Analyzing Driving Safety Using Vehicle-Water-Filled Rutting Dynamics Model and Simulation

Yandi Zhang, Bobo Yuan, and Yukun Chou

School of Highway, Chang’an University, Xi’an, Shaanxi 710064, China

Correspondence should be addressed to Yandi Zhang; 506347241@qq.com

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Rutting is one of the major asphalt pavement distresses that could cause hydroplaning and lead to roadway safety concerns on a rainy day. However, there is still no theoretical methodology with simulation to evaluate and predict the driving safety caused by rut-induced hydroplaning using vehicle dynamics. This paper proposes a methodology, based on a new developed “vehicle-water-filled rutting” open-loop vehicle dynamics model analyzed by CarSim (a professional vehicle dynamic software), to simulate and compute the impact of unbalanced water-filled rutting on driving stability/safety with a special focus on the vehicle’s lateral dynamic stability, including lateral offset and lateral acceleration. Analysis results show the following: (1) The unbalanced water depths in left rutting and right rutting lead to the different friction between left rutting and right rutting and make the vehicle wander left and right uncontrollably along the roadway. (2) When the vehicle speed is greater than 80 km/h and the rutting width exceeds 0.7 m, the unbalanced water-filled rutting begins to affect the vehicle’s lateral stability apparently and very likely threaten the driver’s life. (3) By computing the vehicle’s lateral offset and acceleration in different water widths and lengths in the hydroplaning situation, this paper proposes the rutting width and length thresholds for vehicle oversteer and instability, based on which the vehicle risk level is proposed. RISK I is the situation where vehicle’s lateral offset exceeds 1.025 mm which likely causes vehicle running into the adjacent lane (the danger can be avoided if there is no vehicle in the adjacent lane), RISK II is the situation where the vehicle’s tires begin to work into the nonlinear zone (the vehicle’s lateral acceleration exceeds 0.4 g) with the increase of rutting width and length, which makes the vehicle lose controls irreversibly for drivers, and this situation should arouse more concerns for transportation agencies. The proposed methodology would enable transportation agencies to predict the security risk of rutting and play a vital role for transportation agencies to scientifically establish the relevant specifications (e.g., rutting maintenance) that proactively trigger the maintenance and rehabilitation to prevent potential safety concerns from happening. Recommendations on future researches, including taking braking stability and real rutting conditions of the proposed model into consideration, are also continued in the future study.

1. Introduction

As one of the major asphalt pavement distresses, rutting not only affects the quality of the roadway roughness and decreases the driving comfort but also indirectly reduces the pavement skid resistance on rainy days and likely leads to hydroplaning danger, especially when the roadway is poorly drained [1–3]. The standard “Technical Specifications for Maintenance of Highway Asphalt Pavement,” published by Ministry of Transport of China, defined the threshold of rutting maintenance as 25 mm for first-class highways and expressways. However, more and more researchers [4–8] pointed out that, as the only rutting evaluation indicator, the rutting depth without driving safety consideration, especially the impact of rutting geometrical features (depth, length, and width) on vehicle driving safety, is not reasonable enough for rutted roadway maintenance. What is more, the extent (length and width) of the water filled in a rutting should be considered as the major factor affecting the driving safety.

In recent years, many fruitful studies on the safety assessment of rutting have been conducted. Using the computational fluid dynamics (CFD) to approach 3D finite element simulation of the action between the pavement
surface, tires, and water, T. F. Fwa et al. found that tire load, tire inflation pressure, and tire tread pattern affect the critical hydroplaning speed apparently. Based on this, they recommended that the critical hydroplaning speed and vehicle braking distance should be the major evaluation indexes considered to redetermine the rutting depth margin for pavement maintenance [6]. Based on the relationship between water depth and vehicle control stability on a rainy day, the allowable rutting depth computed theoretically by Shi-fa Xu is 10–12.5 mm [7]. Some researchers have verified and explored the present rutting index classification based on driving safety. In addition, they have suggested that the maximal rutting depth, rutting width, maximum probable water area in a rutting, and the average curvature radius of a rutting should be also applied to characterize rutting’s features [4, 5, 8, 9]. According to the simulation results of Automatic Dynamic Analysis of Mechanical Systems (ADMAS), Jin Xu pointed out that when a vehicle was driving on the water surface, the difference between the left and right tires’ peripheral velocity in a given time is the major cause of a vehicle’s slipping to the left or the right. Meanwhile, the longer a vehicle drives on a rutted pavement filled with water, the larger the difference between the left and right tires’ peripheral velocities is, which leads to a greater sideslip possibility for a vehicle [10], which proved that the rutting length and width have an apparent effect on driving safety. Fwa [11] presents a study to develop an analytical procedure for rut depth intervention level based on the concept of skid resistance intervention level. This method relies on the already known standardized skid resistance threshold and the skid resistance-vehicle speed curves for different ponded rut depths through a contact model between tires and water established by using the finite element method. Wenting Luo [12] used IMU and 1 mm 3D laser data to evaluate hydroplaning risk based on Gallaway WFD model. This model is used by Federal Department of Transportation to predict hydroplaning speeds. One of the researchers, Fengzhao [13], used Automatic Dynamic Analysis of Mechanical Systems (ADAMS) to simulate differential friction skidding situations. Hang Lu [14] established rutting-vehicle dynamic models based on mechanical equilibrium and geometric relationship, including roll and yaw motions of vehicles. Zhengqiang Feng [15] established vehicle model and rutting road model by Car-Sim, and the rutting with different depths was added to the pavement model. Five driving stability indexes of lateral acceleration, roll angle, yaw rate, breaking distance, and offset distance were selected, and their thresholds were established.

Research shows that water depth, width, and length in rutting have significant effects on driving safety; however, quantitative studies on the impact of rutting features on driving safety are still scarce. However, the impacts on driving safety caused by water in rutting are not the negligible issues and should exactly arouse the transportation agencies’ concerns. Based on hydromechanics and vehicle dynamics, this paper (1) analyzes the vehicle dynamics mechanism in the unbalanced water-filled rutting situation and develops the “vehicle-water-filled rutting” open-loop model, (2) considers the vehicle lateral offset and acceleration in the different water widths and lengths as safety assessment indexes, proposes the rutting width and length thresholds for vehicle oversteer and instability, and (3) quantitatively analyzes the impacts of rutting lengths, widths, and water depths on the driving safety at different speeds and provides more effective, objective, and scientific maintenance suggestions for transportation managers.

1.1. Analysis of Vehicle Longitudinal Stability in Water Section. According to the analysis above, the rut evaluation indicator presented by highway agencies has little consideration with the impact of driving safety. In recent years, many highway researchers have begun to pay attention to the safety assessment of rutting and conduct some preliminary studies on the impact of water in rutting, and they mostly focus on the hydroplaning.

A vehicle’s longitudinal stability, which includes dynamic performance and driving performance, is the essential evaluation indicator for driving safety. The friction coefficient, the ratio of the frictional force of the roadway to the vertical vehicle load, between a tire and road is the major factor affecting driving and braking performance. With the increase of water depth, the contact area between tires and the roadway will decrease, which leads to the decrease of the friction coefficient. When the roadway is separated from the tire by water, the friction coefficient will be zero and hydroplaning will occur. The United States Federal Highway Administration (FHWA) says that a rutting depth that exceeds 5.08 mm (0.2 in) will cause hydroplaning [16].

As shown in Figure 1, RD refers to the rutting depth presented by highway agencies; RD_{cw} refers to the maximum water depth in a rutting. By analyzing data computed from a hydroplaning simulation, T. F. FWA pointed out that, for a given speed, when the water depth ranges from 0 to 5 mm, the friction coefficient will decrease nonlinearly with the water depth; however, the friction coefficient decreases linearly as water depth exceeds 5 mm [6, 17]. With the mathematical regression of the hydroplaning data, the linear equation of water depth in rutting and friction coefficient at different speeds is computed as follows:

\[
\varphi - 0.3696 = -0.01155(h - 5)V = 60 \frac{\text{km}}{\text{h}},
\]

\[
\varphi - 0.1921 = -0.01106(h - 5)V = 80 \frac{\text{km}}{\text{h}},
\]

\[
\varphi - 0.0800 = -0.00574(h - 5)V = 100 \frac{\text{km}}{\text{h}},
\]

\[
\varphi - 0.0502 = -0.00398(h - 5)V = 120 \frac{\text{km}}{\text{h}},
\]

where \( \varphi \) is the friction coefficient between tire and roadway; \( h \) represents the rutting water ponding depths; \( V \) is the car’s speed.

In general, “a rutting” actually occurs in pairs on the roadway. According to the vehicle dynamics, when the water depth in right rutting is different from the one in left rutting,
the friction coefficient of right rutting differs from the one of left rutting, and the force states between the right wheel and left wheel are also different, which makes the vehicle sideslip. Therefore, the vehicle’s driving instability is mainly caused by the difference of water depth in right rutting and left rutting rather than by the water depth (or rutting depth) itself.

Considering a front-wheel drive (FWD) vehicle, the left-front wheel (wheel A) is moving on the water-filled rutting at a given speed, while the right-front wheel (wheel B) is moving on the dry pavement, as shown in Figure 2. Based on the vehicle dynamics, the center of the left-front tire emerges the yawing force $F_Y$ in the $Y$ direction. Assuming that the sliding speed is $\Delta v$, a resultant velocity ($v'$) is formed and the tire will travel along $v'$ direction instead of the original running path along $cc'$. Without the complicated impact of rutting sidewall, the angle of wheel’s sideslip will increase at a great rate and the wheel will sideslip partially with $F_Y$’s increase. When $F_Y$ achieves the limit of the lateral friction, the wheel will sideslip completely. The maximal yawing force depends on the friction condition between the tire and the road (i.e., the vertical load, tire tread pattern, tire inflation pressure, and water depth in a rutting affect the action).

Assume that, in the process of turning a vehicle, the process of the force on tires can be simply regarded as two equilibrium equations: mechanical equilibrium equation and moment equilibrium equations, expressed, respectively, as follows:

\[ F_{Y1} + F_{Y2} = ma_y, \]  
\[ F_{Y1}a - F_{Y2}b = I_z\dot{\omega}_r, \]

where $F_{Y1}$ and $F_{Y2}$, respectively, are the yawing forces of the front wheel and the rear wheel; $m$ is the vehicle’s mass; $a_y$ is centroid acceleration; $I_z$ is the centroid rotational inertia of the vehicle; and $\dot{\omega}_r$ is the yaw angular acceleration.

According to equations (2) and (3), the sum of $F_{Y1}$ and $F_{Y2}$ equals $ma_y$, but the distribution of $F_{Y1}$ and $F_{Y2}$ depends on $I_z\dot{\omega}_r$. With inertia torque’s increase, $F_{Y1}$ will increase and $F_{Y2}$ will conversely decrease. Figure 3 shows the force situation of the vehicle’s steady-state circular motion. The following could be deduced from Figure 2:

\[ F_{Y1}a - F_{Y2}b = 0 \Rightarrow \frac{F_{Y1}}{F_{Y2}} = \frac{b}{a}. \]

When the left driving wheel runs into the water zone, the right drive wheel’s friction coefficient will be larger than the left one. The friction force of the driving wheels begins to be different due to the change of the friction coefficient, which generates a yaw moment $F_Xa_d$, as shown in Figure 2. The torque equilibrium equation turns to be as follows:

\[ F_{Y1}a + F_Xa_d = F_{Y2}b = 0. \]  

(5)

According to equation (5), $F_{Y1}$ will decrease, and $F_{Y2}$ will increase relatively; on the contrary, the front sideslip angle of vehicle will decrease and the rear one will increase, which leads the vehicle to sideslip. If the vehicle still moves at a high speed or accelerates, the vehicle will move with forward acceleration and relevant yaw angular acceleration $\dot{\omega}_r$. The front wheel suffers ground reactive force in the longitudinal and lateral directions, and the vehicle will sideslip seriously and even may be out of control.

For a given speed, the water length and the width in rutting have apparent effects on the travel time of the vehicle in the water-covered section of a roadway. The travel time is directly proportional to the yaw moment of the couple $F_Xa_d$. The bigger $F_Xa_d$ is, the greater the possibility of sideslip is. Therefore, a vehicle’s stability includes two major problems: one is keeping the vehicle on its path, which is assessed by the lateral offset; the other is maneuvering the vehicle’s stability, which is assessed by lateral acceleration [18–23].

Because the numerical analysis and computing is a very complicated work, this paper uses the dynamics analysis and simulation software CarSim, which has been successfully and widely applied by many world-known automobile manufacturers, to compute the vehicle’s lateral offset and lateral acceleration at different water-filled rutting condition.
2. “Vehicle-Water-Filled Rutting” Open-Loop Dynamics Model

2.1. Model Hypothesis. The proposed “vehicle-water-filled rutting” open-loop dynamics model in this paper makes the following hypotheses about the relationship between the actual motions of a vehicle and the roadway conditions:

1. The longitudinal slope and the cross slope of the roadway model have very little effects on the driving safety and are set to be zero [24], and the road is straight and flat.

2. The tire’s lateral distortion characteristics are in a linear range when the lateral acceleration of the vehicle is below 0.4 g [18–20]; the model ignores the effects of the ground tangential force on a tire’s lateral distortion characteristics due to the small driving force.

3. The model ignores the effect of aerodynamic force.

4. The change of tire’s characteristics caused by the change in the load of the left and right tires is ignored in this model; the effect of a tire’s aligning torque is also ignored in the model.

5. The impact of a driver on vehicle is ignored in the model.

6. The impact of the sidewall angle of rutting and the longitudinal change of rutting depth is ignored in the model.

2.2. Simulation Software Introduction. Because the numerical analysis and calculation is a very complicated job, this paper uses the dynamics analysis and simulation software CarSim, which was developed by University of Michigan Transportation Research Institute (UMTRI) and is widely applied by many world-known automobile manufacturers, to compute and analyze the vehicle dynamical equations.

2.3. Vehicle Parameter Settings. In this paper, the dynamics analysis software (CarSim) is used to develop the vehicle model. The vehicle structures include a two-way cartridge front and rear independent suspension, a rack-and-pinion steering gear, a pendular strutting independent suspension front-drive axle (IFDA) with QS, caliper disc brakes (front wheels), self-adjusting drum brakes (rear wheels), and front-wheel drive (FWD). The essential parameters in CarSim are shown in Table 1 (setting is shown in Figure 4).

2.4. Settings for Rutted Roadway Filled with Water. In the simulation analysis, the length of the roadway section is 1000 m. In order to ensure that the vehicle runs steadily at the expected speed before the water section, the vehicle in the simulation begins to travel into the water section after travelling 350 m on the dry pavement along the central line. The length of the water section is 650 m; the width of pavement in the model is 3.75 m; the friction coefficient of the dry pavement is set to be 0.8 [19–21]. As the general friction between newly dry pavement and tire is 0.8, the region of water is set to be in the left rutting, as shown in Figure 5 (blue line in Figure 5). The coefficient is set from 0.01 to 0.1 which is related to the depth of the rutting (the linear equation [1–4] of water depth in rutting and friction coefficient at different speeds). Assume that the right rutting has no water and the coefficient is set to be 0.8, the same as the dry pavement.

As shown in Figure 5, the expected driving line is along the center line (blue line in Figure 5). In practice, the vehicle wanders along the red line and orange line because of the water in left rutting (the friction force is different between the left and right tires in this situation). In this paper, the dangerous situation includes two risk levels based on the proposed “vehicle-water-filled rutting” open-loop dynamics methodology [25].

1. RISK I: When the water length and width in rutting are long enough, the vehicle’s lateral acceleration exceeds 0.4 g, and the vehicle’s wheels will work into the nonlinear zone (shown in Figure 6, right zone of the red curve, a tendency to oversteer). The vehicle is out of control (orange driving line shown in Figure 5) and is hardly handled for general drivers in this situation. Often accidents happen especially in this situation.
In this situation, although the water length and the water width in rutting are not enough to make the vehicle lose control, the rutting vehicle still likely runs into the adjacent lane and crashes the adjacent vehicles when the vehicle’s lateral offset exceeds 1.025 mm (the red line shown in Figure 5). However, if there is no vehicle in the adjacent lane, the risk could be avoided by adjusting the steering wheel immediately.

Figures 7 detailedly explains the “vehicle-water-filled rutting” open-loop dynamics model proposed in this paper (models for the impact of water length, water width, and combined length and width on vehicle lateral stability).

In Figure 7(a), the length and the friction coefficient (changing from 0 to 0.1) of water-filled rutting are the variables in the model. Besides, the water-filled rutting width is set to be 1.875 m. In Figure 7(b), rutting width is only variable and ranges from 0.7 m to 1.6 m. Besides, the length and the friction coefficient (changing from 0 to 0.1) of water-filled rutting are, respectively, set to be 650 m and 0 (hydroplaning situation). In Figure 7(c), the length and the width of water-filled rutting change, respectively, from 50 m to 400 m and from 0.8 m to 2.0 m.

In order to analyze the vehicle’s response to the water-filled rutted roadway without directional interference, the steering wheel and the brake are always released and the directional control is open loop; that is, the driver does not control the current system by using the feedback from the control itself. Therefore, the open-loop control mode is used in this paper to analyze the open-loop motion of the vehicle.

### Table 1: Structure parameters of vehicle.

<table>
<thead>
<tr>
<th>Dynamical parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of full equipment</td>
<td>M</td>
<td>1210 (empty vehicle) + 70 (driver)</td>
<td>kg</td>
</tr>
<tr>
<td>Size of full equipment</td>
<td>L x W x H</td>
<td>4680 x 1700 x 1423</td>
<td>mm</td>
</tr>
<tr>
<td>Roll inertia</td>
<td>Ixx</td>
<td>524.26</td>
<td>kg-m²</td>
</tr>
<tr>
<td>Pitch inertia</td>
<td>Iyy</td>
<td>2552.25</td>
<td>kg-m²</td>
</tr>
<tr>
<td>Yaw inertia</td>
<td>Izz</td>
<td>2644.52</td>
<td>kg-m²</td>
</tr>
<tr>
<td>Front wheelbase</td>
<td>A</td>
<td>1300</td>
<td>mm</td>
</tr>
<tr>
<td>Rear wheelbase</td>
<td>B</td>
<td>1356</td>
<td>mm</td>
</tr>
<tr>
<td>Front tread</td>
<td>db</td>
<td>1414</td>
<td>mm</td>
</tr>
<tr>
<td>Rear tread</td>
<td>dt</td>
<td>1422</td>
<td>mm</td>
</tr>
<tr>
<td>Height of Mass center</td>
<td>h0</td>
<td>500</td>
<td>mm</td>
</tr>
</tbody>
</table>

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**Figure 4: Parameter settings in CarSim.**

(2) RISK II: In this situation, although the water length and the water width in rutting are not enough to make the vehicle lose control, the rutting vehicle still likely runs into the adjacent lane and crashes the adjacent vehicles when the vehicle’s lateral offset exceeds 1.025 mm (the red line shown in Figure 5). However, if there is no vehicle in the adjacent lane, the risk could be avoided by adjusting the steering wheel immediately.

Figures 7 detailedly explains the “vehicle-water-filled rutting” open-loop dynamics model proposed in this paper (models for the impact of water length, water width, and combined length and width on vehicle lateral stability).

In Figure 7(a), the length and the friction coefficient (changing from 0 to 0.1) of water-filled rutting are the variables in the model. Besides, the water-filled rutting width is set to be 1.875 m. In Figure 7(b), rutting width is only variable and ranges from 0.7 m to 1.6 m. Besides, the length and the friction coefficient (changing from 0 to 0.1) of water-filled rutting are, respectively, set to be 650 m and 0 (hydroplaning situation). In Figure 7(c), the length and the width of water-filled rutting change, respectively, from 50 m to 400 m and from 0.8 m to 2.0 m.

In order to analyze the vehicle’s response to the water-filled rutted roadway without directional interference, the steering wheel and the brake are always released and the directional control is open loop; that is, the driver does not control the current system by using the feedback from the control itself. Therefore, the open-loop control mode is used in this paper to analyze the open-loop motion of the vehicle.

2.5 Verification of Model for Stability Simulation. The dynamics analysis software CarSim is applied to develop the “vehicle-water-filled rutting” open-loop dynamics model
and analyze the driving safety of vehicle, so it is necessary to verify the model for stability simulation. The validation methods, respectively, are the emergency double lane change in ISO standard (shown in Figure 8(a)) and the pylon course slalom test in “Controllability and Stability Test Procedure for Automobiles in China” (GB/T 6323-2014), shown in Figure 8(b) [26, 27].

Figure 8(a) shows the standard test field for ISO double lane. The ISO and VDA lane-change test is used to evaluate the handling performance of a vehicle and is an integral part of the vehicle design procedures and vehicle assessment. Based on 3 cone lanes with a total length of 225 meters, a change about double lane is defined, which must be completed with maximum speed. After starting into the entry lane, the vehicle throttle is released so that the entire maneuver is completed in the overrun mode with the top gear and an engine speed of at least 2000 rev/min. At the end of the entry and exit lane, the velocity is measured. The entry velocity is increased gradually. If no cones are overturned, the test would be passed.

Figure 8(b) shows the standard test field for the pylon course slalom test. The pylon course slalom test is the test method for vehicle control stability required in practice “Controllability and Stability Test Procedure for Automobiles in China” [27], which can estimate effectively the vehicle’s maneuverability and steering performance. In the test, the test stake is set at regular intervals in the proving ground. The indicators (such as hand-wheel angle, steering force, yaw velocity, angle of roll, and lateral acceleration) can be measured when the car weaves its way through the test stakes.

The reference speed is 65 km/h based on the standard in GB/T 6323-2014, and the friction coefficient of pavement is 0.8 (dry pavement). The comparison of the simulation results and standards is shown in Table 2.

It can be indicated from Table 2 that, taking the standards as the reference, the simulation results of the emergency double lane change and the pylon course slalom are within allowable limits. Therefore, the “vehicle-water-filled rutting” open-loop dynamics model in this paper is reasonable and accurate for stability simulation.

2.6. Analysis of Simulation Results. Previous practical engineering experience [10] proves that the longer a vehicle travels on a water-covered roadway section, the greater in magnitude the vehicle will sideslip from the design path and the higher the possibility that the vehicle loses control. Therefore, the travel time on the water section is the major controlling factor for vehicle’s stability. Rutting width and length directly affect the travel time on the water section for a given speed. The longer rutting width and length are, the more obvious the yaw moment affects the vehicle based on the theoretical analysis above.
Rutting Width is set to be 1.875 m. 

Water zone

Dry Pave ment

Rutting Length is variable

Rutting depth is variable

Driving direction

1.875 m

1.7 m

1.025 m

350 m

(a)

1.875 m

1.7 m

1.025 m

350 m

Rutting Length is 650 m

Rutting Width is variable, changing from 0.7 m to 1.6 m

Friction coefficient of the left water-filled rutting is 0.

Water in the Rutting

Dry Pave ment

(b)

1.875 m

1.7 m

1.025 m

350 m

Rutting length is variable, changing from 50 m to 400 m

1. Rutting Width is variable, changing from 0.8 m to 2.0 m.
2. Friction coefficient of water-filled rutting is 0.

(c)

Figure 7: “Vehicle-water-filled rutting” open-loop dynamics model. (a) Analysis model for the impact of water length and depth on vehicle lateral stability. (b) Analysis model for the impact of water width on vehicle lateral stability. (c) Analysis model for the combined impact of water width and length on vehicle lateral stability.

Field Rod

Guide String

Guide String

Entrance

Exit

S_0

S_1

S_2

S_3

S_4

S_5

S_6

D

B_1

B_2

Field Rod

Guide String

Guide String

Entrance

Exit

S_0

S_1

S_2

S_3

S_4

S_5

S_6

L

D

Figure 8: Standard test fields for stability simulation. (a) Standard test field for emergency double lane change (S_0 = 50 m; S_1 = 15 m; S_2 = 30 m; S_3 = S_4 = 25 mm; S_5 = 30 m; S_6 = 50 m; D = 3.5 m; B_1 = 1.1b + 0.25 = 2.12 m; B_2 = 1.2b + 0.25 = 2.29 m; B_3 = 1.3b + 0.25 = 2.46 m. b refers to vehicle’s width, 1.7 m). (b) Standard test field for pylon course slalom (D = 2.48 m; S_0 = 50 m; S = 100 m; L = 30 m).
2.7. Impact of Water Length in Rutting on Driving Safety.

This paper applies CarSim to simulate and compute the vehicle lateral offset and lateral acceleration in the water-covered section of the roadway at different speeds and rutting lengths. The rutting width is assumed to be 1.875 m in the model. The friction coefficient of left water-filled rutting ranges from 0 to 0.1, and Figure 9 shows the simulation results when friction coefficients are, respectively, 0, 0.02, 0.04, 0.06, 0.08, and 0.1. Figure 10 shows the simulation results when friction coefficients are, respectively, 0, 0.01, 0.02, and 0.03.

The simulation result shows that, for a given speed, the lateral offset and the lateral acceleration vary apparently with the decrease of the friction coefficient. The following is indicated from Figures 9 and 10:

1. From the computing results of lateral offset, when the friction coefficient is below 0.02, the vehicle may rush out of lane and lose control even if the speed is 60 km/h due to the high yawing force and inertia force. However, for the rutted roadway of which friction coefficient exceeds 0.02, the yawing force and the inertia force are not enough to make the vehicle sideslip all the time, which have little impact on the lateral handing stability. When the friction coefficient exceeds 0.08, the vehicle cannot sideslip into the adjacent lane even if the speed is 120 km/h. As the friction coefficient exceeds 0.2, the water in the rutting has almost no effect on the vehicle’s lateral stability, while the vehicle cannot lose control and the water in the rutting has almost no effect on the handing stability when the friction coefficient exceeds 0.02.

2. For the vehicle’s lateral stability, when the friction coefficient is below 0.01, the speed is the major influencing factor of safety distance. As the friction coefficient exceeds 0.02, the lateral stability stays within the safety margin for the low-speed vehicle (60 km/s −), but, for the high-speed vehicle (120 km/h +), the lateral stability will stay in the safety margin as long as the friction coefficient exceeds 0.07. For the water-covered section of which friction coefficient is below 0.02, the safety distance in which the vehicle is out of control decreases with the increase of speed and the decrease of the friction coefficient.

(3) Based on the computing data, the safety distance of lateral acceleration decreases on an average of 35 m with increase of per 10 km/h, so the speed has more apparent effect on the lateral acceleration than lateral offset. For a given speed, when the friction coefficient is below 0.02, the safety distance of lateral acceleration increases on an average of 37 m with the increase of 0.01 for the friction coefficient. Therefore, the friction coefficient has more apparent effect on the lateral acceleration than on the lateral offset as well.

2.8. Impact of Water Width in Rutting on Driving Safety.

This paper applies the dynamics analysis software (CarSim) to simulate and computes the vehicle’s lateral offset and acceleration in the water section at different speeds. According to analysis of impact of water length in rutting on driving safety, the friction coefficient ranging from 0 to 0.02 has an apparent effect on the driving safety. Because of the limitation of paper space, this paper mainly analyzes the impact of water width on driving safety in the hydroplaning situation (i.e., the friction coefficient of water-filled rutting is 0). Besides, the rutting length is set to be 650 m in the simulation. Figures 11 and 12 show the simulative lateral offset and lateral acceleration at different water widths, respectively ($W_{rw}$, the sum of the widths of right rutting and left rutting).

For a given water length in rutting (Figure 11), when the water width is smaller than 0.7 m, the lateral offset is tiny down to be ignored. However, this offset will change apparently when the width exceeds 0.8 m. Vehicle wanders along the driving path as the yawing force can not afford the offset continuously which is influenced by the lateral friction force and inertia force. Vehicle wanders dramatically when the water width exceeds 1.6 m.

The simulation results for different rutting widths ranging from 0.7 m to 2.0 m indicate the following:

<table>
<thead>
<tr>
<th>Test item</th>
<th>Standard</th>
<th>Simulation result for emergency double lane change</th>
<th>Simulation result for pylon course slalom</th>
<th>Allowable absolute error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference speed (km/h)</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>—</td>
</tr>
<tr>
<td>Steering wheel angle (deg)</td>
<td>65.3</td>
<td>66.4</td>
<td>65.9</td>
<td>±2</td>
</tr>
<tr>
<td>Yaw rate (deg/s)</td>
<td>13.3</td>
<td>13.6</td>
<td>13.5</td>
<td>±0.5</td>
</tr>
<tr>
<td>Slip angle (vehicle) (deg)</td>
<td>3.0</td>
<td>3.12</td>
<td>3.08</td>
<td>±0.15</td>
</tr>
<tr>
<td>Lateral acceleration (m/s²)</td>
<td>4.3</td>
<td>4.42</td>
<td>4.39</td>
<td>±0.15</td>
</tr>
</tbody>
</table>
Figure 10: Lateral acceleration at different rutting lengths and speeds ($g_m = -0.4 \, g$). (a) $\mu = 0$, (b) $\mu = 0.01$, (c) $\mu = 0.02$, and (d) $\mu = 0.03$. 

Figure 9: Lateral offset from design path at different friction coefficients and speeds ($L_m = 1.025 \, \text{mm} \); $\mu$ refers to friction coefficient between tire and rutting surface). (a) $\mu = 0$, (b) $\mu = 0.02$, (c) $\mu = 0.04$, (d) $\mu = 0.06$, (e) $\mu = 0.08$, and (f) $\mu = 0.1$. 
When the rutting width ranges from 0 to 0.7 m, the water in the rutting has little effect on the lateral stability and handling stability due to the vehicle’s short travel time in water section.

When the rutting width ranges from 0.7 to 1.6 m, the water width has an apparent effect on the lateral stability and handling stability. However, the vehicle’s maximum lateral offset and lateral acceleration still stay within the safety margin even if the vehicle runs at 120 km/h. Therefore, the vehicle will have no chance to run into the adjacent lane or lose control, and the driver can take control of the vehicle by manipulating the steering wheel.

The maximum lateral offset and the maximum lateral acceleration exceed the safety margin when the vehicle runs on the 1.6 m wide water-filled rutting section. In this situation, the vehicle may run into the adjacent lane and collide with other vehicles and even lose control, while the driver cannot control the vehicle by manipulating the steering wheel.

### Table 3: Critical rutting length and water depths with speeds (m).

<table>
<thead>
<tr>
<th>Speed</th>
<th>Friction coefficient</th>
<th>0</th>
<th>0.01</th>
<th>0.02</th>
<th>0.03</th>
<th>0.04</th>
<th>0.05</th>
<th>0.06</th>
<th>0.07</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 km/h</td>
<td>$RD_{cw}$</td>
<td>22</td>
<td>21</td>
<td>21</td>
<td>20</td>
<td>19</td>
<td>18</td>
<td>17</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>$L_H$</td>
<td>135</td>
<td>135</td>
<td>156</td>
<td>195</td>
<td>291</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>$L_C$</td>
<td>323</td>
<td>352</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>100 km/h</td>
<td>$RD_{cw}$</td>
<td>19</td>
<td>17</td>
<td>15</td>
<td>14</td>
<td>12</td>
<td>10</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>$L_H$</td>
<td>121</td>
<td>121</td>
<td>137</td>
<td>156</td>
<td>173</td>
<td>195</td>
<td>265</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>$L_C$</td>
<td>310</td>
<td>323</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>120 km/h</td>
<td>$RD_{cw}$</td>
<td>18</td>
<td>15</td>
<td>13</td>
<td>10</td>
<td>8</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>$L_H$</td>
<td>116</td>
<td>116</td>
<td>129</td>
<td>145</td>
<td>157</td>
<td>168</td>
<td>183</td>
<td>212</td>
</tr>
<tr>
<td></td>
<td>$L_C$</td>
<td>254</td>
<td>301</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Note. $RD_{cw}$ refers to critical water depth in rutting, mm; $L_H$ and $L_C$, respectively, refer to critical water lengths in rutting of lateral stability and control stability, m.

Figure 11: Lateral offset from design path at different rutting widths and speeds. (a) $W_{rw} = 0.7$ m, (b) $W_{rw} = 0.8$ m, (c) $W_{rw} = 1.0$ m, (d) $W_{rw} = 1.2$ m, (e) $W_{rw} = 1.4$ m, and (f) $W_{rw} = 1.6$ m.

#### 2.9 Combined Impact of Rutting Length and Width on Driving Safety

Based on the analysis above, the impact of water length and width on driving safety is apparent. Therefore, it is necessary to analyze the combined impact of water length...
and width; the vehicle’s lateral stability at different combinations of rutting length and width is simulated using CarSim at hydroplaning situation. Besides, based on the simulation results in Figures 11 and 12, when the rutting width is below 0.7 m, water in rutting hardly affects vehicle’s lateral stability and handing stability for any rutting length. Therefore, the rutting width ranging from 0.8 m to 2.0 m is selected in the simulation. Results are shown in Figure 13.

The following can be concluded from the simulation results in Figure 13:

(1) When rutting width exceeds 0.8 m, the water in the rutting begins to apparently affect vehicle’s lateral stability. Table 4 lists the water length and width threshold of lateral stability. It is indicated that, rather than controlling the steering wheel, decreasing speed is the most efficient way to avoid the danger of sideslip, especially when the vehicle runs at high speed into a water-covered rutted roadway.

(2) When rutting length is below 100 m, the maximum lateral offset of a low-speed (60 km/h) vehicle is more than that of a high-speed vehicle due to the longer travel time for low-speed vehicle. In this situation, water in the rutting has an apparent effect on low-speed vehicles when the water width ranges from 1.0 m to 1.4 m and hardly affects the vehicle’s lateral stability when the width exceeds 1.4 m. In this situation, only rutting length and speed together affect the vehicle’s lateral stability.

(i) With the change of rutting length from 100 m to 300 m, the vehicle’s travel time could be longer, and the lateral offset begins to increase. In this situation, the maximum lateral offset of high-speed vehicle exceeds the one of the low-speed vehicle. Figure 13 indicates that, for a given speed, the maximum lateral offset does not change obviously, which proves that the rutting length has no longer been the influencing factor of lateral stability.

(ii) When the rutting length exceeds 300 m, the vehicle’s maximum lateral offset increases sharply; especially when the rutting width exceeds 1.6 m and the speed exceeds 80 km/h, the vehicle will sideslip into the adjacent lane. In this situation, decreasing speed is not an effective way to ensure the vehicle’s lateral stability, even if the vehicle runs at 60 km/h.

(3) The simulation results in Figure 13 show that only when the rutting width exceeds 1.6 m and the rutting length exceeds 150 m is there a risk of the vehicle
Figure 13: Maximum lateral offset at different combinations of water length and width (\(L_R\) refers to rutting length; \(L_m\) = 1.025 mm). (a) \(L_R = 50\) m, (b) \(L_R = 100\) m, (c) \(L_R = 150\) m, (d) \(L_R = 200\) m, (e) \(L_R = 250\) m, (f) \(L_R = 300\) m, (g) \(L_R = 350\) m, and (h) \(L_R = 400\) m.

Table 4: Water length and width threshold of lateral stability.

<table>
<thead>
<tr>
<th>Speed</th>
<th>60 km/h</th>
<th>80 km/h</th>
<th>100 km/h</th>
<th>120 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_{HF})</td>
<td>≥161 m</td>
<td>≥135 m</td>
<td>≥121 m</td>
<td>≥116 m</td>
</tr>
<tr>
<td>(W_{rw})</td>
<td>≥1.6 m</td>
<td>≥1.6 m</td>
<td>≥1.5 m</td>
<td>≥1.5 m</td>
</tr>
</tbody>
</table>
sideslipping into the adjacent lane. Inattentive or slow-responding driving may easily cause the danger.

Figure 14 shows that, for a given speed, water in a rutting section of roadway hardly affects vehicle control stability, as the rutting width is below 0.7 m. Therefore, the rutting width ranging from 0.8 m to 2.0 m is similarly selected in the model. The simulation results are shown in Figure 14.

Based on vehicle dynamics theory, a tire in a water-covered section of roadway will be within a nonlinear area when vehicle lateral acceleration exceeds 0.4 g. The vehicle will lose control completely and the situation will be very dangerous for drivers. Table 5 lists the water length and width threshold of control stability. If the rutting length and width are below the threshold in Table 5, the driver can take effective measures to adjust the vehicle. It has been proved that decreasing speed is the most efficient way to avoid the danger of losing control.

(1) When the water length is below 100 m, the maximum lateral acceleration of a low-speed vehicle exceeds that of a high-speed vehicle due to the longer travel...
time for low-speed vehicle. Besides, rutting width has little effect on vehicle’s control stability when the rutting width exceeds 1.2 m. In this situation, only rutting length and speed affect the vehicle’s lateral stability together.

(2) With the water length increasing from 100 m to 300 m, the vehicle’s travel time begins to be longer and the lateral acceleration begins to increase. In this situation, the maximum lateral acceleration of a high-speed vehicle gradually exceeds the one of low-speed vehicle. Figure 14 indicates that when rutting width changes from 0.8 m to 1.4 m, the maximum lateral acceleration does not obviously change, which proves that the water length has not been the major influencing factor of control stability in this situation. However, once rutting width exceeds 1.4 m, the maximum lateral acceleration will change, apparently with speed and rutting width and length changing.

(3) When rutting length exceeds 300 m, the vehicle’s maximum lateral acceleration increases sharply with rutting width, length, and speed, especially when the rutting width exceeds 1.2 m and the speed exceeds 80 km/h. When the rutting width changes from 0.8 m to 1.2 m, a water-covered section has little effect on rutting width, length, and acceleration, and the speed is the only controlling factor. Besides, it is worth noting that when the rutting length exceeds 350 m, the vehicle is likely to lose control even if the vehicle runs at 60 km/h. In this situation, decreasing speed is, also, not an effective measure to ensure the vehicle’s lateral stability.

The safety margins of rutting length and width for RISK I and RISK II are shown in Table 6. For example, when vehicle runs at 120 km/h, it will run into the adjacent lane in 3.48 s when the rutting length exceeds 116 m and the rutting width exceeds 1.5 m, which is too fast for drivers to handle the vehicle soberly. What is more, when the rut length increases to 254 m, the vehicle will turn into an uncontrolled situation in 7.62 s, which should arouse more concerns for both drivers and transportation agencies.

### 3. Conclusions and Recommendations

Unbalanced rutting situation (friction coefficients between left rutting and right rutting are different) could cause hydroplaning and lead to driver safety concerns on a rainy day. However, there is still no theoretical methodology to assess the driving potential risk caused by rut-induced hydroplaning. Based on the vehicle dynamics theory, this paper proposed a dynamics methodology and developed a "vehicle-water-filled rutting" model to assess the impact of water-filled rutting on driving safety. The following summarizes the research findings:

(1) A new “vehicle-water-filled rutting” model is developed to analyze the impact of water in different rutting geometrical features (rutting depth, length, and width) and speed on driving safety. The proposed model was computed by CarSim, vehicle dynamic software to analyze the driving stability under different hydroplaning-induced (related to the water depth and speed) situations.

(a) The unbalance of tire-roadway friction between right rutting and left rutting is directly impacted by water depth filled in rutting. With the difference of tire-roadway friction between right rutting and left rutting being below 0.07, the water gathered in rutting begins to impact the vehicle’s lateral stability.

(b) Water width in rutting is the second major factor impacting the vehicle’s lateral stability: when water width is below 0.7 m, there is not any effect of water on driving safety, even though the water length is big enough or speed is high enough. With the water width above 0.7 m, water length begins to affect driving safety apparently. In this situation, vehicle’s travel time in water zone depends on the rutting length and speed itself; meanwhile, the impact of water width on vehicle’s travel time begins to decrease accordingly. When the water width is above 1.4 m, the speed and water length affect the driving safety sharply so that the impact of water width becomes very

<table>
<thead>
<tr>
<th>Risk assessment</th>
<th>Rutting feature</th>
<th>Design speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>60 km/h</td>
</tr>
<tr>
<td>RISK I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( L_w )</td>
<td>( \geq 354 m )</td>
<td>( \geq 323 m )</td>
</tr>
<tr>
<td>( W_w )</td>
<td>( \geq 1.8 m )</td>
<td>( \geq 1.8 m )</td>
</tr>
<tr>
<td>RISK II</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( L_w )</td>
<td>( \geq 161 m )</td>
<td>( \geq 135 m )</td>
</tr>
<tr>
<td>( W_w )</td>
<td>( \geq 1.6 m )</td>
<td>( \geq 1.6 m )</td>
</tr>
</tbody>
</table>
poor. The high-speed vehicle’s allowable reaction time for driver is significantly shorter than the one of low-speed vehicle, which should arouse enough concerns for drivers.

(2) Risk-level classification has been proposed to quantify the safety concerns in this paper. Vehicle’s lateral offset (the vehicle may run into the adjacent lane and crash the adjacent vehicles when its offset exceeds 1.025 mm) and lateral acceleration (when the lateral acceleration exceeds 0.4 g, the vehicle may turn into oversteer and lose control) are proposed as risk assessment indexes, and the safety margins of rutting width and length for RISK I and RISK II are proposed in Table 6. For example, when vehicle runs at 120 km/h, it will run into the adjacent lane in 3.48 s when the rutting length exceeds 116 m and the rutting width exceeds 1.5 m, which is too fast for drivers to handle the vehicle soberly. What is more, when the rut length increases to 254 m, the vehicle will turn into an uncontrolled situation in 7.62 s, which should arouse more concerns for both drivers and transportation agencies. From this study, the following recommendations are made:

(1) In addition to the lateral stability and control stability, the braking stability is also one of the major factors impacting the driving safety. However, the process of braking during the vehicle’s sideslip is very complicated, so the mathematical model of braking is more difficult to build up. Still, studying the braking stability is very significant and could be researched in the future.

(2) This study has only taken the hydroplaning situation into consideration. The impact of different situations affected by combinations of rutting length and width at different friction coefficients can be further computed using the proposed method.

(3) The proposed method and evaluation indicators should be modified and expanded precisely for analysis on the impact of the continuous change of the rutting depths along the driving directions.

Considering that there are still no relevant assessment indexes and assessment methods or research on potential driving risk caused by water-filled rutting, this paper recommends that the rutting geometrical features (rutting depth, length, and width) and vehicle speed should be taken as the safety assessment indexes. In addition, the vehicle dynamic theory used in this paper for safety assessment should be considered to offer guidance and suggestion for present highway agencies.

**Data Availability**

The data used to support the findings of this study are included within the article.

**Conflicts of Interest**

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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**References**


