A STUDY OF VARIABLES ASSOCIATED WITH WHEEL SPIN-DOWN AND HYDROPLANING

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Vehicles operating on wet pavements suffer impairment of their steering and braking capabilities. Tests have shown that this condition worsens as the vehicle speed increases and that at a critical ground speed the vehicular wheel is separated from the pavement by a layer of fluid. This is said to be hydroplaning. When this occurs the steering ability of the vehicle is completely lost, and the braking capability is greatly diminished. The spin-down (reduction in wheel speed) of a wheel is an indication of a loss in the tire-ground frictional force and is regarded by researchers as a manifestation of hydroplaning. Spin-down occurs when the hydrodynamic lift effects combine to cause a moment that opposes the normal rolling action of the tire caused by the drag forces. As ground speed increases, the tire becomes detached from the pavement, which decreases the ground friction on the tire. Also as ground speed increases, the center of hydrodynamic uplift forces moves forward of the axle, which causes a moment that opposes the drag forces on the tire; as this moment increases, spin-down begins. This report uses wheel spin-down as a criterion for evaluating the wet-weather properties of a portland cement concrete pavement and a bituminous surface and considers the effects of water depth, tire inflation pressure, tire tread depth, and wheel load. The study was performed by conducting full-scale tests on a hydroplaning trough 800 ft long, 30 in. wide, and 4 in. deep. Water depths up to 0.8 in. can be maintained in the trough.

TIRE HYDROPLANING or aquaplaning comes about from fluid pressures that are developed at the tire-pavement interface. When these pressures become large and the total hydrodynamic force developed on the tire from these pressures equals the total load the tire is carrying, hydroplaning occurs. At this instant, theoretically the tire loses contact with the pavement and skims over the surface in the same manner that a water skier glides along a water surface. The hydroplaning condition, as manifested by wheel spin-down (reduction in speed of wheel), occurs at a particular vehicular speed that is a function of the pavement surface, fluid properties, and various physical and geometrical wheel parameters.

The hydroplaning phenomenon undoubtedly causes a loss in the directional stability of a vehicle and can be considerably aggravated if the vehicle is traveling on a curve or is exposed to high cross winds. Further, as is reported in the literature, the application of brakes to the hydroplaning vehicle does not improve conditions because the braking-friction coefficients approximate free-rolling coefficients at ground speeds approaching the critical hydroplaning speed. Tests have shown that once spin-down begins, the required decrease in ground speed that caused hydroplaning can be sizable before "spin-up" occurs.

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Concern about the hydroplaning problem has been limited essentially to the air transportation industry because of the high take-off and touch-down speeds associated with modern aircraft. Consequently, a large majority of the research done on the hydroplaning problem has been by people associated with agencies like the Langley Research Center of the National Aeronautics and Space Administration (NASA). These people have made significant theoretical and experimental contributions (1, 2, 3). Due to their primary objectives, most of the research concerned airplane tires, which differ in construction and inflation pressures from ground vehicle tires. The tests were usually aimed at investigating the overall problem and analyzing the effects caused by displacing the water on the pavement. A vast amount of research concerning the variables associated with hydroplaning and particularly friction characteristics and effects of pavement texture and material has been conducted by British researchers (4, 5, 6). A review of the works more nearly associated with the research investigation reported in this paper is presented in the original report.

SELECTION OF PARAMETERS

Pavements

Two pavements were selected for the study. The first pavement was a burlap drag-finished concrete pavement with an average texture of 0.018 in. as measured by the silicone putty method. This type of pavement was considered typical of existing concrete pavements of low macrotexture. The second pavement was a bituminous surface treatment with rounded river gravel and stone between -⅝ in. and +No. 4 used as cover stone. An average texture of 0.146 in. as measured by the silicone putty method was obtained. This pavement was selected because it represents as coarse a pavement as the driving public tolerates, the criterion being noise level.

Water Depths

Various water depths were considered, and values were selected so that the influence of this variable could be adequately evaluated. Consequently the depth selected for the concrete pavement varied from 0.12 to 0.70 in., whereas the depth selected for the bituminous surface treatment varied from 0.25 to 0.70 in. Lower water depths were considered for this pavement, but the vehicular ground speed that would produce spin-down was not achievable.

Tire Inflation Pressures

Tire inflation pressures varying from 18 to 36 psi in 6-psi increments were selected for both pavements. It was felt that these values not only were representative of pressures found in the tires of most ground vehicles but also would provide a good basis for studying the effect of this parameter. Higher pressures were not selected because the test tow vehicle was unable to attain a high enough ground speed to produce sufficient data for these regions.

Wheel Load

Wheel loads of 800 and 1,085 lb were selected in the evaluation on the concrete pavement. The latter load was used because of its specification as the ASTM skid trailer standard and the former because it represented a realistic wheel load and provided a wide enough variation to detect the effects of this parameter. Only the 1,085-lb load was used in the evaluation of the bituminous surface treatment inasmuch as no appreciable variation in the results was observed in the evaluation of the concrete pavement when the 800-lb load was used.

Tires

Eight tires were selected for the study and are given in Table 1. It was felt that a wide range of tires would provide an adequate evaluation of the effects of tire geometry, stiffness, and tread depth.

EXPERIMENTATION

The tests were conducted on a sloped trough shown in Figures 1 and 2 (7). The trough is 800 ft long, 30 in. wide, and 4 in. deep. No difficulty in obtaining water depths of up to 0.7 in. above the pavement asperities was encountered with the two pavements. To be able to better interpret the data, we took water depth readings (Fig. 2) at various trough locations. The variation in the readings was more pronounced for the bituminous surface treatment. Ideal conditions involving no wind were difficult to achieve, so the data collected contain the influence of winds varying from 5 to 15 mph. This did not seem to affect the data because adequate water recovery times to reach equilibrium conditions between tests were allowed.

The tow truck and instrumented test trailer are shown in Figure 3, and a photograph of a typical test is shown in Figure 4. From these photographs it can be seen that the trailer is positioned so that, as the tow vehicle proceeds down the trough, straddling it, the test trailer has one of its wheels in the trough. The ground speed from the fifth wheel and the speed of the test wheel of the trailer are sensed by identical tachometer generators. The output from the generators is fed into a Hewlett-Packard 320 recorder that contains its own amplifier circuits. The two wheel speeds are simultaneously recorded as analog traces on a strip chart. The fifth-wheel speed is also displayed to the driver on a digital voltmeter.

DISCUSSION OF RESULTS

The critical or "total" hydroplaning speed is the speed at which the hydrodynamic pressure force is in equilibrium with the load carried by the tire. However, this speed is not necessarily the speed at which wheel spin-down is initiated, and, according to Horne and Dreher (2), wheel spin-down can commence at ground speeds considerably lower than the critical hydroplaning speed. In fact, according to them the front wheel spin-down for tandem wheels occurred at 70 percent of the predicted hydroplaning speed. These researchers reached the same conclusions in another report (1) and stated that total spin-down for their data, which included aircraft tires, takes place between 80 and 120 percent of the predicted hydroplaning speed. This report also points out that further increases in ground speed resulted in less tire-fluid exposure time in the trough due to the increased ground speed and a more uniform hydrodynamic pressure in the tire-ground contact region when hydroplaning prevails. This latter effect causes a reduction in the wheel spin-down torque. Thus, spin-down should be regarded as a manifestation of hydroplaning and not as the only criterion to determine the critical hydroplaning speed. To determine this speed more precisely requires that the effects of the braking force, yaw or side force, and fluid drag force be investigated.

For the experimentation conducted on the Texas Transportation Institute's hydroplaning trough, wheel spin-down was the only criterion used to indicate hydroplaning. For this reason, we decided to evaluate the two pavements discussed previously and to discuss the effects of the various hydroplaning parameters on the basis of several spin-down percentages.

Figure 5 shows a comparison of the results obtained at 10, 32, and 60 percent spin-down and the equation presented by Horne and Dreher (2). Even though the data for a treaded tire were selected, the water depth was greater than the tire tread depth, thus making the results fall within the stated limitations of the Horne equation. The curves show that the values of 32 and 60 percent spin-down bound Horne's values and that the 10 percent values are within 70 percent of the values predicted by the equation. It can also be seen that the curves of experimental results have approximately the same slope as Horne's values. This makes the results quite encouraging.

Figure 6 shows the results obtained for a smooth tire and for Horne's equation. For these data, the agreement was not so good as it had been for the previous case. Here, even at 100 percent spin-down, the hydroplaning speed predicted by Horne's equation cannot be reached. Also, even though the slopes of three experimental curves are nearly the same, they tend to differ from that of the equation. However, it should be emphasized that spin-down is only a manifestation of hydroplaning and that even for 10

Table 1. Tires selected for study.

Tire No.	Manu-facturer	Size	Type
1	A	7.75 by 14	Bias ply, full tread depth
2	A	7.75 by 14	Bias ply, ½ tread depth
3	A	7.75 by 14	Bias ply, smooth
4	B	F70-14	Wide tire, full tread depth
5	C	7.75 by 14	Bias ply, full tread depth
6	ASTM[a]	7.50 by 14	Full tread depth
7	D	7.75 by 14	Bias ply, full tread depth
8	D	7.75 by 14	Bias ply, smooth

[a] ASTM E-17 traction standard.

Figure 1. Hydroplaning trough.

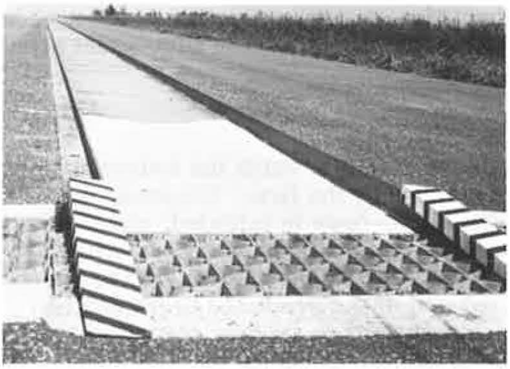


Figure 2. Typical water depth reading taken before test on hydroplaning trough.

Figure 3. Tow truck and instrumented test trailer.

Figure 4. Typical test run on hydroplaning trough.

Figure 5. Comparison of experimental results and Horne and Dreher's equation for full-tread depth tire.

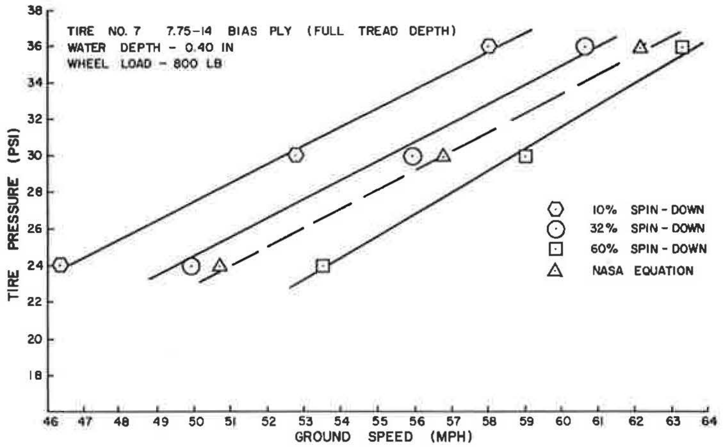
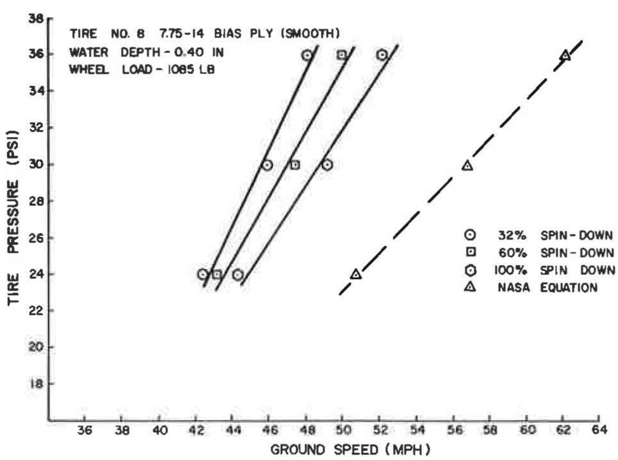


Figure 6. Comparison of experimental results and Horne and Dreher's equation for smooth tire.



percent spin-down the ground speed is at least 70 percent of the predicted hydroplaning speed. Results obtained for other tires tend to follow similar patterns.

Figures 7, 8, and 9 show plots of vehicle ground speed versus percentage of spin-down for tire No. 4 when various inflation pressures, water depths, and pavements are considered. Figure 7 shows some of the effects of increasing the tire inflation pressure. For example, a pressure increase of 6 psi requires an increase of approximately 4 mph to cause a 20 percent spin-down; however, this is not true for the 18-psi pressure at which no spin-down was obtained for vehicle speeds up to 64 mph. This may be attributed to the fact that a decrease in the inflation pressure does not necessarily worsen a tire's hydroplaning behavior because the effect of the decreased contact pressure due to a larger contact area may be offset by a longer contact length. However, it should not be concluded that a hazardous condition does not prevail. It is possible for the tire frictional force to be reduced significantly without having the spin-down torque overcome the spin-up torque. Consequently, no spin-down will occur. For these cases, it might be desirable to perform skid tests and measure the friction coefficient for several tire inflation pressures. This would give the variation of the friction coefficient with tire inflation pressure and could indicate that a hydroplaning condition can be approached without any wheel spin-down.

Figures 10 and 11 show the effect of varying the wheel load from 800 to 1,085 lb. The results for the smooth tire are plotted in Figure 10 and indicate that an increase in the wheel load increases the ground speed that is required to produce a 10 percent spin-down of the wheel. However, Figure 11 indicates that, for a tire with full tread depth, the reverse takes place. This type of behavior is possible inasmuch as spin-down is closely associated with tire characteristics.

Figure 12 shows a comparison of tires No. 4 (wide tire) and No. 7 (bias ply). The results indicate that, to produce the same spin-down, the bias ply tire required greater ground speeds than did the wide tire. This tends to agree with studies performed by other researchers, which indicate that the hydroplaning speed decreases with a decrease in the tire aspect ratio (height/width).

Figure 13 shows the effects of tire tread depth on spin-down. The data, taken for smooth and full-tread depth bias ply tires (tires No. 7 and No. 8), show that a new tire requires a significantly larger ground speed to produce the same spin-down as a smooth tire. For example, in order to produce 10 percent spin-down for a water depth of 0.4 in. and a tire inflation pressure of 36 psi, the tire with the full tread depth required a ground speed of 57 mph, whereas the smooth tire only required a speed of 46.5 mph.

Figures 14 and 15 show the effects of the two pavements tested. Figure 14 shows the results obtained for a bias ply (tire No. 1), full-tread depth tire and shows that spin-down was obtained without difficulty on the concrete pavement and that realistic trends were demonstrated when the tire inflation pressure and water depth were varied. For the bituminous surface treatment, spin-down was only obtained at a water depth of 0.7 in. If spin-down is to be taken as an indication of hydroplaning, it can be concluded that a hazardous condition will not normally occur when typical water depths found on most well-drained roads are encountered. A water depth of 0.7 in. can be regarded as being high.

Figures 10 through 15 contain plots of water depth versus ground speed for various parameters. These curves show that the ground speed required to produce 10 percent spin-down always increases with a decrease in the water depth. This fact indicates that there is a low enough water depth for which wheel spin-down and probably hydroplaning do not occur.

From the electronic instrumentation data it was observed that wheel spin-down began almost immediately after the test trailer entered the hydroplaning trough. The trailer travel distance in the trough before the maximum spin-down was obtained for a particular test varied mainly with the trailer speed upon entering the trough. For example, when tire No. 4 with an inflation pressure of 24 psi was tested on the bituminous pavement with a water depth of 0.7 in., it took approximately 80 ft to reach a total spin-down of 20 percent when the vehicle speed upon entering the trough was 48 mph. How-

Figure 7. Effect of vehicle ground speed on wheel spin-down with water depth of 0.25 in.

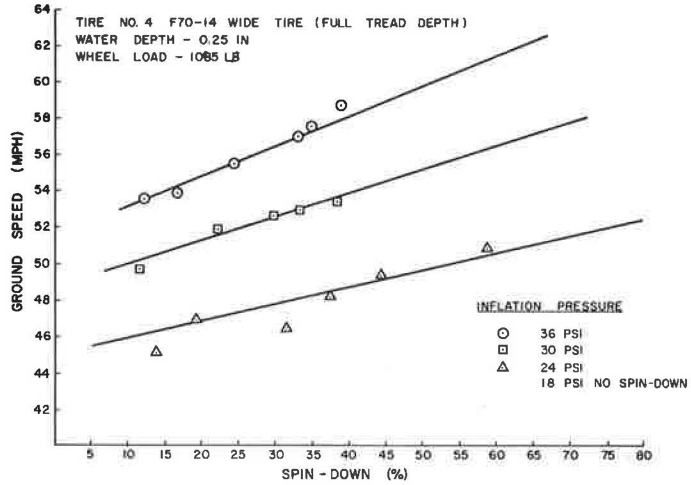


Figure 8. Effect of vehicle ground speed on wheel spin-down for concrete pavement with water depth of 0.40 in.

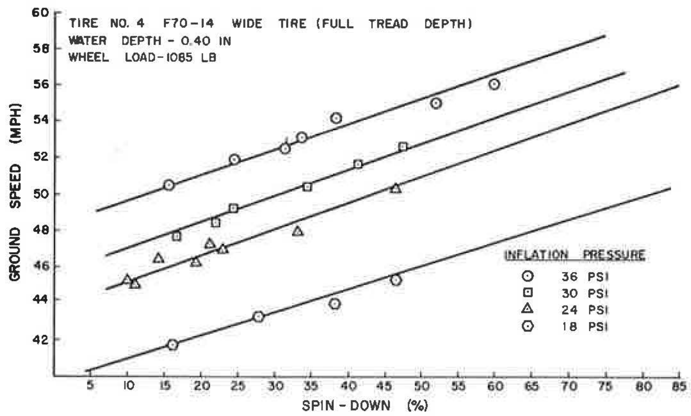


Figure 9. Effect of vehicle ground speed on wheel spin-down for bituminous surface treatment.

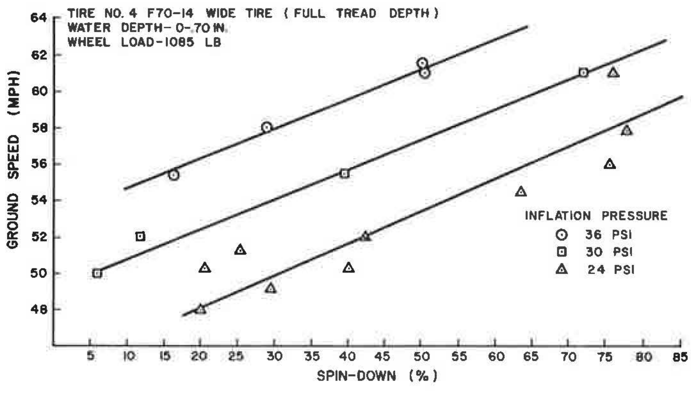


Figure 10. Effect of water depth and wheel load on ground speed required to produce 10 percent spin-down (tire No. 8).

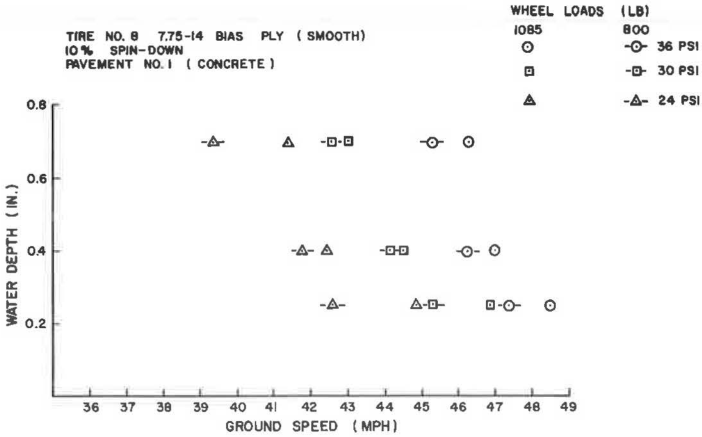


Figure 11. Effect of water depth and wheel load on ground speed required to produce 10 percent spin-down (tire No. 7).

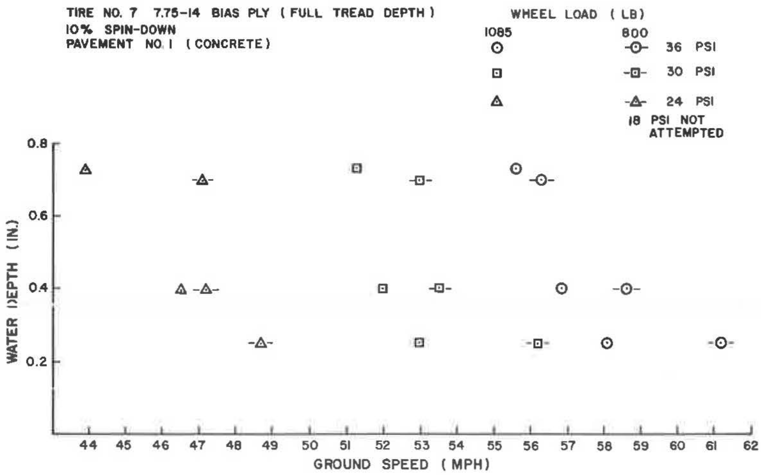


Figure 12. Effect of water depth and tire aspect ratio on speed required to produce 10 percent spin-down.

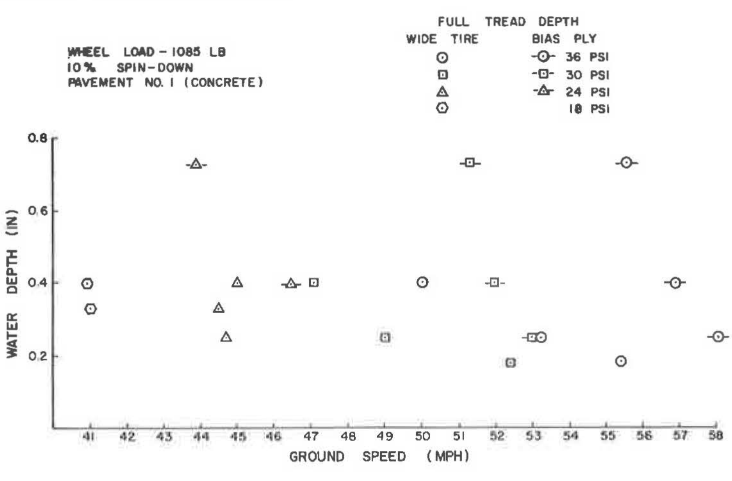


Figure 13. Effect of water depth and tread depth on speed required to produce 10 percent spin-down.

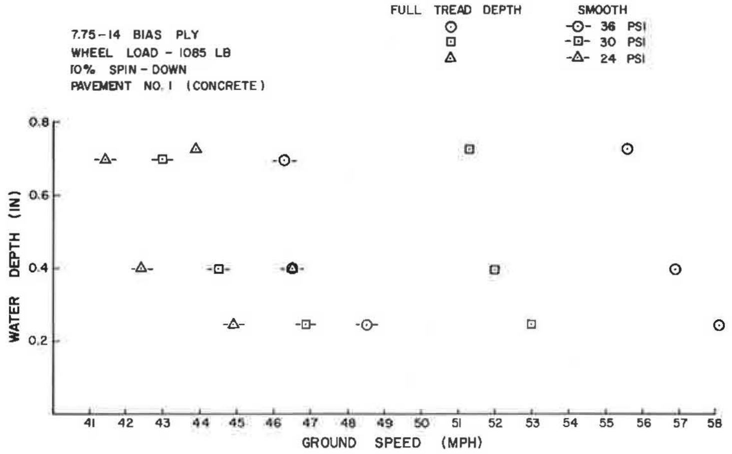


Figure 14. Comparison of concrete and bituminous surface treatment (tire No. 1).

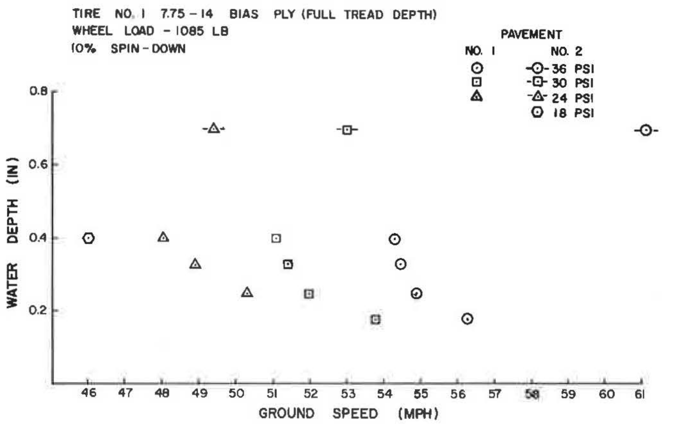
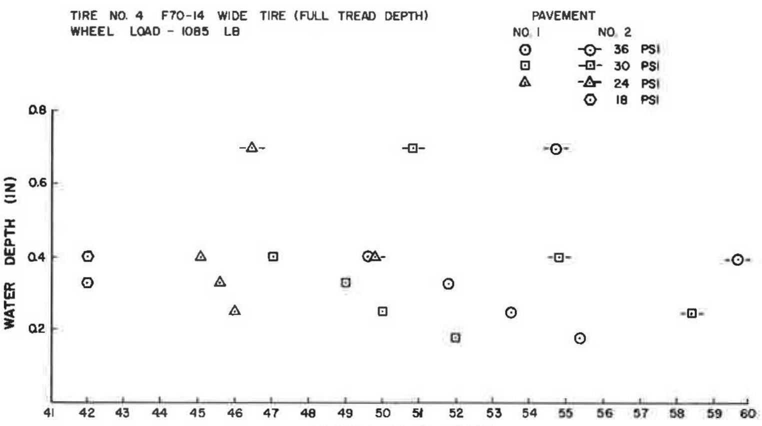


Figure 15. Comparison of concrete and bituminous surface treatment (tire No. 4).



ever, when the entry speed was increased to 58 mph, it took 240 ft of travel before the final spin-down of 78 percent was attained; after 80 ft the tachometer generator traces indicated a wheel spin-down of approximately 20 percent.

Thus, it can be concluded that loss of traction occurs as soon as the wheel of a vehicle comes in contact with a flooded pavement. If the flooded portion of pavement is not long and the vehicle is not subjected to abnormal maneuvers, the tractive force can probably be regained without a hazardous condition existing. For a given vehicular ground speed that is high enough to cause wheel spin-down, the possibility of a hazardous condition existing increases with increasing length of flooded pavement.

APPLICABILITY TO SAFE WET-WEATHER SPEEDS

In recent legislative action, the state of Texas has given authority to the highway commission to set wet-weather speed limits at specific places on Texas highways. Although by no means encompassing all the factors that should be considered in determining safe speeds, the current data on hydroplaning give indications of the speeds that result in a potentially marginal condition with regard to vehicle control. Hydroplaning is only one of the many factors that must be considered in determining safe speeds. It is limited to the case in which a significant depth of water is encountered on the roadway due to an exceptionally high-intensity rain or to poor drainage, puddles, wheel ruts, low cross slope, and the like.

In the discussion presented in this section, it is assumed that a 10 percent spin-down of a free-rolling automobile wheel signifies the approach of a control problem, due to either a loss of stopping capability or a loss in directional control. In this section the 10 percent spin-down speed will be called the "critical speed."

Figures 16, 17, and 18 show approximate curves representing the data developed at this time. The effects of pavement texture, tire pressure, and tire type or condition are shown by these curves. Several tires are used to illustrate the various effects.

Tires 7 and 8 represent full tread depth and smooth bias ply respectively. Tire No. 4 is a full tread depth with a wide tire configuration. The wheel load in all cases is 1,085 lb.

The influence of pavement texture on partial hydroplaning speed (as indicated by 10 percent spin-down) is significant. An increase in critical speed from 47 to 60 mph is indicated at a water depth of $\frac{1}{4}$ in. when the macrotexture is increased from 0.018 to 0.145 in. This difference apparently decreases slightly as water depth increases. These macrotextures are average values determined by the silicone putty method.

The effect of tire pressure is shown in Figure 17. The tire pressures of 24 to 36 psi shown in this figure account for approximately 70 percent of the range of tire pressures observed in a study of 501 wet-pavement accidents in Texas (8).

Figure 17 shows that, at a water depth of 0.1 in., the critical speed increases by approximately 10 mph (from 48 to 58 mph) as tire pressure increases from 24 to 36 psi. This difference becomes much smaller at greater water depths.

The effect of three different tires on critical speed is shown in Figure 18. Unlike the effects of texture and pressure, the differences between these tires increase as the water layer becomes thicker. At a water depth of $\frac{1}{2}$ in. the critical speed varies from 43 to 51 mph. It is notable that the full-tread depth, wide tire falls between the bias ply, smooth and bias ply, full-tread depth as related to critical speed.

Figure 19 shows the consolidation of individual wheel tire pressure graphs (8). Although it is obvious from the curves presented that there is no one critical speed that is appropriate for the range of pavement, pressure, and tire parameters investigated, it is obvious that partial hydroplaning, and thus some loss of control, results at speeds significantly below the usual speed limit on major rural highways in Texas. No critical speeds below 40 mph were found, and a speed of 50 mph seems to be the roughly approximated median value for all parameters investigated.

It is therefore suggested that a reduction of speed to 50 mph be considered on any section of highway where water can accumulate to depths of 0.1 in. or more during wet periods. Further improvements in the safety of these sections can be made if a high-macrotexture surface can be produced and maintained.

Figure 16. Effect of texture on hydroplaning.

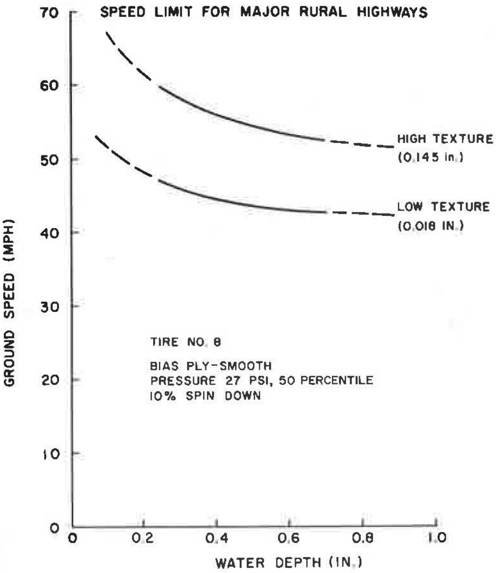


Figure 17. Effect of tire inflation pressure on hydroplaning.

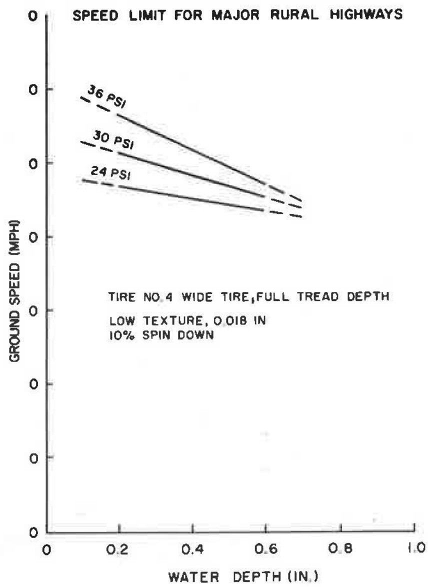


Figure 18. Effect of tire type on hydroplaning.

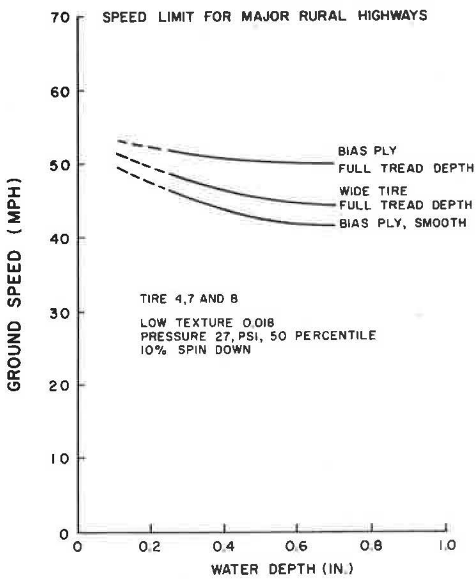
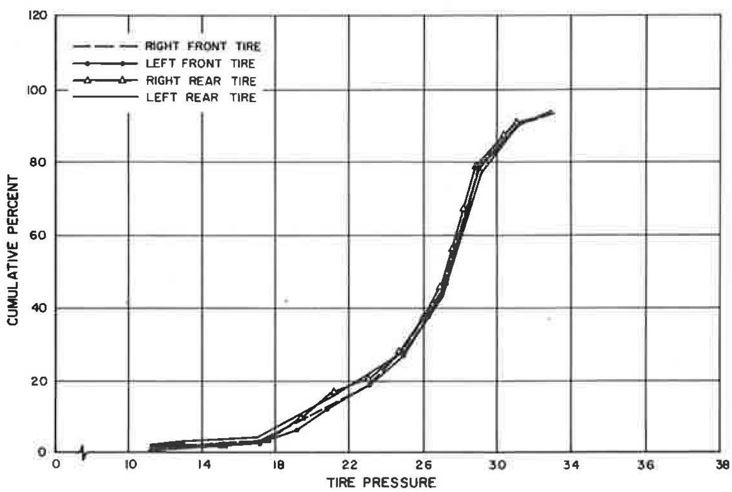


Figure 19. Comparison of tire pressures—accident sample.



CONCLUSIONS

The following general conclusions are based on the data obtained from the tests and the criterion that 10 percent spin-down causes a sufficient reduction in the frictional coefficient such that vehicle stability is affected.

1. Wheel spin-down is normally initiated at a ground speed that falls within 70 percent of the critical hydroplaning speed predicted by Horne and Dreher's equation.
2. The ground speed required to initiate spin-down on full-tread depth tires is higher than the speed required with smooth tires.
3. Decreasing the tire inflation pressure normally has the effect of lowering the ground speed at which a certain amount of spin-down occurs.
4. Decreasing the tire aspect ratio (height/width) causes a decrease in the ground speed required to initiate spin-down.
5. Increasing the wheel load while maintaining the same inflation pressure for a smooth tire increases the gound speed at which spin-down is initiated. The reverse takes place for a full-tread depth tire.
6. An increase in the water depth decreases the speed at which wheel spin-down is initiated.
7. The bituminous surface treatment requires a higher ground speed to cause spin-down than the concrete pavement.
8. Total spin-down (wheel stops rotating) may occur at ground speeds lower than those predicted by Horne's equation.
9. Even though a tire may not have reached the total hydroplaning speed as predicted by Horne's equation, a hazardous condition may exist when the wheel has spun down and its frictional characteristics have been impaired.
10. Many factors must be considered in determining safe wet-weather speeds. From a hydroplaning standpoint, it is suggested that a reduction of speed to 50 mph be considered on any section of highway where water can accumulate to depths of 0.1 in.

ACKNOWLEDGMENTS

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