ANALYSIS OF EFFECTIVENESS OF LONGITUDINAL GROOVING AGAINST HYDROPLANING

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By

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ABSTRACT

Longitudinal pavement grooving has been applied in highways to reduce occurrences of hydroplaning at accident prone locations. However, to date there has not been a systematic study of its effectiveness against hydroplaning. This can be attributed to the difficulty in conducting such experiments and the extreme complexity of theoretical analysis involved. This paper presents a numerical model to simulate the hydroplaning phenomenon and conducts a systematic study on the effectiveness of various designs of longitudinal grooving against hydroplaning. The analysis covers groove widths of 2 to 10 mm, grove depths of 1 to 10 mm, and groove center-to-center spacing of 5 to 25 mm. Groove dimensions are found to have significant effects on the effectiveness of a grooving design against hydroplaning. The results show quantitatively how the use of larger groove width and depth, and smaller groove spacing would reduce hydroplaning risk by computing the changes in the expected hydroplaning speed. For the range of groove dimensions studied, the expected hydroplaning speed for a typical passenger car increases by about 2.8 km/h for every mm increase of groove depth, by about 3.5 km/h for every mm increase of groove width, and by about 1.0 km/h for every mm decrease of groove spacing. The model is also applied to evaluate the hydroplaning potential of different grooving designs used in practice and past studies, and to explain the conflicting findings of past studies on whether longitudinal pavement grooving does improve traction and reduce hydroplaning risk.

Keywords: Longitudinal pavement grooving, groove dimensions, 3-D finite-volume model, hydroplaning, hydroplaning speed; friction coefficient; tire pressure.

INTRODUCTION

Hydroplaning is a pneumatic tire operating condition in which water on a wet runway or highway is not displaced from the nominal tire-ground contact area by a rolling or by a moving but non-rotating tire at a rate fast enough to allow the tire to make contact with the pavement surface, as would be in the dry pavement surface. At the critical hydroplaning speed, the steering ability of the tire is completely lost and the braking ability drops dramatically. The pioneer experiments conducted at the NASA Langley Research Center in the late 1960s led to the development of the well-known NASA hydroplaning equation as shown in Equation (1) that is still widely used today *(1)*.

$$v_p = 10.35\sqrt{p} \tag{1}$$

where the hydroplaning speed v_p is in mph and the tire inflation pressure p is in psi. (1 psi = 6.895 kPa; 1 mph = 1.609 km/h)

Horne and Dreher *(1)* and Horne and Joyner *(2)* were among the first to provide a comprehensive explanation on the various coefficients that are capable to cause tire hydroplaning. Since then, various studies have been conducted to study on the different ways to reduce the occurrence of hydroplaning. In particular, the use of pavement groovings to reduce hydroplaning occurrences has been widely studied. While transverse grooving has been found to produce significant improvement in traction control and reduction in hydroplaning occurrences in runways, the use of longitudinal grooving often showed little or no improvement in traction even though there was a reduction in hydroplaning occurrences *(3, 4, 5)*. On the other hand, longitudinal grooving tends to be favored by highway agencies as only one lane at a time needs to be closed during maintenance, unlike transverse grooving where the whole road section have to be closed *(6, 7, 8)*. No detailed study to-date has been conducted to offer an insight into the effectiveness of longitudinal pavement grooving against hydroplaning. Therefore it is of interest to pavement engineers to understand how the use of longitudinal pavement groovings can affect the potential of hydroplaning occurrences.

This paper presents a numerical model to simulate the hydroplaning phenomenon and conducts a systematic study on the effectiveness of various designs of longitudinal grooving against hydroplaning. First, the important parameters of the numerical simulation model are briefly described. Next, the effects of pavement groove dimensions on hydroplaning potential are analyzed. Finally, the significance of the applications of longitudinal pavement groovings in highways is discussed, giving reference to the current practices in various states. The paper also offers some explanations to the seemingly conflicting findings in past literature related to the results of experimental studies on longitudinal pavement grooving.

SIMULATION MODEL USED IN THIS STUDY

This paper studies the hydroplaning phenomenon of a locked wheel traveling over a longitudinally grooved pavement surface covered with a film of water. To facilitate comparison with the experimental measurements of NASA *(1, 3)*, a constant water film thickness of 7.62 mm (0.3 in) is adopted in the analysis. The properties of water and air at 20^{o}C are used in this study. The density, dynamic viscosity and kinematic viscosity of water at 20^{o}C are 998.2 kg/m^3, 1.002 x 10^{-3} Ns/m^2 and 1.004 x 10^{-6} m^2/s respectively *(9)*. The density, dynamic viscosity and kinematic viscosity of air at standard atmospheric pressure and 20^{o}C are 1.204 kg/m^3, 1.82 x 10^{-5} Ns/m^2 and 1.51 x 10^{-5} m^2/s respectively *(10)*. Hydroplaning is assumed to have occurred when the average ground hydrodynamic pressure under the wheel is equal to the tire pressure, when i.e. the hydrodynamic lift force is equal to the wheel load. The coefficient of friction can be obtained from the simulation by dividing the sum of the horizontal forces by the sum of the uplift forces acting on the tire.

Shown in Figure 1 is the deformed profile at the onset of hydroplaning is based on the experimentally measured data reported by Horne and Joyner *(2)*. In this study, the pavement micro-texture was assumed to be zero. As shown in Table 1, the following range of pavement groove dimensions was studied: groove widths from 2 mm to 10 mm, groove depths from 1 mm to 10 mm, and groove center-to-center spacing from 5 mm to 25 mm. The total number of groove designs analyzed was 132. These ranges of dimensions are selected based on common longitudinal groove dimensions reported in the literature *(11, 12, 13)*.

The numerical hydroplaning simulation model used in this study is based on the one developed by the authors *(14)*. This proposed model made use of computational fluid dynamics to simulate the fluid flow and the model takes into account the effects of turbulence and free surface fluid flow. The model has been verified against the NASA hydroplaning equation and the friction coefficients of different plane pavement surfaces with varying micro-texture. The software FLUENT *(15)*, which is based on the finite-volume method, was adopted for the present study.

The boundary conditions and the initial conditions adopted are also shown in Figure 1. The upstream boundary conditions consist of a pair of inlets, namely a velocity inlet of 7.62 mm (0.3 in.) thick for water and a velocity inlet of 76.2 mm (3 in.) thick of air. A uniform velocity profile is used. The simulated speed is first kept as 86.5 km/h (53.8 mph) which is the hydroplaning speed predicted by the NASA hydroplaning equation and is then varied between 0 km/h and 300 km/h at 15 km/h intervals to derive the hydroplaning speed-tire pressure relationships. The inlet is placed at a distance of 300 mm away from the leading edge of the wheel so as to allow for any possible formation of bow wave. The side edges and the trailing edge are modeled as pressure outlets with the pressure set as 0 kPa (i.e. atmospheric pressure). The top boundary is set as a pressure outlet at the atmospheric pressure and the top boundary is placed at a distance of 25.4 mm (1 in.). It is noted that the centre-line of the wheel can be treated as a plane of symmetry. The locations of the boundaries have been chosen such that they would not have any significant effect on the average ground hydrodynamic pressure under the wheel. 6-node wedge elements and 8-node hexahedral elements are used to represent each finite volume in the simulation and convergence analysis has found that using ten 8-nodes hexahedral elements is required in the hydroplaning region.

EFFECTS OF PAVEMENT GROOVE DIMENSIONS ON HYDROPLANING

The main results of the simulation analysis are the expected hydroplaning speeds and the friction coefficient at the onset of hydroplaning. The computed hydroplaning speeds and friction coefficients of all the 132 designs of groove dimensions are presented in Table 2. The respective effects of varying groove depth, groove width and groove spacing are analyzed in the following sub-sections. A raise in the hydroplaning speed means that the risk of hydroplaning will be reduced, while an increase in friction coefficient implies that the traction will be improved.

Effect of Groove Depth on Hydroplaning

For easy presentation, the discussion is focused on groove designs with groove spacing of 20 mm. The computed results, extracted from Table 2, for different groove depths are summarized in Table 3. For the case of 2 mm groove width, the predicted hydroplaning speeds range from 87.2 km/h for a 1 mm groove depth to 95.6 km/h for a 10 mm groove depth. The friction coefficients experienced by the wheel at incipient hydroplaning are found to vary from 0.0978 to 0.1174 as groove depth changes from 1 mm to 10 mm. These correspond to a percentage increase in hydroplaning speed of 0.84% to 10.52%, compared to the NASA predicted hydroplaning speed of 86.5 km/h for a smooth plane pavement and a percentage increase in friction coefficient of 1.35% to 21.66%, as compared to the associated friction coefficient of 0.0965 during incipient hydroplaning for the smooth plane pavement surface. The higher friction coefficient and hydroplaning speed associated with a larger groove depth indicates the benefit gained in reducing hydroplaning risk and the loss of braking control at incipient hydroplaning.

As can be seen from Table 3, similar trends of changes in hydroplaning speed and friction coefficient respectively with groove depth are also found for designs with other groove widths. It is noted that the percentage increases in hydroplaning speed and friction coefficient with groove depth are larger for groove designs having a larger groove width.

Figure 2 shows the relationships between hydroplaning speed and tire-pressure for different groove depths, for the case of 20 mm groove spacing with 5 different groove widths. Similar patterns of relationships to those shown in Figure 2 are also found for groove spacing of 5 mm, 10 mm, 15 mm and 25 mm respectively. It can be observed that for any given tire pressure, a larger groove depth for a given groove spacing and width would lead to a higher hydroplaning speed. This is within expectation because of the fact that there would be larger outlet space along the grooves that allow water to escape from the tire imprint region. These plots also reveal that the impact of increasing groove depth on the hydroplaning speed increases with the magnitude of the tire pressure.

Effect of Groove Width on Hydroplaning

For easy presentation, the discussion is again focused on groove designs with groove spacing of 20 mm. The computed results, extracted from Table 2, for different groove depths are summarized in Table 4. Consider the cases of groove design with a 6 mm groove depth, the predicted hydroplaning speeds range from 92.25 km/h for a 2 mm groove width to 115.55 km/h for a 10 mm groove width. The friction coefficients experienced by the wheel for a passenger car tire of tire inflation pressure of 186.2 kPa during incipient hydroplaning are found to vary from 0.1090 to 0.1631 as groove width changes from 2 mm to 10 mm. These correspond to a percentage increase in hydroplaning speed of 6.65% to 33.58% compared to the NASA predicted hydroplaning speed of 86.5 km/h, and a percentage increase in friction coefficient of 12.95% to 69.02% as compared to the associated friction coefficient of 0.0965 during incipient hydroplaning for the smooth plane pavement surface.

As can be seen from Table 4, similar trends of changes in hydroplaning speed and friction coefficient respectively with groove width are also found for designs with other groove widths. The results show that the percentage increases in hydroplaning speed and friction coefficient with groove width are higher for a larger groove depth.

Figure 3 shows the relationship between hydroplaning speed and tire-pressure for different groove widths, for the case of 20 mm groove spacing with 4 different groove depths. Similar patterns of relationships are also found for groove spacing of 5 mm, 10 mm, 15 mm and 25 mm respectively. It can be observed from Figure 3 that for any given tire pressure and given groove depth and spacing, a larger groove width would produce a higher hydroplaning speed. These plots also reveal that the impact of increasing groove depth on the hydroplaning speed increases with the magnitude of the tire pressure.

Effect of Groove Spacing on Hydroplaning

For easy presentation, the discussion is focused on groove designs with of 2 mm groove width. The computed results, extracted from Table 2, for different center-to-center groove spacing are summarized in Table 5. For the cases with groove depth of 6 mm, the predicted hydroplaning speeds range from 105.01 km/h for 5 mm groove spacing to 91.53 km/h for 25 mm groove spacing. The friction coefficients experienced by the wheel for a passenger car tire of tire inflation pressure of 186.2 kPa during incipient hydroplaning are found to vary from 0.1072 to 0.1410 when groove spacing decreases from 25 mm to 5 mm. These correspond to a percentage increase in hydroplaning speed of 21.40% to 5.82% and a percentage increase in friction coefficient of 11.09% to 46.11% with a decrease of groove spacing from 25 mm to 5 mm, with respect to the NASA predicted hydroplaning speed and its associated friction coefficient for the smooth plane pavement surface. The higher friction coefficient and hydroplaning speed associated with a smaller center-to-center groove spacing indicates the benefit gained in reducing hydroplaning risk and the loss of braking control at incipient hydroplaning.

As can be seen from Table 5, similar trends of changes in hydroplaning speed and friction coefficient respectively with groove spacing are also found for designs with other groove depths. The magnitude of percentage increase in hydroplaning speed and friction coefficient with groove spacing are higher for a larger groove depth.

Figure 4 shows the relationships between hydroplaning speed and tire-pressure for different groove spacing, for the case of 2 mm groove width with 4 different groove depths. Similar patterns of relationships are also found for groove widths of 4 mm, 6 mm, 8 mm and 10 mm respectively. It can be observed from Figure 4 that for any given tire pressure and given groove depth and width, a smaller groove spacing would produce a higher hydroplaning speed. These plots also reveal that the impact of decreasing groove spacing on the hydroplaning speed increases with the magnitude of the tire pressure.

Relative Effects of Groove Depth, Width and Spacing

The preceding sub-sections have discussed the effects of groove depth, width and spacing on the hydroplaning speed and friction coefficient at incipient hydroplaning. It is noted that in general, a larger groove width, groove depth and a smaller groove spacing would result in a larger hydroplaning speed and a higher friction coefficient at incipient hydroplaning. For a practical range of longitudinal grooving designs having groove width ranging from 2 mm to 6 mm, groove depth ranging from 2 mm to 8 mm and groove spacing ranging from 10 mm to 20 mm, the hydroplaning speed is found to vary from 88.74 km/h to 124.16 km/h and the friction coefficient during incipient hydroplaning varies between 0.1010 and 0.2056. This corresponds to percentage increases of the hydroplaning speed over the NASA hydroplaning speed by 2.58% to 43.54%, and the corresponding increase in friction coefficient by 4.66% to 113.11%. Such a large range and magnitude in percentage increases in hydroplaning speeds and friction coefficients respectively suggest that it is important to select appropriate groove dimensions through analysis of their effects in order to achieve the desired outcomes of installing the longitudinal grooves.

To make a comparison between the relative effects of groove width, depth and spacing on hydroplaning, an effectiveness index can be in terms of the magnitude of change in hydroplaning speed that per unit change of a particular groove dimension. This effectiveness index with the unit of km/h/mm can be calculated for the 132 cases of groove design analyzed in this study, as given in Table 6, for the three different tire pressures (100 kPa, 200 kPa and 300kPa). A total of 330 data points of the effectiveness index for groove depth can be computed out of the 396 data considered for the different cases as shown in Figure 5(a). There are also 300 data points of the effectiveness index for groove width as shown in Figure 5(b) and 288 data points of the effectiveness index for groove spacing as shown in Figure 5(c).

It is seen that with the given range of practical groove dimensions studied in this paper, for each mm increase in groove depth, the raise in hydroplaning speed that can be achieved falls within the range of 0 to 9 km/h with a mean of 2.799 km/h/mm. For each mm increase in groove width, the raise in hydroplaning speed falls within the range of 0 to 16 km/h with a mean of 3.558 km/h/mm. For each mm decrease in groove spacing, the raise in hydroplaning speed falls within the range of 0 to 5.25 km/h with a mean of 1.057 km/h/mm. It can be observed that groove width provides the largest effectiveness indices compared to groove depth and spacing. This indicates that groove width is an important factor in reducing hydroplaning occurrences and could be a primary factor in groove design. Groove depth is perhaps the next important factor followed by the groove spacing by comparing the frequency distribution plots and the mean effective index. However, one point to note is that unlike groove width and depth, the range of spacing adopted in practice is typically much larger than that for the groove width or depth. This means that in practice, spacing could be a more convenient measure in combating hydroplaning.

SIGNIFICANCE OF LONGITUDINAL GROOVES IN COMBATING HYDROPLANING

The simulation model proposed in this paper provides a useful way to evaluate the hydroplaning risk of different grooving designs. ACPA *(11)* proposes the use of longitudinal pavement groovings on highways with a typical groove design of 3 mm in width, and 6 mm in depth at 20 mm spacing. Based on the simulation model proposed in this paper, it can be found that the predicted hydroplaning speed is 94.4 km/h for a typical passenger car with tire pressure of 186.2 kPa.

The friction coefficient predicted at incipient hydroplaning is found to be 0.1128. Upon comparison with the NASA hydroplaning equation, it indicates that the ACPA longitudinal pavement grooving design provides a 9% increase in hydroplaning speed. The corresponding friction coefficient at the onset of hydroplaning is 0.1128 against 0.0965 for an ungrooved pavement.

Some of the state practices for longitudinal pavement grooving can also be examined using the proposed simulation model. Caltrans *(12)* specifies the use of longitudinal pavement grooving of 2 mm wide, 3 mm to 7 mm deep, and a spacing of 19 mm. Based on the simulations from the proposed model, the predicted hydroplaning speed is found to range from 89.6 km/h for a 3 mm groove depth to 92.9 km/h for a 7 mm groove depth, compared to the NASA predicted hydroplaning speed of 86.5 km/h for ungrooved pavement with a tire pressure of 186.2 kPa. The friction coefficient at incipient hydroplaning is between 0.1031 and 0.1109. ADOT *(13)* specifies the use of longitudinal pavement grooves of 3 mm in width, 5 mm in depth at 19 mm spacing on highways and PennDOT specifies them to be 3 mm wide and at least 5 mm deep at 19 mm spacing. The ADOT design would give a predicted hydroplaning speed of 93.1 km/h and friction coefficient of 0.1115 at incipient hydroplaning, while the PennDOT design would give at least 93.1 km/h for hydroplaning speed and at least 0.1115 for the friction coefficient at incipient hydroplaning. Groove dimensions recommendations of other studies *(3, 16, 17, 18)* can also be evaluated using the data of Table 2.

The computed results indicate that there is a wide range of hydroplaning speeds and friction coefficients associated with the practical range of groove dimensions and this helps to explain why there have been arguments on whether the provision of longitudinal pavement grooving does improve traction and reduce hydroplaning potential. Past experimental measurements typically considered only specific groove dimensions and as can be seen from Table 2, the improvements in hydroplaning speed and friction coefficient in particular, may or may not be substantial enough to be picked experimentally.

For example, a typical longitudinal groove design adopted in past experimental studies (*3, 16, 17)* measures 3 mm in width, 3 mm in depth and 19 mm in spacing would produce only a hydroplaning speed of 90.6 km/h and friction coefficient at incipient hydroplaning of 0.1056. The improvement in both hydroplaning speed and friction coefficient are rather marginal and difficult to detect experimentally. This extremely low friction coefficient is comparable to that of the smooth plane surface and would lead to the experimental conclusion of the past studies that longitudinal pavement grooving would not provide traction control during hydroplaning even though there can be a reduction of hydroplaning occurrences. However, if the groove has dimensions of 6 mm width, 6 mm depth and 10 mm spacing, the hydroplaning speed and the friction coefficient will be increased to 114.5 km/h and 0.1730 respectively. In this case, the difference in friction would be much more discernable than the former case.

CONCLUSION

This paper has presented a numerical model to simulate the hydroplaning phenomenon and conducted a systematic study on the effectiveness of various designs of longitudinal grooving against hydroplaning. The analysis covers groove widths of 2 to 10mm, groove depths of 1 to 10 mm, and groove center-to-center spacing of 5 to 25 mm. Groove dimensions are found to have significant effects on the effectiveness of a grooving design against hydroplaning. The results show quantitatively how the use of larger groove width and depth, and smaller groove spacing would reduce hydroplaning risk by computing the changes in the expected hydroplaning speed and friction coefficient at incipient hydroplaning. For the range of groove dimensions studied, the expected hydroplaning speed for a typical passenger car increases by about 2.8 km/h for every mm increase of groove depth, by about 3.5 km/h for every mm increase of groove width, and by about 1.0 km/h for every mm decrease of groove spacing. The model is also applied to evaluate the hydroplaning potential of different grooving designs used in practice and past studies, and to explain the conflicting findings of past studies on whether longitudinal pavement grooving does improve traction and reduce hydroplaning risk. The analysis presented in this paper suggests that the proposed model could serve as a useful tool for the design and evaluation of longitudinal grooves in highway pavements.

REFERENCES

1. Horne, W. B. and R. C. Dreher. *Phenomena of Pneumatic Tire Hydroplaning*. NASA TN D-2056, NASA, USA, 1963.
2. Horne, W. B. and U. T. Joyner. Pneumatic Tire Hydroplaning and Some Effects on Vehicle Performance. In *SAE International Automotive Engineering Congress*, 11-15 Jan, Detroit, Michigan, USA. 1965.
3. Horne, W.B. Results from Studies of Highway Grooving and Texturing at NASA Wallops Station. In *Pavement Grooving and Traction Studies*, NASA SP-5073, pp. 425-464, Washington D.C., USA. 1969.
4. Federal Highway Administration. *Pavement Macro-texture Review*, FHWA RD80-505, Final Report. 1980.
5. American Concrete Institute. *Texturing Concrete Pavement*. Reported by ACI Committee 325, Detroit, Michigan. 1988.
6. Highway Research Board. *Skid Resistance*. National Cooperative Highway Research Program Synthesis of Highway Practice, No. 14. 1972.
7. Pennsylvania Transportation Institute. *Skid Resistance Manual*, Submitted to FHWA, Contract No. DTFH-61-88-C-00058. 1988.
8. American Concrete Pavement Association. *Special Report: Concrete Pavement Technology and Research*, SR-902P, Stokie, Illinois, 2000.
9. Chemical Rubber Company. *Handbook of Chemistry and Physics, 69th Edition*, CRC Press, Cleveland, Ohio, 1988.
10. Blevins, R. D. *Applied Fluid Dynamics Handbook*, Van Nostrand Reinhold Co. Inc., New York, 1984.
11. American Concrete Paving Association. Concrete Pavement Fundamentals – Surface Texture. http://www.pavement.com/PavTech/Tech/Fundamentals/fundtexture.html. Last accessed July 2005.
12. State of California Department of Transportation. Section 42: Groove and Grind Pavement. In *Standard Specifications*, State of California Business, Transportation and Housing Agency, Department of Transportation. 1999.
13. International Groove and Grinding Association. State DOT Specifications. http://www.igga.net/specs.html. Last accessed April 2005.
14. Ong, G.P., T.F. Fwa and J. Guo. Modelling Hydroplaning and the Effects of Pavement Micro-Texture. Accepted for publication in the *Transportation Research Record: Journal of the Transportation Research Board*. 2005.
15. *Fluent 6.0 User Guide*. Fluent Inc., Lebanon, New Hampshire, 2000.
16. Farnsworth, E.E. Pavement Grooving on Highways. In *Pavement Grooving and Traction Studies*, NASA SP-5073, pp. 411-424, Washington D.C., USA. 1969.
17. Mosher, L.G. Results from Studies of Highway Grooving and Texturing by Several State Highway Departments. In *Pavement Grooving and Traction Studies*, NASA SP-5073, pp. 465-504, Washington D.C., USA. 1969.
18. Sugg, R.W. Joint NASA-British Ministry of Technology Skid Correlation Study – Results from British Vehicles. In *Pavement Grooving and Traction Studies*, NASA SP-5073, pp. 361-410, Washington D.C., USA. 1969.

LIST OF TABLES AND FIGURES

TABLE 1 Groove Dimensions Used in Analysis

Center-to-center spacing analyzed (mm)	Groove width analyzed (mm)	Groove depth analyzed (mm)
5	2	1, 2, 4, 6, 8, 10
	3	1, 2, 4, 6, 8, 10
	4	1, 2, 4, 6, 8, 10
10	2	1, 2, 4, 6, 8, 10
	4	1, 2, 4, 6, 8, 10
	6	1, 2, 4, 6, 8, 10
	8	1, 2, 4, 6, 8, 10
15	2	1, 2, 4, 6, 8, 10
	4	1, 2, 4, 6, 8, 10
	6	1, 2, 4, 6, 8, 10
	8	1, 2, 4, 6, 8, 10
	10	1, 2, 4, 6, 8, 10
20	2	1, 2, 4, 6, 8, 10
	4	1, 2, 4, 6, 8, 10
	6	1, 2, 4, 6, 8, 10
	8	1, 2, 4, 6, 8, 10
	10	1, 2, 4, 6, 8, 10
25	2	1, 2, 4, 6, 8, 10
	4	1, 2, 4, 6, 8, 10
	6	1, 2, 4, 6, 8, 10
	8	1, 2, 4, 6, 8, 10
	10	1, 2, 4, 6, 8, 10

TABLE 2 Hydroplaning Speeds and Friction Coefficients of Pavements having Different Groove Dimensions for Passenger Cars with 186.2 kPa Tire Pressure

s	*w*	*d*	*U*	*f*	*s*	*w*	*d*	*U*	*f*	*s*	*w*	*d*	*U*	*f*
5	2	1	89.05	0.1014	15	2	4	91.55	0.1072	20	6	8	105.70	0.1464
5	2	2	91.94	0.1078	15	2	6	93.77	0.1094	20	6	10	109.33	0.1580
5	2	4	98.61	0.1242	15	2	8	95.93	0.1180	20	8	1	92.66	0.1041
5	2	6	105.01	0.1410	15	2	10	97.93	0.1233	20	8	2	97.44	0.1147
5	2	8	108.79	0.1522	15	4	1	87.43	0.0987	20	8	4	104.63	0.1330
5	2	10	114.51	0.1696	15	4	2	90.83	0.1058	20	8	6	109.94	0.1490
5	3	1	90.34	0.1043	15	4	4	95.57	0.1172	20	8	8	115.84	0.1663
5	3	2	95.77	0.1170	15	4	6	100.20	0.1294	20	8	10	120.54	0.1820
5	3	4	104.75	0.1413	15	4	8	104.29	0.1410	20	10	1	97.36	0.1144
5	3	6	113.62	0.1679	15	4	10	108.71	0.1541	20	10	2	103.03	0.1273
5	3	8	116.76	0.1790	15	6	1	90.43	0.1060	20	10	4	109.37	0.1442
5	3	10	119.74	0.1901	15	6	2	94.53	0.1152	20	10	6	115.55	0.1631
5	4	1	91.03	0.1064	15	6	4	99.12	0.1275	20	10	8	121.39	0.1826
5	4	2	98.20	0.1241	15	6	6	105.51	0.1458	20	10	10	130.45	0.2109
5	4	4	106.95	0.1496	15	6	8	111.41	0.1643	25	2	1	87.04	0.0966
5	4	6	117.71	0.1840	15	6	10	116.79	0.1825	25	2	2	87.17	0.0968
5	4	8	122.14	0.2012	15	8	1	96.88	0.1137	25	2	4	89.81	0.1031
5	4	10	129.06	0.2280	15	8	2	102.37	0.1267	25	2	6	91.53	0.1072
10	2	1	87.39	0.0981	15	8	4	109.52	0.1464	25	2	8	92.82	0.1105
10	2	2	90.34	0.1042	15	8	6	116.27	0.1683	25	2	10	94.13	0.1139
10	2	4	93.23	0.1109	15	8	8	123.33	0.1907	25	4	1	87.26	0.0973
10	2	6	96.68	0.1217	15	8	10	129.52	0.2135	25	4	2	88.25	0.0995
10	2	8	103.01	0.1351	15	10	1	102.81	0.1274	25	4	4	92.42	0.1096
10	2	10	103.40	0.1368	15	10	2	104.28	0.1314	25	4	6	95.24	0.1167
10	4	1	88.37	0.1009	15	10	4	115.22	0.1615	25	4	8	97.99	0.1239
10	4	2	92.55	0.1100	15	10	6	123.36	0.1880	25	4	10	100.54	0.1310
10	4	4	99.29	0.1269	15	10	8	131.23	0.2172	25	6	1	89.13	0.1022
10	4	6	105.91	0.1453	15	10	10	141.12	0.2531	25	6	2	91.07	0.1067
10	4	8	111.83	0.1634	20	2	1	87.23	0.0978	25	6	4	95.57	0.1172
10	4	10	117.38	0.1817	20	2	2	88.74	0.1010	25	6	6	99.29	0.1278
10	6	1	96.45	0.1204	20	2	4	90.65	0.1052	25	6	8	103.19	0.1386
10	6	2	100.14	0.1294	20	2	6	92.25	0.1090	25	6	10	107.04	0.1499
10	6	4	105.46	0.1448	20	2	8	93.57	0.1129	25	8	1	89.85	0.1055
10	6	6	114.46	0.1730	20	2	10	95.60	0.1174	25	8	2	91.77	0.1085
10	6	8	124.16	0.2056	20	4	1	87.28	0.0990	25	8	4	97.99	0.1235
10	6	10	129.83	0.2293	20	4	2	90.25	0.1047	25	8	6	103.67	0.1390
10	8	1	102.50	0.1297	20	4	4	93.13	0.1115	25	8	8	108.94	0.1544
10	8	2	105.99	0.1365	20	4	6	96.69	0.1204	25	8	10	113.21	0.1684
10	8	4	116.33	0.1675	20	4	8	99.60	0.1284	25	10	1	90.76	0.1078
10	8	6	127.31	0.2045	20	4	10	103.23	0.1387	25	10	2	93.61	0.1124
10	8	8	137.07	0.2420	20	6	1	89.88	0.1066	25	10	4	100.51	0.1300
10	8	10	145.30	0.2773	20	6	2	92.50	0.1107	25	10	6	107.96	0.1506
15	2	1	87.30	0.0979	20	6	4	96.16	0.1196	25	10	8	114.79	0.1711
15	2	2	88.89	0.1011	20	6	6	101.09	0.1329	25	10	10	119.30	0.1878

Note: *s* refers to groove spacing in mm, *w* refers to groove width in mm, *d* refers to groove depth in mm, *U* refers to hydroplaning speed in km/h and *f* refers to the friction coefficient at incipient hydroplaning.

TABLE 3 Effects of Groove Depth on Hydroplaning Speed and Friction Coefficient

(a) Groove designs of 2 mm groove width and 20 mm center-to-center spacing

Groove depth (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
1	87.23	0.84%	0.0978	1.35%
2	88.74	2.59%	0.1010	4.66%
4	90.65	4.80%	0.1052	9.02%
6	92.25	6.65%	0.1090	12.95%
8	93.57	8.17%	0.1129	16.99%
10	95.60	10.52%	0.1174	21.66%

(b) Groove designs of 4 mm groove width and 20 mm center-to-center spacing

Groove depth (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
1	87.28	0.90%	0.0990	2.59%
2	90.25	4.34%	0.1047	8.50%
4	93.13	7.66%	0.1115	15.54%
6	96.69	11.78%	0.1204	24.77%
8	99.60	15.14%	0.1284	33.06%
10	103.23	19.34%	0.1387	43.73%

(c) Groove designs of 6 mm groove width and 20 mm center-to-center spacing

Groove depth (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
1	89.88	3.91%	0.1066	10.47%
2	92.50	6.94%	0.1107	14.72%
4	96.16	11.17%	0.1196	23.94%
6	101.09	16.87%	0.1329	37.72%
8	105.70	22.20%	0.1464	51.71%
10	109.33	26.39%	0.1580	63.73%

(d) Groove designs of 8 mm groove width and 20 mm center-to-center spacing

Groove depth (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
1	92.66	7.12%	0.1041	7.88%
2	97.44	12.65%	0.1147	18.86%
4	104.63	20.96%	0.1330	37.82%
6	109.94	27.10%	0.1490	54.40%
8	115.84	33.92%	0.1663	72.33%
10	120.54	39.35%	0.1820	88.60%

(e) Groove designs of 10 mm groove width and 20 mm center-to-center spacing

Groove depth (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
1	97.36	12.55%	0.1144	18.55%
2	103.03	19.11%	0.1273	31.92%
4	109.37	26.44%	0.1442	49.43%
6	115.55	33.58%	0.1631	69.02%
8	121.39	40.34%	0.1826	89.22%
10	130.45	50.81%	0.2109	118.55%

TABLE 4 Effects of Groove Width on Hydroplaning Speed and Friction Coefficient

(a) Groove designs of 1 mm groove depth and 20 mm center-to-center spacing

Groove width (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
2	87.23	0.84%	0.0978	1.35%
4	87.28	0.90%	0.0990	2.59%
6	89.88	3.91%	0.1066	10.47%
8	92.66	7.12%	0.1041	7.88%
10	97.36	12.55%	0.1144	18.55%

(b) Groove designs of 2 mm groove depth and 20 mm center-to-center spacing

Groove width (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
2	88.74	2.59%	0.1010	4.66%
4	90.25	4.34%	0.1047	8.50%
6	92.50	6.94%	0.1107	14.72%
8	97.44	12.65%	0.1147	18.86%
10	103.03	19.11%	0.1273	31.92%

(c) Groove designs of 4 mm groove depth and 20 mm center-to-center spacing

Groove width (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
2	90.65	4.80%	0.1052	9.02%
4	93.13	7.66%	0.1115	15.54%
6	96.16	11.17%	0.1196	23.94%
8	104.63	20.96%	0.1330	37.82%
10	109.37	26.44%	0.1442	49.43%

(d) Groove designs of 6 mm groove depth and 20 mm center-to-center spacing

Groove width (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
2	92.25	6.65%	0.1090	12.95%
4	96.69	11.78%	0.1204	24.77%
6	101.09	16.87%	0.1329	37.72%
8	109.94	27.10%	0.1490	54.40%
10	115.55	33.58%	0.1631	69.02%

(e) Groove designs of 8 mm groove depth and 20 mm center-to-center spacing

Groove width (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
2	93.57	8.17%	0.1129	16.99%
4	99.60	15.14%	0.1284	33.06%
6	105.70	22.20%	0.1464	51.71%
8	115.84	33.92%	0.1663	72.33%
10	121.39	40.34%	0.1826	89.22%

(f) Groove designs of 10 mm groove depth and 20 mm center-to-center spacing

Groove width (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
2	95.60	10.52%	0.1174	21.66%
4	103.23	19.34%	0.1387	43.73%
6	109.33	26.39%	0.1580	63.73%
8	120.54	39.35%	0.1820	88.60%
10	130.45	50.81%	0.2109	118.55%

TABLE 5 Effects of Groove Spacing on Hydroplaning Speed and Friction Coefficient

(a) Groove designs of 2 mm groove width and 1 mm groove depth

Groove spacing (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
5	89.05	2.95%	0.1014	5.08%
10	87.39	1.03%	0.0981	1.66%
15	87.30	0.92%	0.0979	1.45%
20	87.23	0.84%	0.0978	1.35%
25	87.04	0.62%	0.0966	0.10%

(b) Groove designs of 2 mm groove width and 2 mm groove depth

Groove spacing (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
5	91.94	6.29%	0.1078	11.71%
10	90.34	4.44%	0.1042	7.98%
15	88.89	2.76%	0.1011	4.77%
20	88.74	2.59%	0.1010	4.66%
25	87.17	0.77%	0.0968	0.31%

(c) Groove designs of 2 mm groove width and 4 mm groove depth

Groove spacing (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
5	98.61	14.00%	0.1242	28.70%
10	93.23	7.78%	0.1109	14.92%
15	91.55	5.84%	0.1072	11.09%
20	90.65	4.80%	0.1052	9.02%
25	89.81	3.83%	0.1031	6.84%

(d) Groove designs of 2 mm groove width and 6 mm groove depth

Groove spacing (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
5	105.01	21.40%	0.1410	46.11%
10	96.69	11.78%	0.1217	26.11%
15	93.77	8.40%	0.1094	13.37%
20	92.25	6.65%	0.1090	12.95%
25	91.53	5.82%	0.1072	11.09%

(e) Groove designs of 2 mm groove width and 8 mm groove depth

Groove spacing (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
5	108.79	25.77%	0.1522	57.72%
10	103.01	19.09%	0.1351	40.00%
15	95.93	10.90%	0.1180	22.28%
20	93.57	8.17%	0.1129	16.99%
25	92.82	7.31%	0.1105	14.51%

(f) Groove designs of 2 mm groove width and 10 mm groove depth

Groove spacing (mm)	Predicted hydroplaning speed for 186.2 kPa tire pressure (km/h)	Percent increase over NASA hydroplaning speed for smooth pavement surface	Friction coefficient	Percent increase over friction coefficient at NASA hydroplaning speed
5	114.51	32.38%	0.1696	75.75%
10	103.40	19.54%	0.1368	41.76%
15	97.93	13.21%	0.1233	27.77%
20	95.60	10.52%	0.1174	21.66%
25	94.13	8.82%	0.1139	18.03%

TABLE 6 Hydroplaning Speeds for Different Groove Dimensions and Tire Pressures

s	w	d	p	U	s	w	d	p	U	s	w	d	p	U
5	2	2	100	67.39	15	4	2	100	66.58	20	8	2	100	71.43
5	2	2	200	95.31	15	4	2	200	94.16	20	8	2	200	101.01
5	2	2	300	116.73	15	4	2	300	115.33	20	8	2	300	123.71
5	2	4	100	72.28	15	4	4	100	70.06	20	8	4	100	76.70
5	2	4	200	102.22	15	4	4	200	99.08	20	8	4	200	108.46
5	2	4	300	125.20	15	4	4	300	121.34	20	8	4	300	132.84
5	2	6	100	76.98	15	4	6	100	73.45	20	8	6	100	80.59
5	2	6	200	108.87	15	4	6	200	103.88	20	10	6	200	113.97
5	2	6	300	133.33	15	4	6	300	127.22	20	10	6	300	139.58
5	4	2	100	71.98	15	6	2	100	69.29	20	10	2	100	75.52
5	4	2	200	101.80	15	6	2	200	97.99	20	10	2	200	106.81
5	4	2	300	124.68	15	6	2	300	120.02	20	10	2	300	130.81
5	4	4	100	78.40	15	6	4	100	72.66	20	10	4	100	80.17
5	4	4	200	110.87	15	6	4	200	102.76	20	10	4	200	113.38
5	4	4	300	135.79	15	6	4	300	125.85	20	10	4	300	138.86
5	4	6	100	86.28	15	6	6	100	77.34	20	10	6	100	84.70
5	4	6	200	122.02	15	6	6	200	109.38	20	8	6	200	119.79
5	4	6	300	149.45	15	6	6	300	133.97	20	8	6	300	146.71
10	2	2	100	66.22	15	8	2	100	75.04	25	2	2	100	63.90
10	2	2	200	93.65	15	8	2	200	106.12	25	2	2	200	90.36
10	2	2	300	114.70	15	8	2	300	129.97	25	2	2	300	110.67
10	2	4	100	68.34	15	8	4	100	80.28	25	2	4	100	65.83
10	2	4	200	96.65	15	8	4	200	113.54	25	2	4	200	93.10
10	2	4	300	118.37	15	8	4	300	139.05	25	2	4	300	114.02
10	2	6	100	70.87	15	8	6	100	85.23	25	2	6	100	67.09
10	2	6	200	100.23	15	8	6	200	120.54	25	2	6	200	94.88
10	2	6	300	122.76	15	8	6	300	147.63	25	2	6	300	116.21
10	4	2	100	66.58	15	10	2	100	76.44	25	4	2	100	64.69
10	4	2	200	94.16	15	10	2	200	108.11	25	4	2	200	91.49
10	4	2	300	115.33	15	10	2	300	132.40	25	4	2	300	112.05
10	4	4	100	72.79	15	10	4	100	84.46	25	4	4	100	67.75
10	4	4	200	102.93	15	10	4	200	119.45	25	4	4	200	95.81
10	4	4	300	126.07	15	10	4	300	146.29	25	4	4	300	117.34
10	4	6	100	77.63	15	10	6	100	90.43	25	4	6	100	69.82
10	4	6	200	109.79	15	10	6	200	127.89	25	4	6	200	98.73
10	4	6	300	134.46	15	10	6	300	156.63	25	4	6	300	120.92
10	6	2	100	73.40	20	2	2	100	65.05	25	6	2	100	66.76
10	6	2	200	103.81	20	2	2	200	91.99	25	6	2	200	94.41
10	6	2	300	127.14	20	2	2	300	112.66	25	6	2	300	115.63
10	6	4	100	77.30	20	2	4	100	66.45	25	6	4	100	70.06
10	6	4	200	109.32	20	2	4	200	93.97	25	6	4	200	99.08
10	6	4	300	133.89	20	2	4	300	115.09	25	6	4	300	121.35
10	6	6	100	83.90	20	2	6	100	67.62	25	6	6	100	72.78
10	6	6	200	118.66	20	2	6	200	95.63	25	6	6	200	102.93
10	6	6	300	145.33	20	2	6	300	117.12	25	6	6	300	126.06
10	8	2	100	77.69	20	4	2	100	66.16	25	8	2	100	67.27
10	8	2	200	109.87	20	4	2	200	93.56	25	8	2	200	95.14
10	8	2	300	134.57	20	4	2	300	114.59	25	8	2	300	116.52
10	8	4	100	85.28	20	4	4	100	68.27	25	8	4	100	71.83
10	8	4	200	120.60	20	4	4	200	96.54	25	8	4	200	101.58
10	8	4	300	147.71	20	4	4	300	118.24	25	8	4	300	124.42
10	8	6	100	93.33	20	4	6	100	70.87	25	8	6	100	76.00
10	8	6	200	131.98	20	4	6	200	100.23	25	8	6	200	107.48
10	8	6	300	161.64	20	4	6	300	122.76	25	8	6	300	131.63
15	2	2	100	65.16	20	6	2	100	67.81	25	10	2	100	68.62
15	2	2	200	92.15	20	6	2	200	95.90	25	10	2	200	97.04
15	2	2	300	112.86	20	6	2	300	117.45	25	10	2	300	118.85
15	2	4	100	67.11	20	6	4	100	70.49	25	10	4	100	73.68
15	2	4	200	94.91	20	6	4	200	99.69	25	10	4	200	104.20
15	2	4	300	116.24	20	6	4	300	122.09	25	10	4	300	127.62
15	2	6	100	68.74	20	6	6	100	74.10	25	10	6	100	79.14
15	2	6	200	97.21	20	6	6	200	104.80	25	10	6	200	111.92
15	2	6	300	119.06	20	6	6	300	128.35	25	10	6	300	137.07

Note: s refers to groove spacing in mm, w refers to groove width in mm, d refers to groove depth in mm, p refers to tire pressure in kPa, U refers to hydroplaning speed in km/h

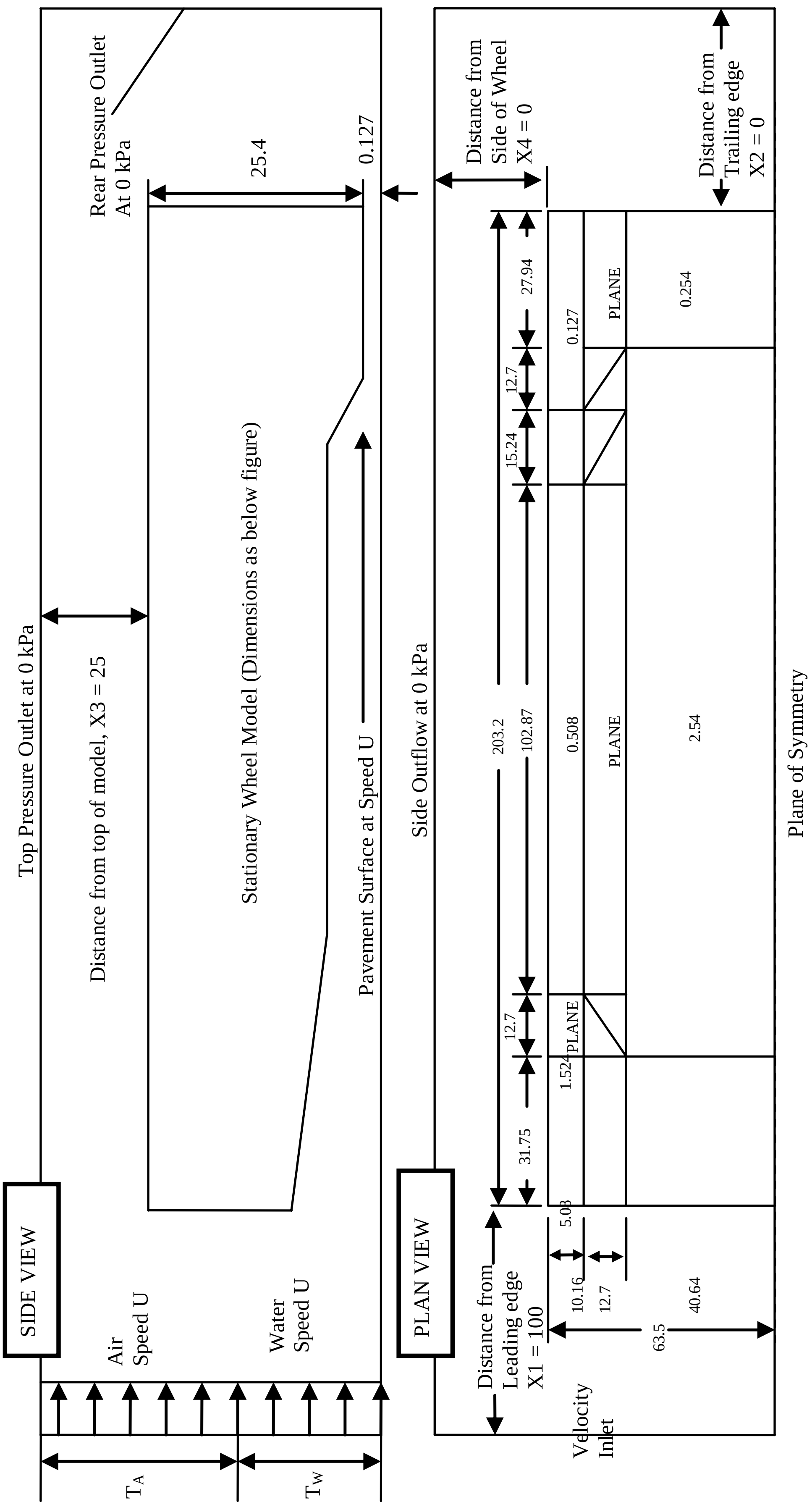
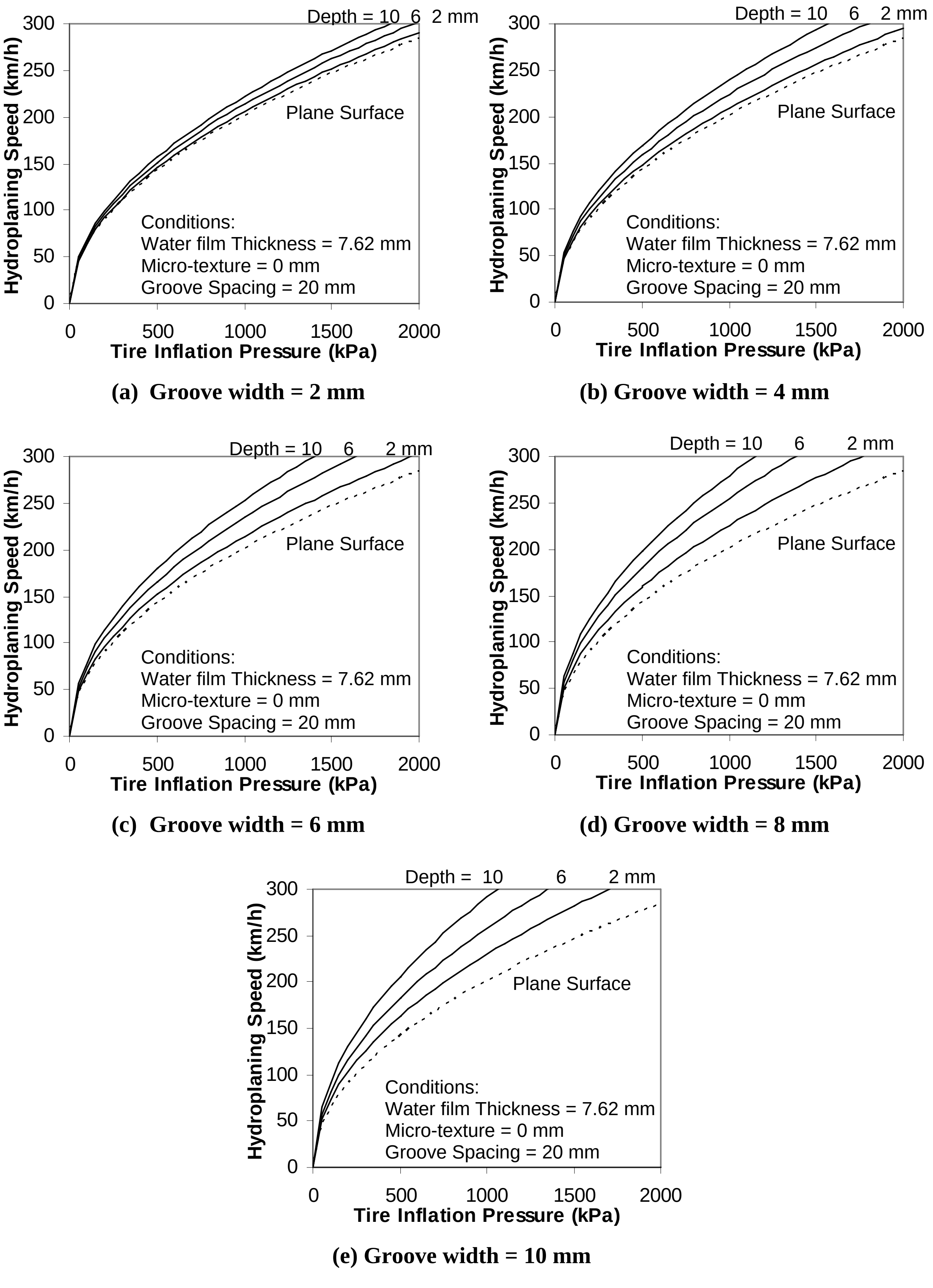


FIGURE 1 Geometry of proposed 3D hydroplaning model (Dimensions are in mm.)(1 in. = 25.4 mm)



(a) Groove width = 2 mm

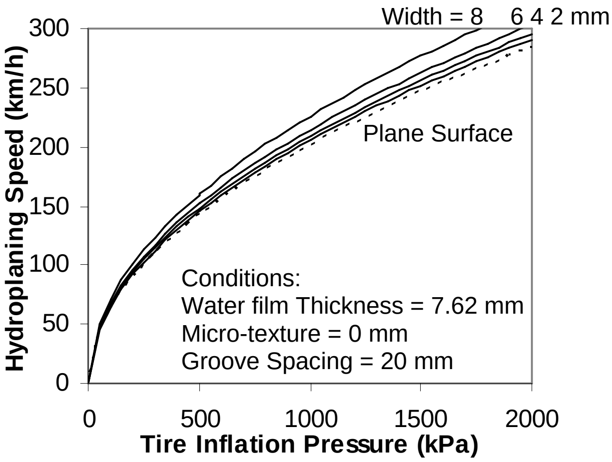
(b) Groove width = 4 mm

(c) Groove width = 6 mm

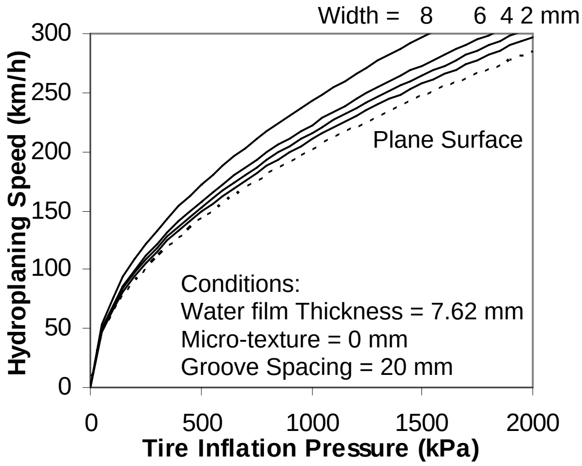
(d) Groove width = 8 mm

(e) Groove width = 10 mm

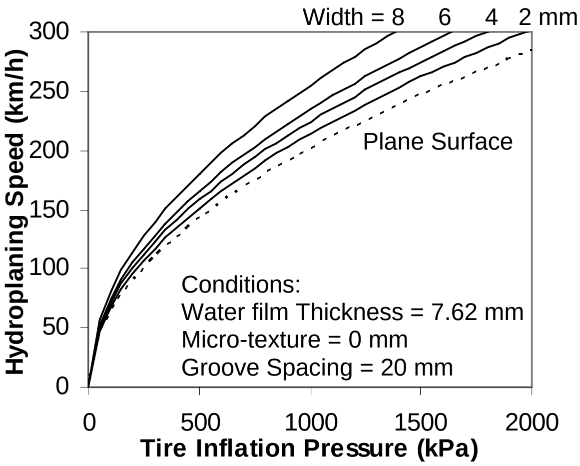
FIGURE 2 Effect of groove depth on hydroplaning as a function of tire pressure



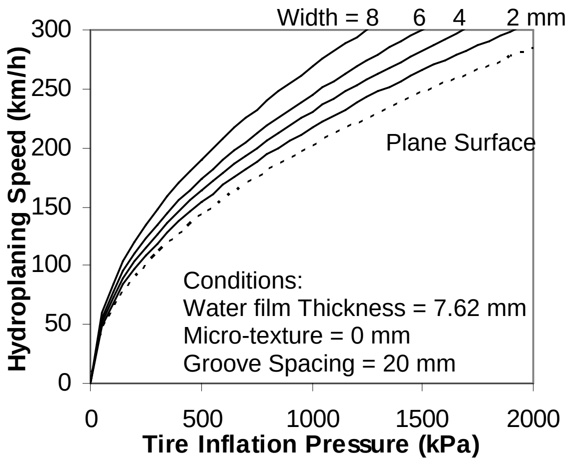
(a) Groove depth = 2 mm



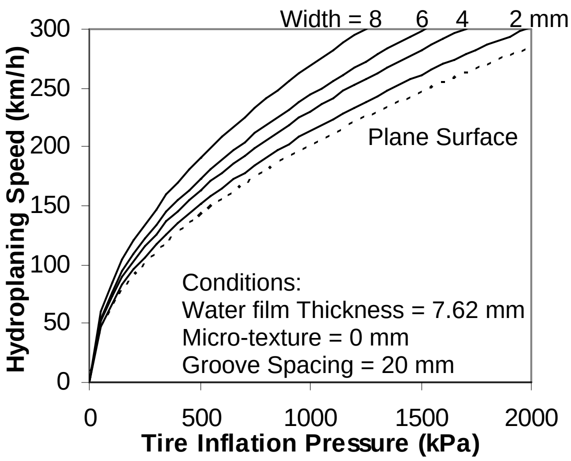
(b) Groove depth = 4 mm



(c) Groove depth = 6 mm

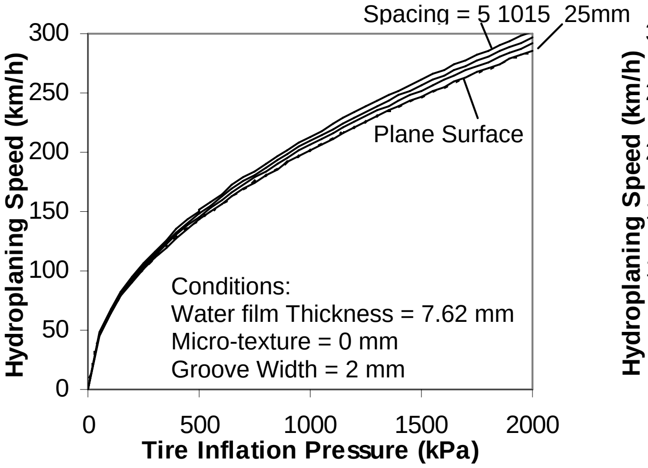


(d) Groove depth = 8 mm

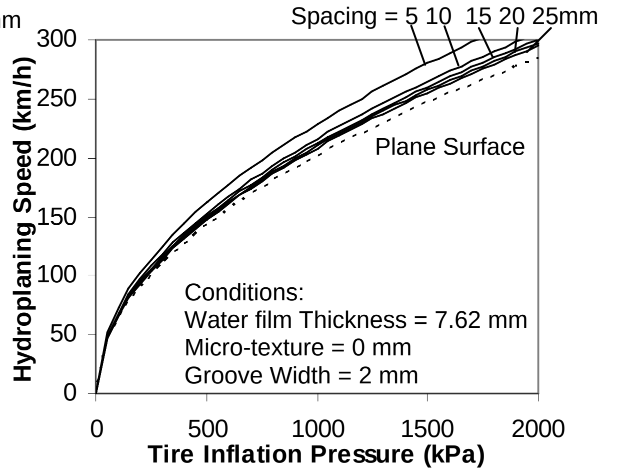


(e) Groove depth = 10 mm

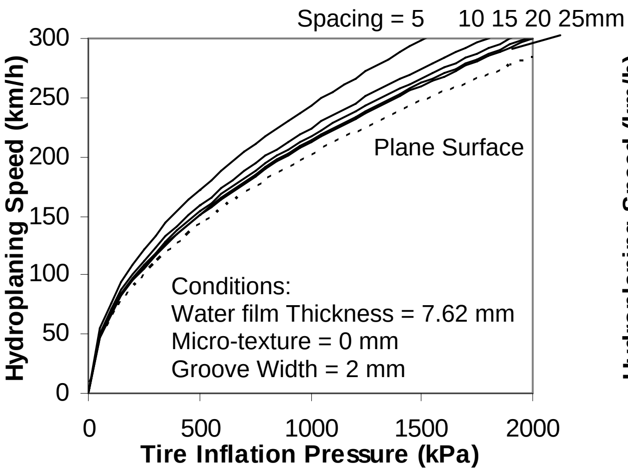
FIGURE 3 Effect of groove width on hydroplaning as a function of tire pressure



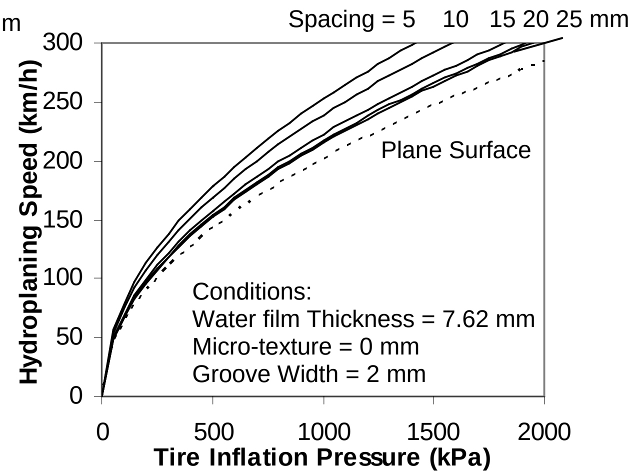
(a) Groove depth = 2 mm



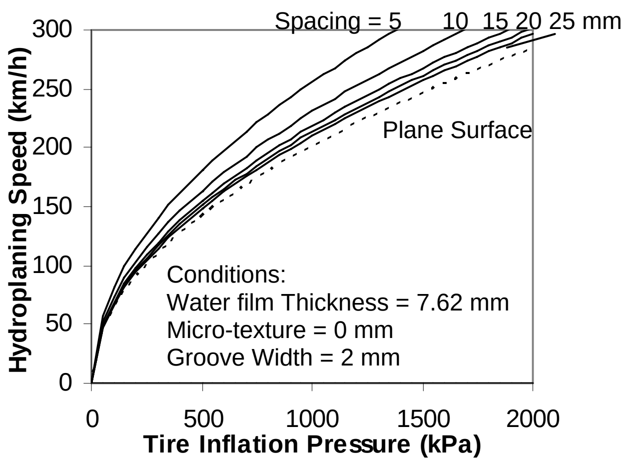
(b) Groove depth = 4 mm



(c) Groove depth = 6 mm

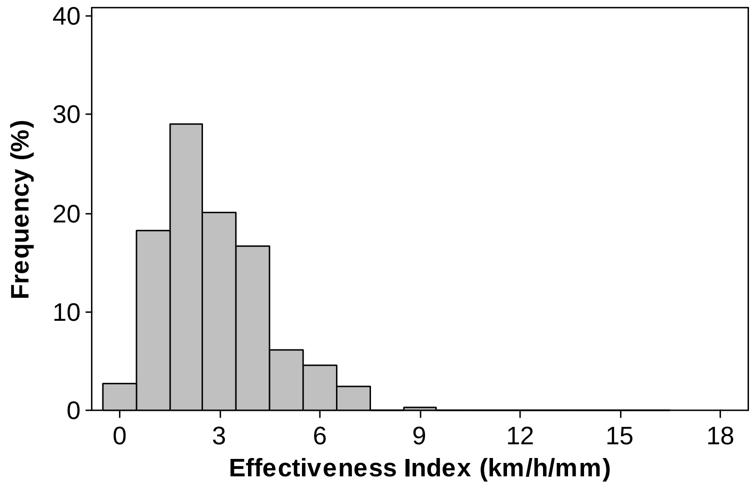


(d) Groove depth = 8 mm

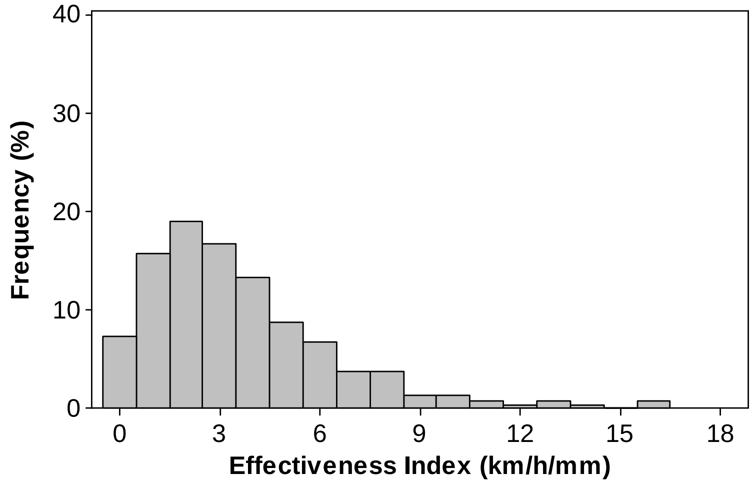


(e) Groove depth = 10 mm

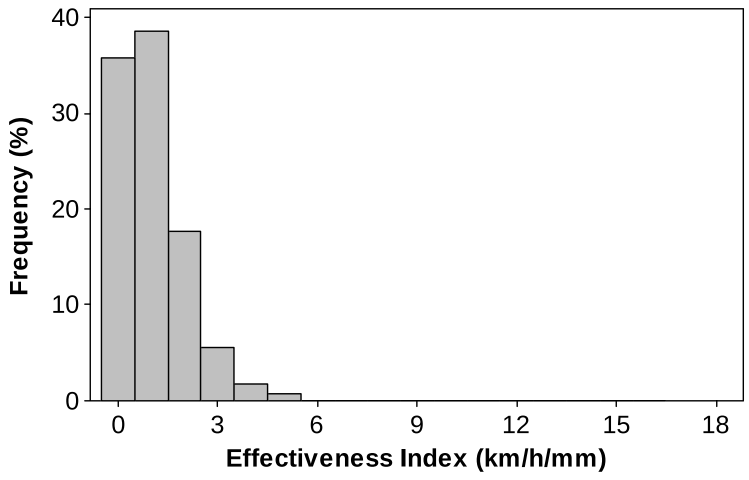
FIGURE 4 Effect of center-to-center groove spacing on hydroplaning as a function of tire pressure



(a) Groove depth



(b) Groove width



(c) Groove spacing

FIGURE 5 Frequency distribution of effectiveness indices of different groove dimensions