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

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Research Report Number 147-1
Variables Associated with Hydroplaning
Research Study Number 2-8-70-147

Sponsored by

The Texas Highway Department
In Cooperation With the
U. S. Department of Transportation
Federal Highway Administration

March 1972

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University
College Station, Texas

TABLE OF CONTENTS

ABSTRACT

An evaluation of the wet weather properties of a portland cement concrete pavement and a bituminous surface treatment is presented. The study uses wheel spin-down as the criterion and considers the effect of water depth, tire inflation pressure, tire tread depth and wheel load. A hydroplaning trough 800 ft. long, 30 in. wide and 4 in. deep was used in obtaining the data. The results indicate that the bituminous surface treatment requires a considerably higher ground speed to cause spin-down than the concrete pavement. Further, even though a single critical speed does not exist for the range of variables selected, a reduction of speed to 50 mph is recommended for any section of highway where water can accumulate to depths of 0.1 inch or more during wet weather periods.

KEY WORDS: highways; hydroplaning; pavements; spin-down.

SUMMARY

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 at a critical ground speed the vehicular wheel is separated from the pavement by a layer of fluid and 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 which opposes the normal rolling action of the tire caused by the drag forces. As ground speed increases, the tire footprint 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 opposing 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 treatment 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.

The most significant findings based on the criterion that spin-down greater than 10% causes a sufficient reduction in the frictional

coefficient so that vehicle stability is affected may be stated as follows:

1. A high macrotexture (bituminous surface treatment with rounded river gravel) pavement requires a considerably higher ground speed to cause spin-down than a low macrotexture (concrete, burlap drag) pavement.
2. Decreasing the tire inflation pressure normally has the effect of lowering the ground speed at which a certain amount of spin-down occurs.
3. Decreasing the tire aspect ratio (height/width) causes a decrease in the ground speed required to produce spin-down.
4. An increase in the water depth causes a decrease in the speed at which spin-down takes place.

* * *

N.B.: It should be emphasized that the conclusions are based upon only one of the manifestations of hydroplaning, viz., wheel spin-down. In order to determine a "total" hydroplaning condition more precisely, some of the other indications of hydroplaning such as loss in braking traction and directional stability should be considered.

IMPLEMENTATION

The speed at which an automobile tire hydroplanes, as defined by the spin-down criterion, is higher when the macrotexture of the pavement is greater. The use of pavements with larger macrotexture will help to reduce the tendency to hydroplane.

In determining safe wet weather speed limits, many factors are involved. Information from this study will be helpful as to what influence texture and water depth have relative to speeds at which hydroplaning should or should not occur.

ACKNOWLEDGEMENTS

These tests and evaluations were conducted on Study No. 2-8-70-147 (HPR-1 (10)) sponsored by the Texas Highway Department in cooperation with the U. S. Department of Transportation, Federal Highway Administration. The opinions, findings and conclusions expressed in this report are those of the authors and not necessarily those of the sponsor.

INTRODUCTION

Tire hydroplaning or aquaplaning comes about from fluid pressures that are developed at the interface of the tire and pavement. 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, the tire theoretically 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 which 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 shown in the literature, the application of brakes to the hydroplaning vehicle does not improve conditions since 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 the ground speed that caused hydroplaning can be sizeable before spin-up occurs.

The hydroplaning problem has normally been of more concern to the air transportation industry due to the higher take-off and touch-down speeds that are associated with the ever-increasing weight and speed of modern aircraft. Consequently, a large majority of the literature and

the research done on the hydroplaning problem has been by personnel 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. 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.

REVIEW OF THE LITERATURE

Theoretical and experimental studies have been made by a number of researchers. The works more nearly associated with the research investigation presented in this report and reviewed during the course of the study are listed in references 1-52.

Saal (41) initially studied the problem in 1935 and developed a model based on two planes approaching each other in a fluid. He assumed the tire contact area to be elliptical and used Reynold's equation to obtain his results. Moore (39) used squeeze film theory to analyze the problem and concluded that the molecular mechanism of viscosity that would be encountered between tire and wet pavement requires further study. Also, he feels the Reynolds-Stefan equation is inadequate to describe this phenomenon.

Horne and Dreher (26) derived an equation to predict the critical speed at which total hydroplaning begins. This equation assumes the load on the tire to be in equilibrium with the dynamic pressure in

front of the tire and neglects the effects of fluid depth. For an experimentally determined lift coefficient of 0.7, Horne develops the equation

$$V_{cr} = 10.35 \sqrt{p} \qquad (1)$$

where

V_{cr} = total hydroplaning speed in statute mph, and

p = tire inflation pressure in psi.

This equation is limited to smooth tires or commercially treaded tires whose tread depth is less than the water film thickness. Reference 26 indicates that the results predicted by Eq. 1 are in reasonable agreement with experimental data obtained for a variety of tires subjected to different loads and inflation pressures.

Gengenbach (19) developed an empirical equation which includes the thickness of the water film and his correlation with test results showed that the total hydroplaning speed was significantly affected by the water film thickness. This contradicted the equation developed by Horne (26). Gengenbach's equation, like Horne's (26) assumed that the wheel load and dynamic pressure were in equilibrium but used the cross section of the water film under the tire contact patch perpendicular to the surface velocity as the area for the force calculation. The area was multiplied by a lift coefficient and the equation to predict the total hydroplaning speed was derived as

$$V = 508 \sqrt{\frac{Q}{B\ t\ C_L}}$$

where

V = total hydroplaning speed in km/hour,

Q = wheel load in KP(1KP= 2.2 lb),

B = maximum width of contact patch in mm,

t = thickness of water film in mm, and

C_L = lift coefficient determined empirically for a particular tire.

Gengenbach concludes that grooving of the tires considerably reduces the lift coefficient and thus increases the critical hydroplaning speed. In his work, tire designs with mainly circumferential grooves achieved C_L reductions of nearly 50% whereas designs with grooves primarily oriented in the lateral direction achieved reductions down to 25% of the smooth tires.

Martin (34) explains the tire hydroplaning phenomenon from the standpoint of theoretical hydrodynamics and then compares theoretical and experimental results. From the study it is concluded that for moderate water depths and grooved tires, the lift coefficient for incipient hydroplaning does not vary appreciably. Also, an inviscid fluid may be assumed except for the case of smooth tires and/or thin films of water.

Dugoff and Ehrlich (13) studied the hydroplaning problem through scale model laboratory experiments and employed dimensional analysis principles to interpret their results. The tests were conducted for smooth tires of rectangular cross-section at various loads and water

depths. The authors interpret Eq. 1 presented in ref. 26 in terms of dimensional analysis principles and indicate that neither fluid gravity forces nor viscosity forces had an appreciable influence on the full-scale tests that were used in the comparison of Eq. 1 and presented in ref. 26. Further, the authors of ref. (13) recommend that the effects of configurational and tread changes to tires, and the partial hydroplaning problem be studied.

Wray and Jurkat (48) derived an empirical equation relating critical hydroplaning speed, water film thickness and nominal contact patch bearing pressure for 8" diameter polyurethane model tires having four different widths and a smooth surface. Upon comparing the results obtained using their formula with Eq. 1, they noted that Horne's equation was bracketed by lines of constant water film thickness having nearly the same slope. This implies that by selecting a certain water depth, Horne's NASA equation can be duplicated with experimental data from the model wheel.

A vast amount of research concerning friction characteristics and effects of the pavement texture and material has been conducted by British researchers (1,2,4,17,18,22,23,35). Allbert (1) discusses the effects of the tire design parameters on hydroplaning and concludes that the most important is the geometric design of the tread pattern. Allbert, Walker and Maycock (2) after investigating various tires and pavement surfaces, conclude that the coefficient of friction for a slipping tire is significantly decreased with an increase in speed on fine-textured surfaces, and to a lesser extent on coarse-textured surfaces.

Further, the tread pattern did not play as significant a role on the coarse-textured surfaces. This implies that tread wear would have a minor effect on a surface of this type. Gough and Badger (22) discuss the effect of tread design on various surfaces and hydroplaning of heavy vehicles fitted with smooth tires and traveling on flooded road surfaces. Their findings on pavement surfaces are similar to those presented in ref. 2. Martin (35) discusses treatments to existing concrete and asphalt surfaces in order to improve their skidding resistance. The materials and methods which may be used in future construction are also described and illustrated.

A large amount of research concerning the variables associated with hydroplaning and particularly pavement texture has also been conducted by American investigators (5,11,14,27,29,32,33,42,49,50). Beaton, Zube and Skog (5) conducted studies on the effect of pavement grooving to reduce wet weather accidents. Their results indicate that pavement grooving parallel to the centerline enhances the wet weather behavior of concrete pavements and the friction value is raised. DeVinney (11) investigated the effects of the tread design and compound, tire construction, and road surface on the hydroplaning problem. He concluded that the vehicle operating speed is the most significant single factor affecting wet skid resistance. Also, a coarse textured surface has the greatest effect on decreasing the significance of speed; tread design, tread compound, tire construction, surface and temperature all play a role with the effects on skid resistance. Horne (27) from his investigation of tires and pavements concluded that tires having smooth or badly

worn treads, and pavements that are worn from heavy traffic or possess too little surface texture are hazardous. Yager (49) discusses the types of tire traction losses on wet roads and the effects of pavement surface contaminants, surface texture, tire tread design and ground speed on pneumatic tire braking and steering capability. From his study, the author concludes that pavement grooving, both transversely and longitudinally, is an effective means for reducing all known phenomena associated with low tire-surface friction. In addition, badly worn tires indicated a significant reduction in the vehicular braking and steering characteristics when compared with new full tread tires.

SELECTION OF PARAMETERS

Pavements

Two different pavements were selected for the study. The first pavement was a burlap drag finish 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, stone size between -5/8 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 in. to 0.70 in. whereas the depth selected for the bituminous surface treatment varied from 0.25 in. 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 psi to 36 psi in 6 psi increments were selected in the evaluation of both pavements. It was felt that these values were not only representative of pressures found

in the tires of most ground vehicles, but would provide a good basis for studying the effect of this parameter. Higher pressures were not selected because the test tow vehicle is unable to attain a high enough ground speed to produce sufficient data for these regions.

Wheel Load

Wheel loads of 800 lb and 1085 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 800 lb load because it not only represented a realistic wheel load, but also provided a wide enough variation to detect the effects of this parameter. Only the 1085 lb load was used in the evaluation of the bituminous surface treatment since 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. They included:

1.	Manufacturer A	7.75-14 Bias Ply - Full Tread Depth
2.	Manufacturer A	7.75-14 Bias Ply - 1/2 Tread Depth
3.	Manufacturer A	7.75-14 Bias Ply - Smooth
4.	Manufacturer B Wide Tire	F70-14 - Full Tread Depth
5.	Manufacturer C	7.75-14 Bias Ply - Full Tread Depth
6.	ASTM E-17 Traction Standard	7.50-14 - Full Tread Depth
7.	Manufacturer D	7.75-14 Bias Ply - Full Tread Depth
8.	Manufacturer D	7.75-14 Bias Ply - Smooth

It was felt that this 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 the sloped trough shown in Figures 1 and 2 and described in reference 51. 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 has been encountered for the two pavements discussed earlier. In order to be able to better interpret the data, water depth readings as shown in Figure 2 were taken at various trough locations. The variation in the readings was more pronounced for the bituminous surface treatment. Ideal conditions involving no wind are difficult to achieve so the data collected contain the influence of winds varying from 5 to 15 mph. This effect did not seem to affect the data since 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 how 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 which 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.

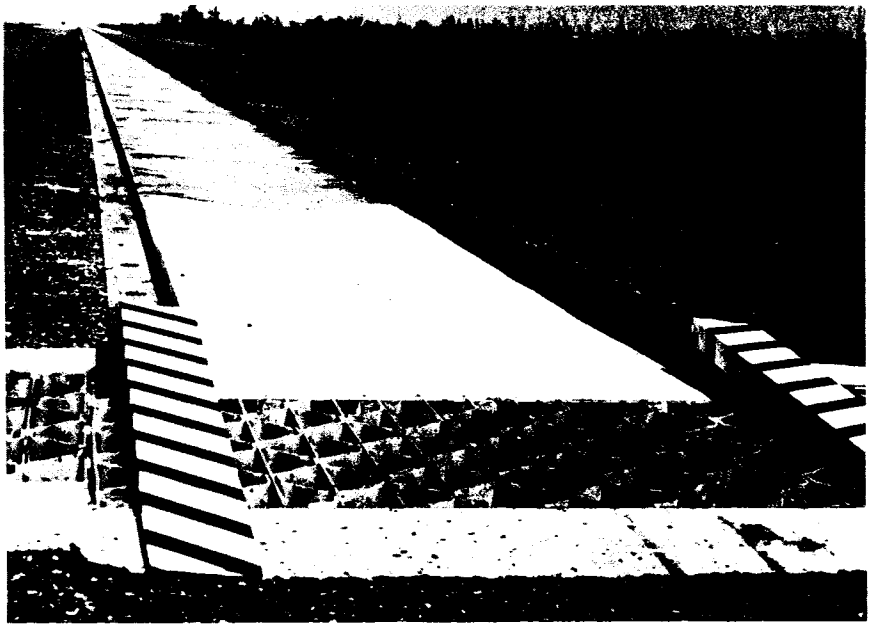

Figure 1. Texas Transportation Institute's Hydroplaning Trough

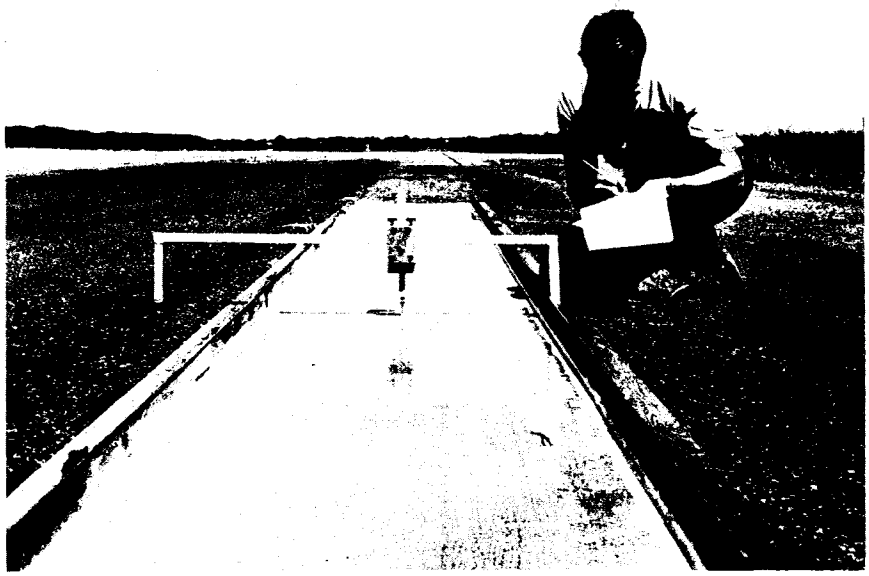

Figure 2. Typical Water Depth Reading Taken Before Test on Hydroplaning Trough

Figure 3. Tow Truck and Instrumented Test Trailer

Figure 4. Typical Test Run on Hydroplaning Trough

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 Reference 26, wheel spin-down can commence at ground speeds considerably lower than the critical hydroplaning speed. In fact, according to this reference, the tests indicated that for tandem wheels, the front wheel spin-down occurred at 70% of the predicted hydroplaning speed. Reference 12 reaches the same conclusions and also states that total spin-down, for their data which involved aircraft tire, takes place between 80 and 120% of the predicted hydroplaning speed. This reference 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. In order to determine this speed more precisely, it is necessary to investigate the effects of the braking force, yaw or side force and the fluid drag force.

For the experimentation which was conducted on the Texas Transportation Institute's hydroplaning trough, wheel spin-down was the only criterion used to indicate hydroplaning. For this reason it was decided

to evaluate the two pavements discussed previously and discuss the effects of the various hydroplaning parameters on the basis of several spin-down percentages.

Figure 5 presents a comparison between the results obtained at 10%, 32% and 60% spin-down and the equation presented by Horne in Reference 26. 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 Horne's equation. The curves show that the values of 32% and 60% spin-down bound Horne's values and that the 10% values are within 70% 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 compares the results obtained for a smooth tire and for Horne's equation. For these data the agreement was not as good as it had been for the previous case. Here, even at 100% 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% spin-down the ground speed is at least 70% of the predicted hydroplaning speed. Results obtained for other tires tend to follow similar patterns and are depicted in Figures 7-9.

Figures 10-17 show plots of vehicle ground speed versus percent spin-down for various tires, inflation pressures, water depths and

pavements. Figure 10 shows some of the trends 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% spin-down, however, this is not true for the 18 psi pressure where no spin-down was obtained for vehicle speeds up to 64 mph. The cause for this may be attributed to the fact that a decrease in the inflation pressure does not necessarily worsen a tire's hydroplaning behavior since 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, because it is possible for the tire frictional force to be reduced significantly and yet not have the spin-down torque overcome the spin-up torque and consequently have no spin-down. 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 18 and 19 show the effect of varying the wheel load from 800 lbs to 1085 lbs. The results for the smooth tire are plotted in Fig. 18 and indicate that an increase in the wheel load increases the ground speed that is required to produce a 10% spin-down of the wheel. However, Figure 19 indicates that for a full tread depth tire the reverse takes place. This type of behavior is possible since spin-down is closely associated with tire characteristics.

Figure 20 compares tire No. 4 (wide tire) and No. 7 (bias ply). The results indicate that the bias ply tire required greater ground speeds to produce the same spin-down. 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 21 clearly demonstrates the effects of tire tread 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% 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 22 and 23 depict the effects of the two pavements tested. Figure 22 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 (pavement #1) and that realistic trends were demonstrated when the tire inflation pressure and water depth were varied. For the bituminous surface treatment (pavement #2), 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 18-23 contain plots of water depth versus ground speed for various parameters. These curves show that the ground speed required to produce 10% 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 at entering the trough. For example, considering the gravel pavement and using tire No. 4 with an inflation pressure of 24 psi and a water depth of 0.7 in., it took approximately 80 ft to reach a total spin-down of 20% when entering the trough at 48 mph. However, when the entry speed was increased to 58 mph it took 240 ft of travel before the final spin-down of 78% was attained; after 80 ft the tachometer generator traces indicated a wheel spin-down of approximately 20%.

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, it can be said that the possibility of a hazardous condition existing increases with increasing length of flooded pavement.

APPLICABILITY TO

SAFE WET WEATHER SPEEDS

In recent legislative action, Section 167 of Senate Bill No. 183, 62nd Legislature, 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 which should be considered in determining safe speeds, the current data on hydroplaning give indications of the speeds which result in a potentially marginal condition with regard to vehicle control. Hydroplaning gives only one of the many factors which must be considered in determining safe speeds. It is limited to the case when 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, etc.

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

Figures 24, 25 and 26 show approximate curves which represent 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. Wheel load in all cases is 1085 lbs.

The influence of pavement texture on partial hydroplaning speed (as indicated by 10% spin-down) is significant. An increase in critical speed of 13 mph, from 47 to 60 mph, is indicated at a water depth of 1/4 inch when the macrotexture is increased from 0.018 in. 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 illustrated by Figure 25. The tire pressures of 24 psi to 36 psi shown in this figure account for approximately 70% of the range of tire pressures observed in a study of 501 wet pavement accidents in Texas (52).

Figure 25 shows that at a water depth of 0.1 inch, 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 26. Unlike the effects of texture and pressure, the differences between these tires increase as the water layer becomes thicker. At a water depth of 1/2 inch 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 27 shows the consolidation of individual wheel tire pressure graphs as reported in reference (52). Although it is obvious from the curves presented that there is no <u>one</u> 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 inch 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.

CONCLUSIONS

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

1. Wheel spin-down is normally initiated at a ground speed that falls within 70% of the critical hydroplaning speed predicted by Horne's NASA equation.
2. The ground speed required to initiate spin-down on full-tread depth tires is higher than the speed required to cause spin-down on 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 ground 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 (surface number 2) 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 NASA 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 inch.

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FIGURES

Tire No. 7 7.75-14 Bias Ply (Full Tread Depth)
Water Depth - 0.40 in.
Wheel Load - 800 lbs

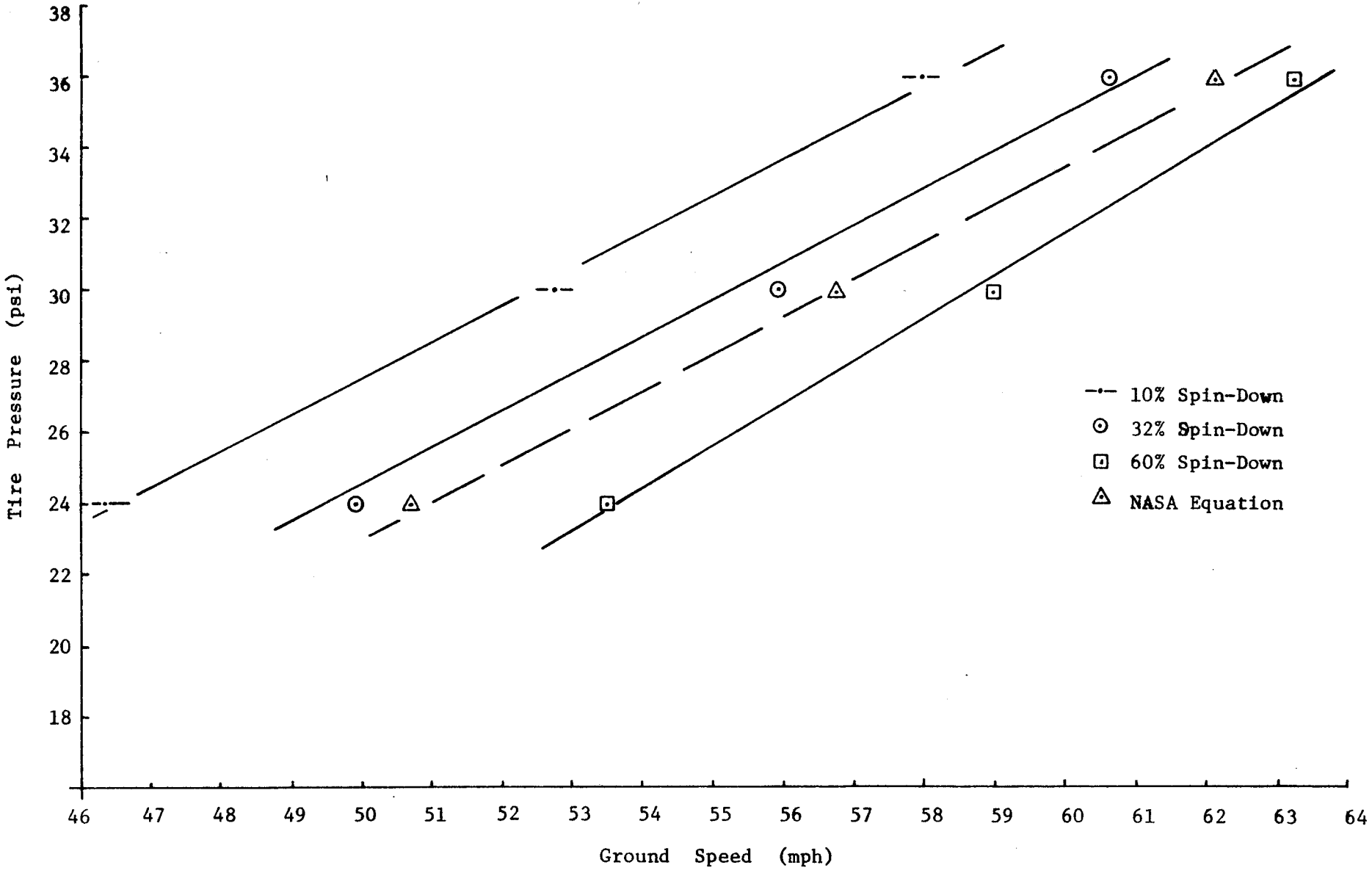

FIGURE 5 COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR CONCRETE PAVEMENT

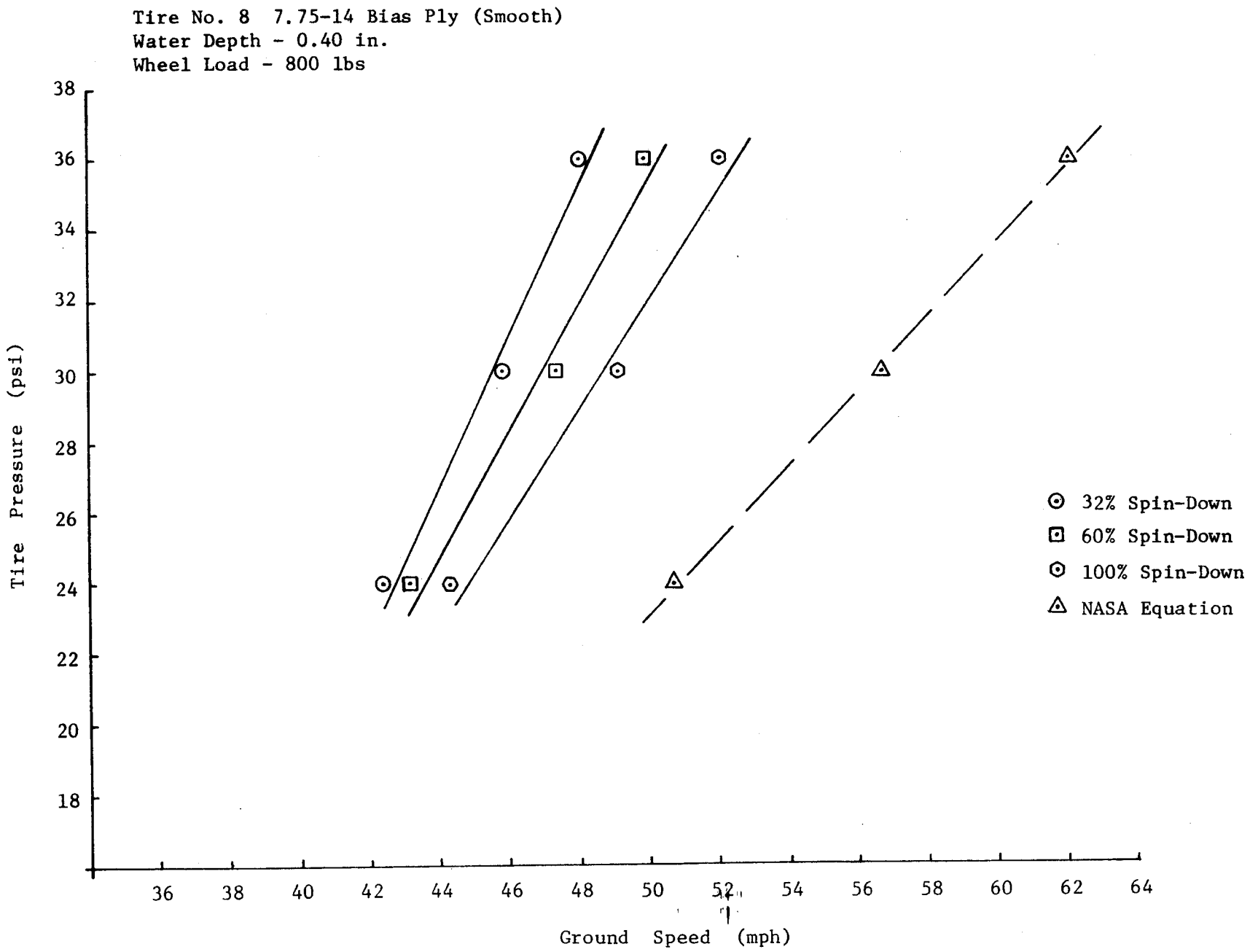

FIGURE 6 COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR CONCRETE PAVEMENT

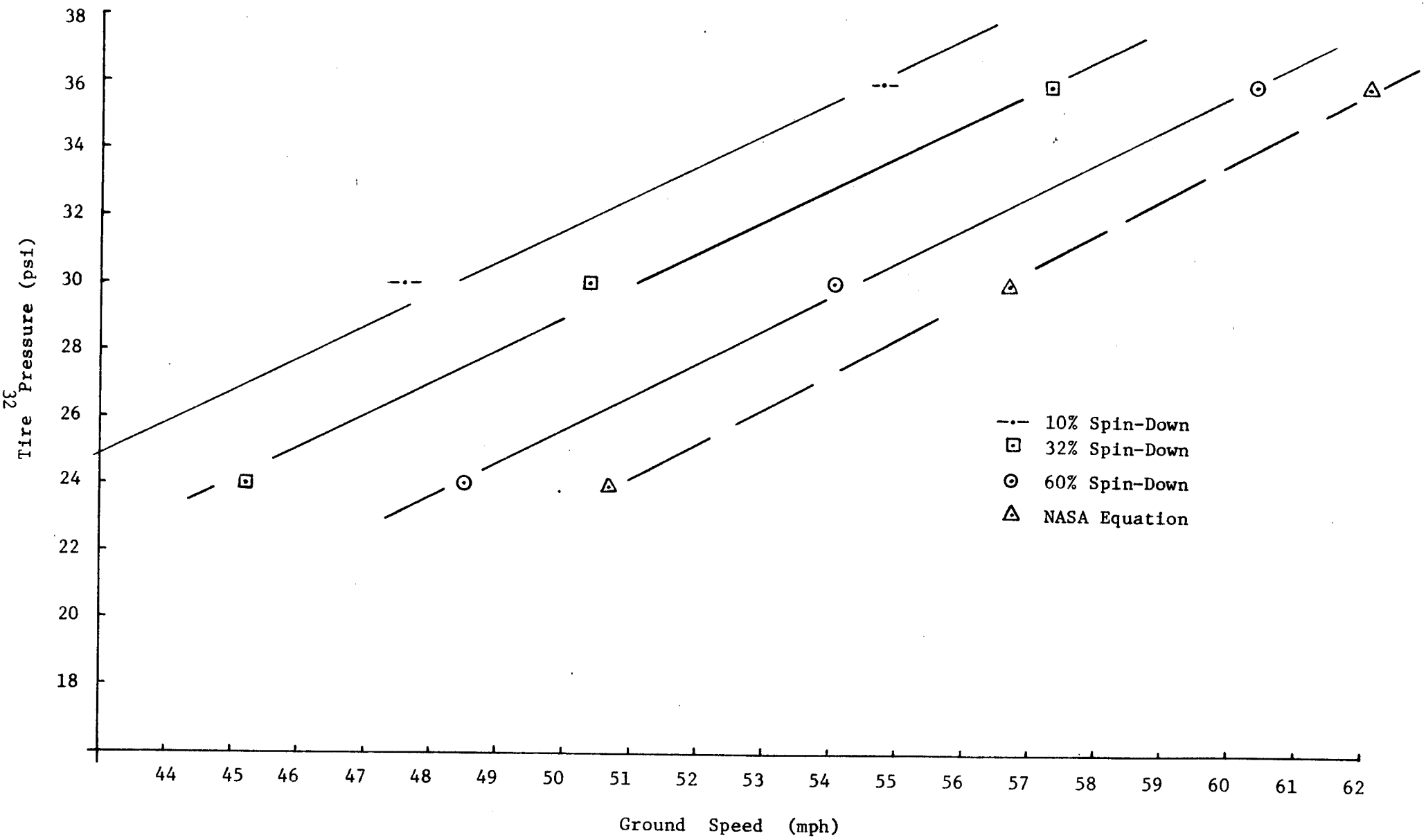

FIGURE 7 COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR CONCRETE PAVEMENT

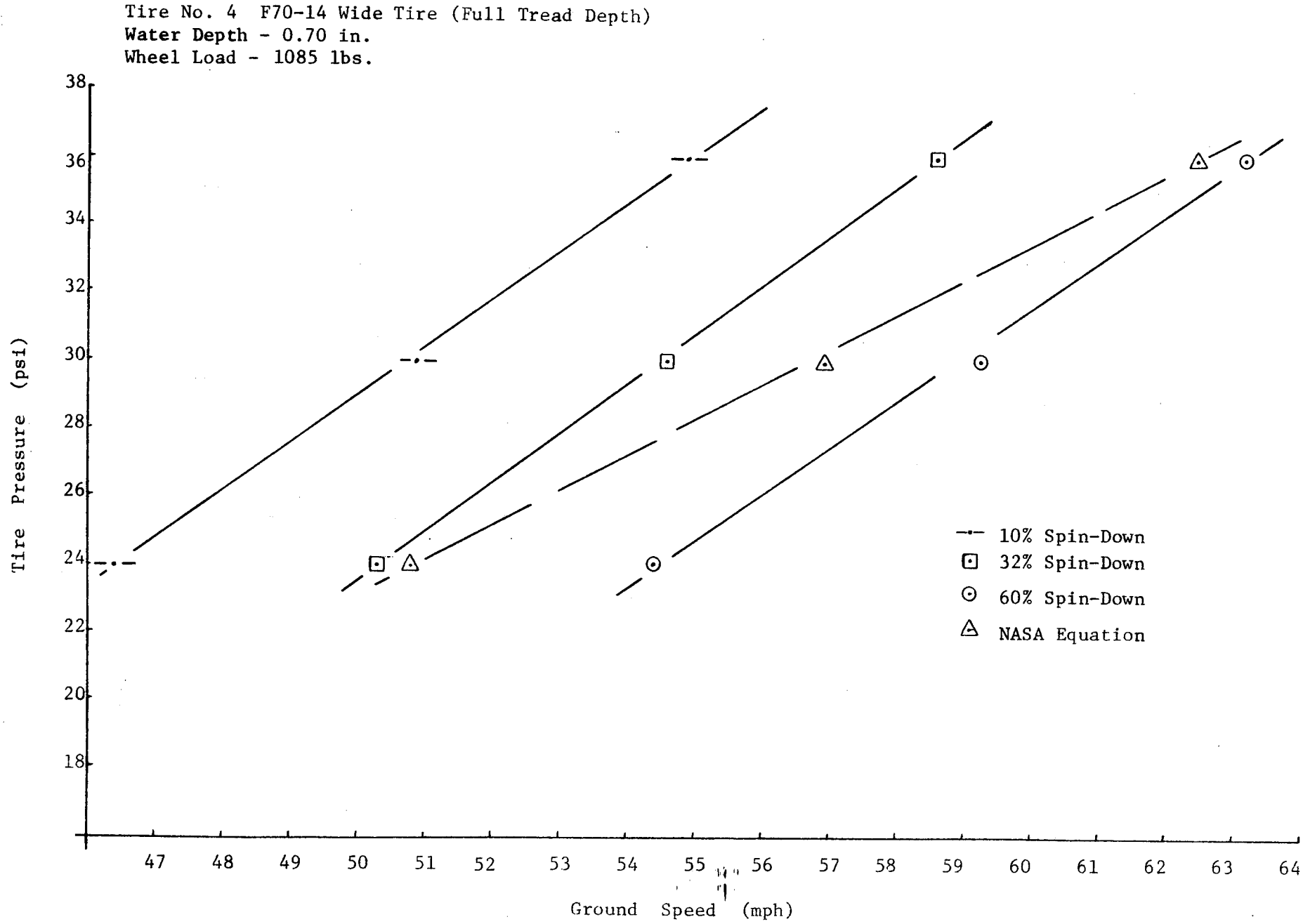

FIGURE 8 COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR BITUMINOUS SURFACE TREATMENT

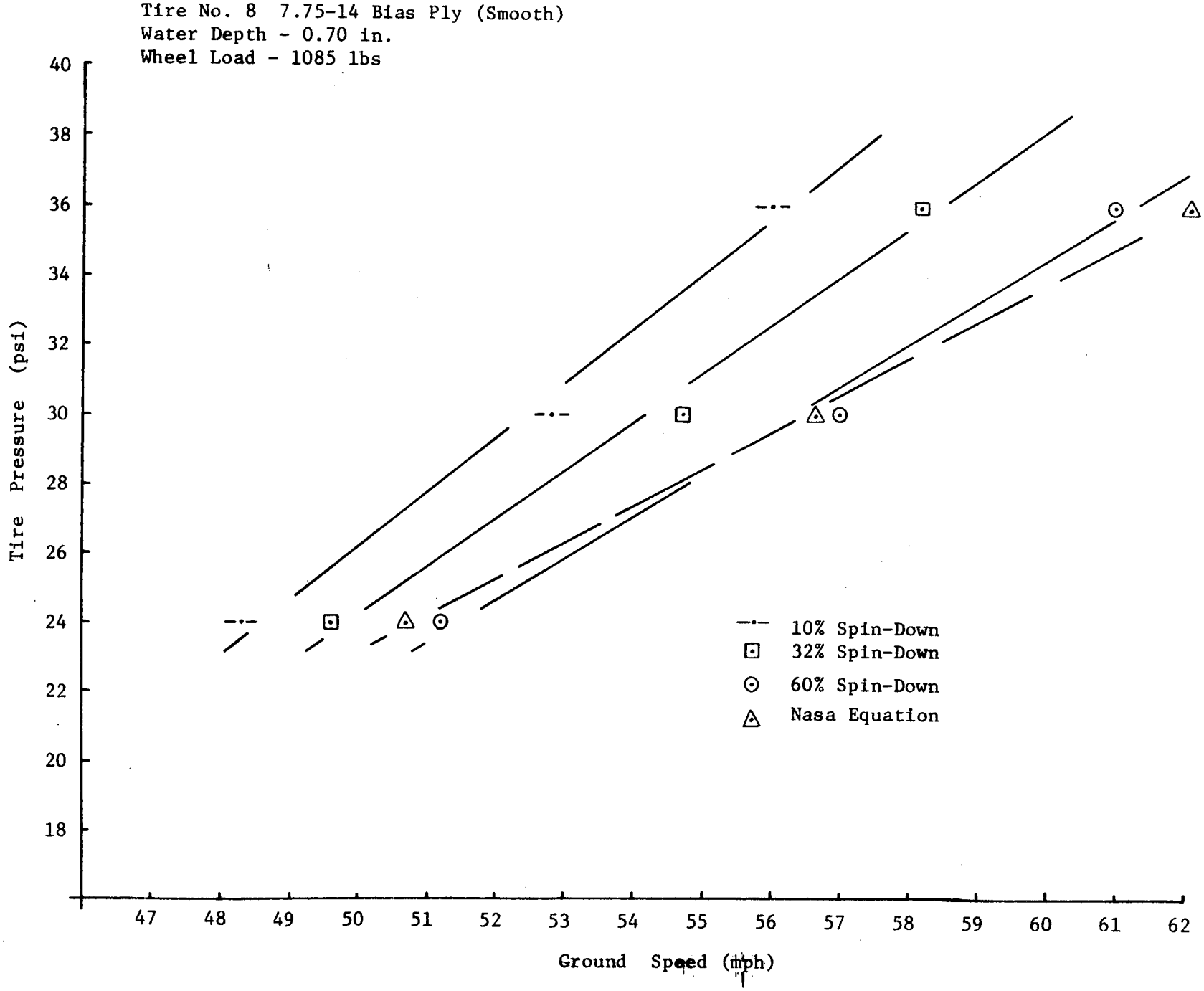

FIGURE 9 COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR BITUMINOUS SURFACE TREATMENT

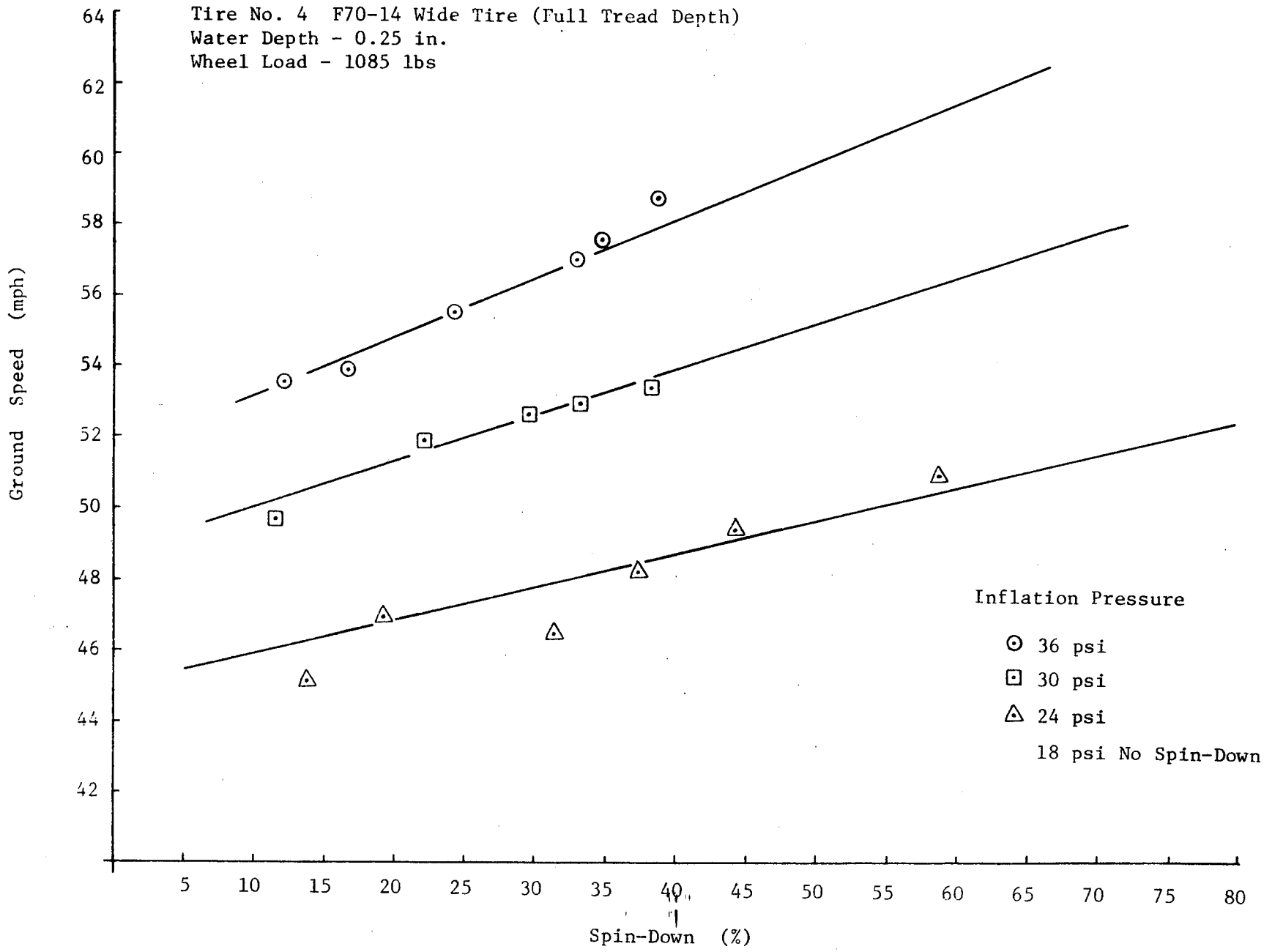

FIGURE 10 EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR CONCRETE PAVEMENT

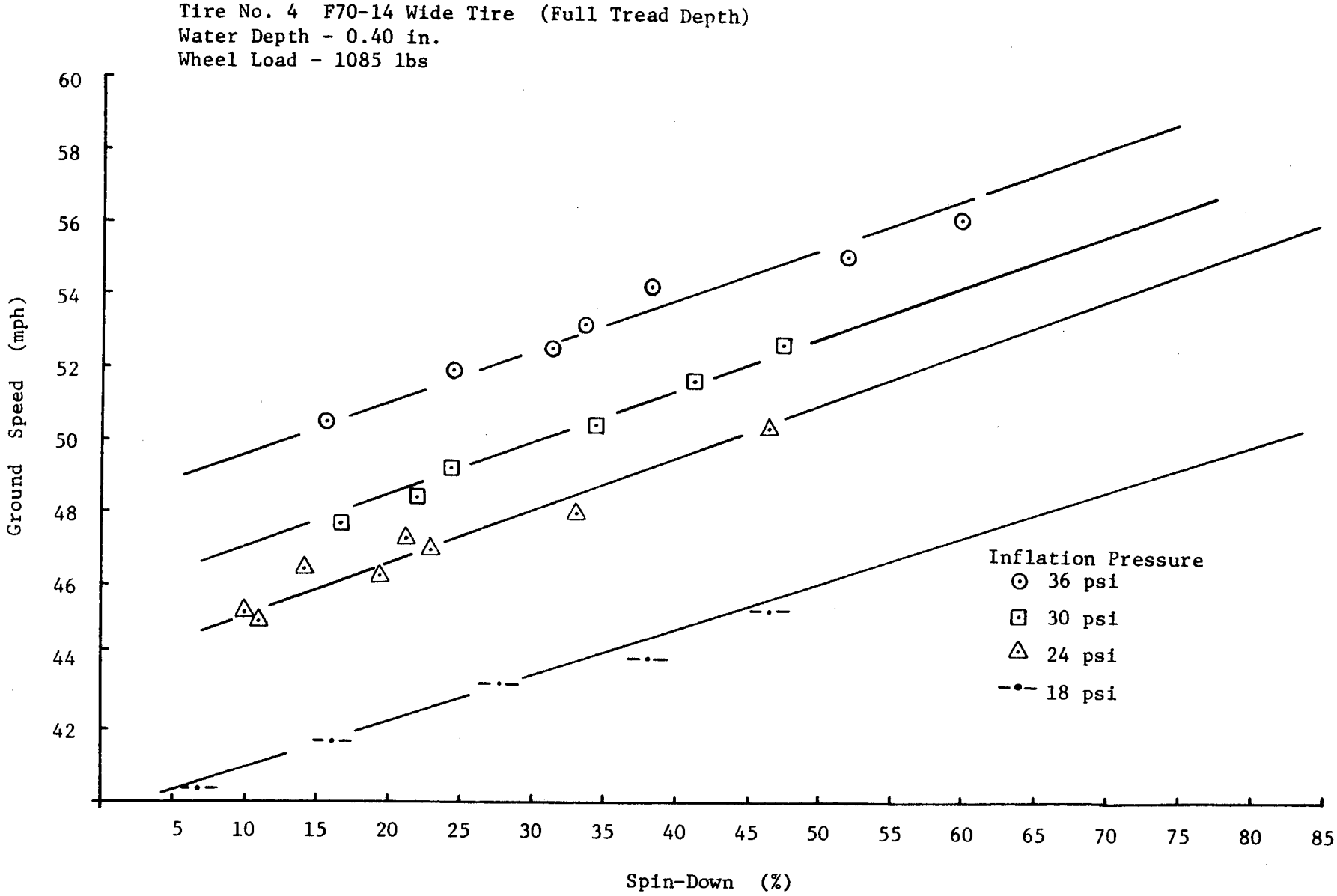

FIGURE 11 EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR CONCRETE PAVEMENT

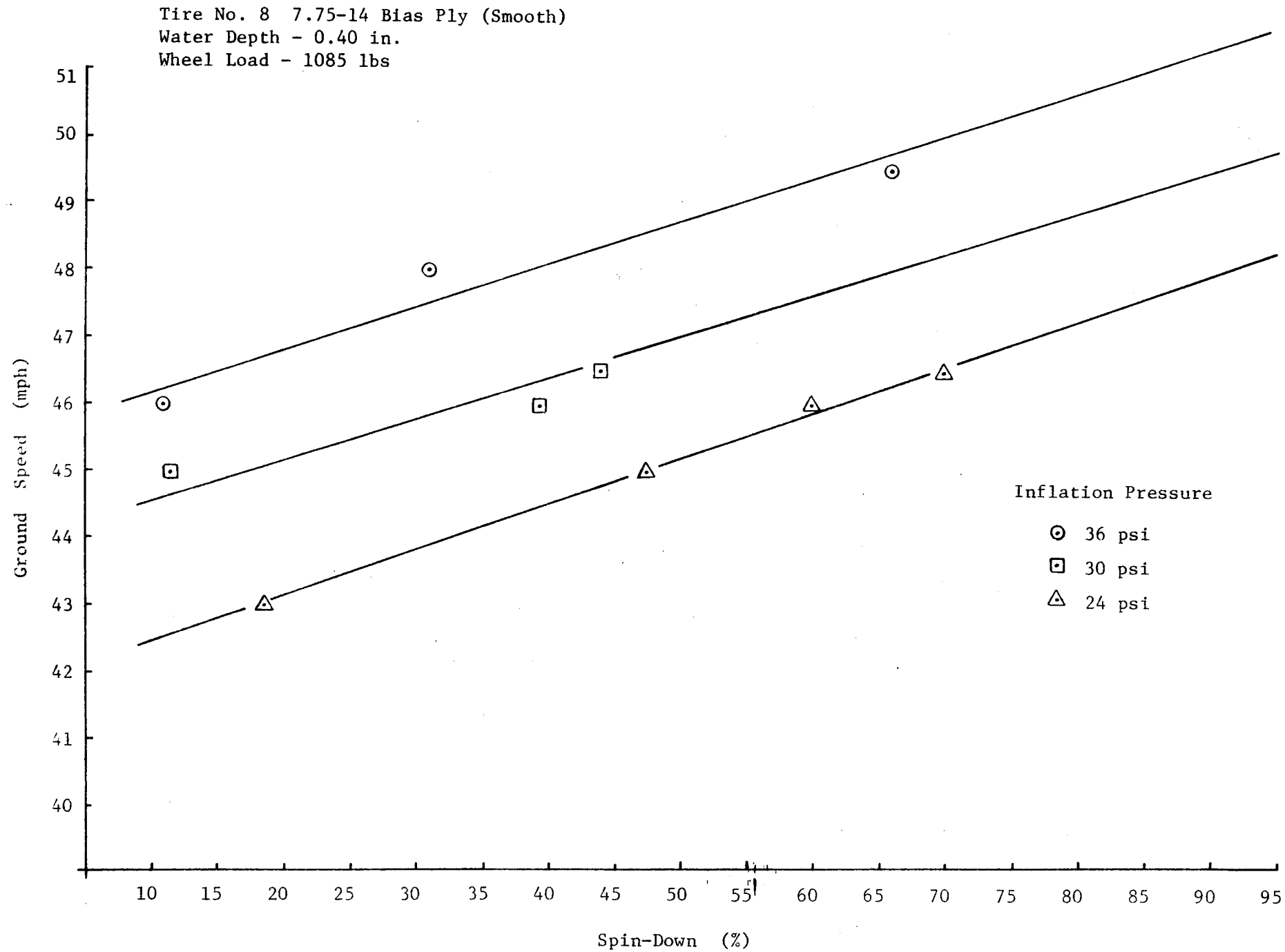

FIGURE 12 EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR CONCRETE PAVEMENT

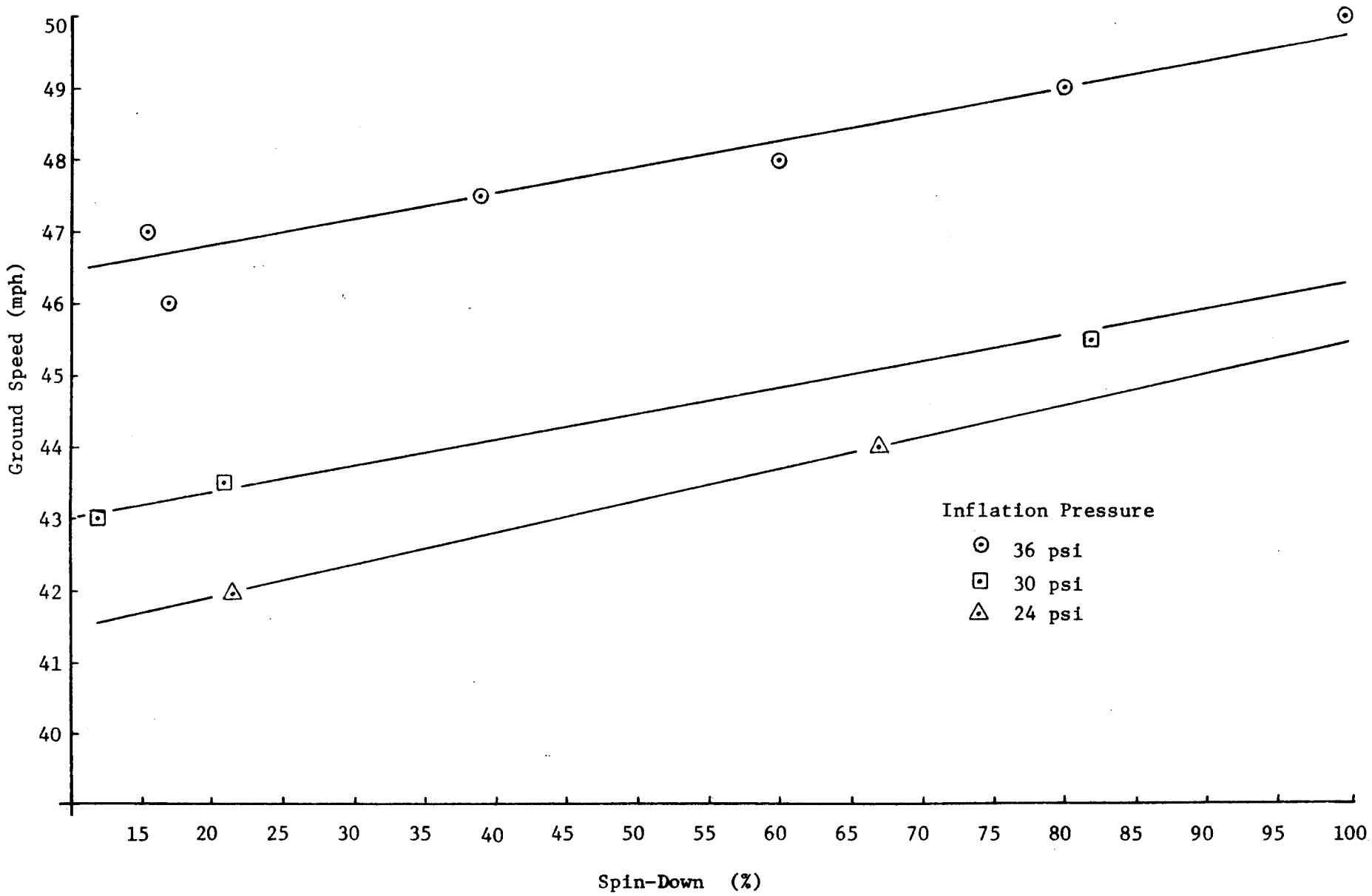

FIGURE 13 EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR CONCRETE PAVEMENT

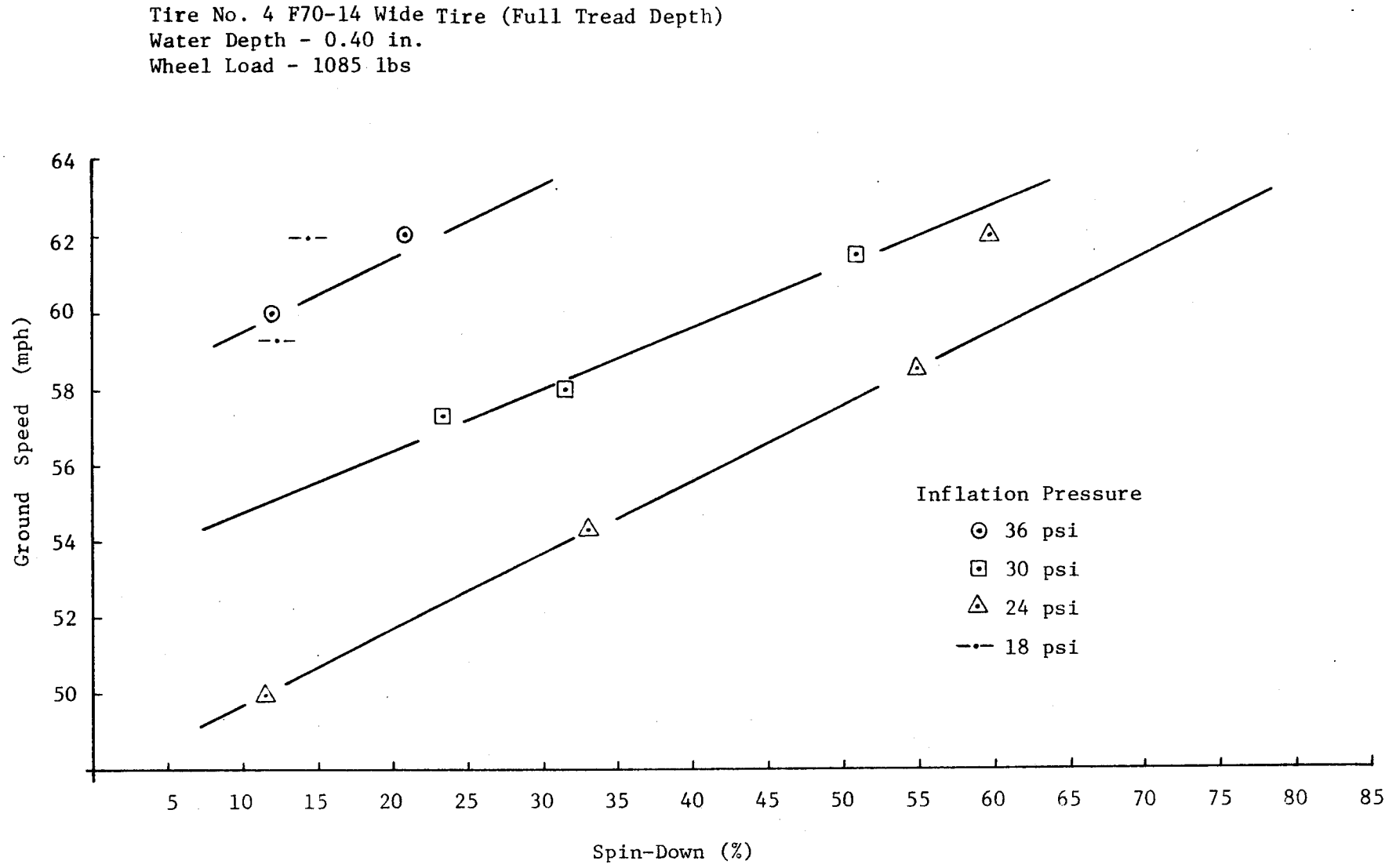

FIGURE 14 EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR BITUMINOUS SURFACE TREATMENT

Tire No. 4 F70-14 Wide Tire (Full Tread Depth)
Water Depth - 0.70 in.
Wheel Load - 1085 lbs

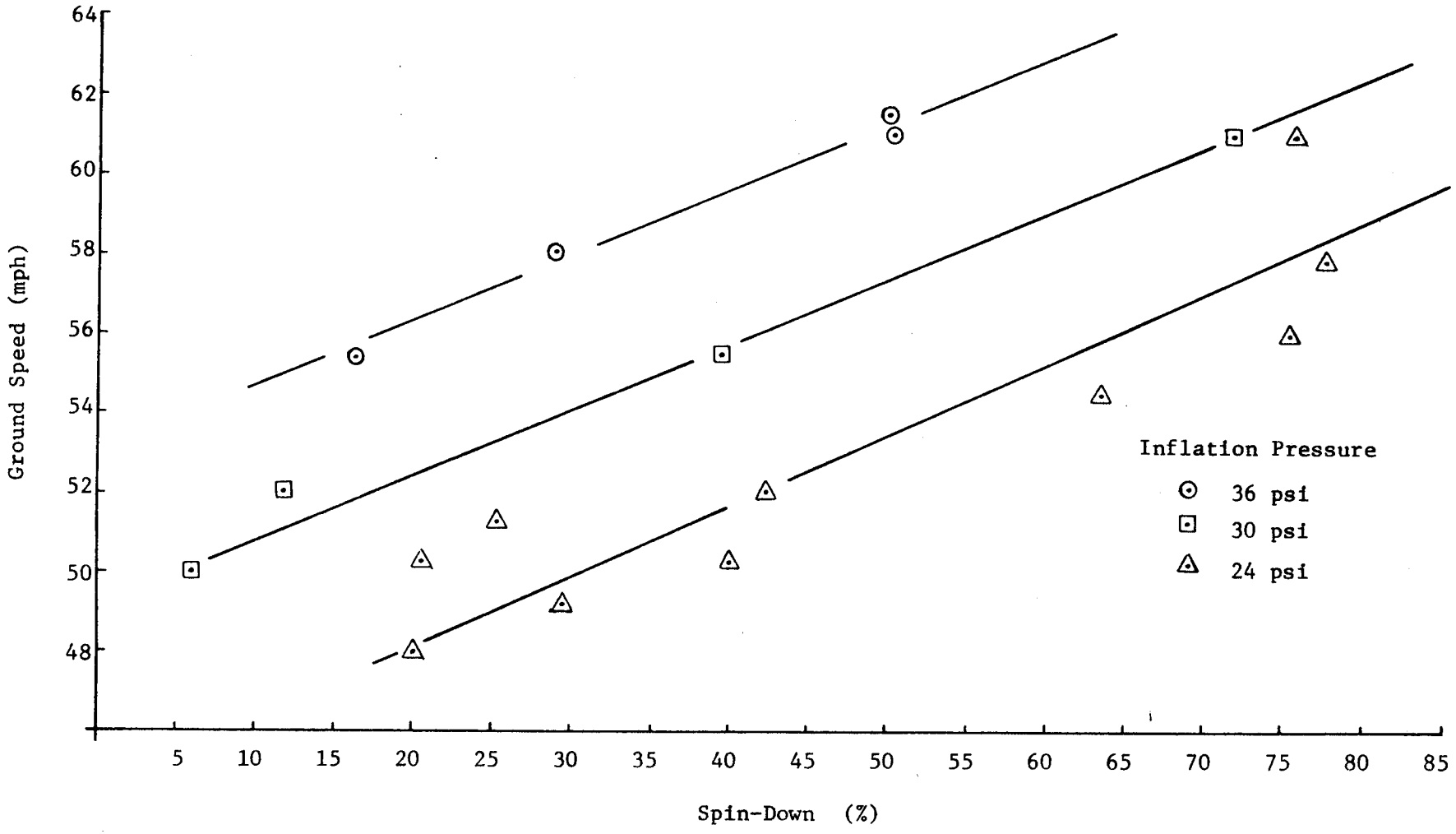

FIGURE 15 EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR BITUMINOUS SURFACE TREATMENT

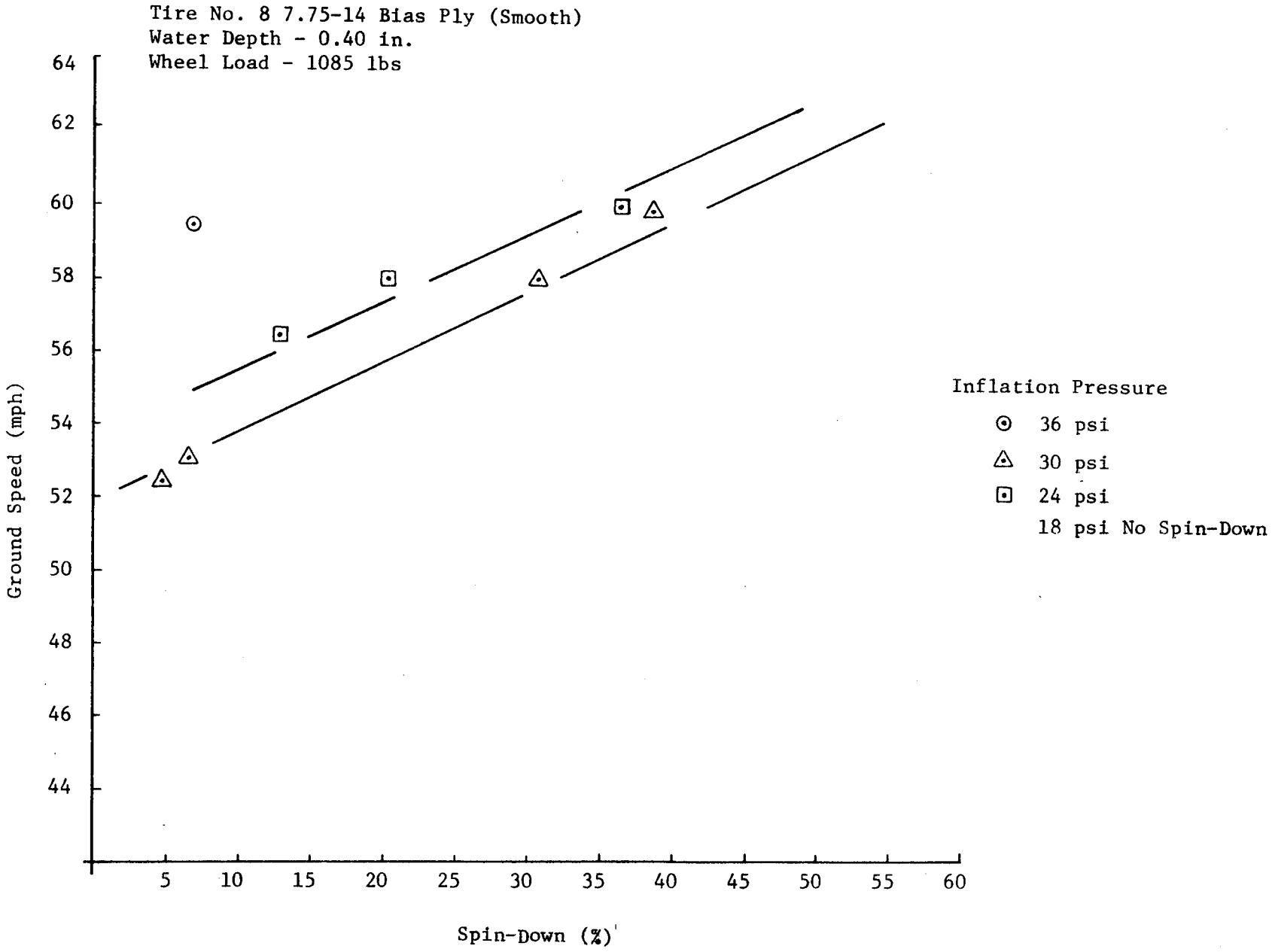

FIGURE 16 EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR BITUMINOUS SURFACE TREATMENT

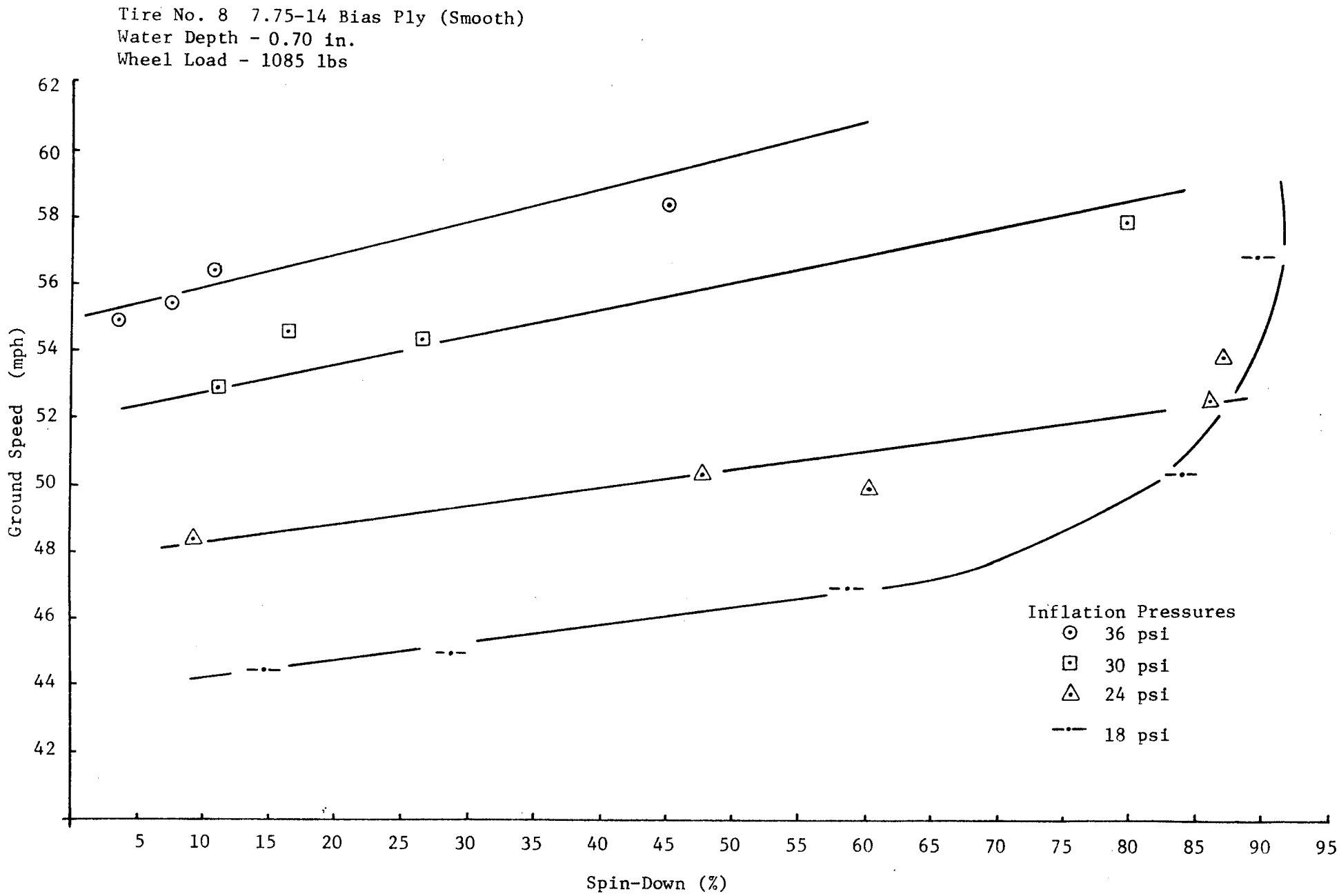

FIGURE 17 EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR BITUMINOUS SURFACE TREATMENT

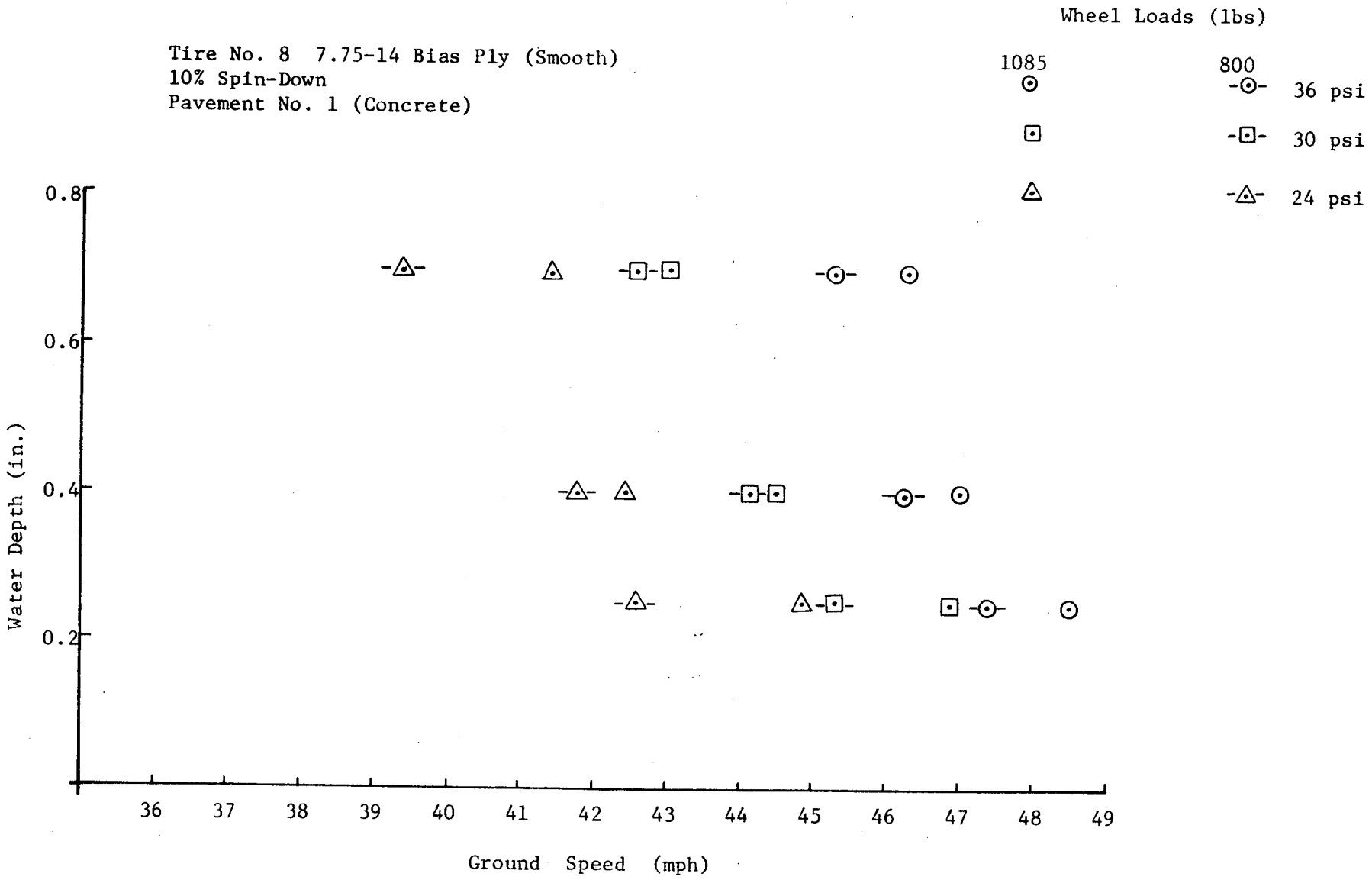

FIGURE 18 EFFECT OF WATER DEPTH AND WHEEL LOAD ON GROUND SPEED TO CAUSE 10% SPIN-DOWN

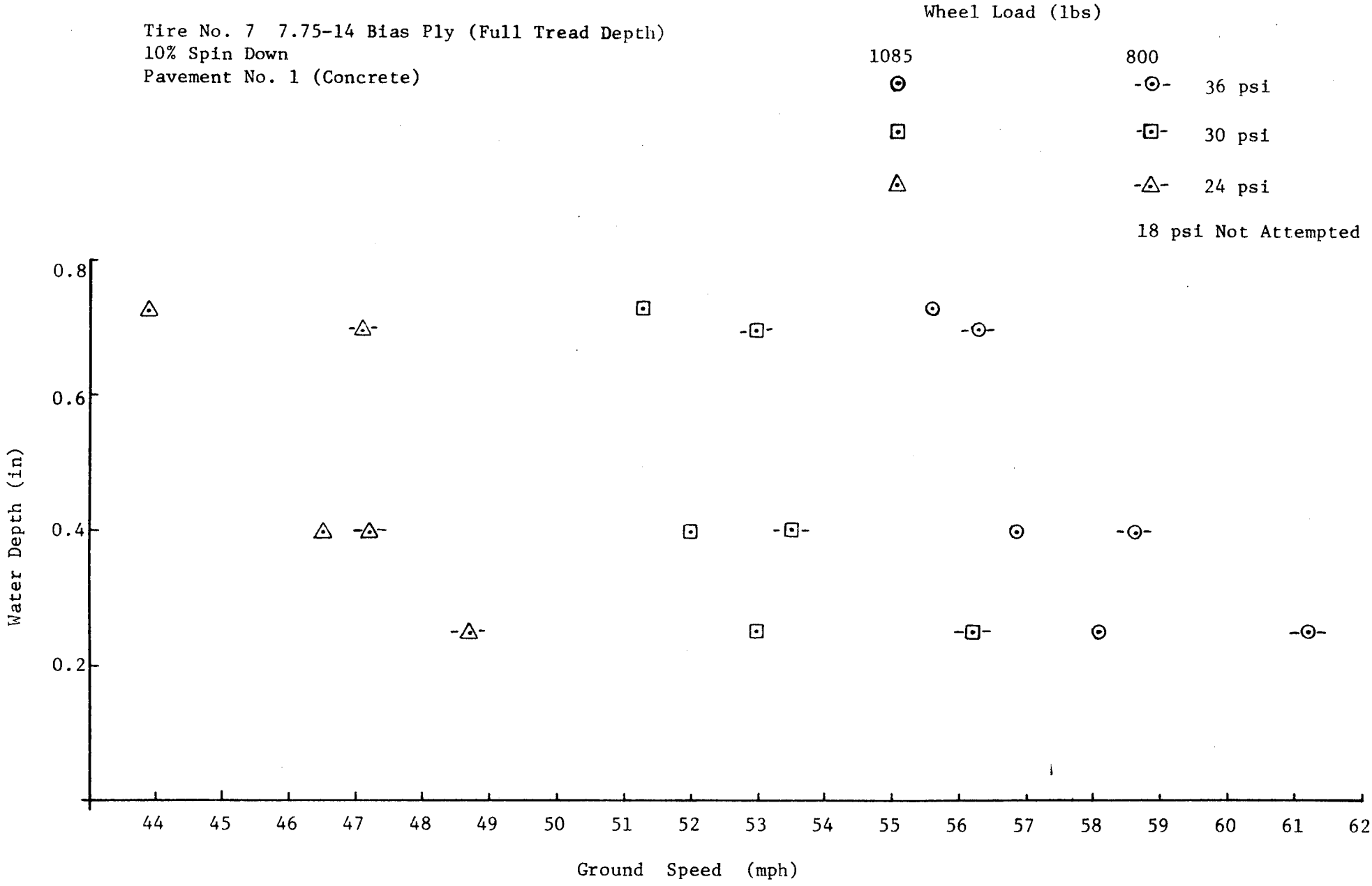

FIGURE 19 EFFECT OF WATER DEPTH AND WHEEL LOAD ON GROUND SPEED TO CAUSE 10% SPIN-DOWN

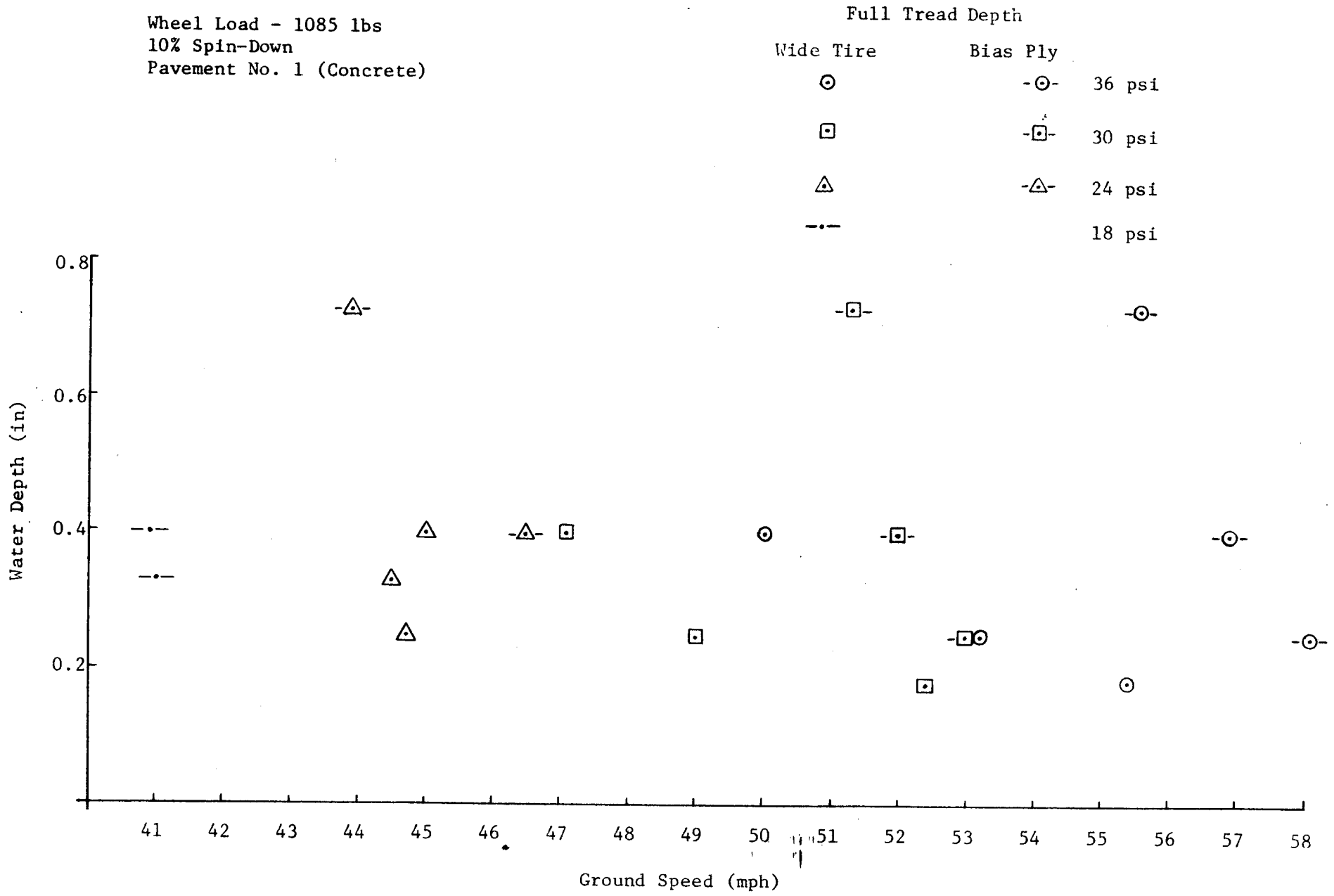

FIGURE 20 EFFECT OF WATER DEPTH AND TIRE ASPECT RATIO ON SPEED TO CAUSE 10% SPIN-DOWN

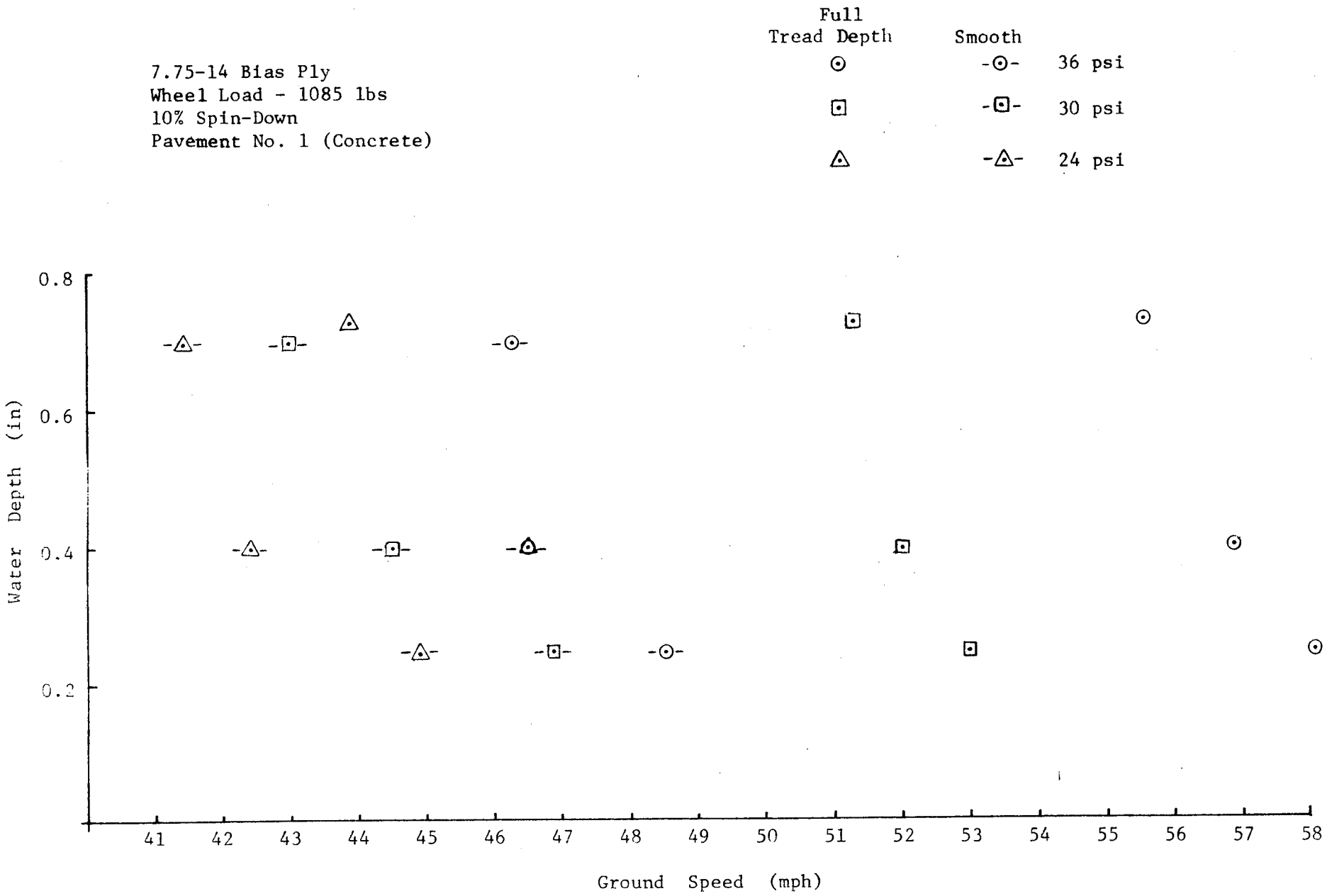

FIGURE 21 EFFECT OF WATER DEPTH AND TREAD DEPTH ON SPEED TO CAUSE 10% SPIN-DOWN

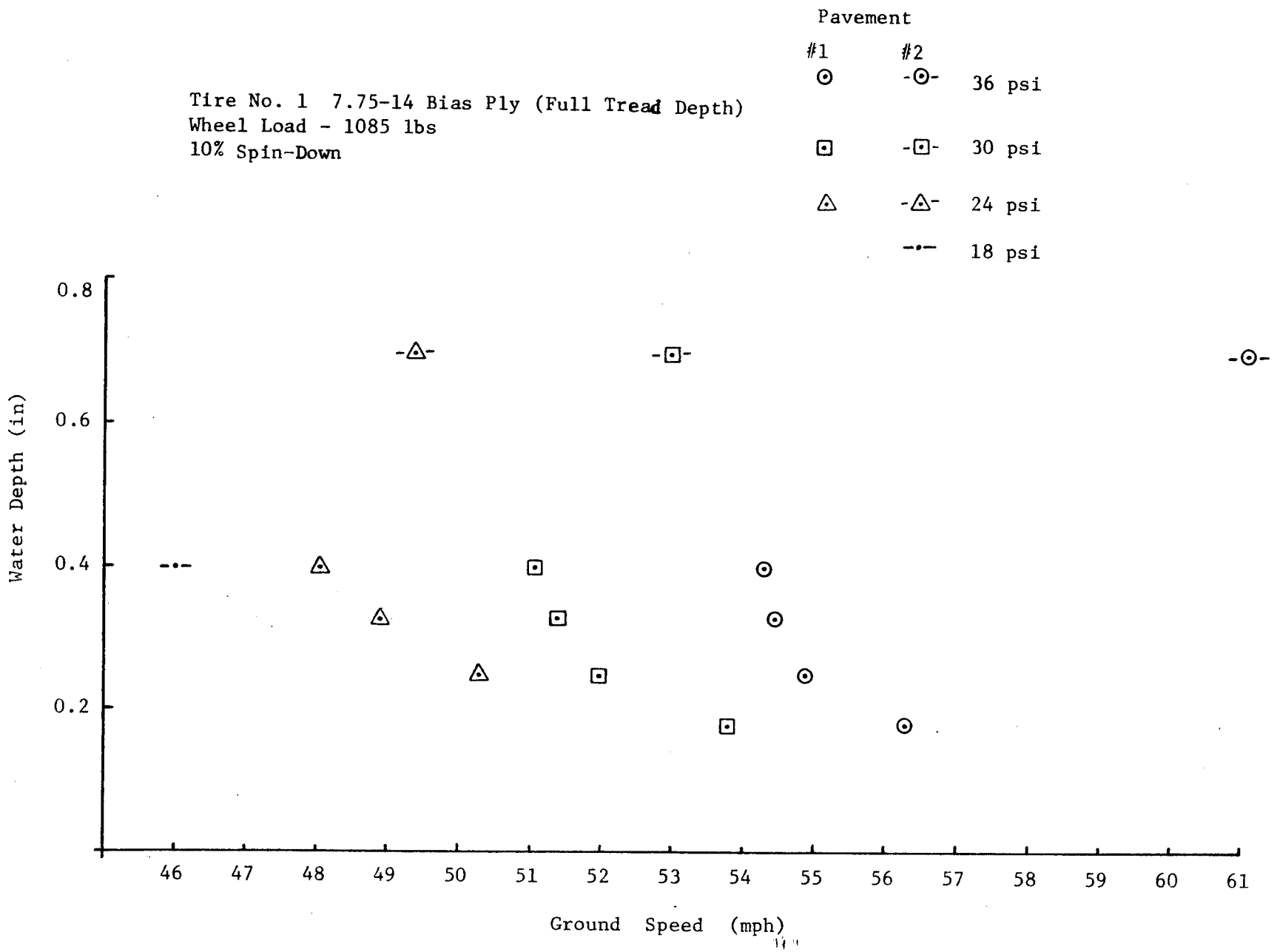

FIGURE 22 COMPARISON OF CONCRETE AND BITUMINOUS SURFACE TREATMENT

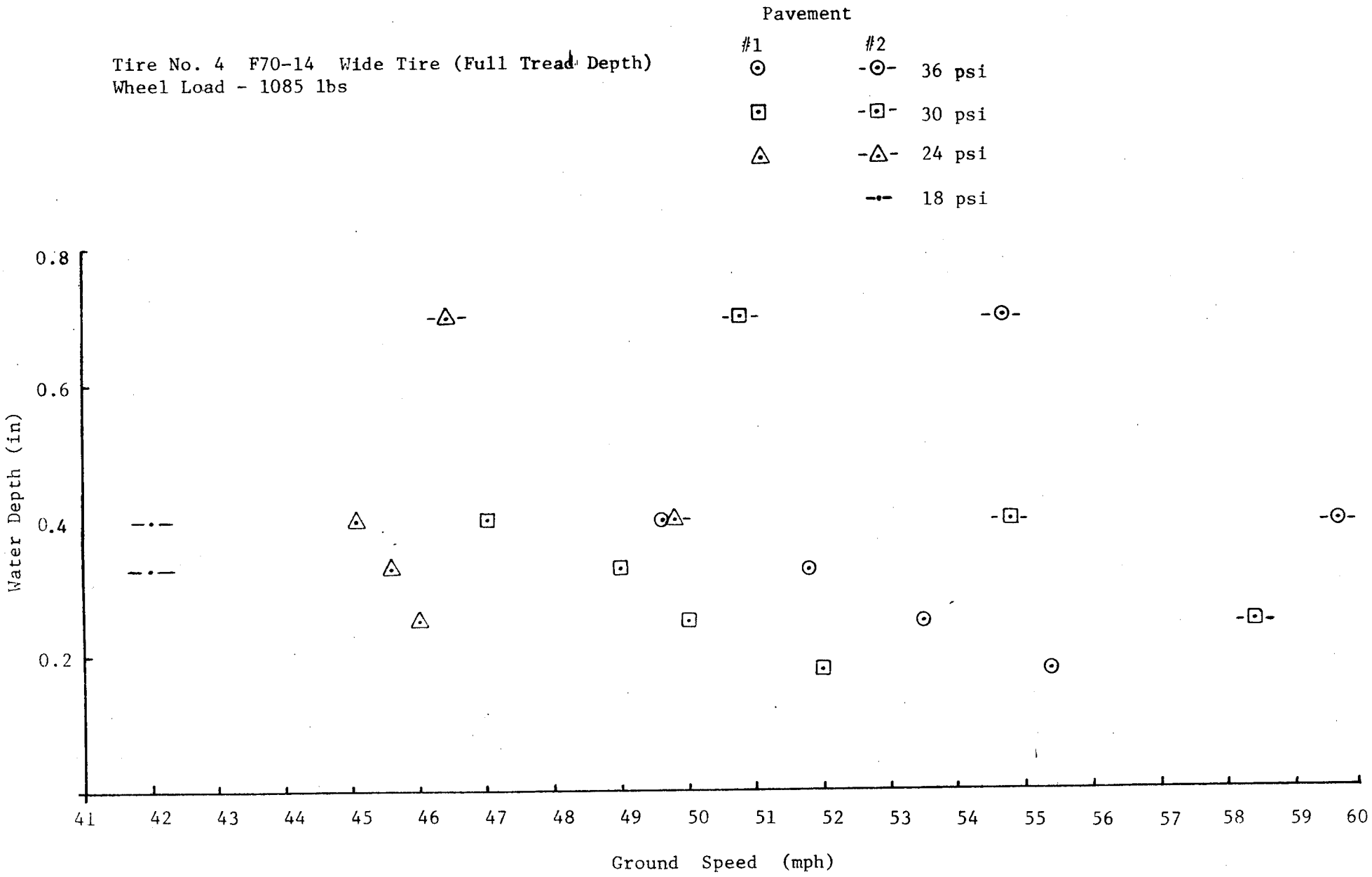

FIGURE 23 COMPARISON OF CONCRETE AND BITUMINOUS SURFACE TREATMENT

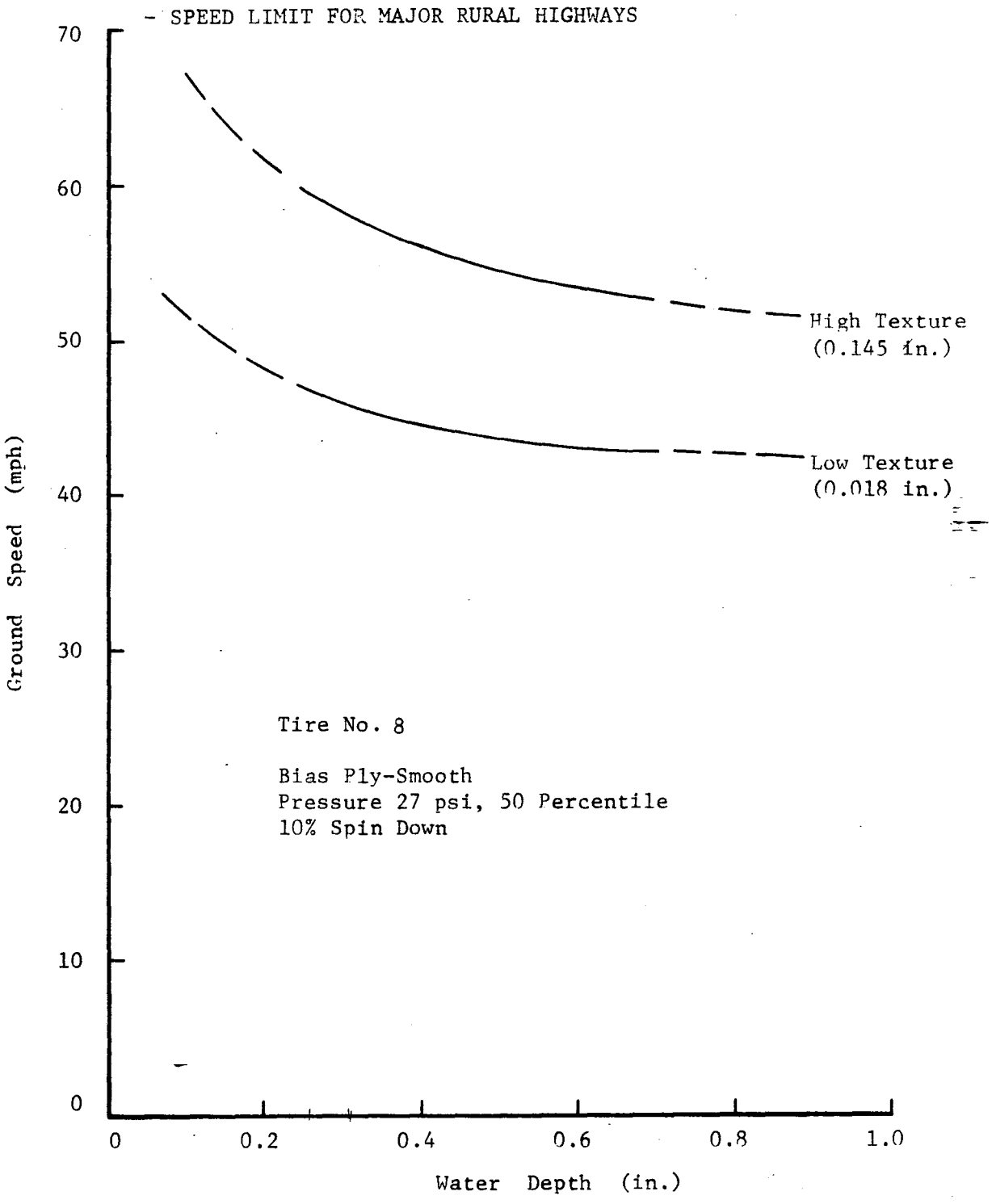

FIGURE 24 EFFECT OF TEXTURE ON HYDROPLANING

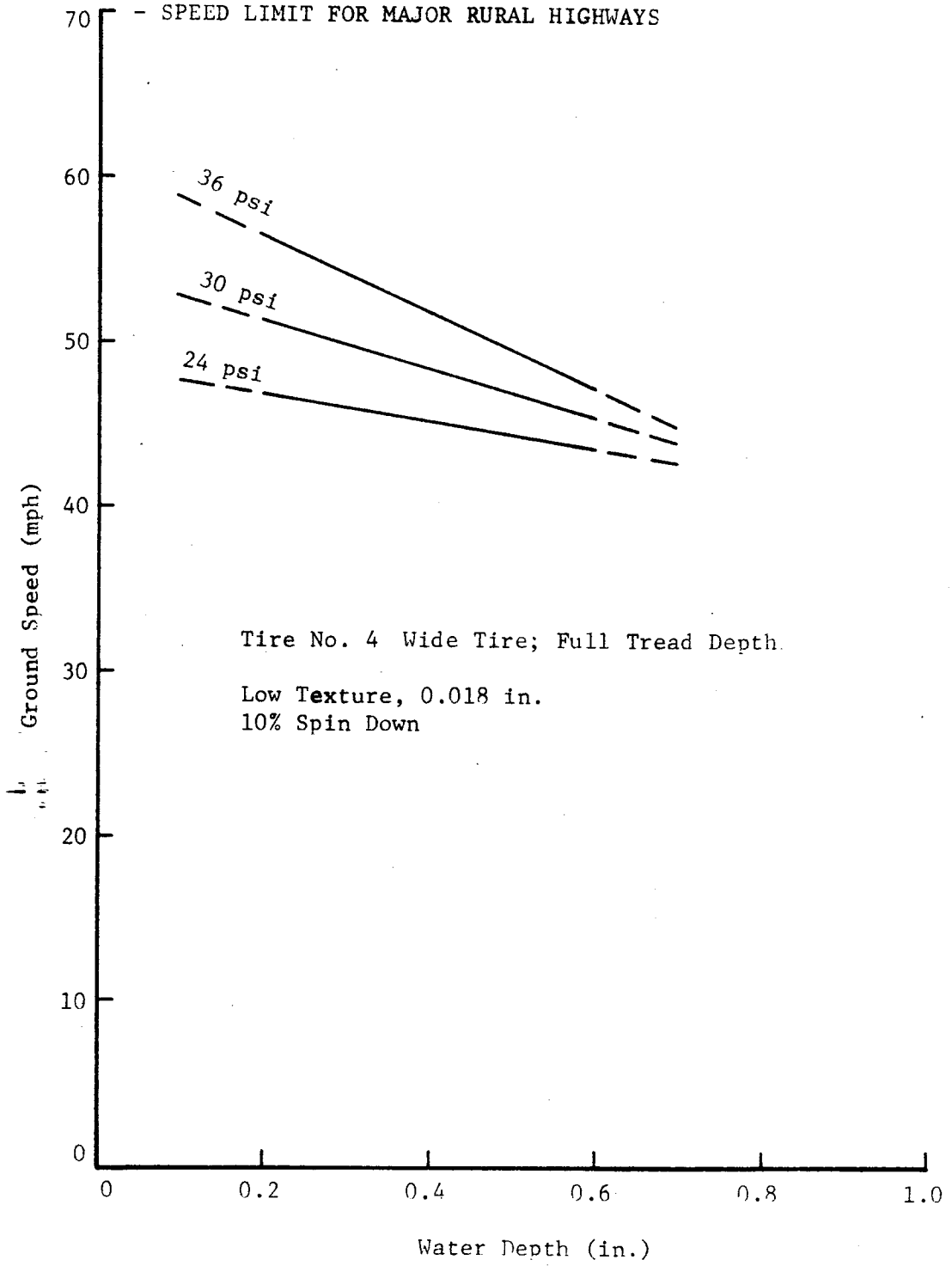

FIGURE 25 EFFECT OF PRESSURE ON HYDROPLANING

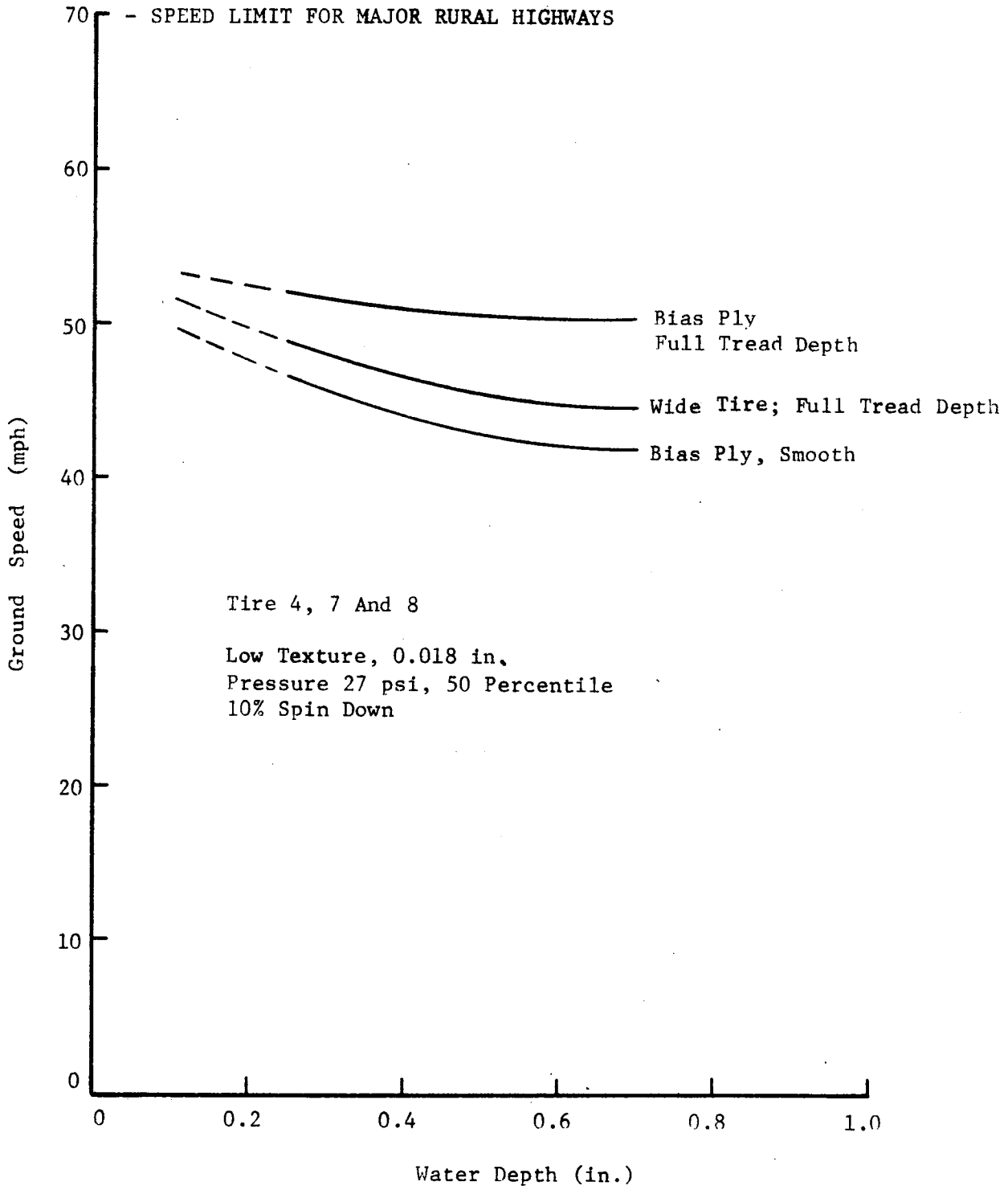

FIGURE 26 EFFECT OF TIRE ON HYDROPLANING

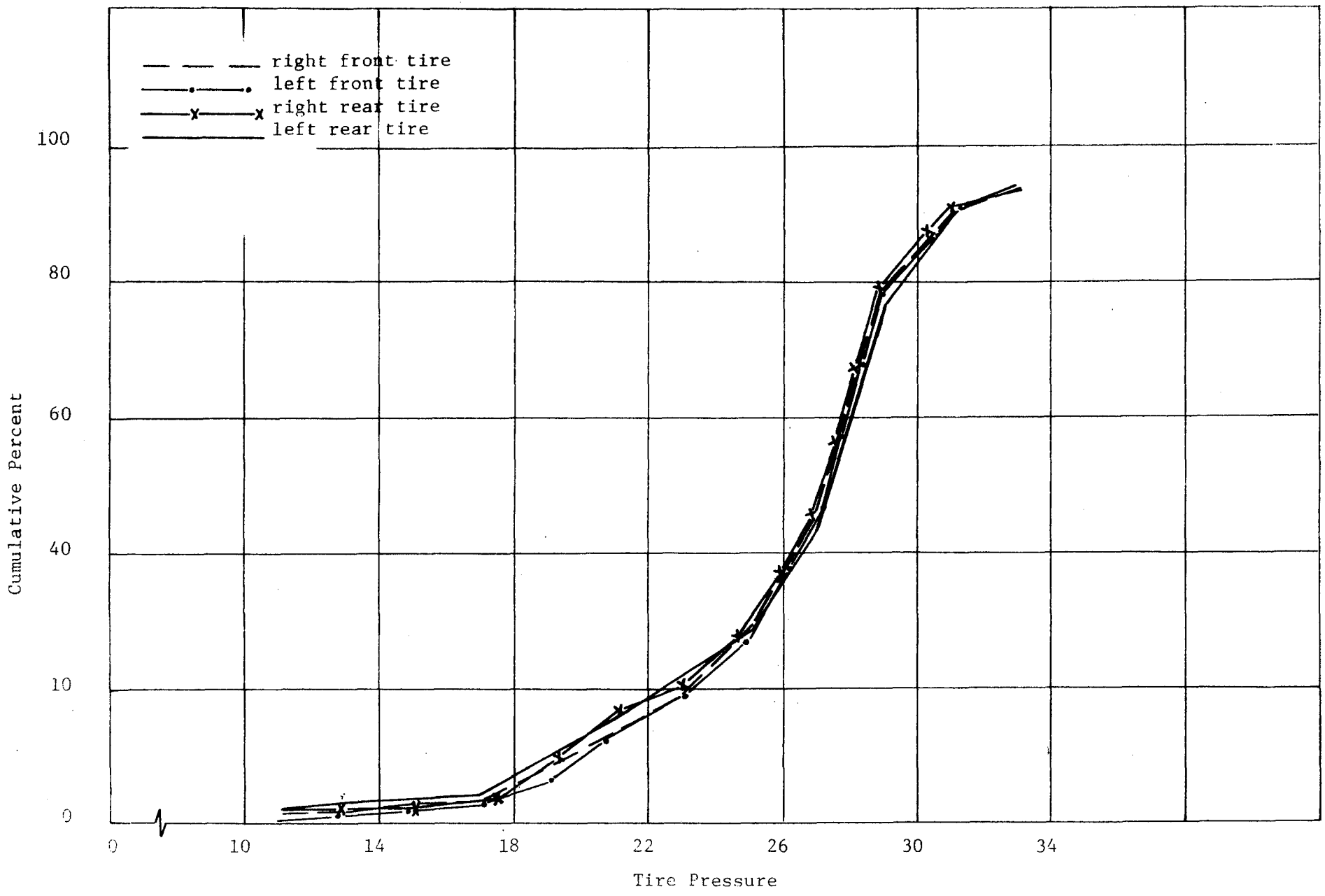

FIGURE 27, COMPARISON OF TIRE PRESSURES - ACCIDENT SAMPLE