Evaluating Hydroplaning Potential of Rutted Highway Pavements

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Abstract: Hydroplaning is a major cause of accidents in wet-weather driving on highways. The presence of surface runoff or ponding on pavement surface can cause a fast moving vehicle to hydroplane if the vehicle speed equals or exceeds the hydroplaning speed. Rutted highway pavements present increased safety risks because the ruts along their wheel paths collect water during wet weather, thereby reducing the hydroplaning speed due to the higher water depths along the rutted wheel paths. This paper proposes an analytical framework to evaluate the hydroplaning potential of rutted highway pavements using a finite-element computer simulation model. An analysis is presented to show that the presence of ruts has a significant effect on the vehicle hydroplaning speed of a rutted pavement over the range of rut depths commonly encountered on expressways and major arterials where traffic speeds are high and hydroplaning is an important safety concern.

Keywords: Hydroplaning Speed, Hydroplaning Potential, Highway Pavement, Hydroplaning Simulation Model, Rut Depth, Rutted Pavement

1. INTRODUCTION

Traffic safety studies from various parts of the world indicate that approximately 20\% of all road traffic accidents occur in wet weather conditions (Ivan et al., 2012; Mayora and Pina, 2009; McGovern et al., 2011; Murad and Abaza, 2006). The proportion of wet-weather accidents is considered to be significant and deserving special attention. Although there are no detailed statistics or evidence on the exact causes of wet-weather accidents, it is generally believed that low skid resistance and hydroplaning speed (i.e. vehicle speed at which hydroplaning occurs) are major factors leading to the accidents (Alvarez et al., 2006; Ivan et al., 2012; McGovern et al., 2011).

When a vehicle hydroplanes on wet pavement, the driver will lose steering and braking control because the tires are supported on a layer of water and there is practically no frictional resistance offered to the tires (Hicks et al., 2000; Ivan et al, 2012). This situation happens when the thickness of pavement surface water is sufficiently thick, and the vehicle speed is high enough that the hydrodynamic uplift generated under the moving vehicle tires causes the tires to be separated from the pavement surface (Horne and Dreher, 1963; Browne, 1975). The factors that influence vehicle hydroplaning speed include water film thickness, tire properties and pavement surface properties. Studies have found that hydroplaning speed decreases (i.e. hydroplaning potential increases) as the water film thickness on pavement surface increases. In other words, vehicle hydroplaning potential increases with water film thickness.

On a rutted highway pavement during rainy days, the water depths along the ruts of its...
two wheel paths are thicker than the non-rutted portion of the pavement. Since ruts typically occur along the wheel paths of a pavement lane, the actual water film thickness along the ruts have direct effect on vehicle hydroplaning potential. Computation of vehicle hydroplaning speed on a rutted pavement will lead to under-estimation of the safety risk if the presence of ruts is ignored in the evaluation of hydroplaning speed. This paper proposes a procedure to evaluate the hydroplaning potential of rutted pavements using a computer simulation model, and presents an analysis of hydroplaning speed to illustrate the steps involved, and the order of magnitude of under-estimation of hydroplaning speed resulted if rut depth is not considered in the analysis.

2. OBJECTIVE AND SIGNIFICANCE OF STUDY

Rutting is a major distress form commonly found in asphalt pavements, especially when the ambient temperature is high as in a hot tropical climate or during the summer months of temperate countries. Rutting is a traffic loading induced distress form along the two wheel paths of a traffic lane. It is caused by the accumulation of irreversible (or permanent) deformation in all pavement layers under the action of repeated traffic loading.

It is generally known that pavement rutting could lead to driving safety problems such as hydroplaning and skidding (AASHTO, 1989; Hicks et al., 2000; Fwa et al., 2012). The driving safety risk arises from the presence of water in the ruts. Two scenarios of traffic operating conditions can be identified with the safety risks of rutted pavements:

Scenario A: After a rainfall has stopped and no more water is flowing on the pavement surface, there is still water trapped in the ruts along the wheel paths;

Scenario B: During a rainfall, there is surface runoff flowing on the pavement surface and the ruts along the wheel paths are flooded with water.

There are some differences between the two above-mentioned scenarios in terms of vehicle operating speed and surface water depth. For Scenario A, vehicle speeds could be close to the vehicle operating speeds in dry weather, and water depth in the ruts can be defined closely by the depth of the ruts. On the other hand, in Scenario B, vehicle speeds are likely to be somewhat lower than the dry-weather vehicle operating speeds, but the water depth in this case would be higher than that in Scenario A because the ruts would be flooded and in addition there is a layer of surface runoff flowing on the pavement surface. In other words, along the rutted wheel paths, Scenario A would have higher vehicle speeds but also a higher hydroplaning speed; whereas under Scenario B, the vehicle speeds would be lower, but the hydroplaning speed would also be lower because of thicker water depth. Therefore, it is necessary to examine both scenarios to identify their safety risks for the purpose of ensuring wet-weather driving safety.

In view of the high proportion of wet-weather road accidents as highlighted in the INTRODUCTION of this paper, it is of practical significance to study the safety risks associated with both Scenarios A and B. The hydroplaning potential associated with Scenario A has been studied by Fwa et al. (2012). In this paper, the reductions in hydroplaning speed under Scenario B as compared to Scenario A are analyzed, and the safety implications thereof are highlighted.

3. SCOPE OF STUDY

The hydroplaning potential of a vehicle traveling on a pavement can be assessed by
comparing the traveling speed of the vehicle with the hydroplaning speed of the pavement. A vehicle will hydroplane if its speed is equal to or exceed the hydroplaning speed. The hydroplaning potential of a vehicle can be measured by calculating how much lower the vehicle speed is below the hydroplaning speed. The closer is the vehicle traveling speed to the hydroplaning speed, the higher is the hydroplaning potential. Hence, it is important to calculate accurately the hydroplaning speed of a pavement. A pavement with a high hydroplaning speed will give a low vehicle hydroplaning potential, and a pavement with a low hydroplaning speed will present a high hydroplaning potential.

The focus of the present study is placed on expressways and major arterials where both the vehicle speeds and traffic volume are high. The analysis in this study considers the case of a standard passenger car traveling on a highway pavement. The two main variables of interest related to the computation of hydroplaning speed are water film thickness and pavement wheel path rut depth. The ranges of the two variables studied are selected to cover the normal highway operating conditions of expressways and major arterials. The magnitudes of water film thickness considered range from 0 to 10 mm, and the magnitudes of rut depth from 0 to 15 mm.

Specifically, the skid resistance and hydroplaning speed analysis of rutted highway pavements are performed for the following values of the two variables: the values of water film thickness on the pavement surface are 0, 1, 3, 5, 7 and 10 mm; and the values of rut depths considered are 0, 1, 3, 6, 9, 12 and 15. The 0 mm rut depth refers to the case of a pavement with no rut, and is used as the reference case to represent an analysis where the skid resistance and hydroplaning speed are evaluated without considering the presence of pavement ruts.

4. METHOD OF ANALYSIS

The evaluation of the hydroplaning speed of a vehicle moving on a highway pavement is made based on a theoretical analysis of the interaction among the vehicle tires, pavement surface, and the water present on the pavement surface. Due to the complexity of the theoretical relationships involved, the problem has to be solved by employing a suitable numerical technique. This can be effectively achieved using a computer simulation technique based on the finite element method. In this section, the theoretical basis of the problem formulation, and the method of simulation and solution are presented.

4.1 Theoretical Formulation of Problem

The key analysis in the computation of hydroplaning speed on a highway pavement is the determination of the hydrodynamic uplift acting on the vehicle tires by the pavement surface water. Hydroplaning is said to occur when the total fluid uplift force is equal to the tire load and there is no contact between the tire and the pavement surface. Hydroplaning speed is defined as the vehicle speed at which hydroplaning occurs.

Fluid modeling to correctly compute the hydrodynamic forces in the pavement surface water in contact with the moving vehicle tire in question is crucial in solving the hydroplaning speed problem. This is achieved by applying the complete set of Navier-Stokes equations together with the k-ε turbulence model (Hinze, 1975; Launder and Spalding, 1974) to include the turbulence kinetic energy k and the viscous dissipation ε of the water flow. The final governing equations are given as follows:
\[
\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho k \mathbf{U}) = \nabla \cdot \left[ \frac{\mu_t}{\sigma_k} \nabla k \right] + 2\mu_E \varepsilon_{ij} \varepsilon_{ij} - \rho \varepsilon \tag{1}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \varepsilon \mathbf{U}) = \nabla \cdot \left[ \frac{\mu_t}{\sigma_\varepsilon} \nabla \varepsilon \right] + C_{1\varepsilon} \frac{\varepsilon}{k} k \mu_t \varepsilon_{ij} \varepsilon_{ij} - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \tag{2}
\]

\[
\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{3}
\]

where,

\(
\rho \) : density of water,
\( k \) : kinetic energy of water,
\( \varepsilon \) : viscous dissipation of water,
\( t \) : time,
\( \mathbf{U} \) : velocity vector,
\( \mu_t \) : eddy viscosity defined by Equation (4),
\( \sigma_k \) : numerical constant equal to 1.00,
\( \sigma_\varepsilon \) : numerical constant equal to 1.30,
\( C_{1\varepsilon} \) : numerical constant equal to 1.44,
\( C_{2\varepsilon} \) : numerical constant equal to 1.92,
\( C_\mu \) : numerical constant equal to 0.09, and
\( \varepsilon_{ij} \) : stress tensor.

Solving the above fluid model and its interaction with vehicle tire and pavement surface, together with appropriate boundary conditions, is performed using the finite element simulation technique. The details of the finite element simulation method for the determination of vehicle hydroplaning speed are presented in the next section.

### 4.2 Method of Simulation Analysis

The analytical tool employed in the computation of vehicle hydroplaning speed is a 3-dimensional finite-element hydroplaning simulation model developed by the authors (Ong and Fwa, 2007; Fwa and Ong, 2008). The finite-element simulation model computes the skid resistance and hydroplaning speed of a vehicle with locked wheels sliding on a wet pavement surface covered with a known thickness of water film. It is a theoretical model derived from hydrodynamics theory and solid mechanics principles. The vehicle hydroplaning problem is solved as a coupled fluid-structure-interaction problem with contact modeling.

The simulation model begins with a low vehicle sliding speed and gradually increases the sliding speed. The process of increasing the sliding speed in the simulation analysis is continued until the hydroplaning speed is reached. The hydroplaning speed is the vehicle sliding speed at which hydroplaning occurs when the inertia forces in the water film are high enough to completely separate the vehicle tires from the pavement surface.

Figure 1 shows the finite element mesh model adopted for the current study to evaluate vehicle hydroplaning speed. The model consists of three main sub-models, namely the pneumatic tire sub-model, the pavement sub-model, and the fluid sub-model. The solution procedure involves an iterative process dealing with solving interactions between these sub-models, i.e. tire-pavement contact modeling, fluid-tire-interaction modeling, and fluid-pavement interaction modeling. The final converged solution would yield the following
results:

- Tire deformation profile,
- Fluid drag and uplift forces,
- Tire-pavement normal reaction, and
- Traction forces.

The input data required for the simulation analysis are:

- Tire dimensions: tire radius and width,
- Tire inflation pressure
- Tire elastic properties: modulus of elasticity and Poisson’s ratio of each of the following three components: tire rim, tire sidewalls, and tire tread,
- Magnitude of wheel load,
- Physical properties of water: temperature, density, dynamic viscosity, and kinematic viscosity,
- Pavement properties: modulus of elasticity, and tire-pavement friction coefficient,
- Water film thickness on pavement surface

The theoretical hydroplaning simulation model used in this study has been validated for car tires by the authors (Ong and Fwa, 2007; Fwa and Ong, 2008) using field measured data.

Figure 1. Mesh design of finite element simulation model
5. ILLUSTRATIVE EXAMPLE ANALYSIS

5.1 Problem Description and Study Parameters

The example problem deals with a standard passenger car traveling on a rutted highway pavement on a rainy day. To offer a common reference for the analysis, the ASTM E524 standard G78-15 tire (ASTM, 2014) with a cross sectional radius of 393.7 mm and a tread width of 148.6 mm is adopted for this example. A constant tire inflation pressure of 186 kPa and a constant wheel load of 4.8 kN are adopted for the present study. The properties of water and air at 25°C are used in this study. The density, dynamic viscosity and kinematic viscosity of water are 997.0 kg/m³, 0.890 x 10⁻³ Ns/m³ and 0.893 x 10⁻⁶ m²/s respectively. The density, dynamic viscosity and kinematic viscosity of air at the standard atmospheric pressure and 25°C are 1.184 kg/m³, 1.831 x 10⁻⁵ Ns/m³ and 1.546 x 10⁻⁵ m²/s respectively.

The key problem parameter in the present study is the thickness of water on the pavement surface. In the case of Scenario B described earlier, the total water depth along a rutted wheel path consists of two components: (i) the thickness of water in the flooded rut, and (ii) the depth of the surface runoff flow. This is different from Scenario A where the total water depth is given by just component (i), i.e. the depth of water in the rut.

The input values of water depth are presented in Table 1. The first two columns of Table 1 are the values of the rut depth and surface water flow depth, respectively, considered in the present analysis. They cover the range of rut depths and pavement surface runoff depths commonly encountered in practice. The third column, computed as the sum of the values of the first and second column, gives the total water depth which is the input water depth value for the simulation analysis of hydroplaning speed. Those sets of input water depths associated with the rut depth of 0 mm represent the case of new pavements where there is no rut in the wheel paths. They can also be taken to represent a case of hydroplaning speed computation for rutted pavements where the presence of ruts is ignored.

In the present analysis, the water depth calculation ignores the presence of longitudinal gradient and cross slope in a normal highway pavement. This would not have any significant effect on the analysis since both the gradient and cross slope are small in magnitude. A typical highway pavement will have a longitudinal gradient less than 3%, and a cross slope of 1.5 to 2.0% (AASHTO, 2011). Taking into account both the longitudinal and cross slope in the water depth calculation will give a difference of less than 1.5% in the water depth calculation. This is not considered to be of practical significance in hydroplaning calculation. Hence, longitudinal gradient and cross slope are not entered into the analysis of hydroplaning speed simulation in the present study. This is consistent with the normal practice of hydroplaning estimation in pavement engineering. The results of analysis presented in this study can be applied to normal straight sections of highway pavements in general, with the exception of highways on steep slopes and horizontal curves with high superelevations.

5.2 Results of Hydroplaning Speed Analysis

The computed results of the simulation analysis of hydroplaning speeds are presented in the last column of Table 1. These results are plotted in Figures 2 and 3. Figure 2 plots vehicle hydroplaning speed against rut depth for different flow depths on pavement surface; while Figure 3 plots hydroplaning speed against pavement surface flow depth for pavements with different rut depths. It is noted that in both of the figures, the case of zero rut depth and zero flow depth is not plotted because hydroplaning does not happen on a dry pavement. The case of zero surface water flow depth in Figure 2 presents the computed hydroplaning speeds for
Table 1. Results of hydroplaning speed analysis

<table>
<thead>
<tr>
<th>Rut Depth (mm)</th>
<th>Flow Depth (mm)</th>
<th>Total Water Depth (mm)</th>
<th>Hydroplaning Speed (km/h)</th>
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the condition of Scenario A described earlier (i.e. the case of a rut filled with trapped water after the rainfall has stopped). The case of zero rut depth in Figure 3 presents the computed hydroplaning speeds for the condition of a new pavement without ruts. Both cases serve as useful basis for studying the impacts of rutting on vehicle hydroplaning potential.

The main findings of the simulation analysis can be summarized as follows:

1. The results in Figures 2 and 3 display clearly the effects of rut depth and surface runoff depth on vehicle hydroplaning speed. Vehicle hydroplaning speed decreases (i.e. hydroplaning potential increases) as rut depth increases, and as surface flow depth increases. It can be seen from Figure 2 that both the incremental effect of rut depth and that of surface water flow depth become relatively insignificant only after a rut depth of 10 mm. Since most expressways and major arterials will have rut depths within 10 mm, this means that the effect of rut depth on hydroplaning speed and hydroplaning potential is significant and cannot be ignored.

2. Figure 2 depicts the trends of variation of vehicle hydroplaning speed with rut depth. For any given surface flow depth, the hydroplaning speed decreases (i.e. hydroplaning potential increase) as rut depth increases. The top curve of zero flow depth represents the case of Scenario A. It is seen that Scenario B always has a lower hydroplaning speed (hence a higher hydroplaning potential) than Scenario A. The difference between the hydroplaning speeds of Scenarios A and B is lower for lower rut depths and for higher surface runoff depths. For most expressways and major arterials where travel speeds are relatively high and pavements are maintained to keep rut depths below 10 mm or even lower, the magnitude of the differences in hydroplaning speeds of Scenarios A and B can be significant. The difference can be as much as 6 km/h for 10 mm runoff flow depth on a rut of 2 mm deep.

3. Figure 3 shows the decreasing trends of vehicle hydroplaning speed with surface water flow depth for different rut depths. The curve of zero rut depth gives the hydroplaning speeds for different surface water flow depths without taking rut depth into consideration. Taking this zero rut depth curves as reference, it is seen that ignoring rut depth in the analysis can lead to significant over-estimations of vehicle hydroplaning speeds (i.e. under-estimations of hydroplaning potential). The magnitude of hydroplaning speed over-estimation (i.e. magnitude of hydroplaning potential under-estimation) is higher for lower surface runoff depths and for higher rut depths. For example, by ignoring the presence of rut depth, for a pavement surface with a rut depth of 15 mm and a runoff flow depth of 1 mm, the under-estimation of hydroplaning speed is close to 9 km/h.

In summary, the results of the hydroplaning speed simulation show that the presence of rut in the wheel path of a pavement must be taken into account in the hydroplaning speed analysis of a rutted pavement. Failure to consider rut depth in the analysis would result in over-estimation of the hydroplaning speeds, which is undesirable because it will lead to an under-estimation of hydroplaning potential and safety risk for vehicles traveling on a rutted pavement.

6. CONCLUSION

This paper presents a theoretical framework for the analysis of vehicle hydroplaning potential on a rutted pavement by employing a finite-element computer simulation model of hydroplaning speed. The proposed framework is applied to analyze a typical range of rut
depths and surface runoff flow depths with the purpose of estimating the order of magnitude of vehicle hydroplaning speeds on rutted pavements, and to emphasize the need to consider rut depth in the hydroplaning potential evaluation of rutted pavements. The results of analysis show that the presence of ruts has a significant effect on the vehicle hydroplaning speed of a rutted pavement in the range of rut depths commonly encountered in expressways and major arterials where traffic speeds are high and hydroplaning is an important safety concern. The analysis presented in this paper suggests that the proposed framework of analysis is a useful tool for highway authorities in monitoring the hydroplaning potential of vehicles to ensure safe traffic operations on expressways and major arterials.

Figure 2. Variation of hydroplaning speed with rut depth as a function of pavement surface flow depth

Figure 3. Variation of hydroplaning speed with pavement surface flow depth as a function of rut depth
7. REFERENCES