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A Probabilistic Approach to Hydroplaning Potential and Risk

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Abstract

A major contributor to fatal vehicle crashes is hydroplaning, which has traditionally been reported at a specific vehicle speed for a given operating condition. However, hydroplaning is a complex phenomenon requiring a holistic, probabilistic, and multidisciplinary approach. The objective of this article is to develop a probabilistic approach to predict Hydroplaning Potential and Risk that integrates fundamental understanding of the interdependent factors: hydrology, fluid-solid interactions, tire mechanics, and vehicle dynamics. A novel theoretical treatment of Hydroplaning Potential and Risk is developed, and simulation results for the prediction of water film thickness and Hydroplaning Potential are presented. The results show the advantages of the current approach which could enable the improvement of road, vehicle, and tire design, resulting in greater safety of the traveling public.

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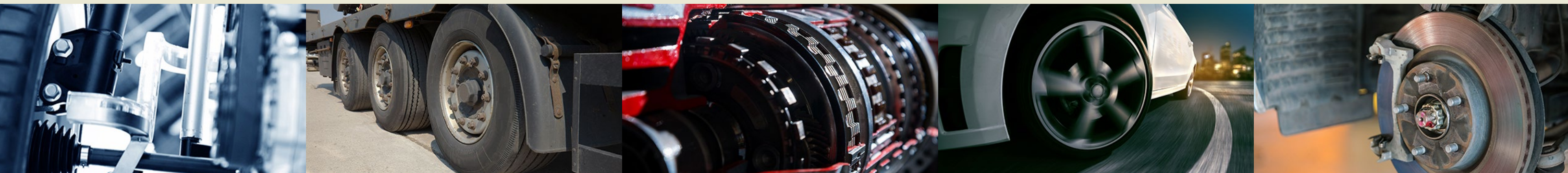


Introduction

One major safety risk facing the traveling public is the potential for hydroplaning. Wet pavements result in about 16% of vehicle crashes in the United States, injuring over 350,000 people and killing over 4,400 each year [1]. Traditionally, hydroplaning has been approached as a geometric design problem. Current guidelines for minimizing hydroplaning potential during road and highway geometric design are based on a limited number of experimental studies and definitions of hydroplaning that emphasize a single hydroplaning speed [2]. However, there is a spectrum of conditions in which hydroplaning becomes a major issue. Understanding the fundamentals of hydroplaning allows interpretation of Hydroplaning Potential and Risk without resorting to a single go/no-go speed.

As with many other safety-related issues, hydroplaning is a complex phenomenon requiring a multidisciplinary approach. Although road design, pavement type, and condition play a major role, the vehicle, the tires, the environment, and the driver are also major contributors to this dynamic phenomenon. The recent advances in fluid-solid interaction (FSI) modeling have allowed detailed interactions between the pavement and the tire to be modeled. Three-dimensional (3D) pavement mapping technology has enabled pavement surfaces to be represented with millimeter accuracy. This technology enables the development of hydraulic models that more accurately predict water film thicknesses (WFT), resulting in more accurate tire models for vehicle dynamic simulation and analysis. With this advanced technology comes a myriad of performance and maintenance capabilities not previously possible. The authors have recently developed a computational fluid dynamics (CFD) model for predicting and understanding the hydrodynamics mechanism of water accumulation and drainage, by which hydroplaning occurs. The prediction of WFT using the developed CFD model was successfully simulated with complex 3D features that occur on real road surfaces, including crucial factors like alignment transitions, cross-slope, grades, and surface distress, such as surface texture and rutting. The FSI modeling has shown the capabilities of predicting hydroplaning when the results are integrated with structural tire models and vehicle dynamics models. In this way, a novel, transformational approach is being undertaken to fundamentally understand the physics behind hydroplaning [3].

There are several issues in synthesizing these research results into an integrated model to estimate Hydroplaning Potential and Risk. These issues are defined in terms of specific steady-state operating conditions in which a vehicle is traveling on a curved road that may have slope, cross-slope, and a water film. First the limit handling capability of the vehicle in the given operating condition must be estimated. Several methods have been developed for measuring the performance capability of a vehicle. In this work, the bounds of this Performance Envelope (PE) are determined by the road geometry and Effective Friction, where the Effective Friction is defined as the maxima of the ratio of tractive force to the normal load at the current operating condition. This differs from the traditional concepts of friction in that the Effective Friction accounts for both the vehicle dynamics (e.g., excess understeer and brake proportioning) and road surface properties (e.g., roughness). The Performance Margin (PM) is then a measure of any additional performance capability that is available beyond the performance required by the current operating condition.

Once the PM is estimated for a given vehicle in a given operating condition, the potential and risk for hydroplaning must be established. The Hydroplaning Potential and Hydroplaning Risk are developed as estimated conditional probabilities. The Hydroplaning Potential is defined herein as the probability that hydroplaning occurs given a specific vehicle/tire combination, WFT, and pavement surface. The Hydroplaning Risk is defined herein as an estimate of the conditional probability of hydroplaning occurring given the pavement surface being considered, and an ensemble measure of the aggregated Hydroplaning Risk. The Hydroplaning Risk is a function of the Hydroplaning Potential, the estimated probability distribution for each vehicle/tire combination on the road, and the estimated probability of a particular WFT occurring given the pavement geometry and the geographical location and rainfall.

The objective of this article is to develop a theoretical, probabilistic approach to predict Hydroplaning Risk that integrates the fundamental understanding of the interdependent factors. The prediction of Hydroplaning Risk is developed through models of hydrology, FSI, tire mechanics, and vehicle dynamics. As an overview, the progression of information in this probabilistic framework is as follows. First the WFT is predicted using hydrology models given the pavement surface geometry and rainfall rate. Next, tires acting in this wet environment are simulated to predict forces on a vehicle. Third, vehicle models are used to predict the PM, which is a function of the vehicle/tire combination, WFT, and pavement geometry. The Hydroplaning Potential is then estimated from the PM, and the Hydroplaning Risk is estimated from the conditional probability of hydroplaning occurring given the pavement surface being considered.

This article is organized as follows. First, background on the use of full Navier-Stokes equations to model the hydrology and resulting WFT on road surfaces is described, followed by the definitions of the PE and the PM. The developments of the Hydroplaning Potential and Hydroplaning Risk are based on the models of hydrology, FSI, tire mechanics, and vehicle dynamics. Simulation results for the prediction of WFT and Hydroplaning Potential are presented to demonstrate the concepts, followed by concluding remarks and references.

Background

Dynamic hydroplaning is a wet-weather condition wherein one or more tires of a moving vehicle are separated from the pavement by a thin film of water. As the layer of water builds up between the tire and the road surface, the vehicle experiences a loss of traction that prevents the vehicle from responding to control inputs, such as steering, braking, or accelerating. Therefore, an accurate prediction of WFT and surface drainage of pavement becomes crucial. However, most water accumulation models used in previous studies for predicting hydroplaning only consider one-dimensional (1D) or two-dimensional (2D) water flow paths (by incorporating the length and slope of the drainage path) and ignore the complex 3D features that occur on real road surfaces [4, 5]. Only very recently has an investigation been performed to understand the fundamental mechanisms of water film [6] by which hydroplaning occurs, specifically the National Cooperative Highway Research Program (NCHRP) Project 15-55: "Guidance to Predict and Mitigate Dynamic Hydroplaning on Roadways." In order to provide a comprehensive analysis over the tire reaction in existence of WFT, FSI problem needs to be solved using finite element (FE) modeling. Since FSI simulation is a very challenging and complex problem, many researchers, both academic and industrial, are exploring new methods for solving FSI. Commercial finite element codes have been used for hydroplaning simulations [4]. Hydroplaning problem can be simulated by assigning different frames (Eulerian or Lagrangian) to the tire and the fluid domain. However it would be impractical to solve FSI by simply considering an Eulerian or a Lagrangian formulation for the entire model. Several approaches have been used to address the FSI problem such as Arbitrary Lagrangian Eulerian (ALE) and Coupled Eulerian Lagrangian (CEL). For the hydroplaning problem, it is a common practice to assign an Eulerian formulation to the fluid and a Lagrangian formulation to the tire.

This method assists to reduce the computational time and the mesh refinement needed for specifying the fluid domain. Water layers around the contact area, where deformed tire and fluid interfere, are equally divided into small size meshes. In the other region away from the contact region, the sizes of mesh are increased, helping to reduce the computation time. In order to model the tire, the steady-state transport (SST) method is implemented, using Abaqus software. In this method, a moving reference frame is used in which the rigid body rotation is described in Eulerian terms and the deformation is described in the Lagrangian term [5].

After defining the contact of the tire tread and pavement, using the SST feature in Abaqus, steady-state rolling is simulated and exported to a transient rolling step to evaluate the effect of the force from the WFT on the tire through co-simulation with CFD code. Equation 1 shows the deformed tire for displacement field u.

$$\nabla\sigma(u)+b=\rho\ddot{u} \quad \text{Eq. (1)}$$

where ρ is the mass density, b is the body force, and σ is the Cauchy stress. Also, to consider the effect of turbulence and multiphase flow, Navier-Stokes equations based on the conservation of mass, the conservation of momentum, and the conservation of energy are utilized in the CFD model shown in Equations 2-4.

$$\frac{\partial\bar{\rho}}{\partial t}+\nabla\cdot(\bar{\rho}\bar{v})=0 \quad \text{Eq. (2)}$$

$$\frac{\partial}{\partial t}(\bar{\rho}\bar{v})+\nabla\cdot(\bar{\rho}\bar{v}\bar{v})=-\nabla p+\nabla\bar{\bar{\tau}} \quad \text{Eq. (3)}$$

$$\frac{\partial}{\partial t}(\bar{\rho}E)+\nabla\cdot\left[\bar{v}\cdot(\bar{\rho}E+P)\right]=\nabla\cdot k_{eff}\nabla\mathrm{T}+\nabla\left(\overline{\overline{\tau_{eff}}}\cdot\bar{v}\right) \quad \text{Eq. (4)}$$

where is p pressure, $\bar{\bar{\tau}}$ is the fluid stress tensor, $\bar{v}$ is the fluid velocity, E is total energy, and k_{eff} is the effective conductivity.

Regarding the interaction of tire with pavement, it is noteworthy that the pavement texture plays a crucial role in the friction coefficient. The two main pavement design key factors affecting the friction coefficient are micro-texture and macro-texture. In wet conditions, the magnitude of the frictional force increases with increased micro-texture which is more effective in preventing hydroplaning at low vehicle speeds. However, macro-texture on the other hand plays a vital role in higher speeds. In the FE model developed to predict the lift and cornering forces, the pavement texture is not implemented in the model while its effects in wet condition is considered in the friction coefficient used for tire-pavement interaction.

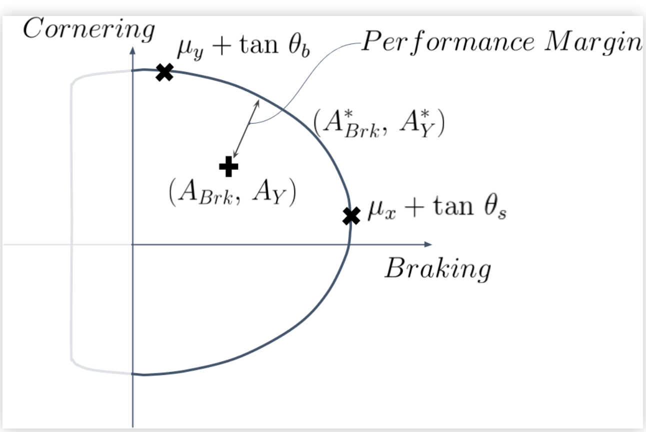
In addition, there are multiple simplification in the governing equations for the surface runoff study, such as the kinematic wave and diffusion wave equations simplified from Saint-Venant equation and the simplification of 1D Saint-Venant equation from full Navier-Stokes equations [7, 8]. The PAVDRN program, developed in NCHRP Project 01-29, "Improved Surface Drainage of Pavements" [9] is one such traditional method. In PAVDRN, WFT has been analyzed by applying the kinematic wave equation to determine water depth along the 1D flow path. Similar work with the kinematic wave equation has also been conducted in Scharffenberg et al. [10], Cunge [11], and Miller et al. [12]. The use of the kinematic wave equations in the study of surface runoff assumes that the flow is uniform with friction slope equal to the bed slope and the change in water film over distance and fluid velocity over time is negligible relative to the bed slope [13]. More recently Gunaratne et al. [14] completed a project for Florida DOT and suggested a different model, but again, this is an empirical model is based on limited experimental data. However, 1D or 2D modeling might not be accurate enough for realistic problems since 3D features occur on real road surfaces all the time. This is a problem because alignment transitions, cross-slope, transversal and longitudinal slopes, together with surface distresses such as rutting, all have an impact on the water flow and can contribute to water accumulation. In this study, a 3D model of roadway surfaces was developed with full Navier-Stokes equations calculated account for important surface and weather factors to predict and understand the hydrodynamics of water accumulation and drainage on a multi-lane highway at cross-slope transitions. The developed model also enables practitioners to understand the underlying physical basis of the methodology and its applicability to varying roadway geometries and operating conditions. A new modeling approach of CFD has been developed and employed in for both 2D and 3D problems. The pavement characteristics, such as roadway geometric characteristics and road surface properties, have been extensively considered and tested in the investigation of water accumulation using CFD with a full three-dimensional calculation of Navier-Stokes equations. Meanwhile, the effects of rainfall rate on the WFT have also been tested and compared with both experimental work [15] and multiple theoretical and empirical correlations, including PAVDRN [16], Gallaway et al. [17], and Reed and Kibler [18].

The PM used in this work [19] draws from several traditional handling metrics for tires and vehicles including the Dugoff Tire Model, the Milliken Moment Method, the Friction Ellipse, and the original definition of the PM [20, 21, 22, 23]. First consider the range of vehicle traction that could be generated for any operating condition. The PE is the maximum vehicle traction that can be generated at any operating condition. It is defined as the limit of performance capability for the entire vehicle and, as such, must include not only the individual tire performance limits but the contribution of the complex vehicle dynamics and, in the case of potential hydroplaning, the WFT. Specifically, the PE is defined by the locus of points for which the Required Acceleration equals the Available Acceleration (both acting in the ground plane). The components of the Required Acceleration for a given operating condition are written as (A_X, A_Y), indicated by a cross in Figure 1, and the components of the Available Acceleration are written as $\left(A_X^*, A_Y^*\right)$, shown as a solid curved line in Figure 1, where the asterisk notation denotes the PE.

The maximum deceleration is $\mu_x + \tan\theta_s$, and the maximum lateral acceleration is $\mu_y + \tan\theta_b$. Note that in the case of wet pavement, the coefficient of friction is also a function of the WFT, so that an effective coefficient of friction must be estimated. Specifically, μ_x and μ_y in the wet pavement condition refer to this effective friction. These two points on the PE are each indicated by a bold “x” in Figure 1.

The PM is defined as the additional performance capability that can be drawn upon beyond that which is demanded

FIGURE 1 Performance Envelope and Performance Margin.



by the current operating condition. Specifically, the PM for a given operating condition is then the minimum difference between the Required Acceleration and the locus of points that define the Available Acceleration. The PM is represented in terms of units of gravity. Note that the distinction between the road plane and the ground plane must be accounted for when the grade or cross-slope become large, which is outside the scope of the current work [19]. The equation for calculating the PM is given in Equation 5. These concepts are exploited when defining the Hydroplaning Potential.

$$PM = \min\left[\sqrt{\left(A^*_{Brk} - A_{Brk}\right)^2 + \left(A^*_Y - A_Y\right)^2}\right], \forall A^*_{Brk}, A^*_Y \quad \text{Eq. (5)}$$

Hydroplaning Potential

The Hydroplaning Potential (H_P) and Hydroplaning Risk (H_R) are developed in this work as estimated conditional probabilities. First consider several sets to describe the vehicle/tire combinations (V), pavement surfaces (S), and WFT (W) being considered. The elements of each set are formed by partitioning of the set (the elements are mutually exclusive and collectively exhaustive). It should be clear that the partitioning of each set can be as course or as fine as is needed. For example, the set of all vehicle/tire combinations could be partitioned as simply as V = {car/bald, car/tread, noncar/bald, noncar/tread}, or the partition could be defined to specify every make, model, and year for each vehicle and make, model, and tread depth for each tire. The important concept is that whenever there is a valid partition of sets, the developments in this work are equally applicable. The results from applying these developments using different partitions will of course vary depending on the quality and refinement of the partition chosen.

The pavement surface partition could include many discrete ranges of grade, cross-slope, roughness, texture, etc. Again, the important concept is that every combination of grade, cross-slope, etc. is indexed separately so that the union of all the combinations accounts for all the pavement surfaces being considered without intersection. Next an event, H, is defined as hydroplaning occurring. The probability that hydroplaning occurs given a specific vehicle/tire combination, WFT, and pavement surface is

$$P(H|V\,W\,S) \quad \text{Eq. (6)}$$

It is proposed that the Hydroplaning Potential, H_P, be defined as an appropriate estimate of this conditional probability. Specifically, it is proposed that the Hydroplaning Potential be estimated from the PM, which is a function of the vehicle/tire combination, WFT, and pavement surface.

$$H_P = \hat{P}(H|V\,W\,S) = f\left(PM\left(V\,W\,S\right)\right) \quad \text{Eq. (7)}$$

Next an admissible function is developed to estimate this conditional probability. An admissible function of the PM should have some required properties and desired characteristics, proposed herein with brief justifications.

- Obey the axioms of probability.
  The function of the PM is an estimate of a conditional probability and, as such, must obey the probability axioms including being nonnegative and less than or equal to one for all values of the PM.
- Be a monotonically decreasing function of all positive finite values of PM.
  The PM is a measure of any additional performance capability that is available. As additional performance capability increases, the probability of hydroplaning must decrease.
- Asymptote to one as the PM approaches zero.
  As the limit of vehicle performance is exceeded, the vehicle hydroplanes with probability of 1. Furthermore, operating the vehicle very near the limit does not significantly change the hydroplaning potential.
- Asymptote to zero as the PM approaches infinity.
  There is always some very small probability of hydroplaning even if the PM is large. The limiting case is that the probability of hydroplaning only approaches zero as the PM approaches infinity.

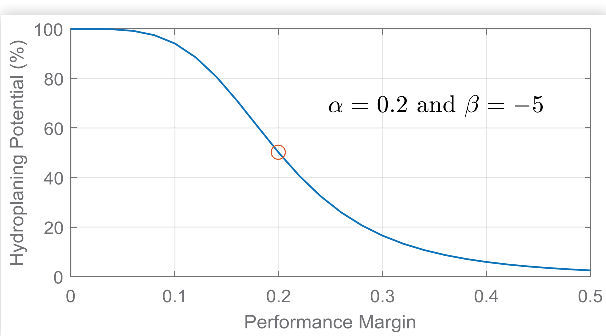
The admissible function proposed as the Hydroplaning Potential is a logistic function of the PM (which, in turn, is a function of the pavement surface, vehicle/tire combination, and WFT). The proposed function, given in Equation 4, is entirely parameterized by two physically intuitive values.

- α is the value of the PM for which there is a 50% probability that hydroplaning will occur, $H_P(PM = \alpha) = 1/2$.
- β is the slope of the curve at $PM = \alpha$, which affects the sharpness of the transition.

$$H_P = \hat{P}(H \mid V\, W\, S) = \left(1 + \left(\frac{PM}{\alpha}\right)^{-4\alpha\beta}\right)^{-1} \qquad \text{Eq. (8)}$$

This admissible function and the corresponding properties and characteristics are best understood in a simple plot as shown in Figure 2. Although tuning the parameters is outside the scope of this theoretical work, an example of parameters used in the figure to demonstrate the concepts is

FIGURE 2 Hydroplaning Potential vs. Performance Margin.



$\alpha = 0.2$ and $\beta = -5$. Notice that the potential for hydroplaning asymptotes to, but does not exceed, one as the PM decreases to zero and asymptotes to, but does not descend below, zero as the PM increases. The median PM is 0.2, shown as a small circle, and the slope at the point is −5.

Hydroplaning Risk

It is further proposed that the Hydroplaning Risk, H_R, is defined as an appropriate estimate of the conditional probability of hydroplaning occurring given the pavement surface being considered, specifically

$$H_R = \hat{P}(H \mid S) \qquad \text{Eq. (9)}$$

Implicit in this statement is that Hydroplaning Risk is defined in the aggregate, for all vehicles at all times traveling over the road surface in question. This is accomplished by establishing the Hydroplaning Potential for sets of vehicle/tire combinations (V) and WFT (W) and then establishing the probabilities of these sets occurring for the road in question.

First recall that V and W are partitioned so that

$$P(H \mid S) = \frac{P(HS)}{P(S)} = \frac{\sum_V \sum_W P(HVWS)}{P(S)} \qquad \text{Eq. (10)}$$

and

$$P(HVWS) = P(H|VWS)P(V|WS)P(W|S)P(S) \qquad \text{Eq. (11)}$$

which is simplified by assuming that the vehicle driven is independent of the WFT and surface

$$P(V|WS) = P(V) \qquad \text{Eq. (12)}$$

combining

$$P(H|S) = \sum_V \sum_W P(H|VWS)P(V)P(W|S) \qquad \text{Eq. (13)}$$

so that

$$H_R = \sum_V \sum_W H_P \hat{P}(V)\hat{P}(W \mid S) \qquad \text{Eq. (14)}$$

Consider the three terms in the double summation in Equation 14. An estimate for the first term is developed in this work as the Hydroplaning Potential, H_P, defined in Equation 8. The second term in the summation is an estimated probability distribution for each vehicle/tire combination on the road, which is outside the scope of this work. The third term is the estimated probability of a particular WFT given the pavement surface (including the geographical location and rainfall). Ideally the WFT is estimated using a 3D model of pavement surface with full Navier-Stokes equations, accounting for important surface and weather factors to predict and understand the hydrodynamics of water accumulation and drainage. Simulation results are provided to elucidate the modeling process used to predict the first and third terms in the double summation in Equation 14.

Simulation Results

Prediction of Water Film Thickness

The third term in Equation 14 is the estimated probability of a particular WFT given the pavement surface (including the geographical location and rainfall), $\hat{P}(W|S)$. Consider an example in which the WFT on a highway cross-slope transition has been predicted in the 3D CFD model with the calculation of full Navier-Stokes continuity and momentum equations. The longitudinal and lateral slopes and geometric characteristics of the highway surface have been specified in a 3D geometric model, shown in Figure 3. The resulting contour plot shows the changes of the highway surface elevation along the longitudinal (x) and lateral (y) directions. Solid white contour lines indicate locations of equal gradient for this example of a cross-slope transition. All the geometric characteristics and pavement texture have been able to be included in this 3D CFD model to investigate and predict WFT under various road conditions and weather conditions.

Figure 4 shows 2 plots for the 2-lane road described by Figure 3 and a 60 mm/h rainfall rate. Figure 4(a) is the predicted WFT distribution as a contour plot, and Figure 4(b) is the predicted fluid direction vector. The shoulders on each side of lanes have been excluded from the figures since the vehicles are not being predicted to travel on the shoulders of the road. Figure 4(a) demonstrates that the contour of WFT accumulates to a greater depth near the region of 0% cross-slope (ZCS) and the inner edge downstream. Figure 4(b) shows the vector distributions of the thin water film. In the normal crown section, where the cross-slopes are –2% on both sides, the velocity vectors are directed toward each edge of the road. However, when the water reaches the ZCS for the outer side of the road, the velocity vectors change directions toward inner side of the road and accelerate. Due to the change of the velocity direction, water accumulates near this ZCS section. This example is intended as a proof of concept for using a 3D CFD model with the calculation of full Navier-Stokes continuity and momentum equations for predicted WFT. More details of the WFT study can be referred to [3].

FIGURE 3 Contour of reference height on pavement surface (2 lanes; S_x % = −1%; lateral slopes marked on the solid lines).

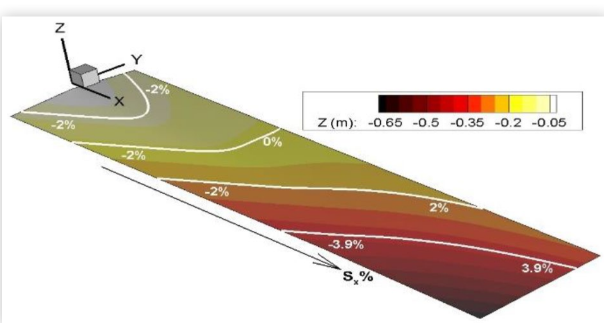
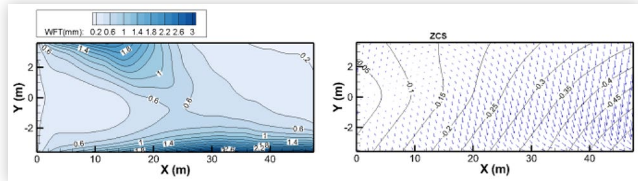


FIGURE 4 WFT distribution and velocity vectors in cross-slope transition: (a) WFT distribution (WFT marked on solid lines); (b) velocity vector of water film (reduction in pavement height marked on solid lines).

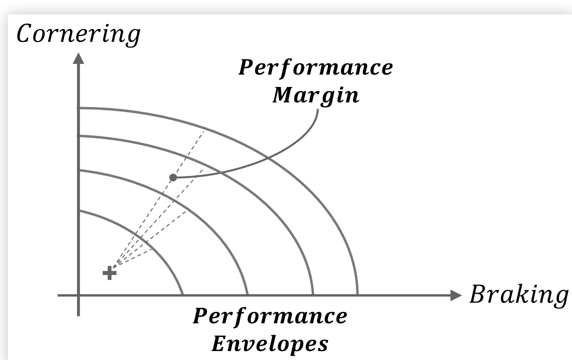


Prediction of Hydroplaning Potential

The first term in Equation 14 is the Hydroplaning Potential, H_P, defined in Equation 8. Consider a particular vehicle/tire combination and pavement surface (including the cross-slope, the $\tan(\theta_b)$, and the slope $\tan(\theta_s)$). For simplicity, consider only 4 distinct elements in the set of possible WFT: W = 0 mm, 2 mm, 4 mm, and 6 mm whose Effective Friction is μ_{dry}, μ_{2mm}, μ_{4mm}, and μ_{6mm}, respectively. The PE is then established and the PM is calculated from Equation 5. The PE and PMs are plotted for the four WFT cases in Figure 5. The outermost PE which is shown as a solid line corresponds to the case in which the road is dry, and the innermost corresponds to the case in which the WFT is 6 mm. The set of PMs are indicated by dashed lines and are calculated from a single operating condition indicated by a cross.

Consider the PMs to be 0.6, 0.5, 0.3, and 0.1, corresponding to WFT 0 mm, 2 mm, 4 mm, and 6 mm, respectively. If the hydroplaning parameters are assumed to be α = 0.2 and

FIGURE 5 Performance for various water film thicknesses.



$\beta = -5$, then the Hydroplaning Potential is calculated from Equation 8. In this specific example, WFT of 0 mm, 2 mm, 4 mm, and 6 mm produces a Hydroplaning Potential of 0.01, 0.02, 0.16, and 0.94, respectively. It is critical to note that this is a specific example being presented to demonstrate the concept and must not be misinterpreted as being true for all scenarios.

Discussion

The contribution of this work is the development of a theoretical framework by which Hydroplaning Risk is predicted. The determination of appropriate hydroplaning parameters (α and β), rainfall rates, road geometry, and vehicle and tire types is application specific and, as such, is outside the scope of this work. It is expected that subsequent work will focus on specific applications.

It should be noted that the term hydroplaning as used in this work is differentiated from the term wet grip that is primarily attributed to the effect of wetness for very small WFT (up to 0.5 mm) on the friction coefficient, specifically to study if the hysteresis component of the friction is more dominant than the adhesion component. In this work, the WFT is much more than the wet grip study, and the effect of the lift force caused by the WFT is playing the main role in the model instead of the tire-pavement friction mechanism.

Conclusion

Hydroplaning is a complex phenomenon requiring a multidisciplinary approach. The holistic approach developed in this work combines hydrology, FSI, tire mechanics, and vehicle dynamics. This novel approach to understand the fundamentals of hydroplaning allows interpretation of Hydroplaning Potential and Risk in a probabilistic framework without resorting to the traditional single go/no-go speed. It is expected that this theoretical framework will enable the development of guidelines for geometric road design and improved vehicle and tire design. It is hoped that this work will help reduce vehicle crashes that occur due to wet pavement and help save the lives of the traveling public.

Contact Information

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Definitions/Abbreviations

Every effort is made to use terminology and nomenclature that are consistent with SAE J670 [24]. Without loss of generalization, the cornering concepts in this work are developed for a left turn. For distinctions between the road plane and the ground plane, see [19].

Ground plane - A horizontal plane normal to the gravitational vector (no slope or cross-slope).

Road plane - A plane representing the road surface passing through the tire contact patches, supporting the tires, and providing the friction necessary to generate tire shear forces.

Tire traction - The vector sum of the tire shear forces acting at the tire contact patch.

Vehicle traction - The vector sum of the actual tire traction forces generated for the specific operating condition.

$\boldsymbol{A_X}$ - Longitudinal acceleration-The longitudinal force divided by the vehicle operating weight, *mg*.

$\boldsymbol{A_Y}$ - Lateral acceleration-The lateral force divided by the vehicle operating weight, *mg*.

Available Acceleration - The maximum vector sum of the longitudinal and lateral acceleration that could be generated for the specific operating condition.

Required Acceleration - The minimum vector sum of the longitudinal and lateral acceleration that must be generated for the specific operating condition.

$\boldsymbol{\tan\theta_b}$ - Cross-slope (crossfall, camber, bank angle) where the positive sense is such that the lower side of the road surface is closer to the center of the turn (a properly banked road).

$\boldsymbol{\tan\theta_s}$ - Slope (grade) where the positive sense is such that the vehicle is heading uphill.

$\boldsymbol{\mu}$ - Coefficient of friction-The available traction divided by the vehicle normal force for a specific operating condition.

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