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Quantifying Hydroplaning Risk: A Monte Carlo Simulation Approach for Enhancing Roadway Safety in Texas

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PRESENTATION OUTLINE

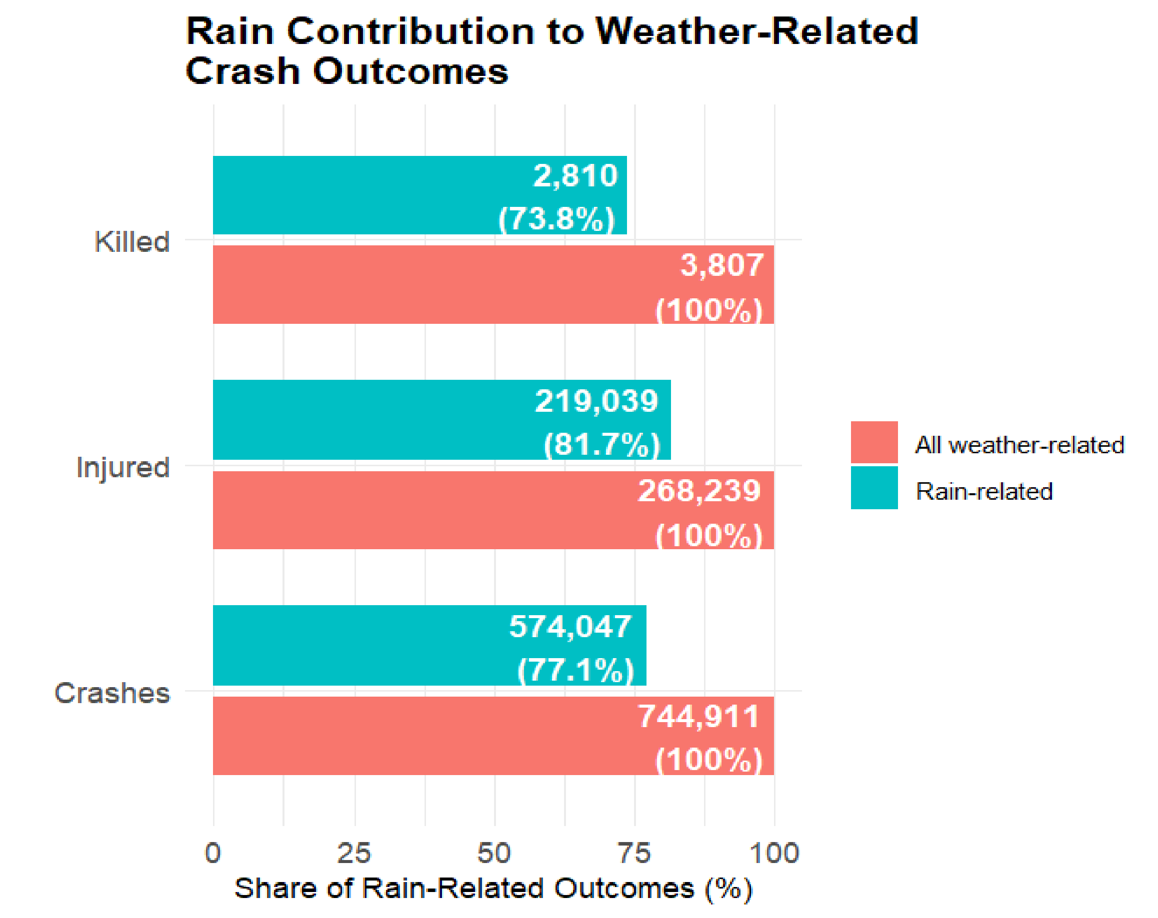
- Background
- Research objectives
- Literature Review
- Methodology
- RESULTS
- Key findings

BACKGROUND

- According to National Highway Traffic Safety Administration (NHTSA) data analysis

- Total weather crashes 744,911 / year
- Rain-related crashes 574,047 / year
- Weather fatalities 3,807 / year
- Rain fatalities 2,810 / year

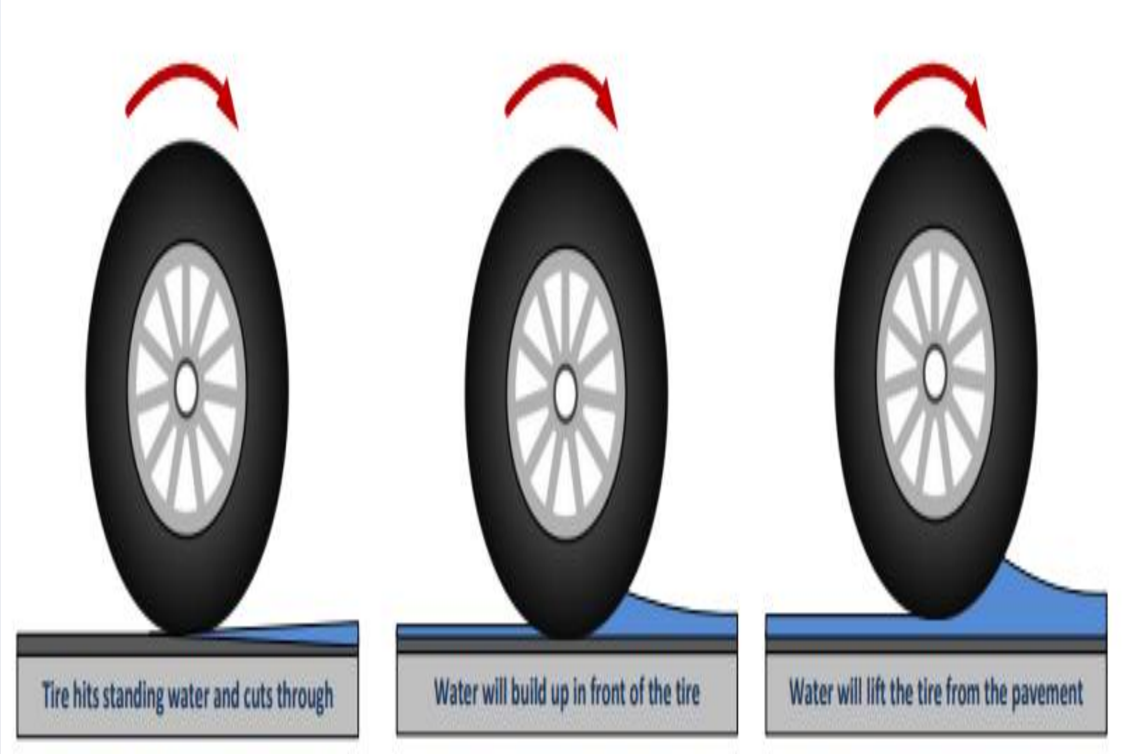
- Texas is among the top states of the US for total annual frequency of hydroplaning high-risk events (Salvi & Kumar, 2022)



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 vehicle from responding to steering, braking, or accelerating.



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

RESEARCH OBJECTIVES

1. To develop a probabilistic framework through Monte Carlo simulation (MCS) to quantify 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

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 speed

THE DATA CHALLENGE: RAINFALL RESOLUTION

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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Non-Stationarity and Outdated Data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.
- Climate change requires models that can account for non-stationary extremes.
- NASA's North American Land Data Assimilation System (NLDAS) real-time dynamic data reanalyzed from observations.

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.

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**.

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:

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

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

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)

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

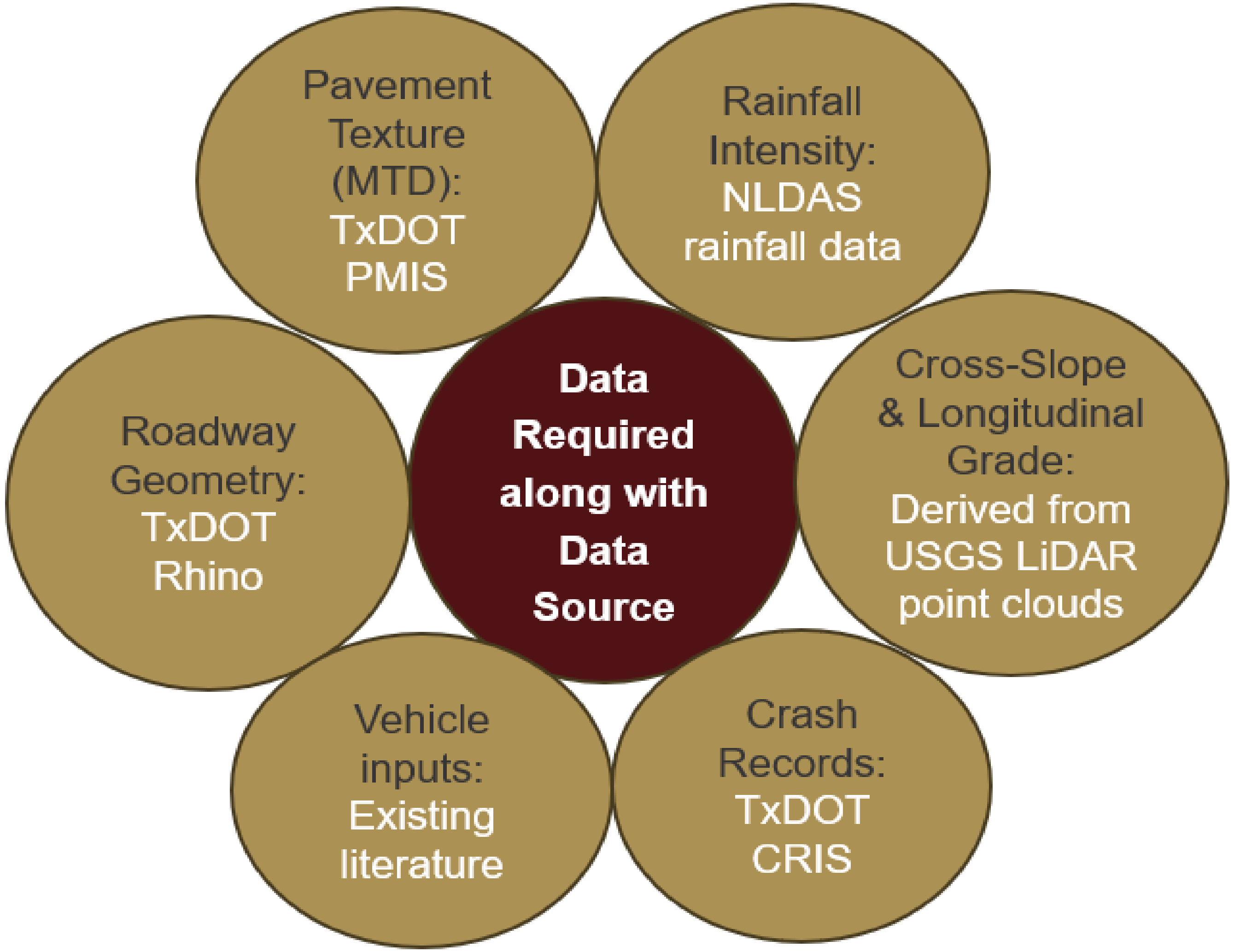
  - Tire Tread Depth →
    - ❖ Follows normal distribution with parameters : Mean and standard deviation
    - ❖ The parameters are obtained for passenger cars from literature.
    - ❖ Mean tread depth = 7/32 inch and standard deviation = 2.4/32 inch

SITE SELECTION & CLASSIFICATION

- Study Area: 35 pavement sections (10-meter length) within Austin district.
- Selection Basis: Hydroplaning-prone locations identified from crash narratives.
- 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

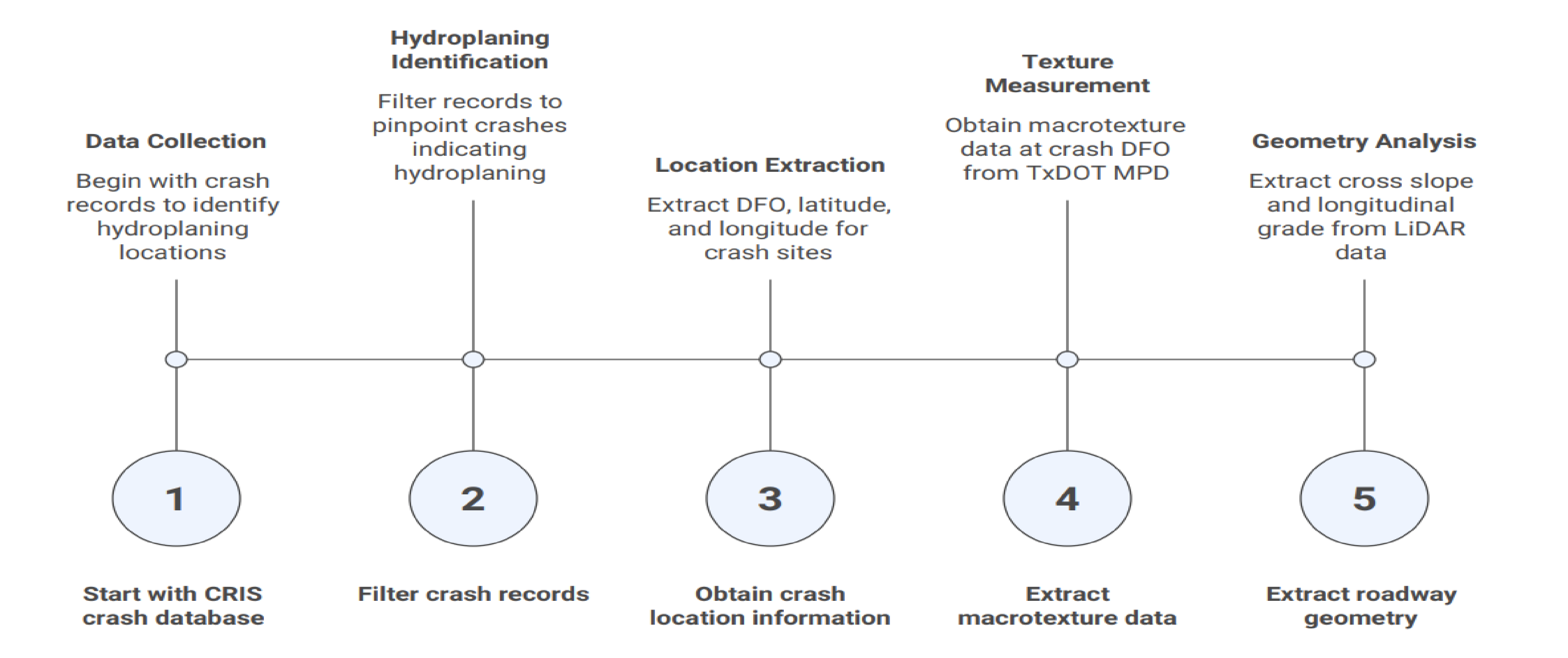
DATASET DESCRIPTION



METHODOLOGY

FRAMEWORK

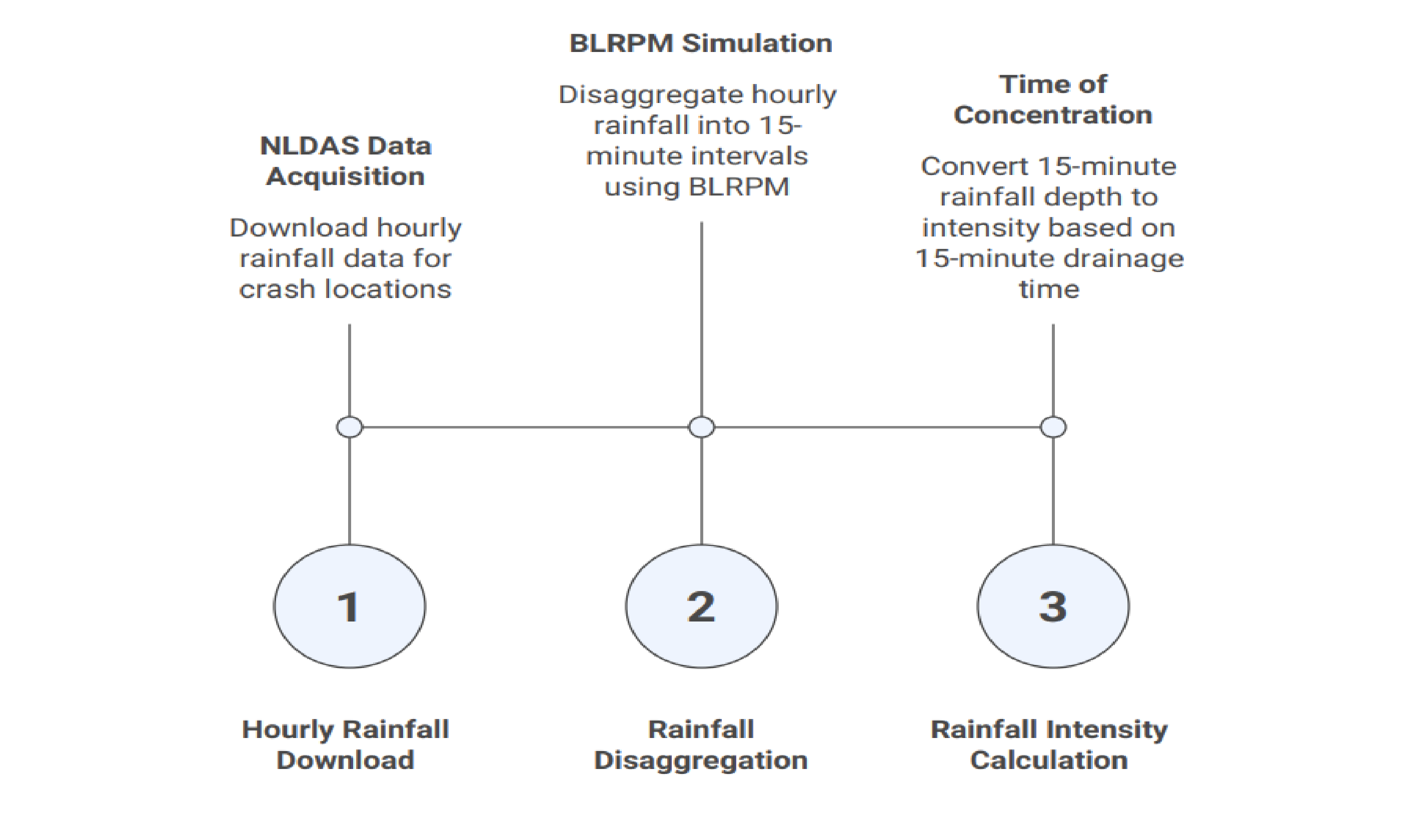
DATA PREPARATION



METHODOLOGY

FRAMEWORK

RAINFALL DATA PROCESSING



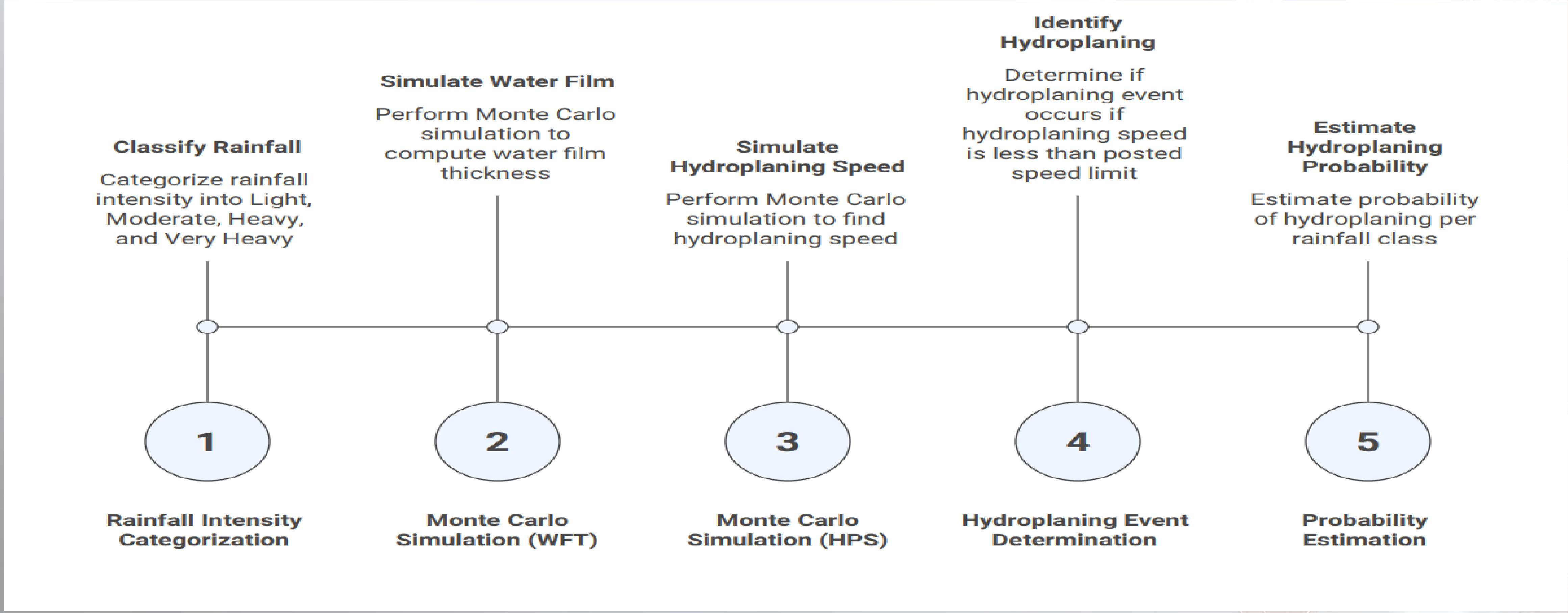
Rainfall Intensity Range, I		Classification
I (mm/h)	I (in/h)	
< 2.5	< 0.1	Light
2.5 ≤ I < 10	0.1 ≤ I < 0.3	Moderate
10 ≤ I < 50	0.3 ≤ I < 2.0	Heavy
≥ 50	≥ 2.0	Very Heavy

Source: World Meteorological Organization (WMO), 2018

METHODOLOGY

FRAMEWORK

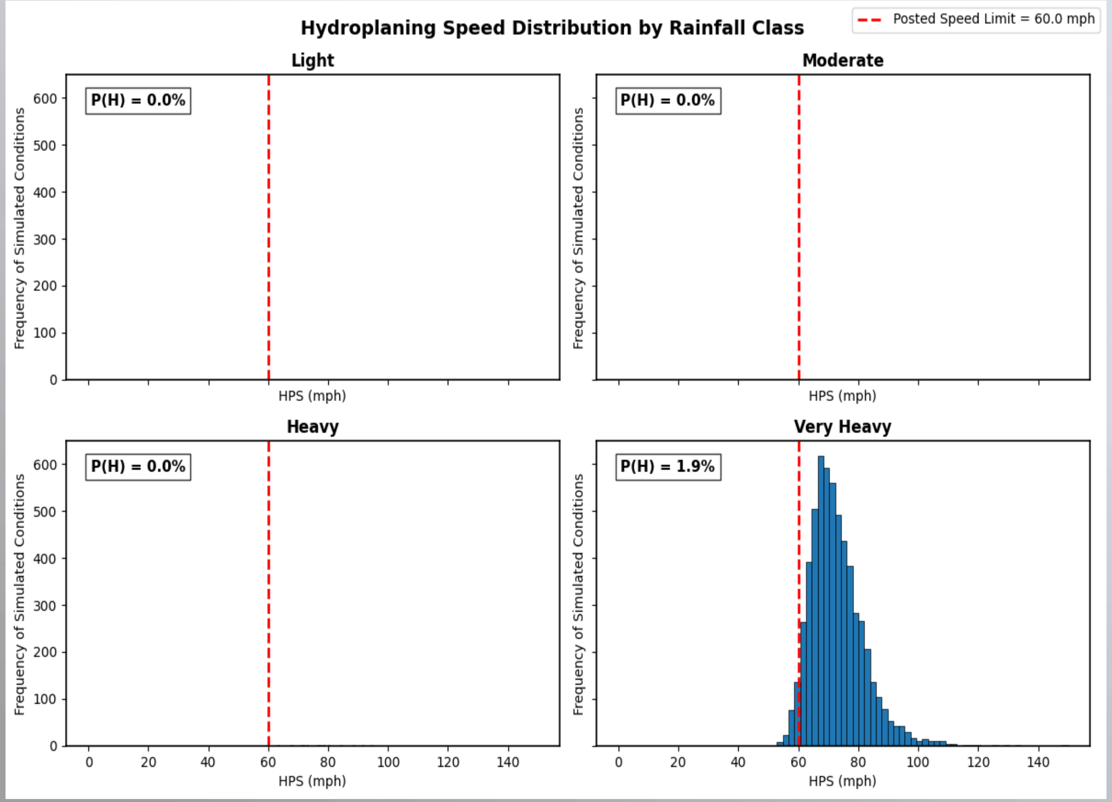
HYDROPLANING PROBABILITY ASSESSMENT UNDER DIFFERENT RAINFALL CONDITIONS



RESULTS

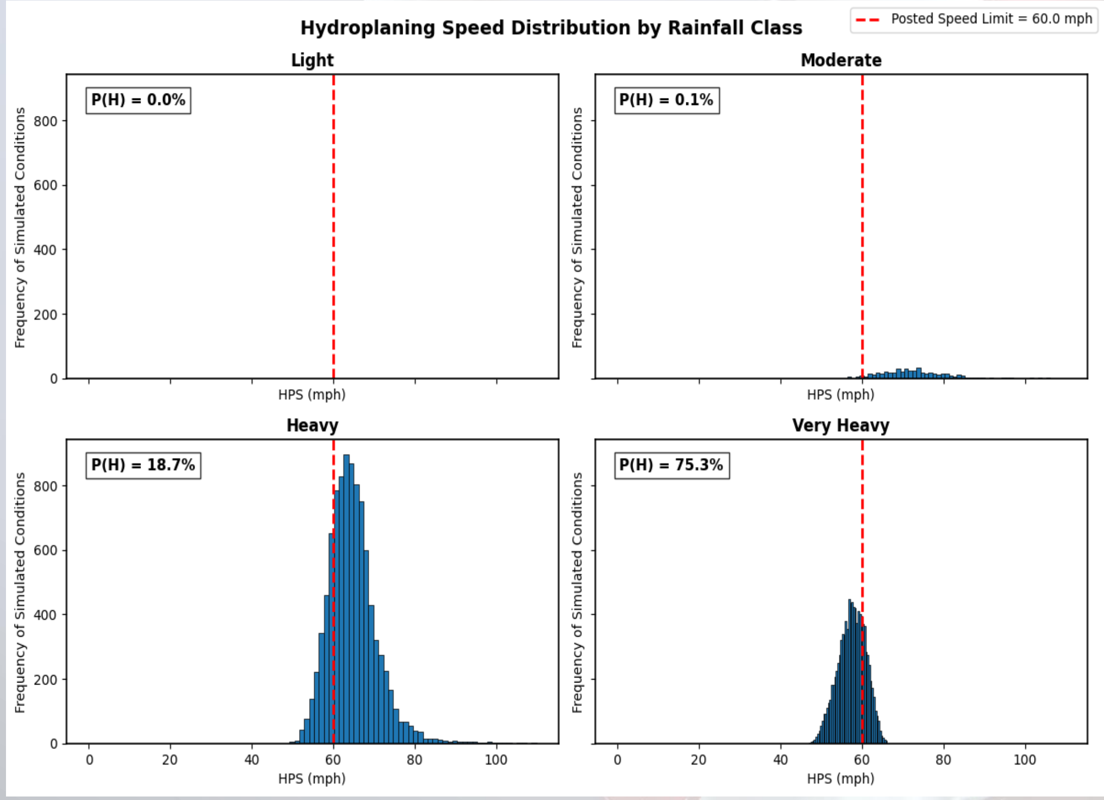
Case A: High MTD, High Cross Slope, High Operating Speed

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

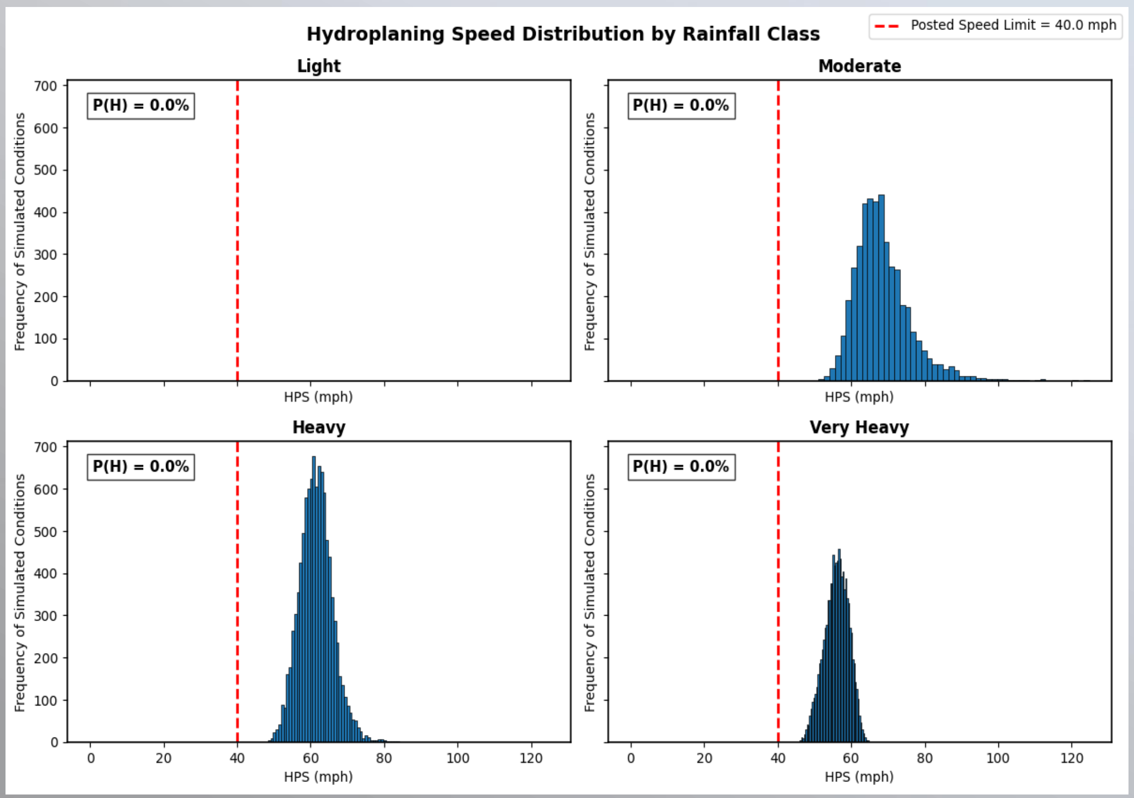
Highway Name: FM0969, Crash DFO: 28.799
MTD = 0.43 mm, Cross Slope = 1.74% and Speed = 60 mph



RESULTS

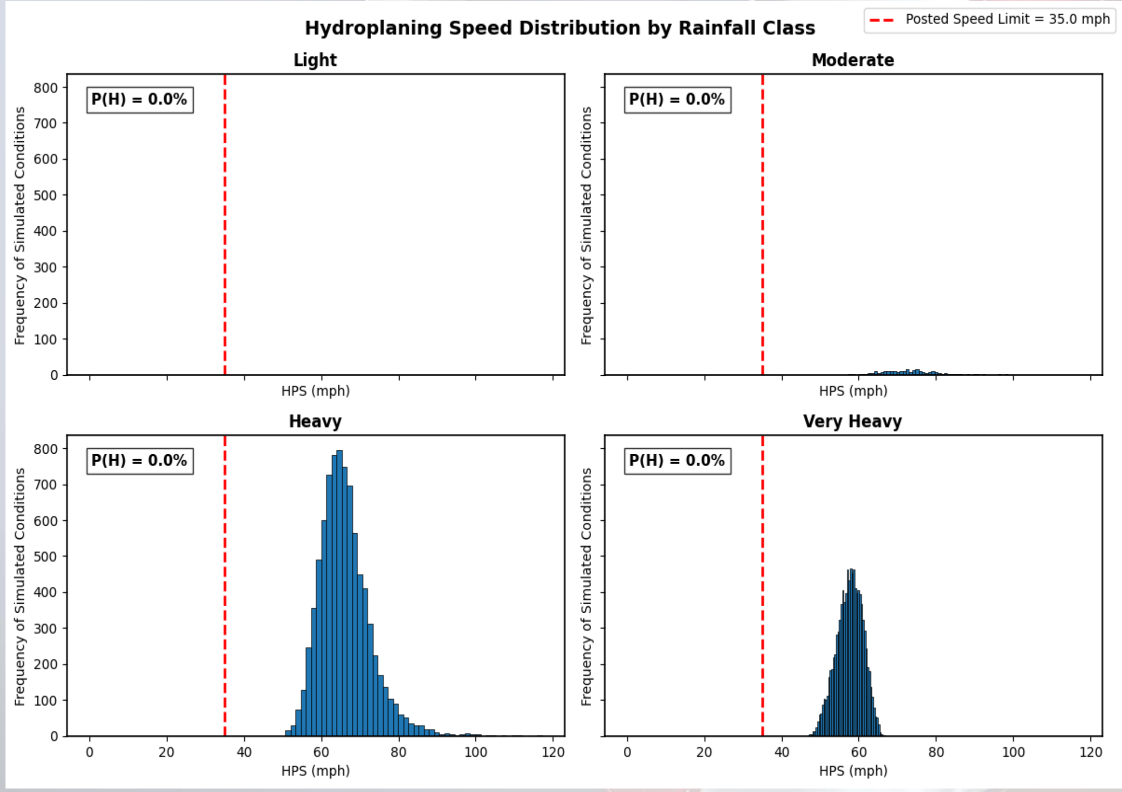
Case C: Low MTD, Low Cross Slope, Low Operating Speed

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



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

  Very heavy rainfall (critical condition)

2. Operating speed drives risk threshold

- Hydroplaning occurs when:

Operating speed > hydroplaning speed (HPS)

- ➢Higher speeds:
  → greater likelihood of exceeding HPS
  → increased risk
- ➢Lower speeds:
  → even under heavy and very heavy rain, risk remains low

KEY FINDINGS

3. Pavement texture (MTD) strongly controls risk.

- High MTD→ maintains higher HPS → lower hydroplaning risk
  - ➢ This trend holds regardless of cross slope (high or low)
- Low MTD→ produces lower HPS → higher hydroplaning risk.
  - ➢ This remains true even when cross slope is high (Case B)

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

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

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