Analyzing Effect of Tire Groove Patterns on Hydroplaning Speed

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Abstract: Hydroplaning is a major safety concern in wet-weather driving. Grooved tires have been commonly used to improve skid resistance and increase the hydroplaning speed. Tire grooves help in the expulsion of water from the tire pavement contact region by providing escape channels. Past researchers have shown that tire groove spacing, groove width and groove depth affect skid resistance. However, analytical tools are unavailable for highway engineers to evaluate hydroplaning speed taking into consideration basic geometric parameters such as tire groove width, groove depth and spacing etc. The present paper describes a numerical analytical tool to study the effect of tire groove spacing, groove width and groove depth on hydroplaning speed by means of earlier verified analytical hydroplaning modeling for tire having transverse groove pattern, longitudinal groove pattern and combined transverse and longitudinal groove pattern on plane pavement surface are analyzed in this paper.

Key Words: Hydroplaning speed, Tire groove spacing, Tire groove width, Tire groove depth

1. INTRODUCTION

Hydroplaning is a major safety concern in wet-weather driving which occurs when the traveling speed of a vehicle becomes so high that the hydrodynamic pressure of the water between its tires and the pavement surface rises and equals the tire inflation pressure. When this condition prevails, the tires become supported on the water film and the driver may lose braking and steering control of the vehicle (Horne et al 1963).

According to past researchers (Horne and Dreher, 1963; Gallaway, 1979), tire grooves help in expulsion of water from the tire pavement contact region by providing escape channels, thus reducing the risk of hydroplaning. Deeper tire groove depth, lesser tire groove spacing and larger tire groove width offers a more effective channel for water flow, hydroplaning takes place at a higher speed due to a lower rate of development of the hydrodynamic uplift force. Thus the tire groove patterns help to increase the minimum fluid depth required for a tire to hydroplane, or in other words they raise the hydroplaning speed at a fixed water depth.

Many different groove patterns are found in the market. However, each of them has different effectiveness in alleviating hydroplaning risk. Maycock (1967) and Gengenbach (1968) conducted many experimental studies to study the effects of width, depth and spacing of tire groove on skid resistance. They showed that width, depth and spacing of the tire grooves have tremendous effect on wet skid resistance. Gilbert (1973) has conducted experimental study on small scale models of circumferential tire, but the measured data could not be easily scaled up to study the hydroplaning behaviors of actual tires. Grogger and Weiss (1996 & 1997) have conducted numerical studies on hydroplaning phenomenon for smooth and longitudinally grooved tires, which do not rotate. However, these earlier studies do not provide a complete picture on the effects of different groove patterns on vehicle hydroplaning.

The present paper aims to find the effect of tire groove spacing, groove width and groove depth on hydroplaning speed by means of analytical hydroplaning modeling for tire having transverse groove pattern, longitudinal groove pattern and block groove pattern (i.e. combination of
transverse and longitudinal groove patterns) on plane pavement surface. The analysis is performed by means of a computer simulation model using a 3-dimensional finite element approach. Computational fluid dynamics techniques are used to simulate the model.

2. STUDY PARAMETERS

The study parameters adopted in the analytical hydroplaning model are presented in this section

2.1 Rib Tire

The ASTM E 501 standard G78-15 tire (ASTM, 2006) with a cross sectional radius of 393.7 mm and a groove width of 148.6 mm are adopted for this study. Figure 1 shows the transverse groove pattern, longitudinal groove pattern and block groove pattern.

The analyses performed in this study consider the following values of model parameters: (a) tire groove centre to centre spacing of 16.8 mm, 20 mm and 25 mm, (b) groove widths of 5.08 mm, 7.0 mm and 8.5 mm, (c) groove depths of 5.08 mm, 7.0 mm and 8.5 mm, (d) fixed surface water depth of 5 mm, (e) tire inflation pressure of 27 psi, (186.2 kPa), and (f) wheel load of 2.41. These parameter values considered are summarized in Table 1.

2.2 Pavement Surface Model

A smooth plane pavement surface is considered for all the analysis presented as this presents the worst case and a conservative estimate of the hydroplaning speed for in-service pavements (Horne et al., 1962; Horne et al., 1963; Horne et al., 1965; Hayes et al., 1981, Fwa et al., 2008). The hydroplaning simulation model used for the analysis is adapted from the 3-dimensional finite-element model developed and validated earlier by the authors (Fwa et al., 2008).

2.2 Material Properties

The properties of water and air at 20°C are used in this study. The density, dynamic viscosity and kinematic viscosity of water at 20°C are 998.2 kg/m³, 1.002 x 10⁻³ Ns/m³ and 1.004 x 10⁻⁶ m²/s respectively (Chemical Rubber Company, 1988). The density, dynamic viscosity and kinematic viscosity of air at standard atmospheric pressure and 20°C are 1.204 kg/m³, 1.82x10⁻⁵ Ns/m³ and 1.51x10⁻⁵ m²/s respectively (Blevins, 1984).

2.3 Geometry of Model and Selection of Boundary Conditions

The hydroplaning phenomenon of a locked wheel sliding on a flooded smooth pavement is modeled in a moving wheel frame of reference. A two-phase flow comprising a layer of air jet and a layer of water jet is considered. The problem can be similarly modeled as a jet with a layer of air and a layer of water, with a smooth pavement surface moving towards the wheel as shown in Figure 2. The tire deformation profile used is the same as that by Ong et al (2005). The geometry of the three-dimensional rib tire model is shown in Figure 3. The upstream boundary
conditions consist of a pair of inlets, namely velocity inlet of 5 mm (about 0.2 in) thickness and a
velocity inlet of 48.26 mm (about 2 in) thick of air. The inlet is modeled at a distance of 200 mm
away from the leading edge of the wheel so as to allow for any possible formation of bow wave.
Side edges and the trailing edges are modeled as pressure outlets with the pressure set as 0 kPa
(i.e. atmospheric pressure). The centre line of the wheel is treated as a plane of symmetry.

3. DESCRIPTION OF MESH USED IN THE ANALYSIS

The finite volume method is employed for the model, using 6-node wedge elements and 8-node
hexahedral elements. Figure 3 shows the mesh of the model geometry used in the simulation.
The optimal number of mesh elements needed to give the converged solution has been tested for
the original model through mesh sensitivity analysis. In tire groove model simulations, different
combinations of finite volume mesh are used, with different number of 8-node hexahedral
elements in the ribs and in the smallest channel in the model, i.e., the hydroplaning region. The
optimal combination of mesh elements in the ribs and the smallest channel needed to give
numerical convergence is tested through the mesh sensitivity analysis and it is found that 10
mesh elements in the ribs and 30 mesh elements in the smallest channel are required to reach
numerical convergence.

4. PROCEDURE TO OBTAIN HYDROPLANING SPEED IN THE ANALYSES

The hydroplaning simulation analysis is conducted in two stages. First, from the initial vehicle
speed of 0 km/h, a relatively large speed increment of 5 m/s (18 km/h) is first applied and a
simulation run is conducted. This is followed by another speed increment and a simulation run.
The process is repeated until the fluid uplift force matches or exceeds the wheel load. This would
provide a first estimate of the hydroplaning speed. Next, starting from a sliding speed slightly
lower than the first estimate of the hydroplaning speed, the sliding speed is increased at a small
speed increment of 0.1 m/s (0.36 km/h) to determine the final simulation hydroplaning speed.

5. RESULTS AND ANALYSIS

5.1 Effect of Tire Groove Width

The computed hydroplaning speeds for 3 tire groove widths of 5.08 mm, 7 mm and 8.5 mm from
simulation analyses of longitudinal, transverse and block tire groove pattern respectively are
presented in Table 2. Each curve in the Figure 4 represents the changes of hydroplaning speed
with the tire groove width. It indicates that at a constant surface water depth and groove depth of
5 mm, the hydroplaning speed increases with tire groove width. The hydroplaning speed at the
tire groove width of 8.5 mm is higher than the value at 5.08 mm tire groove width by 23.3 km/h
for longitudinal tire groove, 18.1 km/h for transverse tire groove and 23.2 km/h for block tire
groove pattern. It can also be observed that for each mm increase in width of the tire groove,
there is an increase of hydroplaning speed of 6.8 km/h for longitudinal tire groove, 5.5 km/h for
transverse tire groove and 7.2 km/h for block tire groove pattern indicating that the effect of
increase in width can be more pronounced for longitudinal and block tire patterns. An examination of the simulation results shows that with wider tire grooves which offer a more effective channel for water flow, hydroplaning takes place at a higher speed due to a lower rate of development of the hydrodynamic uplift force. Therefore, wider tire grooves of the rib tire would have a higher hydroplaning speed, hence a lower hydroplaning risk.

5.2 Effect of Tire Groove Spacing

Using the data of Table 3, the hydroplaning speed is plotted against tire groove spacing in Figure 5 for the purpose of examining how spacing of tire groove would affect the effectiveness of rib tires in reducing hydroplaning risk. Table 3 presents the changes of hydroplaning speed with tire groove spacing of 16.8 mm, 20 mm and 25 mm at a constant water film thickness of 5 mm. The curves in Figure 5 show that hydroplaning speed varies negatively with tire groove spacing for longitudinal, transverse and block patterns. The hydroplaning speed at the tire groove spacing of 16.8 mm is higher than the value at 25 mm tire groove spacing by 15.6 km/h for longitudinal tire groove pattern, 21.2 km/h for transverse tire groove pattern and 18.2 km/h for block tire groove pattern. For each mm decrease in the spacing of tire groove, there is an increase of hydroplaning speed of 1.8 km/h for longitudinal tire groove pattern, 2.5 km/h for transverse tire groove pattern and 2.3 km/h for block tire groove pattern. An examination of the simulation results shows that more spacing between tire grooves increases hydroplaning risk due to reduction in tire groove volume.

5.3 Effect of Tire Groove Depth

Table 4 shows the hydroplaning speed, obtained from simulation analysis at groove depths of 5.08 mm, 7 mm and 8.5 mm for longitudinally, transversely and block grooved tire at a fixed water depth of 5 mm. Using the data of Table 4, hydroplaning speed is plotted against tire groove depth as shown in Figure 6. The figure shows that at any fixed groove depth, hydroplaning speed is highest for block grooved tire followed by transversely grooved tire and longitudinally grooved tire. The curves shows that as the groove depth increases the hydroplaning speed also increases for all the three patterns analyzed. Each mm increase in tire groove depth there increases the hydroplaning speed by 1.6 km/h for longitudinal and transverse tire groove pattern, and 1.8 km/h for block tire groove pattern.

6. CONCLUSION

This paper has presented a verified hydroplaning simulation model for rib tires and the solutions for hydroplaning speeds using the finite element method. The hydroplaning characteristics of the standard ASTM E501 rib tire were studied for different tire groove widths, spacing and depths at fixed water depth of 5 mm. Three different tire groove patterns namely transversely grooved tire, longitudinally grooved tire and block tire groove pattern has been considered in the simulation analysis.

The simulation results showed that a vehicle with a tire having deeper groove depth, lesser spacing and larger groove width has higher hydroplaning speed and thus has lower risk of
hydroplaning, for any given irrespective of their groove pattern. For each mm increase in tire groove depth, decrease in tire groove spacing and increase in tire groove width on an average raises the vehicle hydroplaning speed by 1.6 km/h, 1.8 km/h, and 6.8 km/h respectively for longitudinally grooved tire. For transversely grooved tire the corresponding increases in hydroplaning speed are 1.6 km/h, 2.5 km/h, and 5.5 km/h respectively whereas for block grooved tire the hydroplaning speed increases by 1.8 km/h, 2.3 km/h, and 7.2 km/h respectively.

In general, for a tire with fixed dimensions of tire groove depth, tire groove spacing and tire groove width the block tire pattern has highest hydroplaning speed followed by transversely grooved tire pattern and longitudinally grooved tire. The analysis presented in this paper suggests that the proposed model can be used as useful analytical tool for evaluating hydroplaning risk of vehicles with different tire patterns.

7. TABLES AND FIGURES

Table 1: Parameters considered for analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
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<tbody>
<tr>
<td>Passenger car tire</td>
<td>ASTM E 501 standard G78-15 tire, with 393.7 mm cross sectional radius,</td>
</tr>
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<td></td>
<td>and 148.6 mm groove width</td>
</tr>
<tr>
<td>Tire grooves analyzed</td>
<td>Longitudinal, Transverse and Block</td>
</tr>
<tr>
<td>Pavement surface</td>
<td>Smooth plane surface</td>
</tr>
<tr>
<td>Tire inflation pressure</td>
<td>186.2 kPa</td>
</tr>
<tr>
<td>Wheel load</td>
<td>2.41 kN</td>
</tr>
<tr>
<td>Tire groove width</td>
<td>5.08, 7 and 8.5 mm for all tire groove patterns</td>
</tr>
<tr>
<td>Tire groove rib width (w)</td>
<td>16.8, 20 and 25 mm for all tire groove patterns</td>
</tr>
<tr>
<td>Tire groove depth</td>
<td>5.08, 7 and 8.5 mm for all tire groove patterns</td>
</tr>
<tr>
<td>Water film thickness</td>
<td>5.0 mm</td>
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Table 2: Effect of tire groove width on hydroplaning speed

<table>
<thead>
<tr>
<th>Width of tire groove (mm)</th>
<th>Hydroplaning speed (km/h)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Longitudinally grooved tire</td>
</tr>
<tr>
<td>5.08</td>
<td>98.10</td>
</tr>
<tr>
<td>7.00</td>
<td>111.54</td>
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<tr>
<td>8.50</td>
<td>121.39</td>
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Table 3: Effect of change in spacing on hydroplaning

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<th>Spacing of tread groove (mm)</th>
<th>Hydroplaning speed (km/h)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Longitudinally grooved tire</td>
</tr>
<tr>
<td>16.80</td>
<td>98.10</td>
</tr>
<tr>
<td>20.00</td>
<td>93.40</td>
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<tr>
<td>25.00</td>
<td>82.50</td>
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</table>

Table 4: Effect of tire groove depth on hydroplaning speed

<table>
<thead>
<tr>
<th>Depth of tire groove (mm)</th>
<th>Hydroplaning speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Longitudinally grooved tire</td>
</tr>
<tr>
<td>5.08</td>
<td>98.10</td>
</tr>
<tr>
<td>7.00</td>
<td>102.00</td>
</tr>
<tr>
<td>8.50</td>
<td>103.85</td>
</tr>
</tbody>
</table>
Figure 1 Tire groove patterns analyzed

(a) Longitudinal groove pattern tire

(b) Transverse groove pattern tire

(c) Block groove pattern tire

Figure 1 Tire groove patterns analyzed
Figure 2 Locked wheel sliding on pavement in moving tire’s reference frame
Figure 3 Mesh design for simulation model
G78-15 Tube-less tire of belted bias construction
(393.7 mm X 148.6 mm) on Smooth pavement surface

Tire Inflation pressure: 186.2 kPa
Wheel Load: 4820 kN
Water Depth: 5 mm
Tire Groove Depth: 5 mm
Tire Groove Spacing: 16.8 mm

Figure 4 Effect of Tire groove width on hydroplaning speed

Figure 5 Effect of Tire groove spacing on hydroplaning speed
Figure 6 Effect of Tire groove depth on hydroplaning speed
REFERENCES:
