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Analytical evaluation of impact of groove deterioration on runway frictional performance

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Abstract

Runway pavement grooving has been commonly adopted to minimize the loss of pavement skid resistance during wet weather which has been a causal factor for runway excursions. Experimental studies have demonstrated the benefits of pavement grooving in improving the skid resistance during wet pavement conditions and reducing the risk of hydroplaning. Maintaining the standard groove depth consistently during grooving operations has been an issue due to runway surface unevenness, construction quality control procedures etc. and this may result in a variation of the skid resistance performance along the runway. This paper presents an analytical approach to evaluate the frictional performance under wet pavement conditions and variations due to groove deterioration. A simulation model based on finite element method is first developed to evaluate the wet-pavement skid resistance available to an aircraft on a grooved pavement under a given set of operating conditions. The operating conditions are defined by parameters such as aircraft speed, tire structural properties, pavement surface properties, wheel load, tire inflation pressure, and pavement surface water-film thickness. The results for different groove depths are compared with the skid resistance performance of standard grooves to evaluate their relative performance and assess the acceptable tolerance for groove depth variation which represents different levels of groove deterioration.

Keywords: Skid resistance; pavement grooving; airfield pavements, maintenance management, finite element analysis

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1. Introduction

Runway pavement friction is a key factor with respect to safety of landing aircrafts. During wet weather, pavement skid resistance reduces substantially from its dry weather value (Agrawal (1986), Horne and Leland (1962), Horne (1976), Leland and Taylor (1965)) and this may increase the risk of runway excursion. Wet runway condition is known to be a major contributing factor for runway overrun and veer-off accidents. Wet/contaminated runways were factors

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in both types of accidents during landings and takeoff (nearly 40% of all landing overrun accidents in Europe and 2/3rd worldwide) (Van Es, 2001). Therefore, in order to ensure good friction levels under all weather conditions most runways worldwide are grooved.

The magnitude of the available skid resistance for an aircraft is affected by a large number of factors associated with the aircraft, aircraft tire and braking system, runway surface, and the environment (Horne and Whitehurst, 1969). Pavement grooves were first studied by NASA at the landing-loads track by Horne and Whiteburst (1962). Several experimental studies have been conducted to evaluate the effects of runway grooves on aircraft tire braking performance by Agrawal and Daiutolo (1981), Yager (1969), Williamson (1969), Pasindu and Fwa (2015).

Grooving improves the drainage capacity of the runway surface which controls the water depth on the runway during wet weather. As it allows water flow in the groove channels and accelerates water flow due to increased flow depths and decreased flow resistance in the grooves (compared to water flow through or on top of the pavement surface texture) (Reed et. al. (1984a,), Reed et. al. (1984b), Fwa et.al. (2014)). It also improves the drainage from the tire-pavement contact area, which reduces the hydro-dynamic pressure build-up of water trapped between the moving tire and pavement surface. Therefore, it enables the aircraft tires to maintain adequate contact with the runway surface to utilize of the available wet friction of the pavement thereby reducing the risk of hydroplaning (Agrawal, 1983, 1981)

Grooving increases the average texture depth in pavement surface and as a result improves the drainage area for removal of surface water from tire-pavement contact area. The increase in texture depth from grooves can be estimated by using the Equation 1 (Horne, 1973)

$$T_g = (T(P-2W) + WD)/P \quad (1)$$

where, T_g - grooved pavement texture depth, T - ungrooved pavement texture depth, P - groove pitch, W - groove width, D - groove depth.

Federal Aviation Administration (FAA) advisory circular AC-150/5320-12C (FAA, 1997) recommends all runways servicing turbojets to be grooved. The current standard square groove typical dimensions are ¼ inch (in.) depth, ¼ in. width, and 1 ½ in. center to center spacing (Figure 1). The tolerance for groove depth specified by FAA in Advisory Circular on ‘Standards for Specifying Construction of Airports’ is +/- 2mm from the standard 6mm depth, i.e. the groove depths can vary from 4mm to 8mm. Furthermore, FAA advisory circular AC-150/5370-10G (FAA, 2014) states the tolerance levels for grooved sections as follows. At least 90% of the grooves must be at least 3/16 in. (5 mm), at least 60% of the grooves must be at least 1/4 in. (6 mm), and not more than 10% of the grooves may exceed 5/16 in. (8 mm). This suggests, that groove depth maintenance is a critical aspect to ensure that its intended performance with respect to pavement friction is maintained during operations.

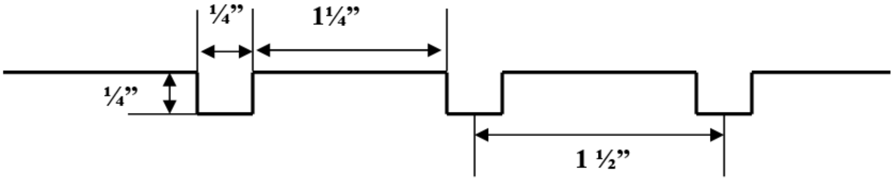


Fig. 1. Standard Groove Design

However, the groove depth can vary during construction of the grooves (FAA, 2010) as well as grooved depth gradually reduces after construction due to the groove deterioration, rubber deposits etc. Reduction of groove depths may result in a loss of skid resistance performance along the runway, which may be detrimental to the safety of the aircrafts. Therefore, it is important to analytically evaluate how this variation would affect the frictional performance of runway grooves with variation in depth.

This paper presents an analytical approach to evaluate the skid resistance of grooves with different depths during wet pavement conditions. A finite element simulation model developed by the authors is used to simulate a smooth aircraft tire skidding on a grooved pavement with a given water film thickness. The simulation results are used to compute the frictional performance of grooved pavements with different groove depths for different water film thicknesses and compared with the performance of the standard grooves. This can form the analytical basis to assess the allowable tolerance for groove depth variation during construction and acceptable level of groove deterioration for maintenance planning.

2. Groove deterioration and maintenance

Groove deterioration can be attributed to several distresses occurring on runway pavements (White and Rodway (2014), Emery (2005), Patterson (2012)). Rubber deposits which accumulate inside grooves, erosion of the asphalt surface edge break, groove migration, chipping of groove edges is some of the common distresses occurring on grooves.

Chipping and spalling of edges of grooves, loss of coarse aggregates along groove walls, rounding off of the edges of grooves, and erosion that washes out the fines or the asphalt binder leaving only exposed aggregates in the grooves results in wear and tear of the grooves. This results in reducing the drainage capacity of the grooves as well as causing impact on riding quality and FOD risks to the aircraft due to lose particles. Groove closure refers to the closing up of grooves caused by deformation of the asphalt mixture of individual grooves leading to reductions of groove widths. Groove collapse happens when the surface asphalt mixture of the grooved pavement disintegrates. Groove migration results in formation of wavy groove pattern due to traffic induced horizontal movements of pavement surface mixtures. Rubber contamination of runway landing zone occurs due to rubber deposit accumulation from aircraft tires during aircraft landing. On an un-grooved pavement, rubber deposit causes a loss of tire-pavement friction. Grooving a runway pavement surface helps to lessen the negative impact of rubber deposits on tire-pavement friction. Rubber deposits on runway pavement surface have to be removed periodically before the friction value falls below a pre-specified level.

These distresses effectively reduce the groove depth and/or width thereby affecting its drainage capacity from the tire-pavement contact area and provide the expected frictional properties during wet pavement conditions. Groove repair is triggered by the extent and severity of the deteriorated grooved pavement section. FAA Advisory Circular AC-150/5320-12C (FAA, 1997) specifies the minimum standards for deteriorated grooved pavement section to initiate maintenance action to restore the grooves. It states that ‘When 40 percent of the grooves in the runway are equal to or less than 1/8 inch (3 mm) in depth and/or width for a distance of 1,500 feet (457 m), the grooves’ effectiveness for preventing hydroplaning has been considerably reduced. The airport operator should take immediate corrective action to reinstate the 1/4-inch (6 mm) groove depth and/or width’. This suggests that groove depth/width are allowed to reduce up to 50% of their original value before maintenance action is required to be triggered. According to Equation 1, the reduction in macro texture when groove depth reduces from 6mm to 3mm is around 50% depending on the macro texture depth of the pavement surface. However, there is limited experimental data based the impact on runway skid resistance to justify the values proposed in the specifications.

In this study, the tolerance levels for initiating maintenance action for deteriorated grooved pavements are investigated using an analytical approach by determining their impact on the frictional characteristics of the runway.

3. Evaluation of skid resistance of grooved pavements

A finite element simulation model for tire-pavement skid resistance had been developed earlier by the authors (Pasindu et. al., 2012, 2015). The finite element analysis computer software, ADINA (ADINA, 2012) is used to simulate the coupled tire-fluid-pavement interaction. The formulation and solution of the simulation model is based on the theory of computational fluid dynamics. It simulates the tire-fluid-pavement interaction and takes into consideration the effects of turbulence and free surface flow. The same simulation model is used for skid resistance analysis. Figure 2 shows the main components of the finite element mesh used for the analysis.

The key element in the computation of skid resistance and hydroplaning speed on a runway pavement is the determination of the hydrodynamic uplift acting on the aircraft tires by the water wedged between the aircraft tire and the pavement. The aircraft speed is gradually increased and the corresponding hydrodynamic uplift at each speed is calculated. Knowing the wheel load and the hydrodynamic uplift, the frictional resistance acting at the tire-pavement contact area can be determined. The available skid resistance at the given aircraft speed may then be computed by means of the following equation (Equation 2):

$$SN_v = 100 \times \frac{F_x}{F_z} \tag{2}$$

Where F_x is the horizontal resistance force to motion, and F_z is the vertical wheel load acting on the tire. The vertical wheel load F_z is an input parameter and its value remains constant throughout the simulation.

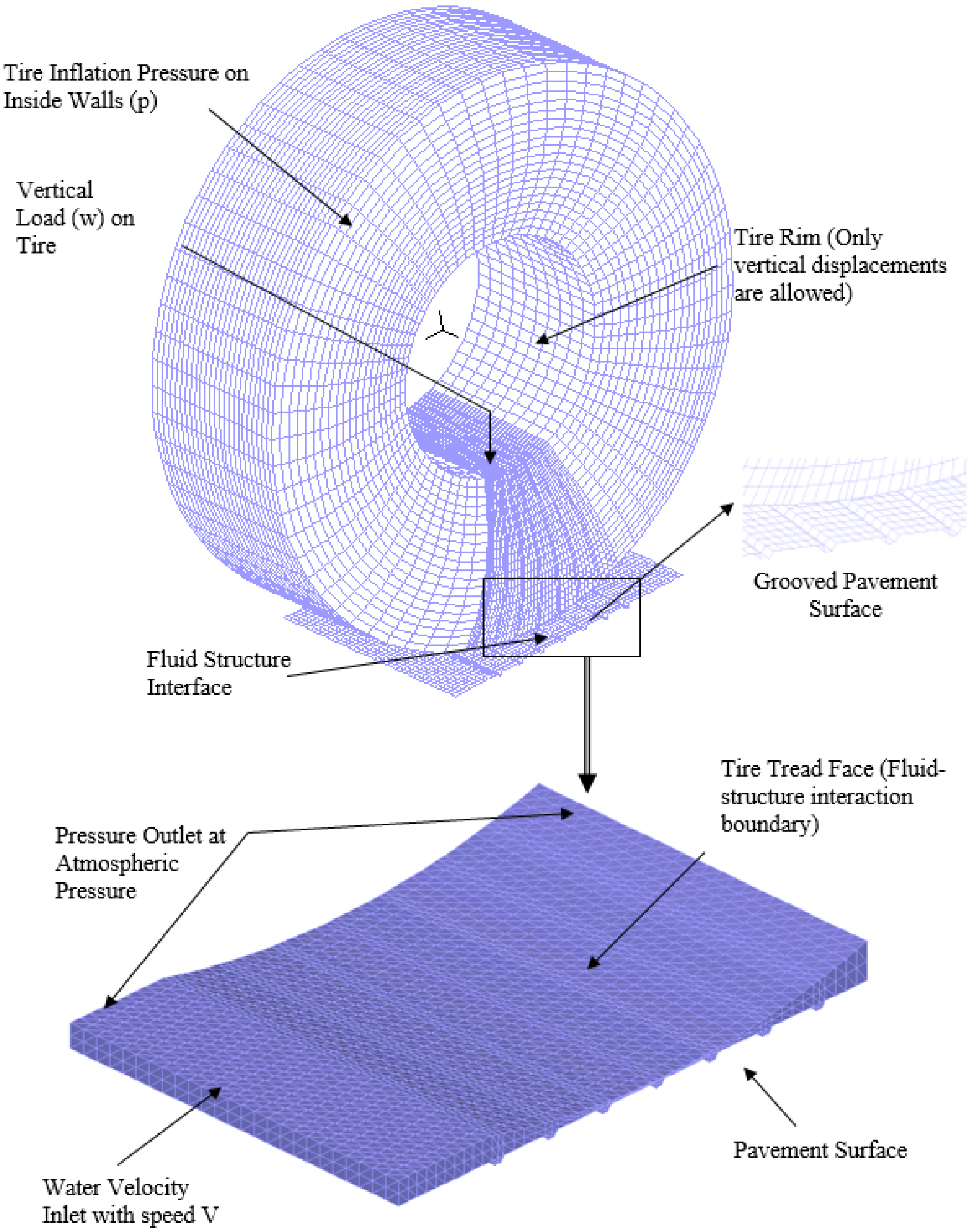


Figure 2. Finite Element Model used for skid resistance analysis

As the aircraft speed is raised, the hydrodynamic uplift increases and the skid resistance falls. When the speed is increased to a sufficiently high level such that the total fluid uplift force is equal to the tire load and there is no contact between the tire and the pavement surface, hydroplaning is said to occur. The aircraft speed at which hydroplaning occurs is defined as the hydroplaning speed. At this speed, the aircraft will lose both braking capability and steering control. In the simulation analysis, the hydroplaning speed is determined as the speed at which the total fluid uplift force is equal to the tire load.

4. Evaluation of skid resistance of grooves for different groove depth

The impact of groove deterioration on the frictional properties of the runway pavement is evaluated using the following illustrative example.

The skid resistance is evaluated for the 49×17 Type VII smooth aircraft tire which used by aircrafts such as Boeing 727. The tire inflation pressure is 1200 kPa, and the wheel load is 125 kN. The standard groove dimensions recommended by FAA are used in the analysis varying only the depth of the groove. The detailed characteristics of the tire model used in the simulation analysis are found in the authors' earlier works on runway pavement skid resistance studies (Pasindu et.al., 2012, 2015).

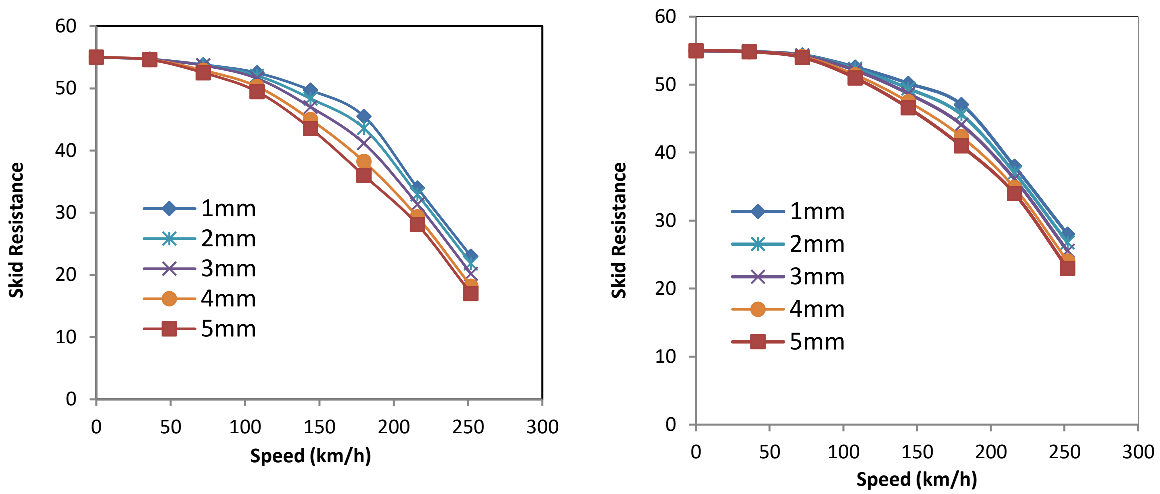
The objective of the analysis is to simulate the variation of skid resistance with different groove depths. Groove depths of 6.3 mm (representing standard groove depth), 5 mm, 4 mm, 3 mm were analyzed representing varying amounts of groove depths that may occur after groove deterioration. Groove depths less than 3mm represent the threshold limit for groove maintenance. Furthermore, to represent different wet weather conditions (rainfall intensities) water film thickness of 1 mm, 2mm, 3mm, 4mm, and 5mm were also considered to evaluate the skid resistance. It must be reiterated that while the skid resistance is compared for a given water film thickness for all groove depths, in reality the water film thickness will be less for higher groove depths for a given rainfall intensity. Currently, water film thickness prediction models for grooved pavements sections are not available to make accurate estimates of water film thickness considering different rain fall intensities and pavement surface properties. Therefore, this study adopts constant water film thicknesses for the purpose of comparison.

4.1. Results of the skid resistance analysis

The results from the simulation model for the groove with different depths are given in Figure 3 and Figure 4.

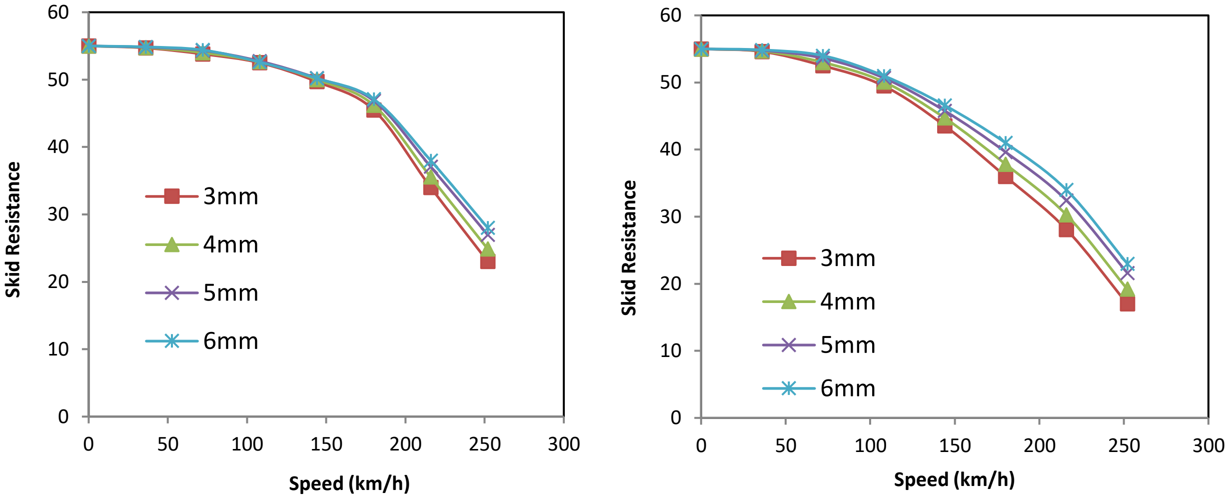
- The skid resistance remains high for all groove depths up to 100 km/h irrespective of the water film thickness or the groove depth.
- For speeds up to 150 km/h the difference in skid resistance is insignificant for different groove depths for water film thickness of 1 mm.
- There is a notable loss of skid resistance with a reduction of groove depth when the water film thickness is 5 mm, especially when the speed exceeds 200 km/h.
- The reduction in SN number for unit decrease in groove depth increases when the groove depth reduces more than 5mm.

Table 1 illustrates skid resistance values and the percentage reduction for different groove depths and water film thickness for operating speeds of 216 km/h and 252 km/h. It is evident based on the results that skid resistance loss is significant for groove depths less than 4 mm. For example, when the groove depth reduces to 3mm, at operating speed of 252 km/h the loss in skid resistance is greater than 20% for water film thickness of 3 mm or more. These are the operating speeds likely to be prevalent during the initial phases after touchdown.


(a) (b)

Note: Test parameters: 49 x 17 Type VII Smooth aircraft tire, tire inflation pressure 1,200 KPa, Static coefficient of friction = 0.55, Wheel load = 125kN

Fig. 3. Skid resistance variation of grooved pavements for water film thicknesses 1mm - 5mm (a). Groove Depth=3mm (b). Groove Depth=6.3mm


(a) (b)

Note: Test parameters: 49 x 17 Type VII Smooth aircraft tire, tire inflation pressure 1,200 KPa, Static coefficient of friction = 0.55, Wheel load = 125kN

Fig. 4. Skid resistance variation of grooved pavements for groove depth thicknesses 3mm - 6mm (a) Water film thickness=1mm (b) Water film thickness =5mm

Table 1. Reduction in skid resistance with groove depth

Operating Speed 216 km/h	**Skid Resistance**				**Percentage Reduction in Skid Resistance**		
	Groove Depth (mm)				Groove Depth (mm)		
Water Film Thickness (mm)	6.3	5.0	4.0	3.0	5.0	4.0	3.0
1	38.0	37.1	35.5	34.0	2.5%	6.5%	10.5%
2	37.1	36.1	34.5	32.9	2.6%	6.9%	11.2%
3	36.1	34.9	33.2	31.4	3.3%	8.3%	13.2%
4	34.9	33.4	31.4	29.3	4.2%	10.0%	15.9%
5	34.0	32.4	30.3	28.1	4.6%	11.0%	17.4%
Operating Speed 252 km/h	**Skid Resistance**				**Percentage Reduction in Skid Resistance**		
	Groove Depth (mm)				Groove Depth (mm)		
Water Film Thickness (mm)	6.3	5.0	4.0	3.0	5.0	4.0	3.0
1	28.0	27.0	24.9	23.0	3.7%	11.2%	17.9%
2	26.8	25.8	23.7	21.9	3.8%	11.5%	18.4%
3	25.6	24.4	22.2	20.2	4.6%	13.2%	20.9%
4	24.1	22.7	20.4	18.2	5.6%	15.4%	24.4%
5	23.0	21.6	19.2	17.0	6.0%	16.5%	26.1%

4.2. Evaluation of braking performance variation of aircraft

Braking distances were computed using the skid resistance (SN) values obtained from the analysis for the similar aircraft considering its typical operating conditions during a landing operation.

The braking distance for an aircraft is given by the following equation (Pasindu et. al. 2012), taking into account the dependency of friction coefficient on aircraft speed.

$$S = \int_0^T \left[V_b - \left([\mu(t)]g + \frac{0.5\,\rho\,[v(t)]^2\,A\,(C_D - [\mu(t)]C_L)}{M} \right) t \right] dt \tag{3}$$

where V_b is the speed at t = 0, which is the speed of the aircraft at onset of braking, $t = T$ is the time at which the aircraft comes to a complete stop, M = mass of the landing aircraft, μ = coefficient of friction, v (t) = aircraft speed at time t, ρ = density of air, A = wing area, C_D = coefficient of drag, C_L = coefficient of lift, μ (t) = coefficient of friction at time t, g = gravitational acceleration

The coefficient of friction is related to skid number, SN by the following relationship

$$\mu = 0.01\,(SN) \tag{4}$$

As explained earlier, the skid number depends on the following factors: aircraft speed (v), wheel load (w), tire pressure (p), surface type (static friction coefficient- SN_0) and water film thickness (tw). In addition, for a grooved pavement the groove pattern (i.e. groove width, depth, and spacing) can also be considered. Hence for a pavement with a particular groove pattern, skid resistance (SN) can be written as a function of all the above factors,

$$SN = f(v, M, L, p, SN_0, tw) \quad (5)$$

where all the variables are as defined earlier. These input parameters are used in the finite element simulation model described earlier and the output will be used to compute the skid number according to Equation 2.

For the purpose of comparison of braking distances for different groove depths, average braking distance was computed for landing operations of a B727 aircraft with mean touchdown speed of 62 m/s, with a standard deviation of 5m/s, weight 62000 kg and runway static friction coefficient of 0.55 representing a standard runway pavement surface. Figure 5 shows the braking distance variation for 3mm, 6mm groove depths as well as un-grooved pavement surface for different water film thickness. The major deviations in braking distance occur for water film thicknesses over 5mm. Both groove levels perform considerably better than the un-grooved pavements.

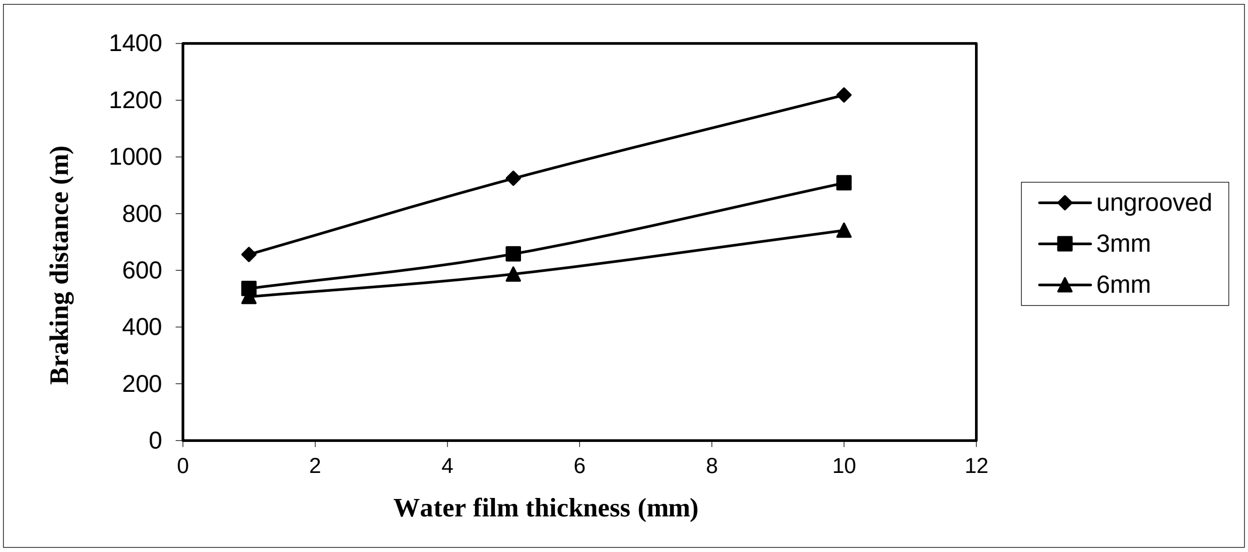


Figure 5. Braking distance comparison for different groove depths and un-grooved pavements

5. Comparison of skid resistance performance of grooves with different depths

The results from the simulation model for the groove with different depths are compared with the results from the analysis of the standard groove's skid resistance. This can be used to assess the frictional performance of the grooves with reduced depths. As shown in Figure 4, for all the water film thicknesses there is no significant loss in skid resistance with the reduction of groove depth (greater than 10% compared to the standard groove SN value) until the speed exceeds 200 km/h. For speeds beyond 200 km/h, the reduction skid resistance varies in the range of 10%-20% when the water film thickness increases from 1mm to 5mm. Therefore, it can be concluded that the groove deterioration has its most significant impact during the initial phases of the aircraft landing operations, which suggests that grooves towards the two ends of a runway are critical to ensure sufficient skid resistance to the aircraft.

Braking distance comparison shows that grooves substantially reduce the braking distance for the different water film thicknesses considered: for 1 mm water film thickness, the braking distance compared to the un-grooved pavement is reduced by 18% and 23% respectively for grooved pavements with groove depths of 3mm and 6mm. Similarly, for 5mm water film thickness the braking distances are reduced by 28% and 36% respectively for grooved pavements with groove depths of 3mm and 6mm. Therefore, we can estimate the relative increase in braking distance due to deterioration of grooving from 6mm to 3mm to be around 5%.

6. Conclusion

The proposed method employs a mechanistic based approach and uses finite element simulation to acceptable tolerance for groove depth variation based on frictional performance. This procedure enables one to better compare the skid resistance of the grooves with different depths under various conditions such as different speed, water film thickness etc. The major reduction in skid resistance occurred at high water depths (5mm) and for operating speeds in excess of 200 km/h which represents the initial phases of a landing operation. Furthermore, the water depths in the order of 5mm above rarely occur on grooved pavements under normal rainfall conditions. Therefore, it can be concluded that the results show that the current acceptable lower limit of groove depth of 3mm does not significantly affect the frictional performance under the used analysis parameters. It has to be noted that the simulation was done using smooth aircraft tires which represent worst case scenario. Therefore, under normal conditions it can be considered that the current tolerance level for groove maintenance initiation is adequate with respect to frictional performance. Similar analysis can be done to evaluate the impact on operating critical aircraft type on a particular airport runway.

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