force equals wheel load.	• Computationally expensive • Requires detailed material properties • Not practical for network level analysis.
University of South Florida (USF) Model (Gunaratne et al., 2012)	$HPS = WL^{0.2} P_t^{0.5} (0.82/WFT^{0.06} + 0.49)$ Where, HPS = Hydroplaning Speed (kmph) WL = Wheel Load (N) P_t = Tire Pressure (kpa) WFT = Water film thickness (mm)	• Struggles to evaluate multiple planes with varying slopes • Model results extremely sensitive to the accuracy of the input parameters such as wheel load and tire pressure.

THE DATA CHALLENGE: RAINFALL RESOLUTION

Temporal Resolution

- Standard rainfall data is hourly.
- Hourly averages cannot capture short duration high intensity rainfall contributing to hydroplaning.

Non-Stationarity and Outdated Data

- NOAA Atlas 14 and USGS Depth-Duration-Frequency (DDF) curves rely on stable climate assumptions.
- Data used for analysis are outdated.
- Climate change requires models that can account for non-stationary extremes.

TOOL: STOCHASTIC RAINFALL MODELLING

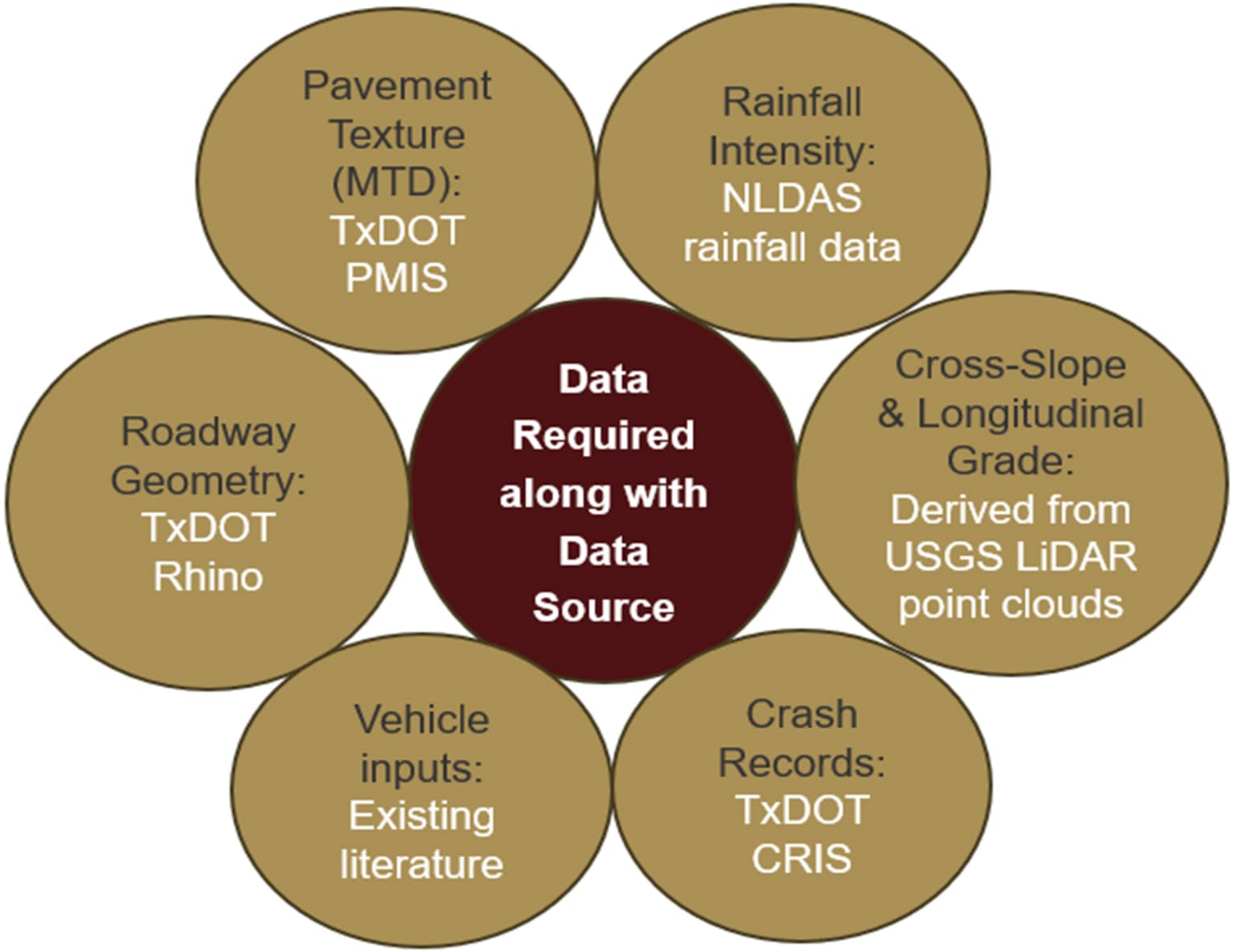
- The Randomized Bartlett-Lewis Rectangular Pulse Model (RBLRPM) solves the resolution and stationarity problem.
- RBLRPM is a widely used disaggregation model in hydrology.
- Function: Generates synthetic, high-resolution (down to 1 minute) rainfall series from coarse resolution data (disaggregation).
- Statistical integrity: preserves key properties of the historical record, particularly skewness (the indicator for extreme, high-intensity peaks).
- Allows us to model the peak intensity that causes WFT.

MODEL SELECTION JUSTIFICATION

Why Gallaway's model? (Gallaway et al., 1971; 1979)

- Comprehensive (multi factor) : Integrates tire pressure, tread depth, MTD, WFT, and wheel spin down.
- More complete than models based on limited variables.
- Robust empirical foundation: Developed from large-scale, multi-year testing (Texas A&M/TTI) across multiple pavement surfaces, including PCC-specific calibration.
- Official & widely accepted: TxDOT Hydraulic Design Manual and Austroads (Road Transport authority of Australia & New Zealand) recommend using this model for hydroplaning assessment; also widely cited in literatures.

DATASET DESCRIPTION



Data Required along with Data Source

Pavement Texture (MTD): TxDOT PMIS

Rainfall Intensity: NLDAS rainfall data

Cross-Slope & Longitudinal Grade: Derived from USGS LiDAR point clouds

Crash Records: TxDOT CRIS

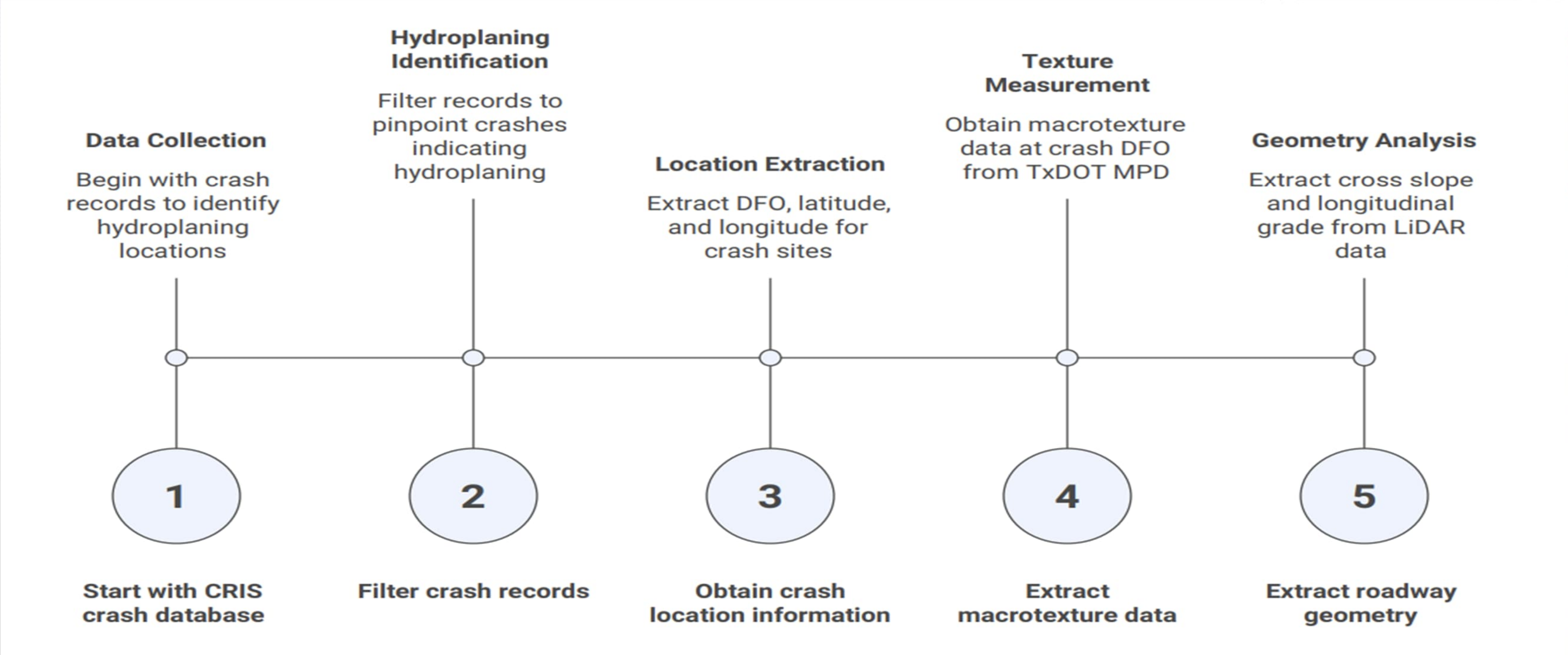
Vehicle inputs: Existing literature

Roadway Geometry: TxDOT Rhino

METHODOLOGY

FRAMEWORK

DATA PREPARATION



Data Collection

Begin with crash records to identify hydroplaning locations

1

Start with CRIS crash database

Hydroplaning Identification

Filter records to pinpoint crashes indicating hydroplaning

2

Filter crash records

Location Extraction

Extract DFO, latitude, and longitude for crash sites

3

Obtain crash location information

Texture Measurement

Obtain macrotexture data at crash DFO from TxDOT MPD

4

Extract macrotexture data

Geometry Analysis

Extract cross slope and longitudinal grade from LiDAR data

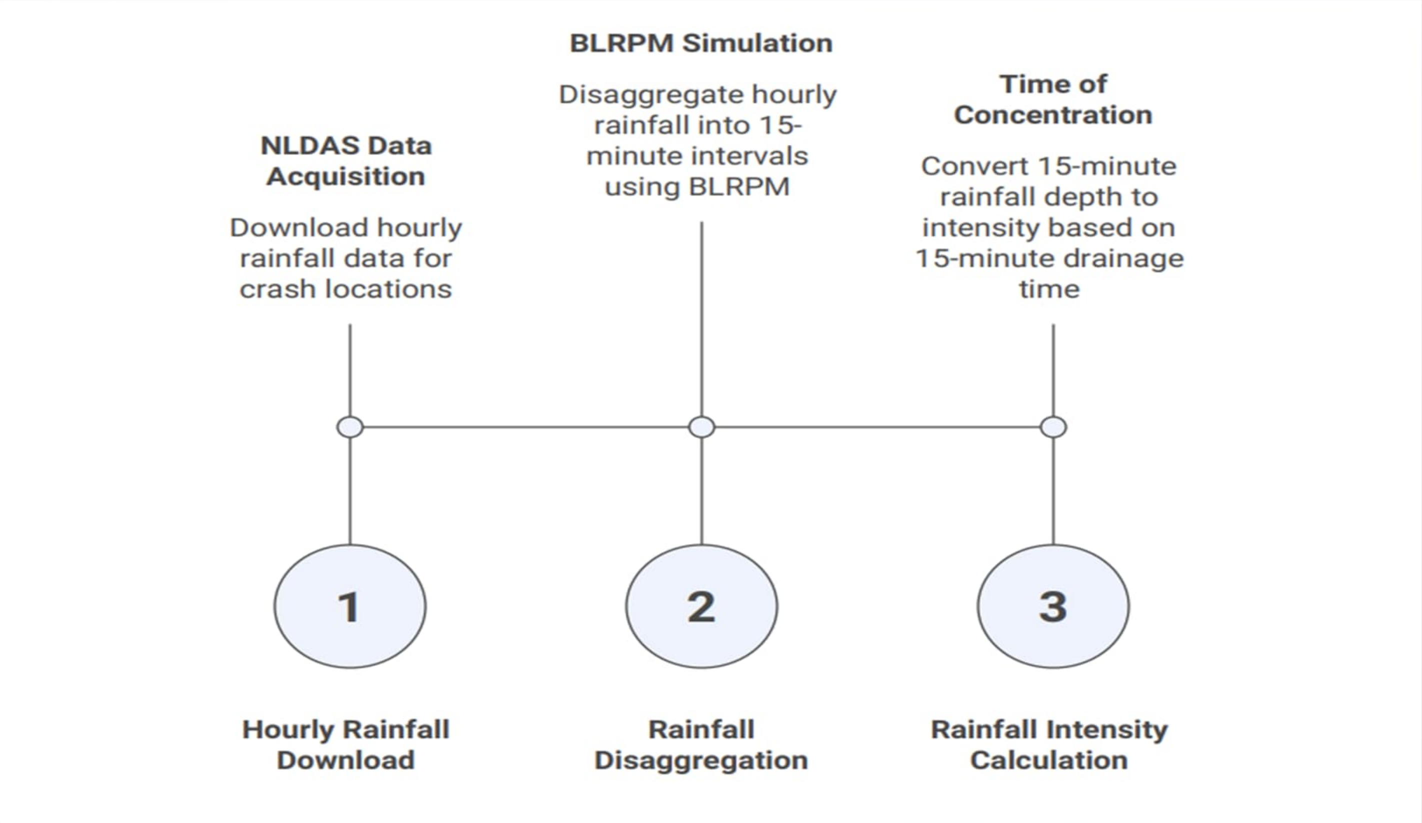
5

Extract roadway geometry

METHODOLOGY

FRAMEWORK

RAINFALL DATA PROCESSING



NLDAS Data Acquisition

Download hourly rainfall data for crash locations

BLRPM Simulation

Disaggregate hourly rainfall into 15-minute intervals using BLRPM

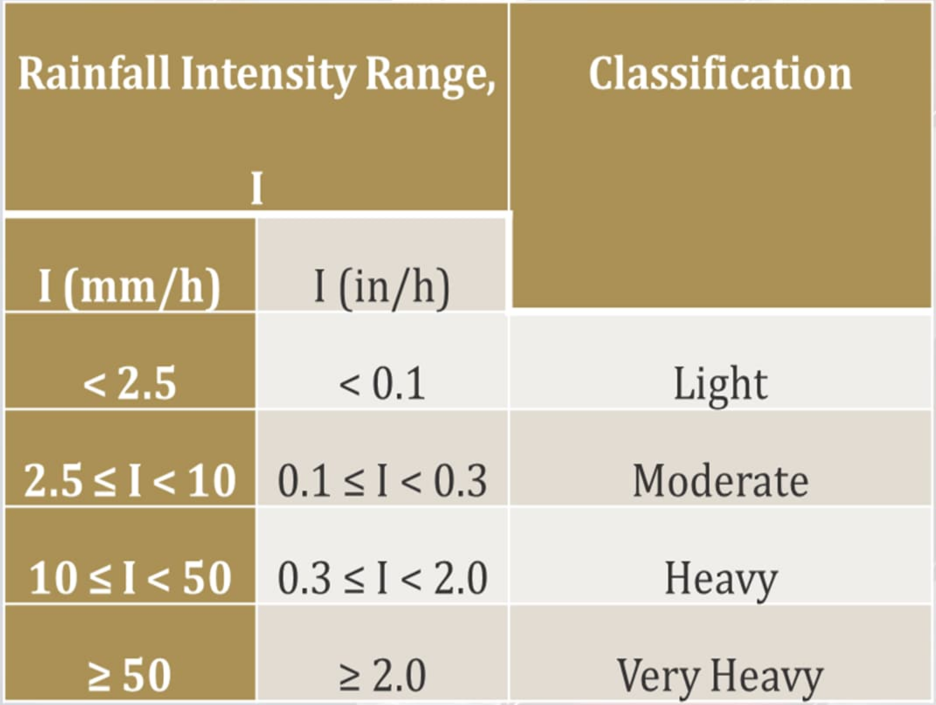
Time of Concentration

Convert 15-minute rainfall depth to intensity based on 15-minute drainage time

Hourly Rainfall Download

Rainfall Disaggregation

Rainfall Intensity Calculation



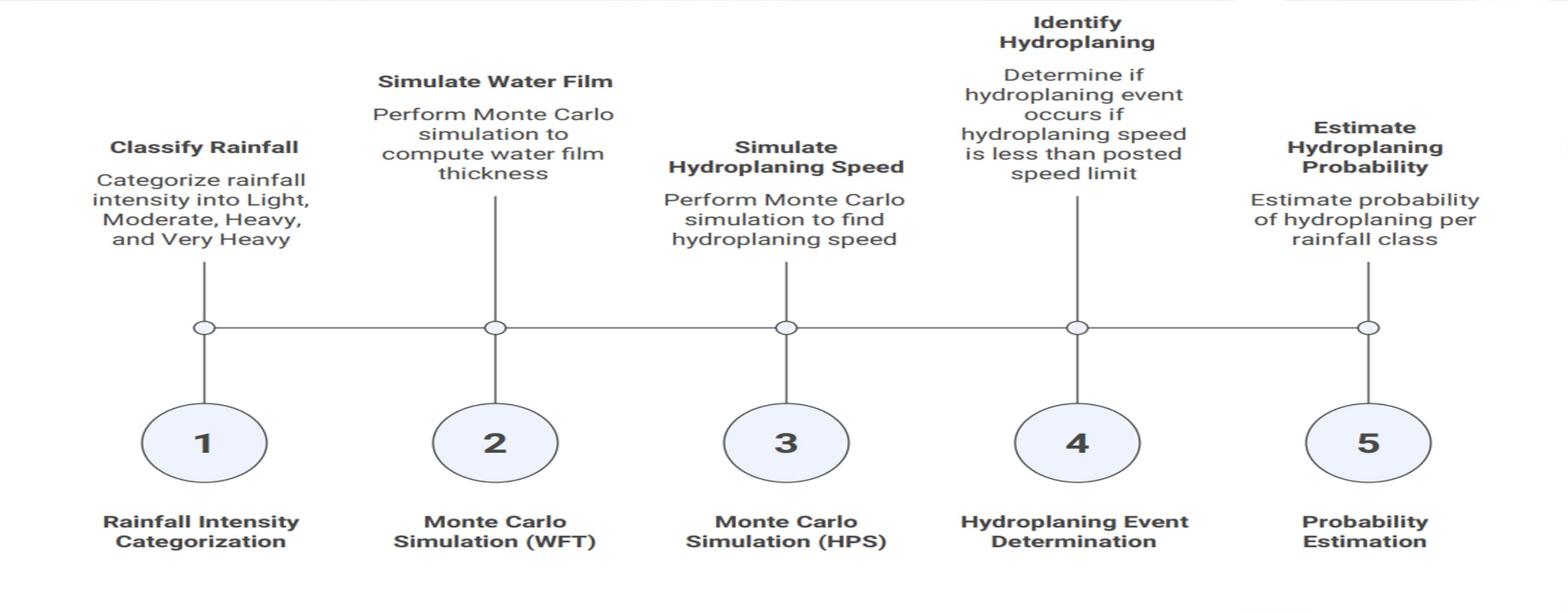
Rainfall Intensity Range, I		Classification
I (mm/h)	I (in/h)	
< 2.5	< 0.1	Light
2.5 ≤ I < 10	0.1 ≤ I < 0.3	Moderate
10 ≤ I < 50	0.3 ≤ I < 2.0	Heavy
≥ 50	≥ 2.0	Very Heavy

Source: World Meteorological Organization (WMO), 2018

METHODOLOGY

FRAMEWORK

HYDROPLANING PROBABILITY ASSESSMENT UNDER DIFFERENT RAINFALL CONDITIONS



1 **Rainfall Intensity Categorization**

Classify Rainfall

Categorize rainfall intensity into Light, Moderate, Heavy, and Very Heavy

2 **Monte Carlo Simulation (WFT)**

Simulate Water Film

Perform Monte Carlo simulation to compute water film thickness

3 **Monte Carlo Simulation (HPS)**

Simulate Hydroplaning Speed

Perform Monte Carlo simulation to find hydroplaning speed

4 **Hydroplaning Event Determination**

Identify Hydroplaning

Determine if hydroplaning event occurs if hydroplaning speed is less than posted speed limit

5 **Probability Estimation**

Estimate Hydroplaning Probability

Estimate probability of hydroplaning per rainfall class

MONTE CARLO SIMULATION

- **Definition:** A Monte Carlo simulation is a mathematical technique used to **estimate the probability of different outcomes** in a process that cannot easily be predicted due to the intervention of random variables.
- **General Principle:** Uses repeated random sampling of input variables such as rainfall intensity and pavement texture to model the probability of uncertain events.
- **Application:** Conducted for selected 10-meter asphalt pavement sections under varying rainfall conditions to compute the specific **probability of hydroplaning**.
- **Number of Iterations:** 10,000 iterations were selected as the convergence threshold, where further increases in sample size yielded negligible changes in the output distribution.

MONTE CARLO SIMULATION

- WFT Model used in the simulation:

$$\mathbf{WFT} = \left[3.38 \times 10^{-3} \times (MTD)^{0.110} (L_f)^{0.430} (I)^{0.590} (S_f)^{-0.420}\right] - \mathbf{MTD}$$

Where

MTD = Mean Texture Depth (in)
L_f = Drainage length (ft)
I= Rainfall intensity (in/hr)
S_f = Slope of flow path (ft/ft)

- S_f and L_f are calculated as follows:

$$S_f = \left(S_x^2 + S_g^2\right)^{0.5} = S_x\left(1 + \left(\frac{S_g}{S_x}\right)^2\right)^{0.5}$$

$$L_f = L_x\left(\frac{S_f}{S_x}\right) = L_x\left(1 + \left(\frac{S_g}{S_x}\right)^2\right)^{0.5}$$

Where,
S_x = Cross slope (ft/ft)
S_g = Longitudinal grade (ft/ft)
L_x = Width of the pavement (ft)

MONTE CARLO SIMULATION

- As the simulation is done for several 10-meter pavement sections, roadway geometry variables such as cross slope, longitudinal grade and width of the pavement are constant per study section.
- Random variables in the WFT equation:

➢ Mean Texture Depth (MTD) →

❖ Follows truncated normal distribution with parameters : mean MTD, standard deviation of MTD, maximum MTD and minimum MTD.
❖ The parameters are obtained from TxDOT’s texture database.

➢ Rainfall Intensity →

❖ Follows lognormal distribution with parameters : Log-mean and Log-standard deviation.
❖ The parameters are obtained by fitting location specific rainfall intensity data.

MONTE CARLO SIMULATION

- HPS Model used in the simulation:

$$HPS = SD^{0.04} P_t^{0.3} (TD+1)^{0.06} A_T$$

Where, A_T is the greater of:

$$A_{T1} = \frac{10.409}{WFT\text{^}0.06} + 3.507 \text{ or } A_{T2} = \left[\frac{28.952}{WFT^{0.06}} - 7.817\right] MTD^{0.14}$$

Where, HPS = Vehicle speed while hydroplaning (mph)
SD = Spin down (percent) (fixed at 10%)
P_t = Tire Pressure (psi)
TD = Tire Tread Depth (1/32 inch)
WFT = Water film thickness (inch)
MTD = Mean Texture Depth (inch)

MONTE CARLO SIMULATION

- WFT generated in the first simulation is used as an input here to find the corresponding hydroplaning speed.
- Random variables in the HPS equation:

➢ Tire Pressure →

❖ Follows normal distribution with parameters : Mean and standard deviation
❖ The parameters are obtained for passenger cars from literature.
❖ Mean tire pressure = 35 psi and standard deviation = 7 psi

➢ Tire Tread Depth →

❖ Follows normal distribution with parameters : Mean and standard deviation
❖ The parameters are obtained for passenger cars from literature.
❖ Mean tread depth = 7/32 inch and standard deviation = 2.4/32 inch

SITE SELECTION & CLASSIFICATION

- Study Area: 35 pavement sections (10-meter length) within Austin district.
- Selection Basis: Locations indicative of hydroplaning and non-hydroplaning identified from police crash narratives filtered by keywords such as “hydroplane”, “wet surface”, “rainy weather”, “standing water”, “loss of control” etc.
- Classification: To ensure a comprehensive representation of roadway conditions, sections were selected based on a multi-parameter framework incorporating mean texture depth, geometric cross-slope, and operational speed, with thresholds defined in the table below.

Variable	High threshold	Low threshold
Pavement Texture (MTD)	> 0.5 mm	≤ 0.5 mm
Drainage Geometry (Cross slope)	> 1.5%	≤1.5%
Operational speed	> 45 mph	≤45 mph

REPRESENTATIVE STUDY SECTIONS

- **Sections indicative of hydroplaning from police crash narratives:**
  - FM0020, Crash DFO: 34.096
  - FM0969, Crash DFO: 28.799
  - RM0165, Crash DFO: 0.002
  - FM3000, Crash DFO: 0.298
  - SH0095, Crash DFO: 56.992

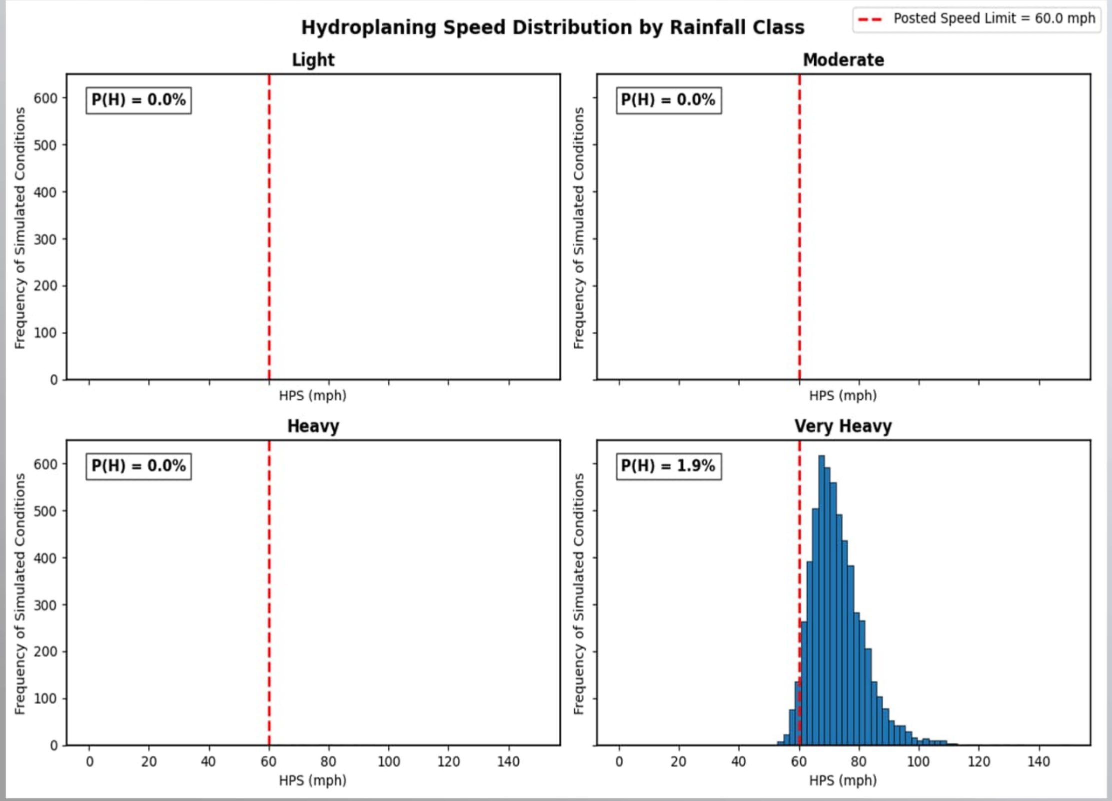
- **Sections indicative of non-hydroplaning from police crash narratives:**
  - US0087, Crash DFO: 597.389
  - FS1825, Crash DFO: 0.56
  - SL0212, Crash DFO: 0.213

RESULTS

Case A: High MTD, High Cross Slope, High Operating Speed

Highway Name: FM0020, Crash DFO: 34.096

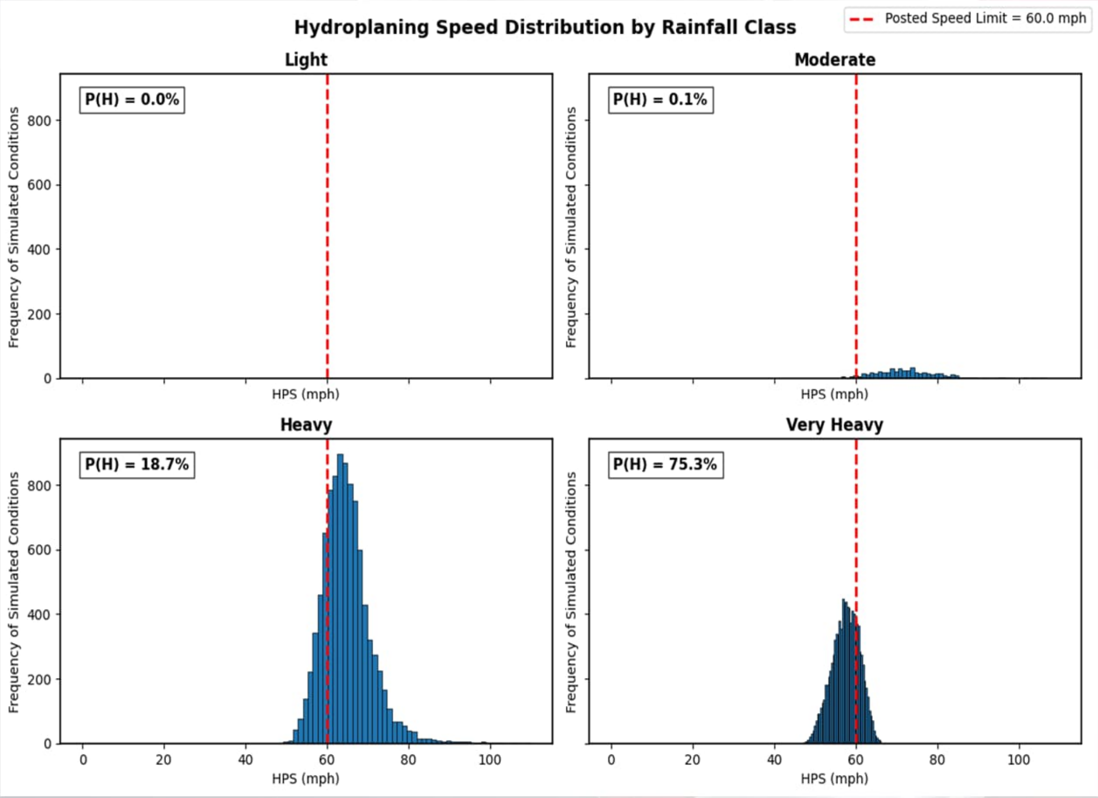
MTD = 1.73 mm, Cross Slope = 1.63% and Speed = 60 mph



Case B: Low MTD, High Cross Slope, High Operating Speed

Highway Name: FM0969, Crash DFO: 28.799

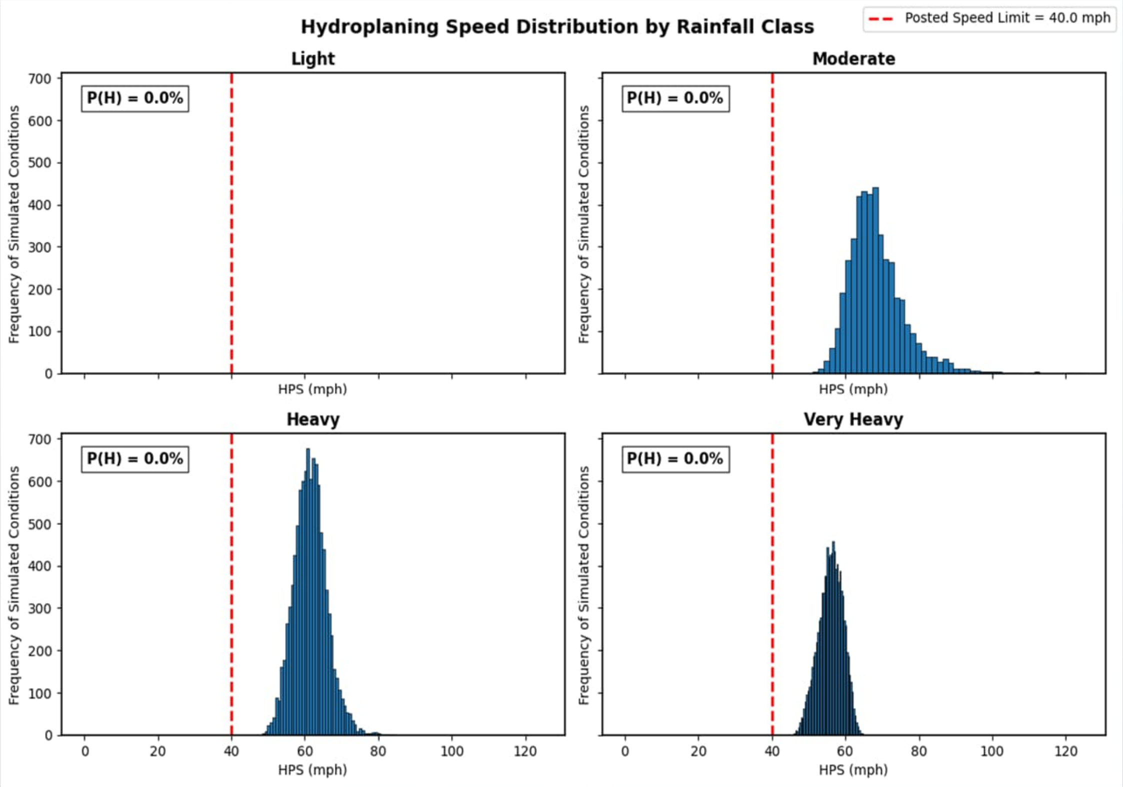
MTD = 0.43 mm, Cross Slope = 1.74% and Speed = 60 mph



RESULTS

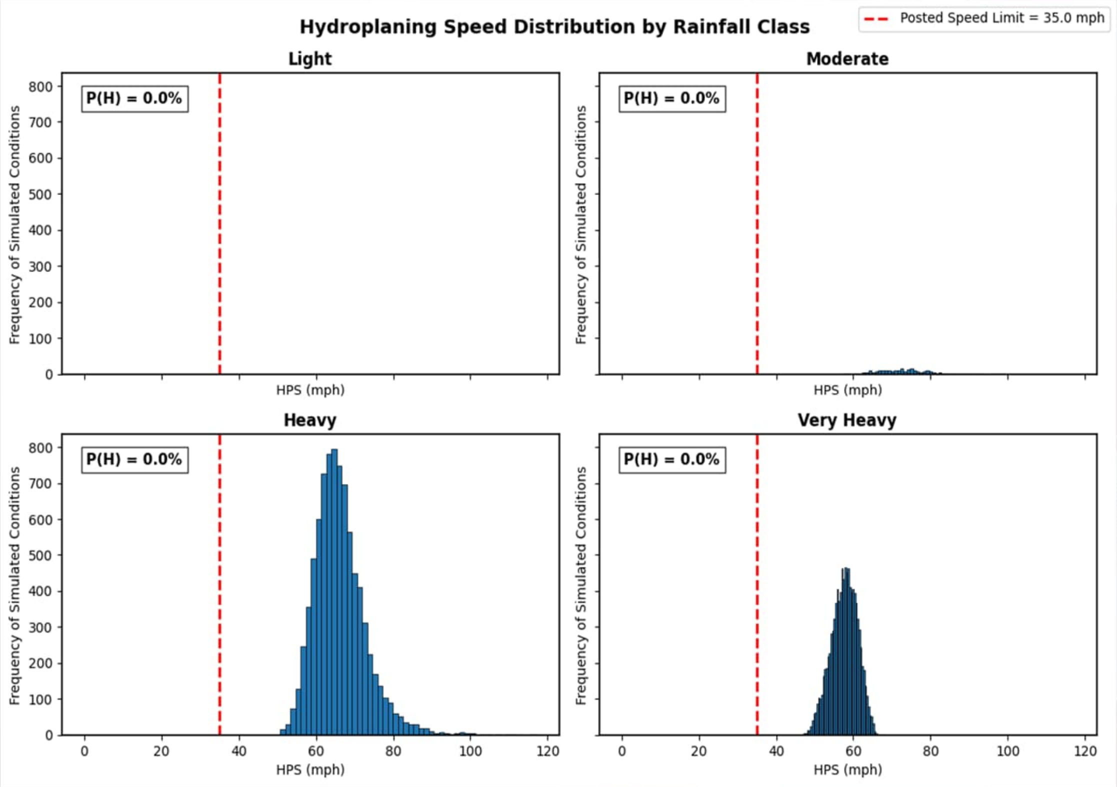
Case C: Low MTD, Low Cross Slope, Low Operating Speed

Highway Name: RM0165, Crash DFO: 0.002
MTD = 0.49 mm, Cross Slope = 0.67% and
Speed = 40 mph



Case D: Low MTD, High Cross Slope, Low Operating Speed

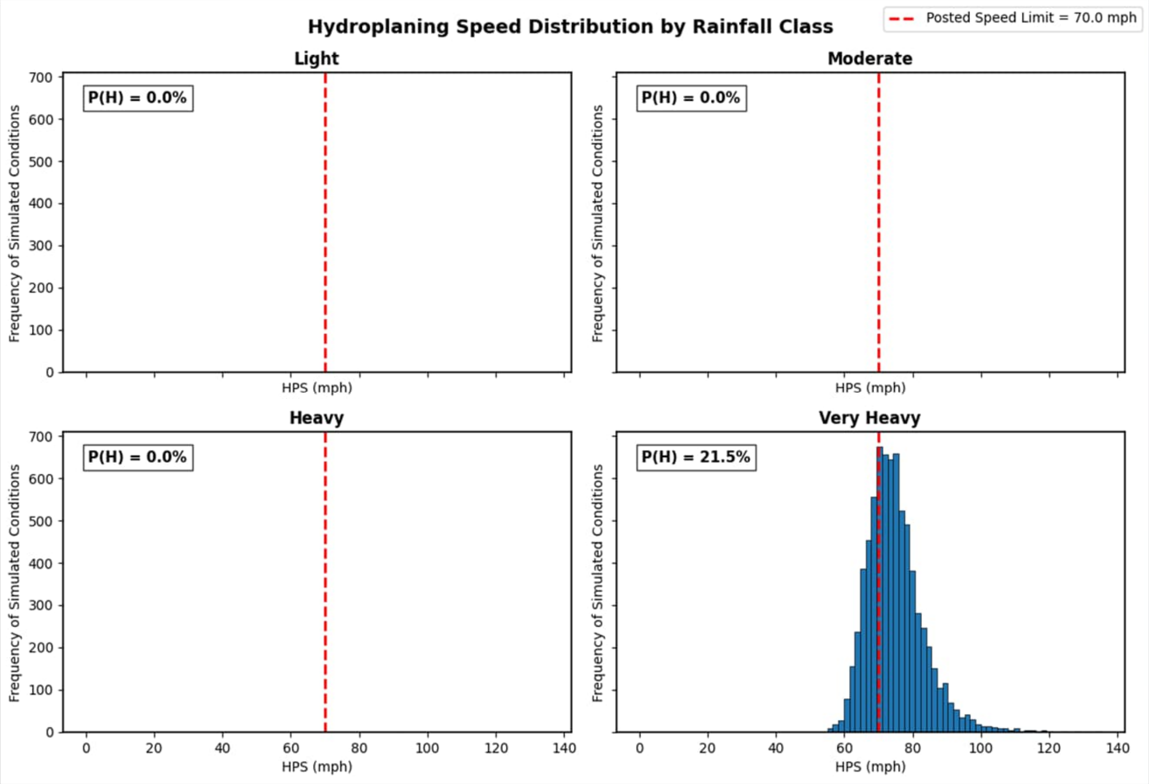
Highway Name: FM3000, Crash DFO: 0.298
MTD = 0.5 mm, Cross Slope = 1.57% and
Speed= 35 mph



RESULTS

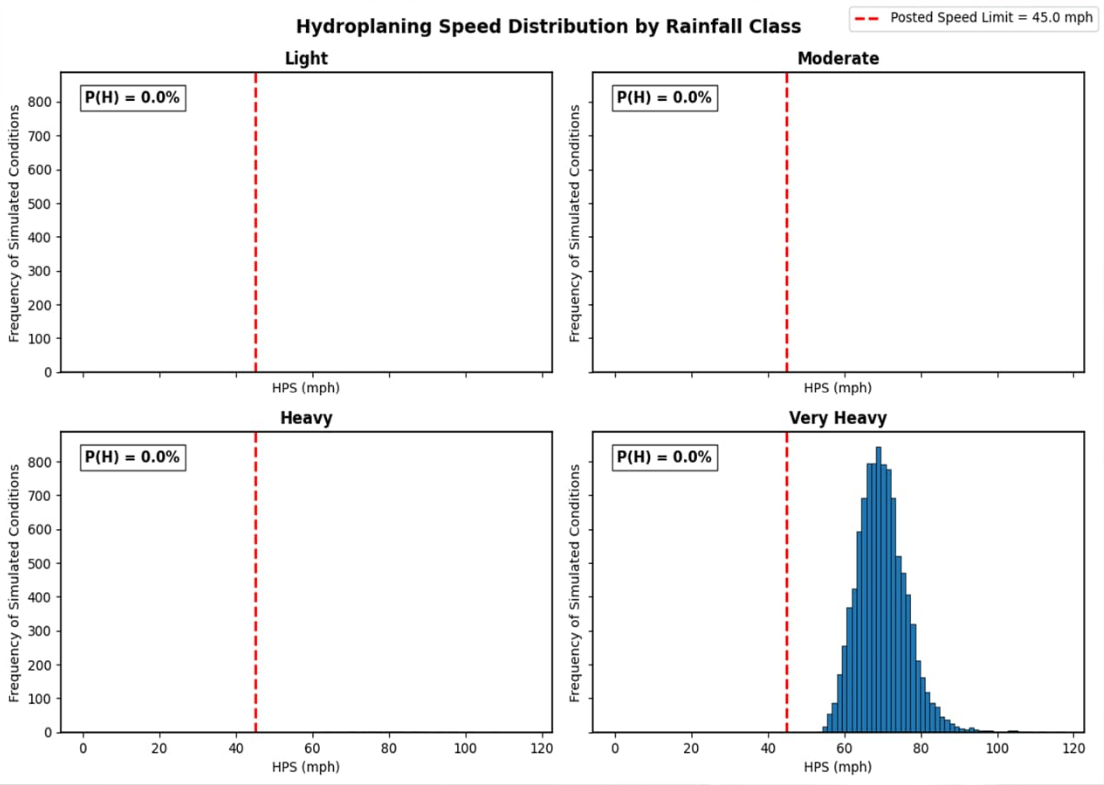
Case E: High MTD, Low Cross Slope, High Operating Speed

Highway Name: US0087, Crash DFO: 597.389
MTD = 2.21 mm, Cross Slope = 1.16% and Speed = 70 mph



Case F: High MTD, Low Cross Slope, Low Operating Speed

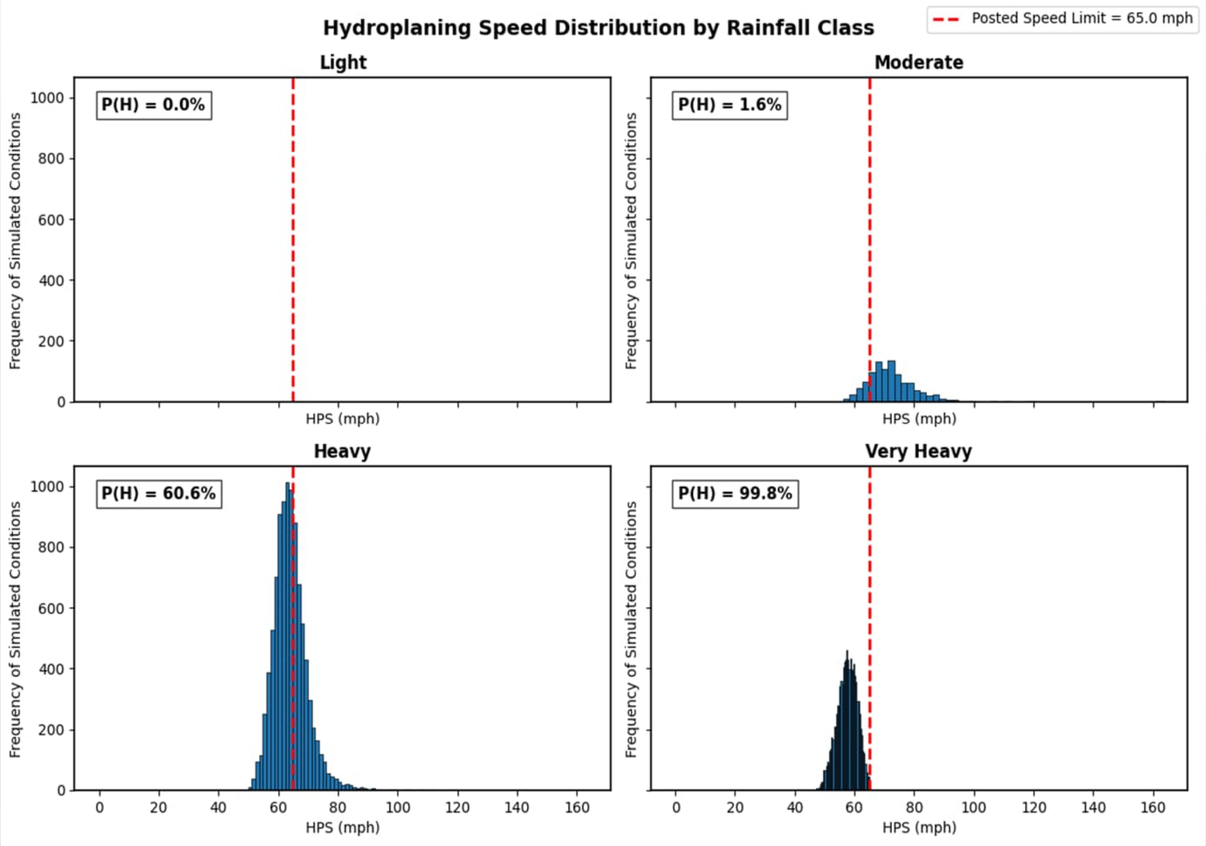
Highway Name: FS1825, Crash DFO: 0.56
MTD= 1.79 mm, Cross Slope = 0.7% and Speed = 45 mph



RESULTS

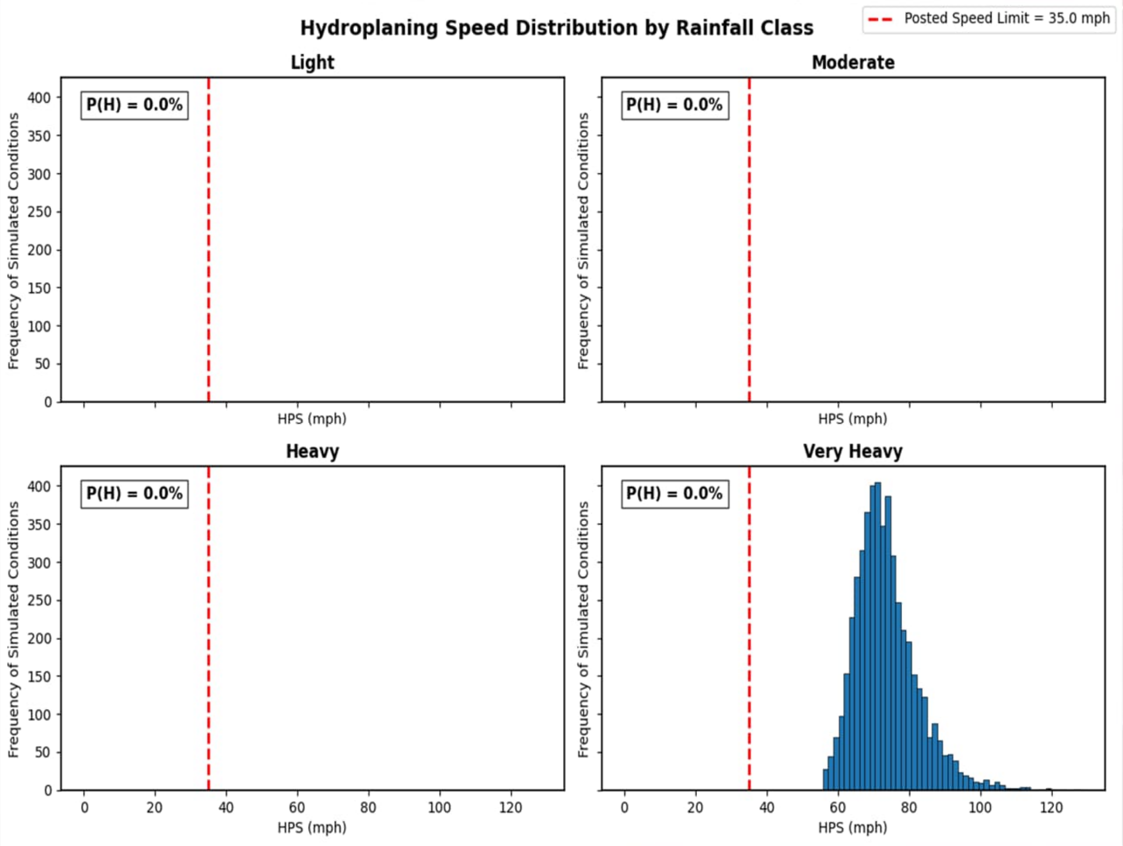
Case G: Low MTD, Low Cross Slope, High Operating Speed

Highway Name: SH0095, Crash DFO: 56.992
MTD = 0.43 mm, Cross Slope = 1.48% and Speed = 65 mph



Case H: High MTD, High Cross Slope, Low Operating Speed

Highway Name: SL0212, Crash DFO: 0.213
MTD = 2.03 mm, Cross Slope = 1.54% and speed = 35 mph



KEY FINDINGS

1. Rainfall intensity is the dominant factor

- Hydroplaning risk is negligible under light and moderate rainfall across all cases.
- Risk increases significantly under heavy rainfall and very heavy rainfall condition.

2. Operating speed drives risk threshold

- Hydroplaning occurs when:

Operating speed > hydroplaning speed (HPS)

- ➢Higher speeds (60-70 mph):
  → greater likelihood of exceeding HPS.
  → increased risk.
- ➢Lower speeds (35-45 mph):
  → even under heavy and very heavy rain, risk remains low.

3. Simulation vs. Narrative Resolution: Monte Carlo simulation acts as a technical filter. Crashes labeled as hydroplaning in low-speed (< 45 mph) narratives (Case C and Case D) are likely wet-surface skidding or ice-related loss of control rather than true dynamic hydroplaning

KEY FINDINGS

4. Pavement texture (MTD) strongly controls risk.

- High MTD→ maintains higher HPS → lower hydroplaning risk
  - ➢ This trend holds regardless of cross slope (high or low)
  - ➢ Case A and E shows low hydroplaning risk even under extreme rainfall.
- Low MTD→ produces lower HPS → higher hydroplaning risk.
  - ➢ This remains true even when cross slope is high (Case B)
  - ➢ Low MTD combined with low cross slope provides worst risk (Case G)

5. Cross slope improves drainage reducing WFT, however, it cannot fully compensate for low MTD.

6. Critical risk combination identified in the pavement section with low MTD, low cross slope, high rainfall intensity (heavy / very heavy) and high operating speed.

7. Minimal risk condition in the pavement section with high MTD, high cross slope, and lower operating speed under light to moderate rainfall.

FUTURE WORKS

- Analyze hydroplaning prone pavement sections from San Antonio district to find if the hydroplaning probability follows the same trend.
- Sensitivity analysis to show the impacts of tire pressure and tire tread depth on hydroplaning.
- Incorporate rutting to analyze the impact of rutting on hydroplaning potential.

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Any Questions?

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