VARIABLES ASSOCIATED WITH AUTOMOBILE TIRE HYDROPLANING

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ABSTRACT

A study of the wet weather characteristics of four different pavements and eight different tires is presented. The pavements studied were a portland cement concrete, a bituminous surface treatment, a hot mix asphalt and a jennite surface. The tires studied were several bias ply tires with different tread depths, a wide tire and a test standard tire. In this study, wheel spin-down was used as the criterion and the variables considered were tire tread depth, tire inflation pressure, water depth, and wheel load. A sloping 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 do the other pavements tested. It was also observed that no single critical speed, necessary for wheel spin-down to occur, exists for the range of variables selected, but it is recommended that there be a reduction of speed to 50 mph for any section of highway on which water can accumulate to 0.1 inch or more during wet weather periods.

Key Words: highways, pavements, hydroplaning, spin-down, surface texture, water depth, tire inflation pressure, tire tread depth.

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. This report uses wheel spin-down as a criterion for evaluating the wet weather properties of several pavements and considers the effects of water depth, tire inflation pressure, tire tread depth and wheel load on the speed to cause spin-down. The study was performed by conducting full-scale tests in 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 pavement which allows water to escape from under the tire requires a considerably higher ground speed to cause spin-down than a low macrotexture 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. Increasing the width of a tire 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 directionsl 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 and possibly internally draining surfaces 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

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INTRODUCTION

As a vehicle travels along the highway, the friction required to perform maneuvers is developed at the tire-pavement interface. The friction developed will depend on such things as the pavement texture, tire configuration, area of the contact zone, tread design, speed, and tire pressure. If this area is contaminated, the friction developed at the interface will be decreased. If the contaminant is water, the possibility of hydroplaning exists.

Hydroplaning is caused by the build up of fluid pressures within the contact zone between the tire and the pavement. These forces can increase to the point where the hydrodynamic uplift equals the downward force exerted on the wheel. At this point the tire is hydroplaning or completely supported by the water layer. When in this condition, the tire has lost all contact with the pavement surface and thus has lost all the tractive force necessary to perform normal or emergency driving maneuvers.

This study has chosen to use wheel spin-down as the indicator of tire hydroplaning. Spin-down is a term describing the loss of angular velocity of a wheel traveling over a flooded pavement as the speed of the vehicle remains constant or increases. Wheel spin-down is caused by the build up of hydrodynamic pressure in the forward portion of the tire-pavement contact area. This force acts to oppose the normal rotating action of the tire and can build up to a point to cause the tire to stop rotating completely. It has been assumed that once spin-down has been initiated some loss of tire-pavement contact has occurred. Once a portion of the contact is lost, the friction developed between the tire and the pavement is decreased and a potentially dangerous situation exists.

The factors being considered in this study are water depth, pavement texture (primarily macrotexture), vehicle speed, wheel load, tire inflation pressure, tire configuration, and tire tread depth. By adjusting each of the variables, the effect each has on the speed at which a certain amount of spin-down occurs can be observed.

Up to this time most research in this area has been done by the aircraft industry, due to the high speeds involved with take-off and touchdown. Because of this, the research has been done using aircraft tires which have very different characteristics from automobile tires. It is the objective of this study to observe what occurs at lower speeds, wheel loads, and tire inflation pressures.

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 that 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

$$V_{cr} = 10.35 \sqrt{p} \tag{1}$$

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 problems 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. The results obtained using their equation were compared to those obtained by Horne's equation (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 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-textures 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 the hydroplaning of heavy vehicles fitted with smooth tires which are 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

Four different pavements have been selected for this study. The first pavement studied was a burlap drag finish concrete surface with an average surface texture of 0.018 in. as measured by the silicone putty method. This pavement was considered to be typical or similar to concrete pavements presently in use. The second pavement tested was a bituminous surface treatment (seal coat) with rounded river gravel, stone size between -5/8 in. and +No. 4 sieve used as cover stone. The average texture of this surface was 0.146 in. measured by the silicone putty method. This high texture composed of fairly loosely bound aggregate is obviously impractical for use on high speed roadways but was chosen simply to show the effect of increasing the macrotexture. A hot mix asphalt was used as the third pavement. An average texture of 0.033 in. was measured by the silicone putty method. This pavement was chosen as one that was similar to those presently in use. The final pavement tested was a clay filled coal-tar emulsion surface (Jennite). This surface had a texture of 0.020 in. as measured by the silicone putty method. This surface was chosen because it was felt that it was similar to a bleeding asphalt pavement or a worn wheel rut.

It should be noted that by measuring the texture by use of the silicone putty method only the macro-texture is indicated. It is impossible to show the magnitude of the micro-texture when using this method. This is shown by the fact that pavement three, the jennite surface has a higher texture than the concrete pavement, surface one. The concrete pavement has a very gritty feeling texture while the jennite is smooth. It is felt that microtexture plays an important part in the reduction of hydroplaning but no quantitative measure of its effect was made in this study. It is possible however to make inferences from the data obtained.

Water Depths

Various water depths were considered and values were selected so that the influence of this variable could be evaluated. The water depths studied on the concrete surface varied from 0.12 in. to 0.70 in. This is a very wide range, with the upper limit being rather impractical, but studied to see just how much effect the water depth had on spin-down and if there was a point past which it had no effect. The depths selected for the bituminous surface treatment (seal coat) varied from 0.25 in. to 0.70 in. This range was considered because when using water depths below 0.25 in. on this particular surface it was extremely difficult to obtain any data, the main reason being that the speeds necessary to cause spin-down at the lower water depths were not achievable with the test vehicle. On the third and fourth surfaces the water depth was varied from 0.12 to 0.40 in. It was found that this is a more realistic range of water depths and that there were ample data produced using these values.

Tire Inflation Pressures

Tire inflation pressures varying from 18 psi to 36 psi in 6 psi increments were selected for evaluation on all four pavements. It was felt that this range of values was not only representative of pressures found in the tires of most ground vehicles, but would also provide an adequate variation or range for studying the effect of the variable. Pressures higher than 36 psi were not selected because the tow vehicle was unable to attain speeds high enough to produce meaningful data.

Wheel Load

Wheel loads of 800 lb. and 1,085 lb. were selected for evaluation on the concrete pavement. The load of 1,085 lb. was used as the basic test weight. This was done because of its specification as the ASTM skid trailer standard. The 800 lb. load was used on the last two tires tested on the concrete surface. This weight was chosen because it was felt that it represented a realistic wheel load and also because it provided enough variation to observe the effect of this parameter. Only the 1,085 lb. load was used when testing the other three surfaces 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 in a sloped trough (0.88'/100') 800 ft. long, 30 in. wide, and 4 in. deep and is shown in Figure 1. The construction procedures and specifications for this facility can be found in reference 51. Because of its configuration and water supply, there was no difficulty encountered in obtaining water depths of 0.7 in. above the pavement asperities. Even though a perfectly level surface was desired, variations in the trough existed. Therefore, in order to better interpret the data, water depths were taken at several points in the trough, as shown in Figure 2. The variation of water depths was most pronounced for the bituminous surface treatment.

It is difficult to obtain constant conditions when performing tests in the open. Therefore, the data contain the influence of temperature and varying winds. Experimentation was halted whenever wind speed was greater than 15 mph. It was felt that this would cause variations in the water depth that would affect the data. It has been observed that wind speed below this point did not affect the data in any way.

The tow vehicle and instrumented test trailer are shown in Figure 3 and a photograph of a typical test is shown in Figure 4. As can be seen from these photographs, the tow vehicle is positioned so as to straddle the trough, while the test trailer is offset so that the left tire of the trailer is positioned in the trough. The ground speed from the fifth wheel and the speed of the test wheel in the trough 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. From this chart the two ground speeds can be compared and the percent spin-down calculated. The fifth wheel or vehicle speed is also displayed to the driver on a digital voltmeter.

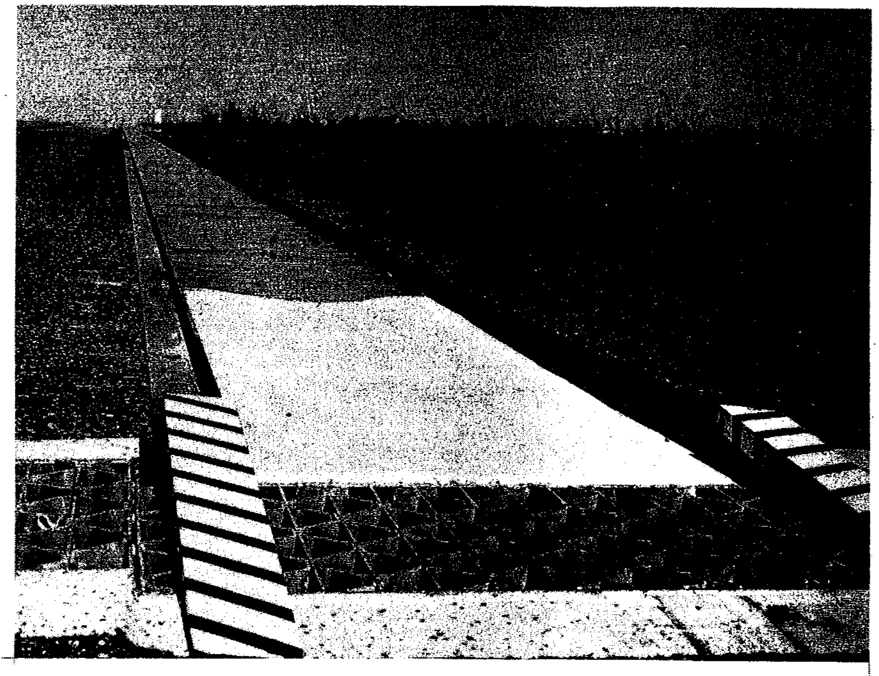

Figure 1. Texas Transportation Institute's Hydroplaning Trough

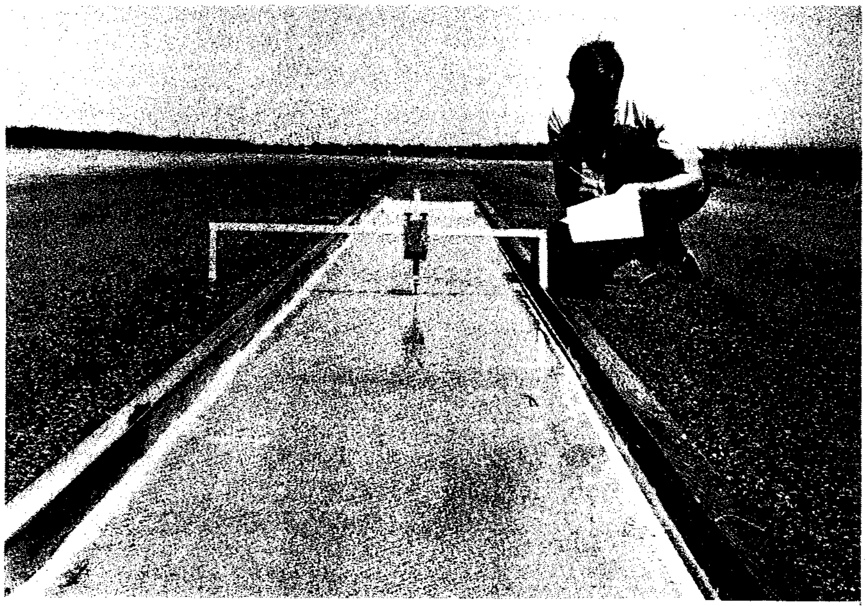

Figure 2. Typical Water Depth Reading Taken Before Test on Hydroplaning Trough

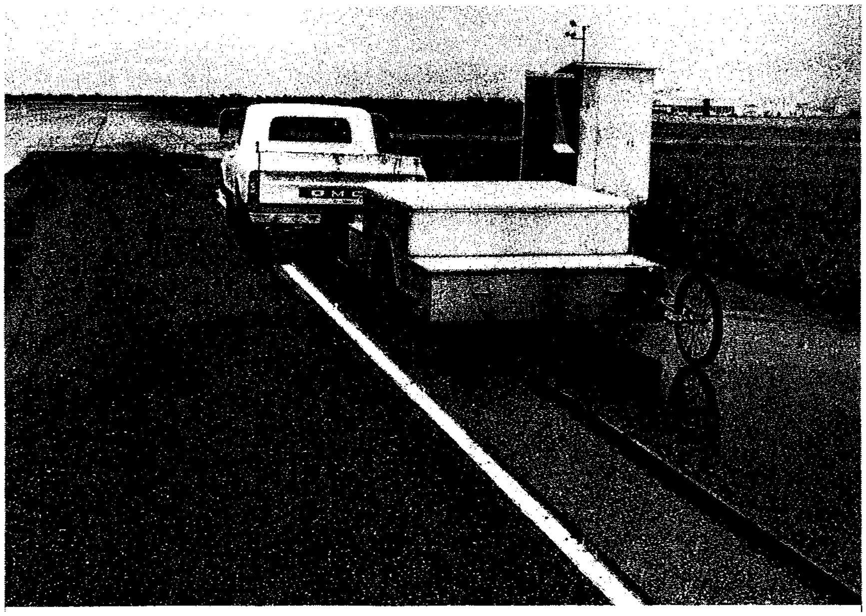

Figure 3. Tow Truck and Instrumented Test Trailer

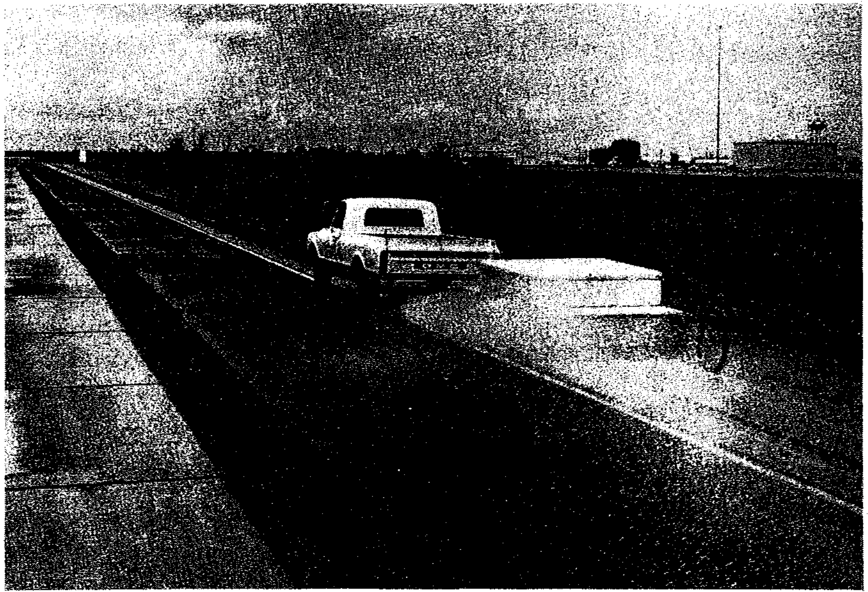

Figure 4. Typical Test Run on Hydroplaning Trough

DISCUSSION OF RESULTS

As defined by Horne (26), the critical hydroplaning speed is that speed at which the hydrodynamic uplift force is in equilibrium with the load carried by the tire. At this speed the tire is being supported completely by the layer of water. However, this is not the speed at which spin-down is initiated. In fact, spin-down can be initiated at speeds considerably below the critical hydroplaning speed. According to Reference 26, in tests run on tandem wheels, spin-down was initiated at speeds that were 70% the value of the predicted hydroplaning speed. In a later report (12), Horne restates this conclusion and also states that total spin-down (wheel stops rotating) can take place between 80% and 120% of the predicted hydroplaning speed. These data were obtained from tests run on aircraft tires.

However, it is dangerous to use spin-down as the only criterion for the determination of hydroplaning. As pointed out by Horne (12), as speed is increased above the critical hydroplaning speed, there is less tire-fluid exposure time due to increased speed and a more uniform hydrodynamic pressure exists in the contact zone. Rather than having the center of force in the forward portion of the contact zone, it has moved toward the center of the zone, thus shortening the moment arm and reducing the amount of spin-down. A similar situation exists for the water skier. As he is being pulled in the water, the force is being exerted more near the tips of the skis, however, as he comes to a plane, the uplift force is positioned more toward the middle of the skis. Therefore, one should not be trapped into the fallacy that if there is no spin-down there is no hydroplaning. Spin-down is only one indication of the hydroplaning phenomenon. Other things such as coefficient of friction and appearance or disappearance of the bow wave should also be considered when determining the hydroplaning speed.

For the experimentation conducted on the Texas Transportation Institute's hydroplaning trough, wheel spin-down was the only criterion used to indicate loss of tire-pavement contact. Because of this, it was decided to evaluate the pavements studied and discuss the effects of the variables on the basis of percent spin-down. By the term percent spin-down, it is meant the amount the test wheel relative ground speed has slowed down in relation to the vehicle spee

Attempts were made to best present the data. It was finally decided that the most effective method would be as a plot of vehicle ground speed vs percent spin-down, showing the plots of the various tire inflation pressures tested. Also, when further comparisons were desired, it was easy to obtain the necessary information from these plots.

Figures 5 thru 18 are examples of these plots. These figures display wheel spin-down characteristics for various tires, surfaces, tire pressures, water depths, tread depths, and vehicle speeds. One of the most notable trends is the effect of tire inflation pressure. As the inflation pressure is increased, the speed required to cause a certain amount of spin-down is also increased. Figure 5, for example, shows that by increasing the inflation pressure by 6 psi, the speed required to cause 10% spin-down is increased by about 4 mph. However, decreasing the tire pressure not always decreases the speed at which a given amount of spin-down will occur. As can be seen in Figure 5 and several others, there was no spin-down obtained at 18 psi for speeds up to 64 mph. It must be remembered, however, that wheel spin-down is only an indication of hydroplaning or tire-pavement contact loss. One explanation for the lack of spin-down is that as the inflation pressure is decreased, the contact area is enlarged. With this enlarged zone, the pressure profile is less uniform and the spin-down torque is decreased to the point where partial hydroplaning can occur without spin-down. Also, once the tire is completely supported by the water layer, the pressure profile is more uniform which causes a decrease or disappearance of spin-down. The phenomenon of decreasing spin-down with increasing speed is shown in Figures 12 and 17. This was normally observed for an inflation pressure of 18 psi, but was also noticed occasionally at a pressure of 24 psi. It is therefore unjustified to assume that if a tire has not spun-down it has not lost pavement contact, in the lower range of inflation pressures. In such cases, it may be helpful to perform skid tests at varying speeds to determine at what speed the coefficient of friction reaches minimum value. At this speed, the tire is hydroplaning.

Figures 5 thru 18 exhibit another interesting point. It should be noticed that each family of curves for a certain tire and water depth are approximately parallel. This was true in all instances. In fact, the curves for the same tire, even as the water depth was varied, showed a similar slope. This would indicate that each tire has its own "hydroplaning characteristics". For example, the steeper the curves the less sensitive the tire is to increases in speed. The closer grouped the curves the less sensitive the tire is to tire inflation pressure changes.

Figures 19 thru 30 are plots of tire inflation pressure vs. ground speeds at 10%, 32% and 60% spin-down. These plots are compared to the equation for critical hydroplaning velocity presented by Horne in reference 26 (i.e. $V_{CR} = 10.35 \sqrt{P}$) where P = tire inflation pressure in psi. Figures 19, 21, 22, and 25 thru 30 show comparisons of tires with full tread depths with Horne's equation. In all cases the experimental plots are parallel with each other, but not necessarily parallel with plots of other tires. This again indicates the possibility that the tires may possess individual characteristics which may affect the speeds at which they hydroplane. These full tread depth tires require comparatively high speed to cause spin-down. Therefore, simply becuase a plot is to the right of the NASA equation does not mean that the tire is definitely hydroplaning. It simply means that the speed required to cause a certain amount of spin-down is higher due to the tire's construction and that there has been at least a partial loss of pavement contact.

Figures 20 and 23 compare the results obtained for a smooth or worn tire with Horne's equation. For these plots, even when total spin-down was compared to the equation, the speeds were far below those predicted. It should also be noticed that the slopes differ from that of the NASA equation. Also, it has been observed that the slopes are affected by the test surfaces. However, the slopes of these plots do not seem to be affected by the water depths at which the tests were run. The water depth did effect the positioning of these plots, that is, it affected the speed at which a certain amount of spin-down would take place. But, as stated by Horne (26), the speeds for even 10% spin-down are within 70% of the speeds predicted by the equation.

As can be seen from the above observations it would be extremely difficult, it not impossible, to derive an equation for hydroplaning velocity that would fit all tires under varying conditions. Horne has done an exceptional job, even though, as he admits, his equation if very limited But the agreement of the data presented with his equation is quite encouraging.

Figures 31 thru 42 are plots of water depth vs. ground speed at which 10% spin-down will occur and are also used to make various comparisons.

Figures 31 and 32 show the effect of varying the wheel load from 800 lbs. to 1085 lbs. The results for the smooth tire are plotted on Figure 31 and indicate that increases in the wheel load increases the speed necessary to cause 10% spin-down. However, the results for a tire with a full tread depth, plotted in Figure 32, indicate the reverse takes place. These data would indicate that the hydroplaning speed is less dependent on wheel load than other variables. The weight was held constant at 1085 lbs. on all other surfaces tested.

Figure 33 shows a comparison of tire No. 4, the F70-14 wide tire, with tire No. 7, a 775-14 bias ply. As can be seen the bias ply tire required higher speeds to cause the same amount of spin-down obtained with the wide tire. This trend was observed on all surfaces tested. These results are in agreement with the findings of other researchers which indicate that the hydroplaning speed decreases as the tire width increases. In other words, the wider the tire, the lower the speed to cause a given amount of spin-down, all other things being equal. This is a fairly obvious conclusion. Returning to the water skier, it is much easier to come to a plane using an aquaplane than two skis, or using two skis than a single ski. The more surface area available, or the larger the contact area, the easier it is to hydroplane. This same trend was observed on all pavements tested.

Figure 34 clearly demonstrates the effect of tire tread depth on spin-down. The data shown are for bias ply tires similar in all aspects but that of tread depth. As can be seen, the speeds to cause spin-down for the worn tire are considerably lower than for the fully treaded tire. In some cases, the difference was as great as 11 mph. Since the tire tread acts as a channel for escape of the water trapped beneath the tire, this is a very important variable. When the tread is worn smooth, there is no drainage but through the voids in the pavement surface. This type of drainage can prove to be ineffective at high speeds which increases the importance of tread depth.

A comparison of the pavements tested is shown in Figures 38 thru 40. As stated previously, the textures for the four pavements tested were 0.018 in., 0.146 in.,0.033 in., and 0.020 in. respectively as measured by the silicone putty method. As can be seen from Figure 38, the speeds to cause spin-down on the bituminous surface treatment (No. 2) are much higher than for the concrete surface (No. 1). In fact very scant data were obtained at depths below 0.70 in. for all tires tested on the bituminous surface. The speeds at which spin-down occurred on the concrete pavements are well below those travelled on high speed roadways. The data presented are those obtained from a bias ply tire with a full tread depth. Figure 39 is a similar comparison using the data obtained from the F70-14 wide tire with a full tread depth. Again, the speeds to cause spin-down on the bituminous surface were higher. Even the speeds to cause spin-down at 0.70 in. on the bituminous surface were higher than those to cause spin-down at 0.40 in. on the concrete surface. These comparisons effectively emphasize the importance of texture.

Figure 40 is a comparison of surface 1 (concrete) with surface 3 (hot mix asphalt). Even though the asphalt pavement was shown to have a higher texture than the concrete (0.033 in. as opposed to 0.018 in.), the speeds necessary to cause spin-down are lower on the asphalt pavement. The reason for this could be the fact that the asphaltic pavement is a rolled surface. Because of this, the texture is comprised of voids in the surface rather than asperities projecting above the plane of the surface. Also because these voids are possibly not inter-connected, they provide no real escape paths for the water trapped beneath the tire.

By comparing surface 3 and 4 shown in Figure 41, it can be seen that the speeds to cause spin-down are higher for the asphalt surface. This result is to be expected. The Jennite surface is a smooth one with very little texture exposed. It is a rounded surface with little or no grittiness and offers poor drainage for trapped water. This surface would be similar to a wheel rut or a bleeding asphalt pavement. It was observed, however, that the speeds to cause spin-down on the Jennite surface were higher than expected in some cases. It is possible that the test tire was actually hydroplaning, thus making the pressure profile more uniform and decreasing the amount of spin-down observed. Further testing would have to be performed in order to determine the cause.

In deriving his equation, Horne neglected the effect of water depth on hydroplaning speed. In this way he implied that as long as the asperities are covered, hydroplaning will occur at a certain speed depending on the tire pressure. From the data collected here it seems that the effect of water depth is more pronounced for some surfaces and tires than for others. Figure 37 shows that increasing the water depth on surface 4 (Jennite) has little effect on the speed at which spin-down occurs. Increasing the water depth on surface 3 (hot mix asphalt) has the effect of decreasing the speed at 10% spin-down as much as 9 mph. (Figure 36) When comparing surfaces 1 and 3 (Figure 40) it can be seen that the water depth has about the same effect on both surfaces when the higher inflation pressures are concerned. But as the inflation pressures are decreased, the apparent effect of the water depth is decreased. There is no real consistency in this change however.

Figure 42 shows a comparison of the bias ply tires tested on surface 4. The speeds shown in these figures are for 10% spin-down, and are plotted against water depth. As can be seen, there is little agreement among the tires as water depth and tire pressure are varied. From the data presented, it appears that tire No. 7 yielded the best results in terms of speed at a given amount of spin-down. Similar results were obtained on the other surfaces tested. From these results it can be seen that even similar tires possess individual spin-down or hydroplaning characteristics. Since the configuration and composition of the tires should be basically the same, the difference could possibly be caused by the tread design. Both tires 1 and 7 have a basic 4 groove tread design. Tire 1 has a small, straight groove around the center of the tread pattern and a pattern of unconnected saw tooth cuts in the tread. This fact seems to be the big difference. Tire 7 also has a 4 groove tread pattern but has a more extensive pattern of cuts which are deeper, wider and inter-connected. Not only is there a continuous pattern of cuts, but it is also connected to the main groove design which allows exit of water from the treads into the cuts which has the effect of easing the pressure build up beneath the tire. Tire 5, on the other hand, is a 6 groove tread design but has no cuts in the treads and only limited siping.

The speed to cause a given amount of spin-down was dependent on a number of variables. The amount each of these variables affected the speed varied with different test conditions. Although there is no set amount that each variable affected the data, a general trend was observed.

In general, the degree of influence of the variables tested on the speed to cause spin-down, from most to least, is as follows: tread depth tire inflation pressure, texture and water depth. It must be remembered that this is simply a general trend and is subject to change depending on the tire tested.

From the electronic instrumentation data, it was observed that wheel spin-down began as soon as the tire came in contact with the water in the hydroplaning trough. The distance the trailer traveled before spin-down reached equilibrium varied as the speed of the vehicle varied. This is due to the time factor involved. In order for the spin-down to reach its maximum value, it is necessary for the spin-down moment to overcome the inertia of the rolling tire which takes a certain length of time. This time period is indicated as distance as the vehicle travels through the trough. For example, considering the bituminous surface treatment and using tire No. 4 with an inflation pressure of 24 psi and a water depth of 0.7 in. (see Figure 10) it took approximately 80 ft. to reach a spin-down of 20% when entering the trough at 48 mph. However, when entry speed was increased to 58 mph it took 240 ft. of travel before a spin-down of 78% was attained; after 80 ft. the tachometer generator traces indicated a wheel spin-down of approximately 20%. The important point here is that the tire is influenced immediately when it comes in contact with the water.

Therefore, it can be concluded that partial loss of pavement contact or loss of traction occurs as soon as the tire 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 is 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 43, 44 and 45 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 44. 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 44 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 45. 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 46 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 performed at the Texas Transportation Institute's Research Annex and the assumption 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. As the tire tread becomes worn, the drainage provided by the tread becomes less efficient and the speed to cause a given amount of spin-down is decreased. Speeds to cause spin-down on worn tires is considerably less than for tires with a full tread depth.
3. Decreasing the tire inflation pressure has the effect of increasing the area of the contact zone. The larger the area of the contact zone, the lower the speed to cause spin-down in most cases.
4. Increasing the tire width has the effect of decreasing the speed to cause a given amount of 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 water depth generally has the effect of decreasing the speed at which wheel spin-down is initiated.

7. An increase in the macrotexture of the pavement increases the speed at which spin-down is initiated. By increasing the macrotexture, the number of drainage channels is increased which makes the drainage of trapped water more effective.
8. An increase in tread depth also has the effect of increasing the effectiveness of drainage of water from beneath the tire and thus increases the speed at which spin-down is initiated.
9. Total spin-down (wheel stops rotating) may occur at speeds lower than those predicted by Horne's NASA equation.
10. 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.
11. 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

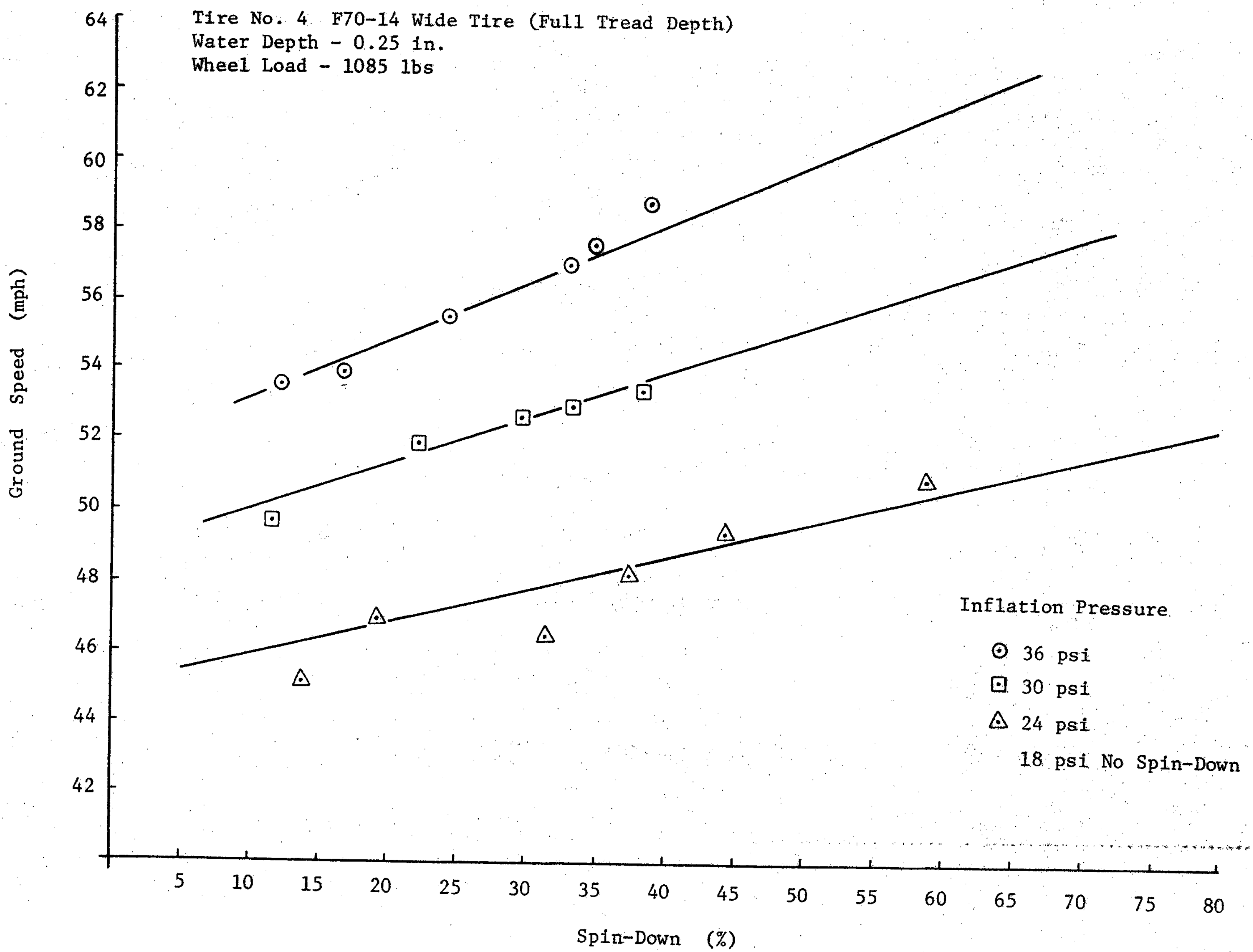


FIGURE 5. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR CONCRETE PAVEMENT.

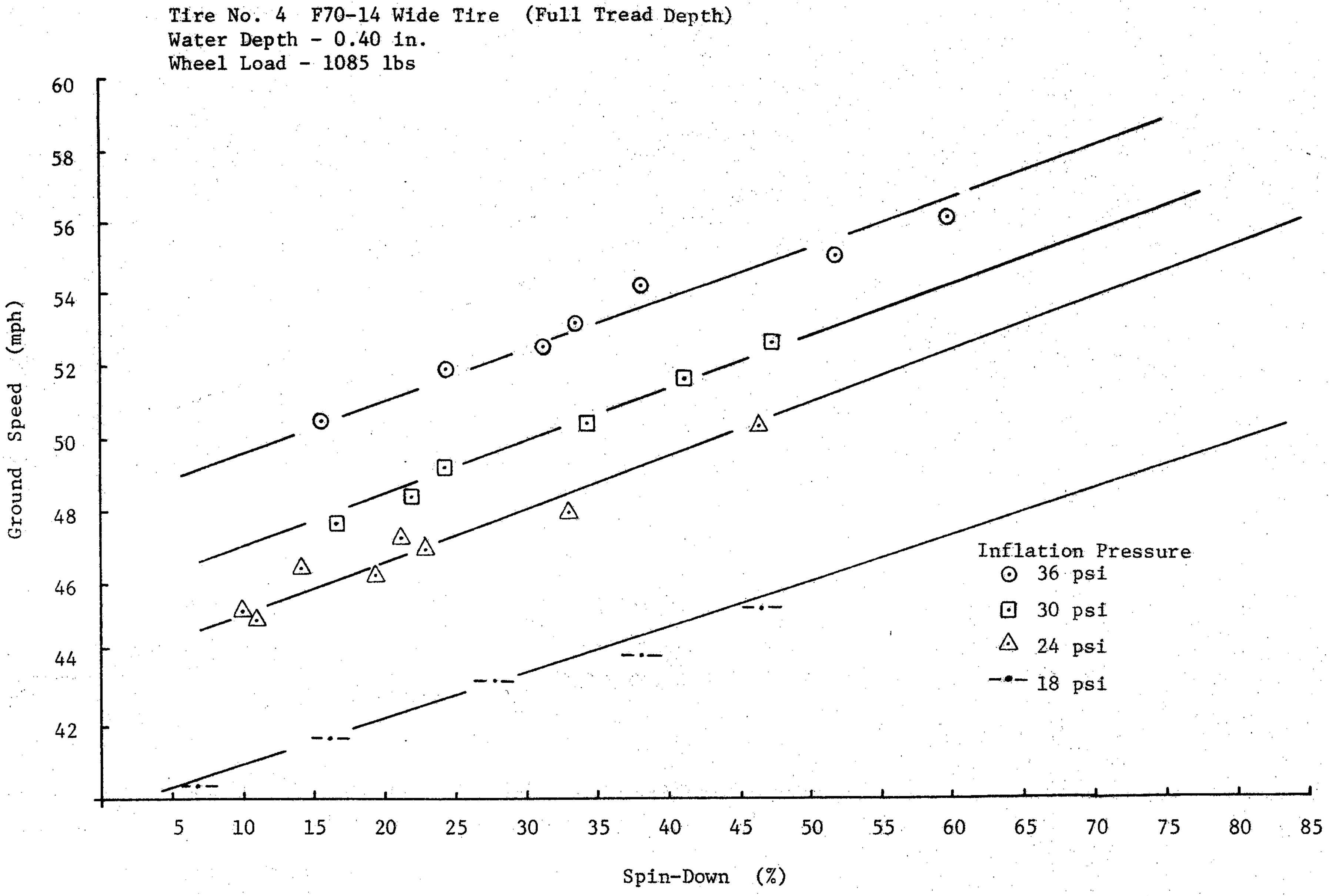


FIGURE 6. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR CONCRETE PAVEMENT.

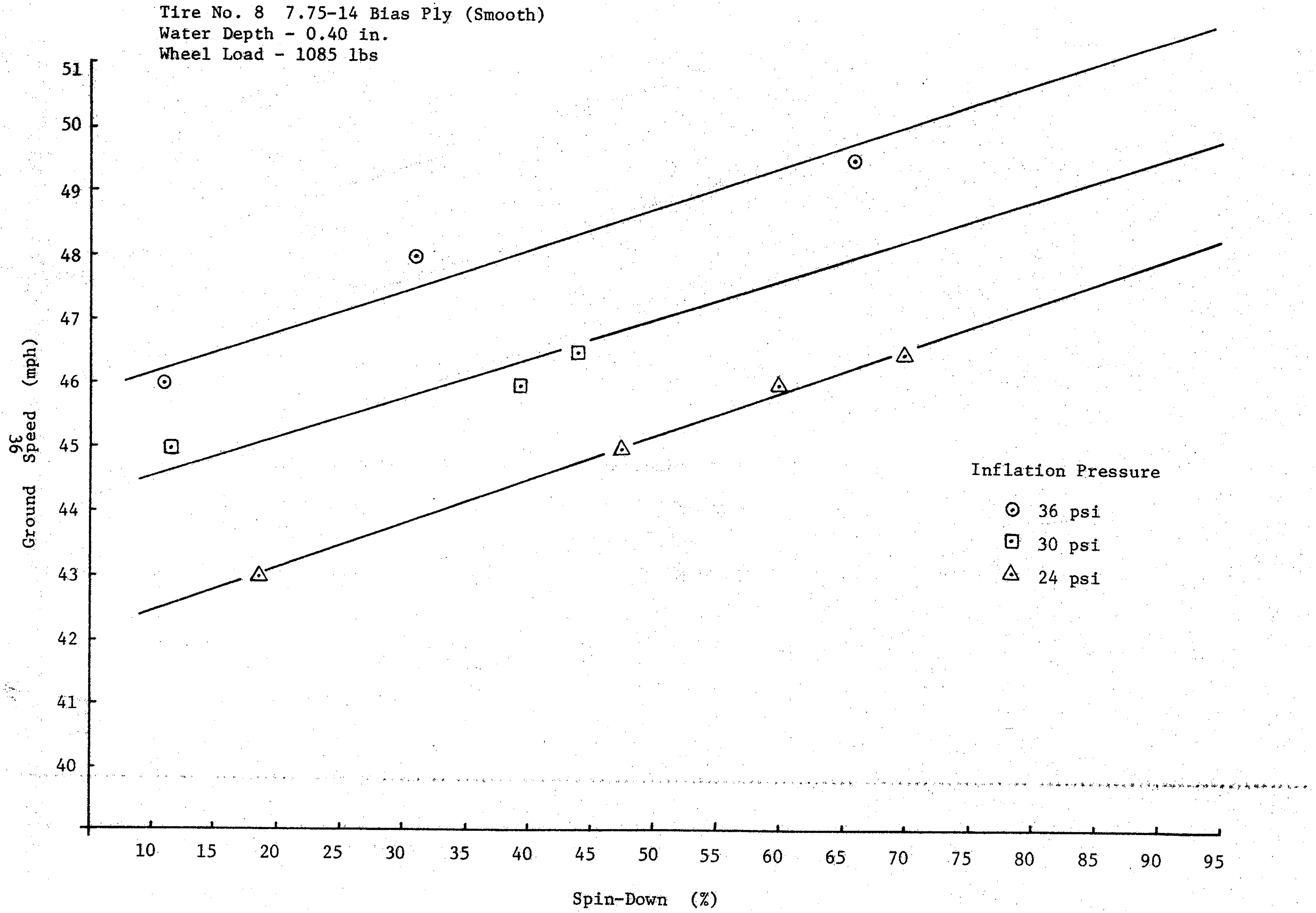


FIGURE 7. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR CONCRETE PAVEMENT.

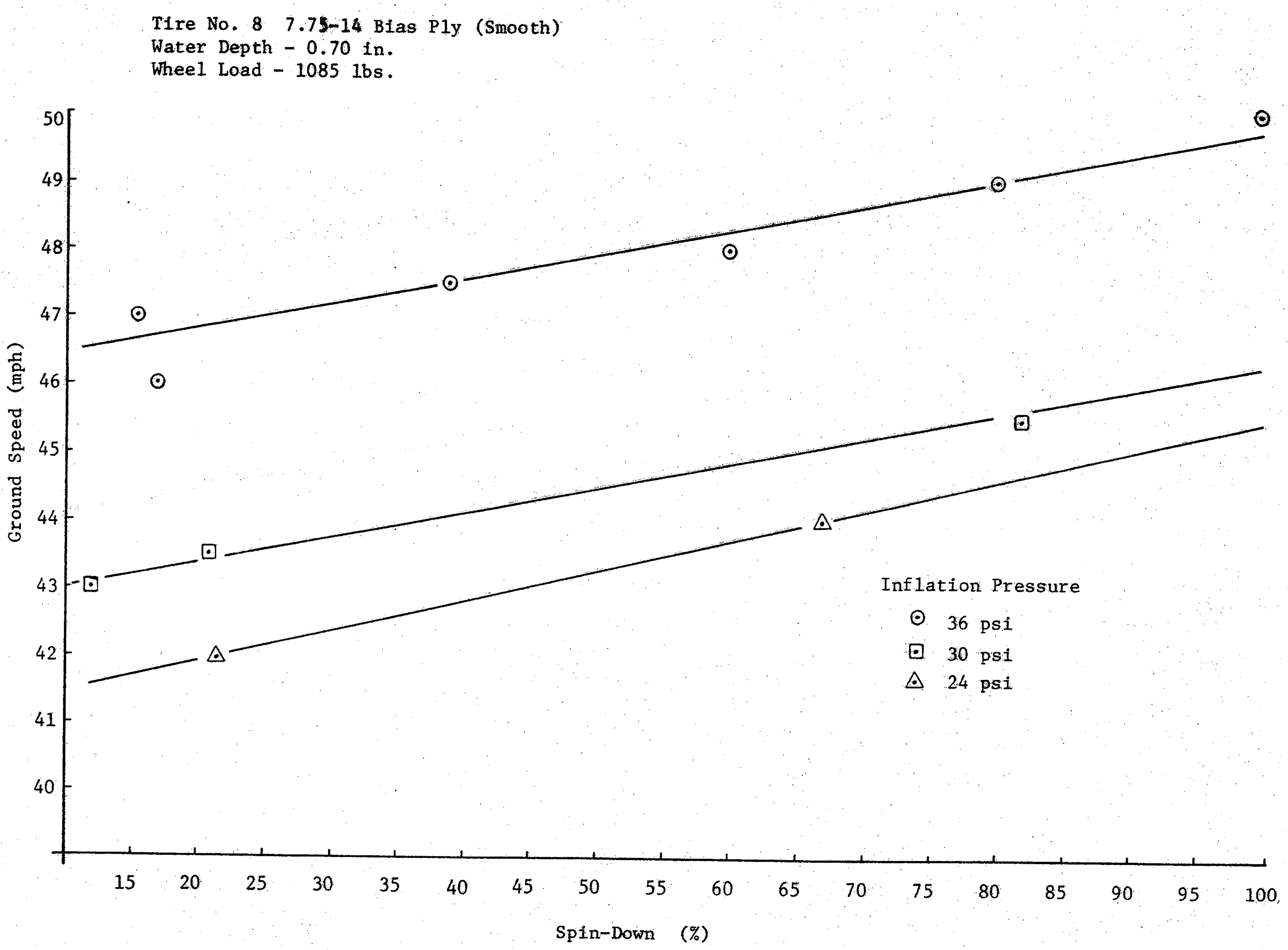


FIGURE 8. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR CONCRETE PAVEMENT.

Tire No. 4 F70-14 Wide Tire (Full Tread Depth)
Water Depth - 0.40 in.
Wheel Load - 1085 lbs

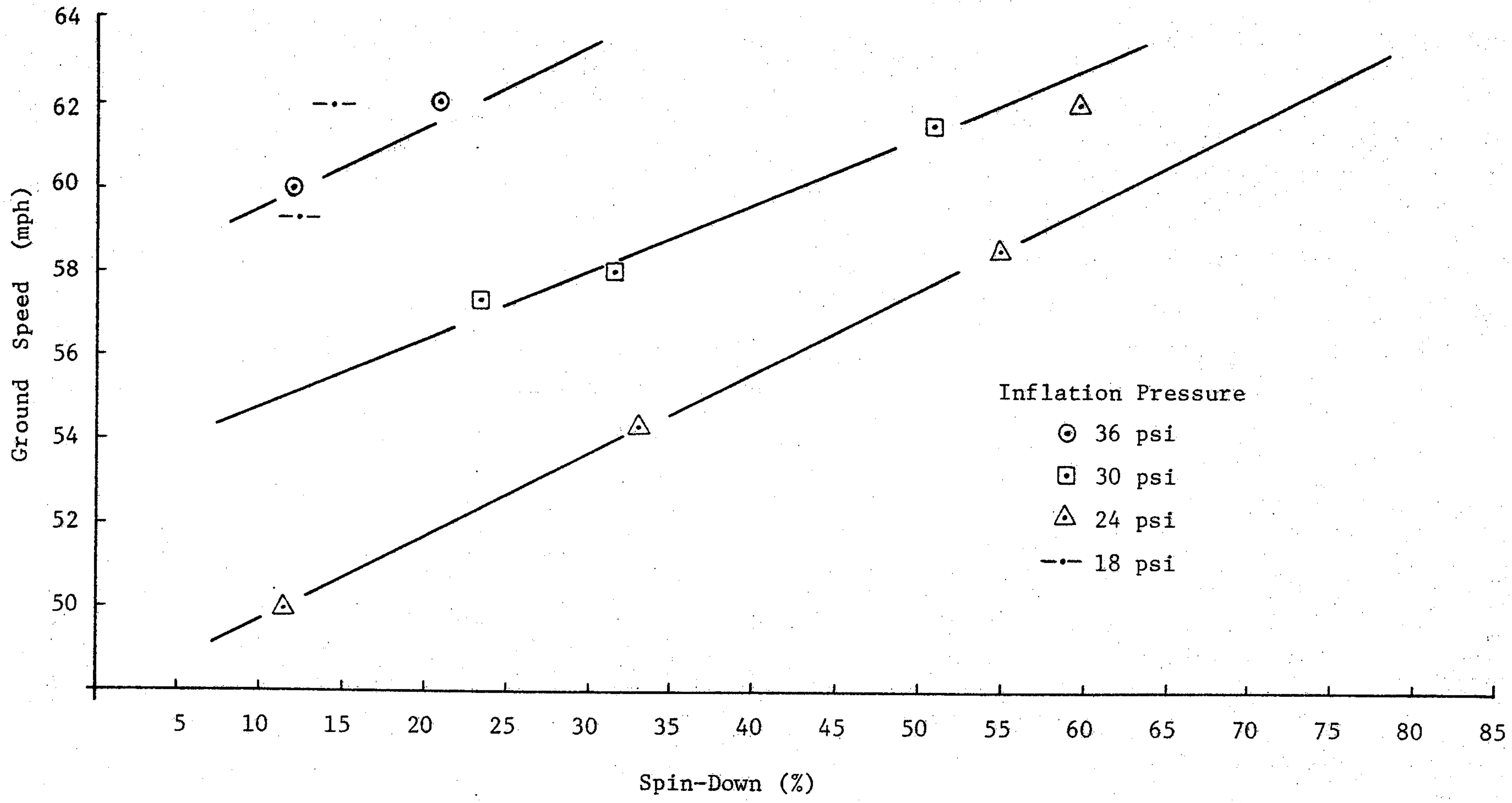
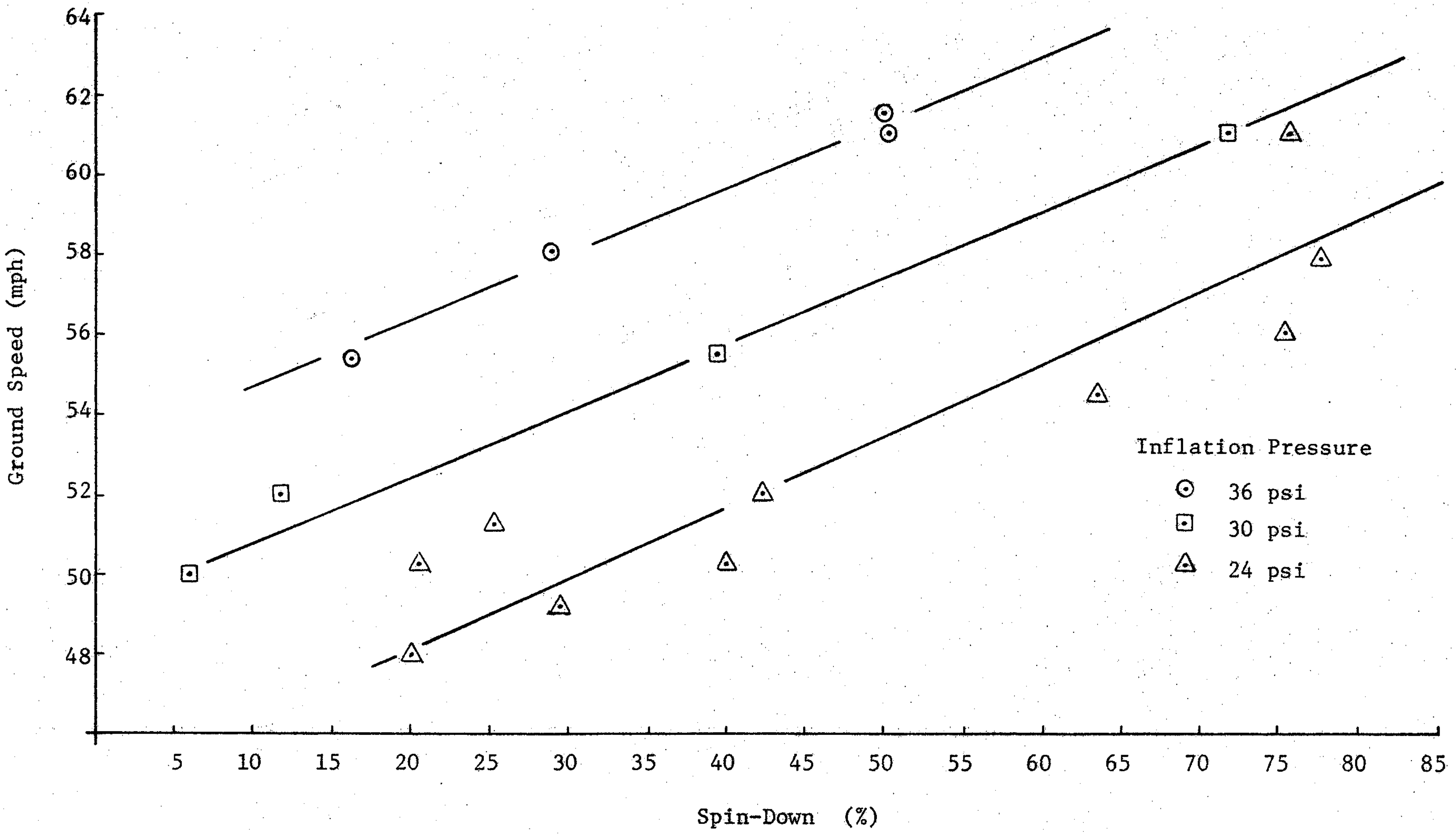


FIGURE 9. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR BITUMINOUS SURFACE TREATMENT.



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

FIGURE 10. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR BITUMINOUS SURFACE TREATMENT.

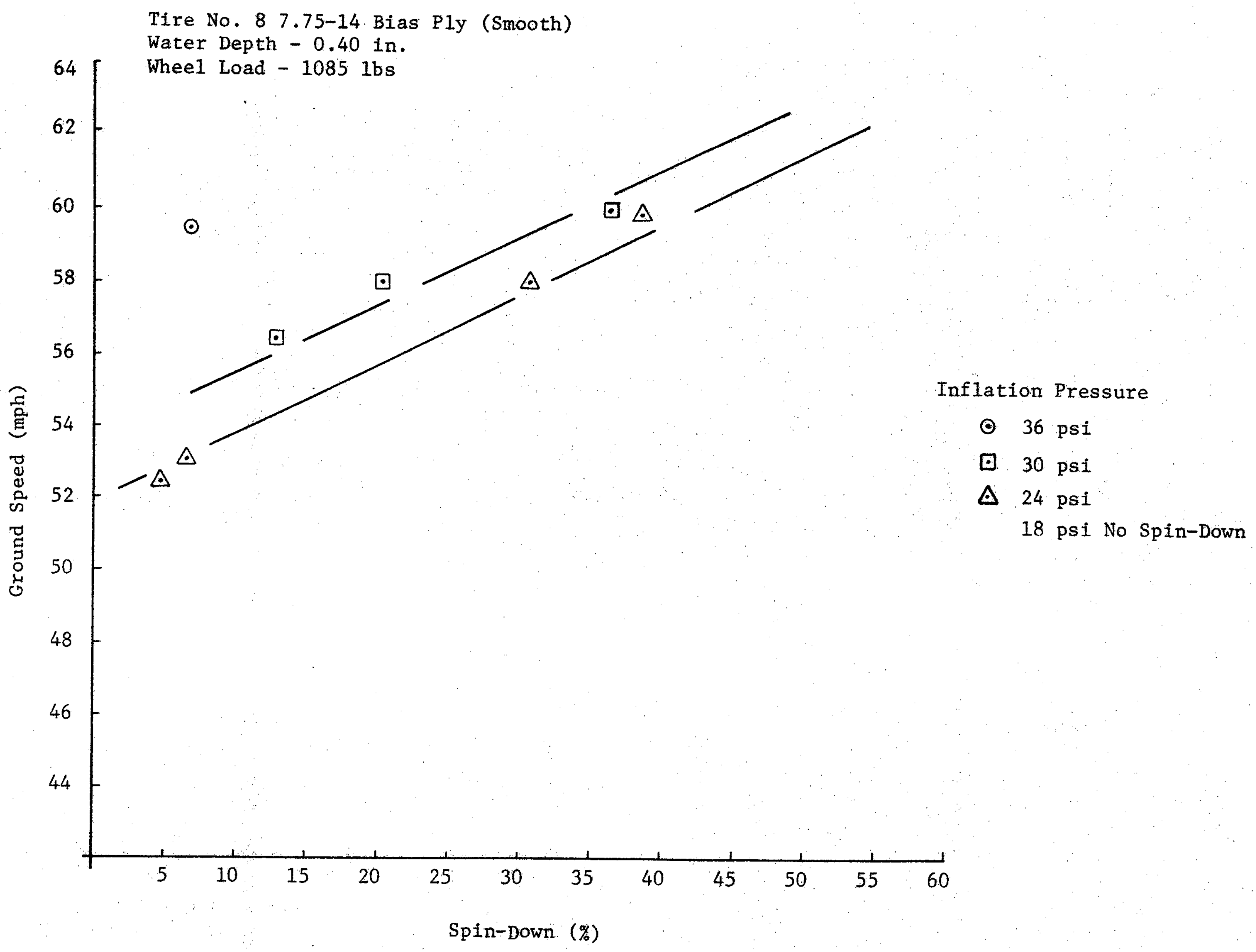


FIGURE 11. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR BITUMINOUS SURFACE TREATMENT.

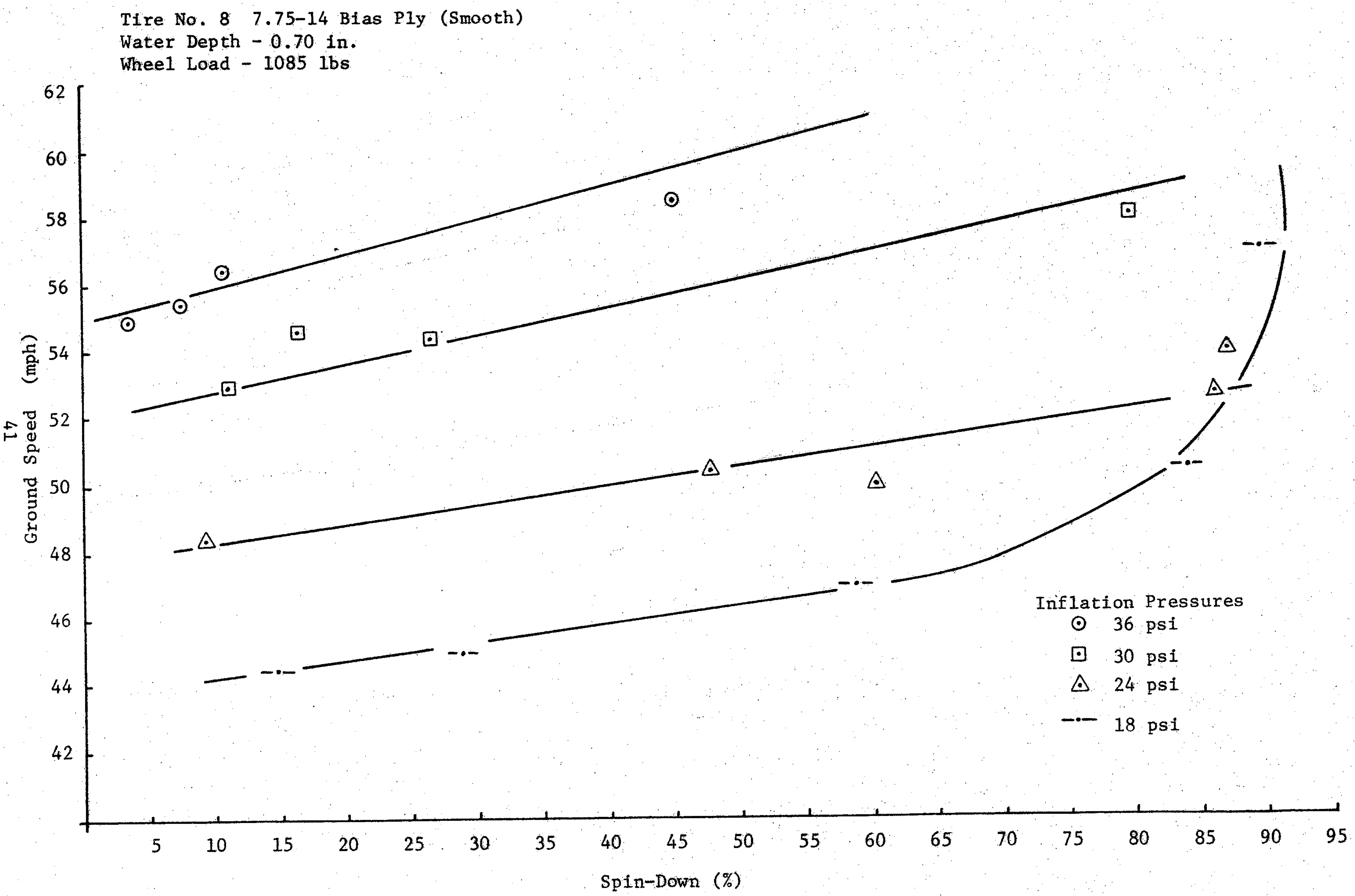


FIGURE 12. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR BITUMINOUS SURFACE TREATMENT.

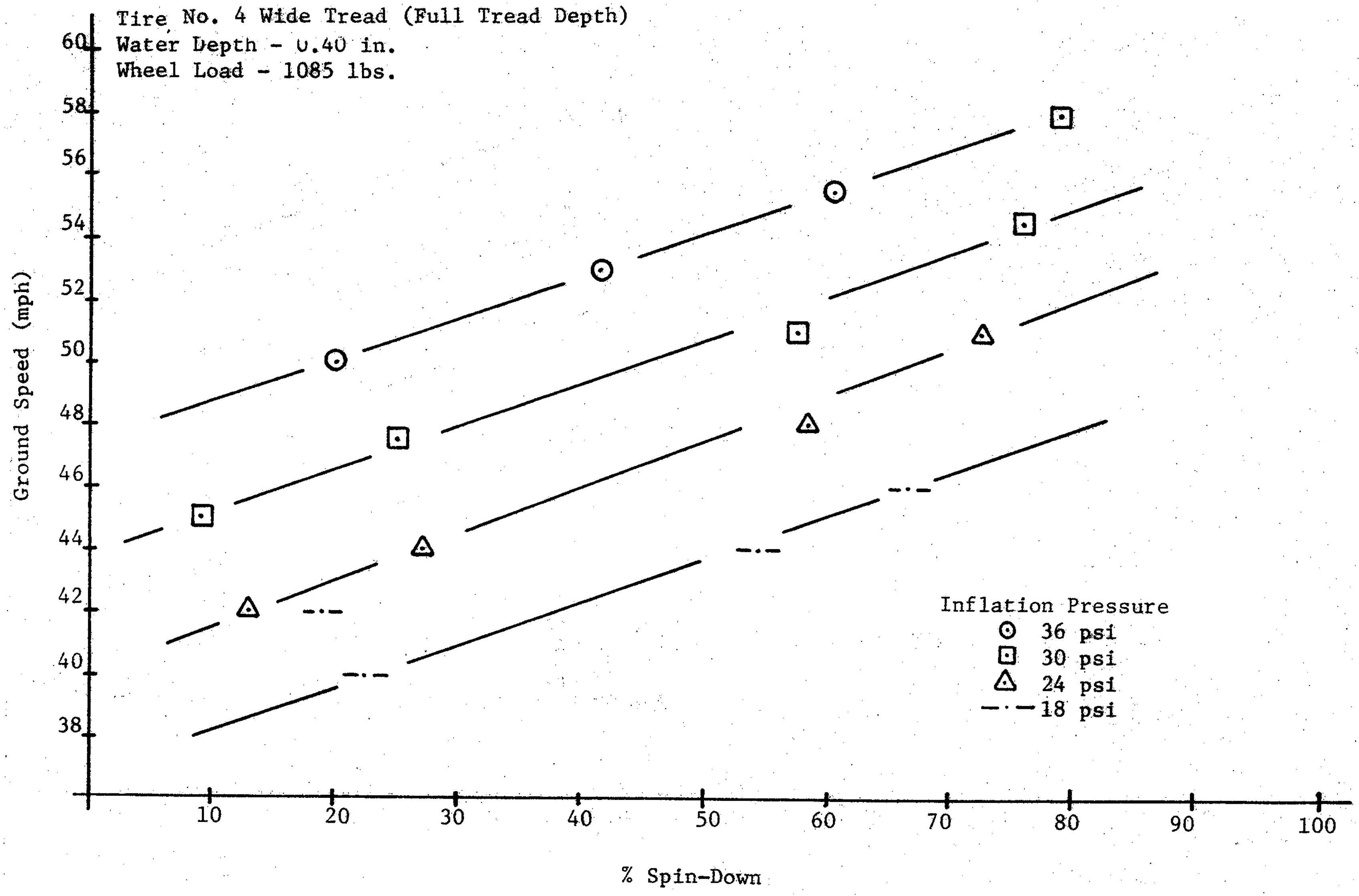


FIGURE 13. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR ASPHALT PAVEMENT.

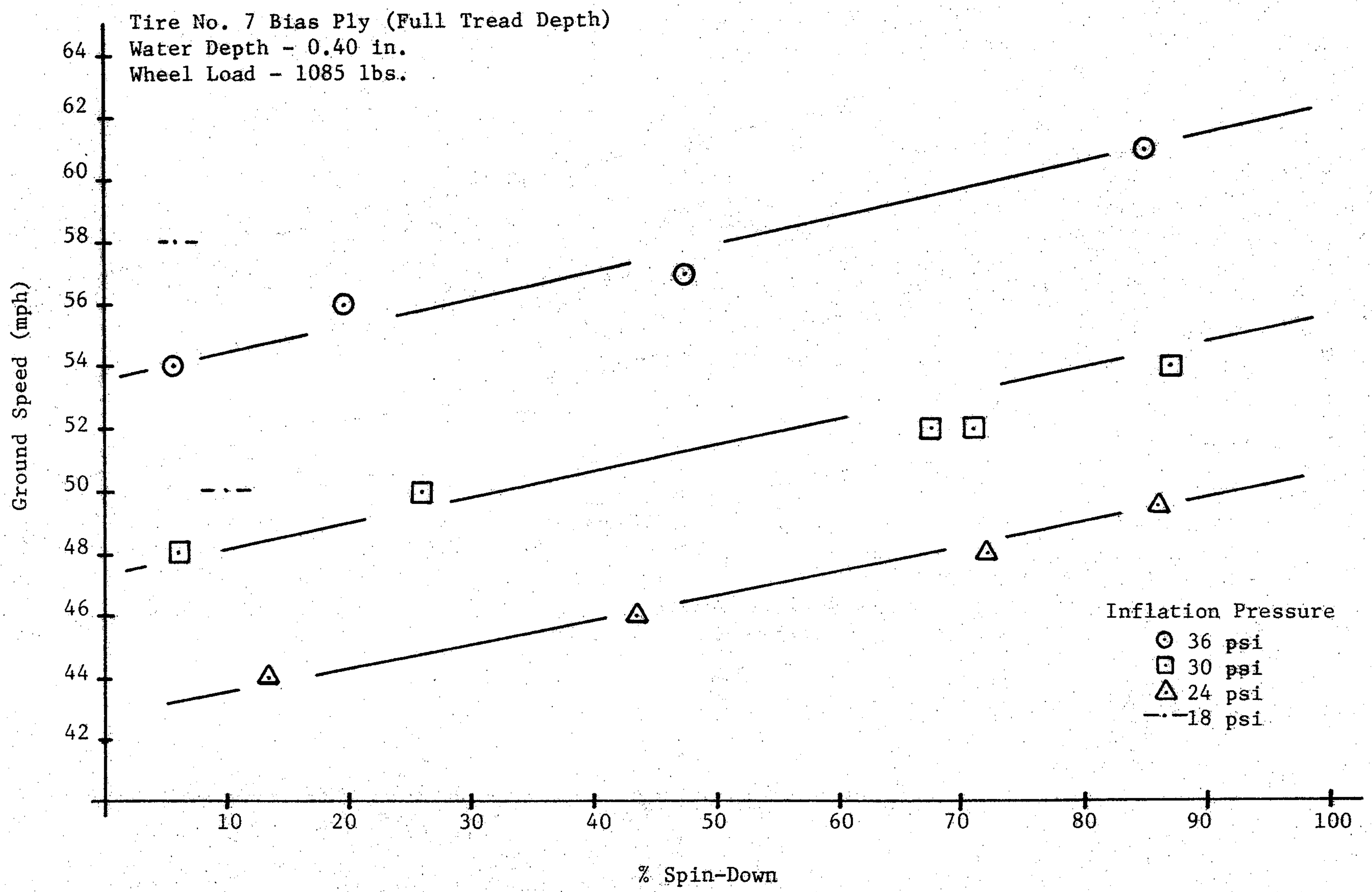


FIGURE 14. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR ASPHALT PAVEMENT.

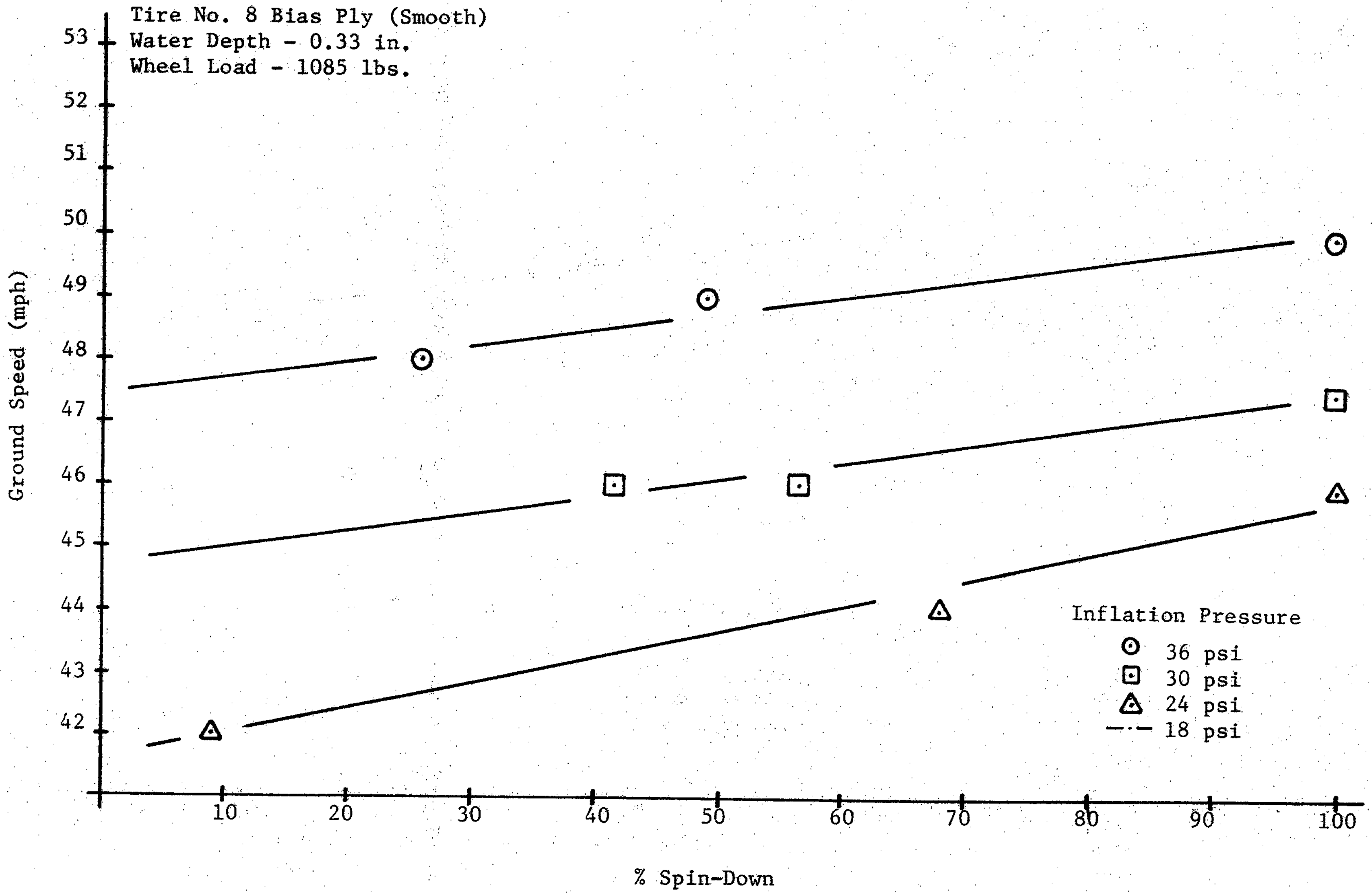


FIGURE 15. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR ASPHALT PAVEMENT.

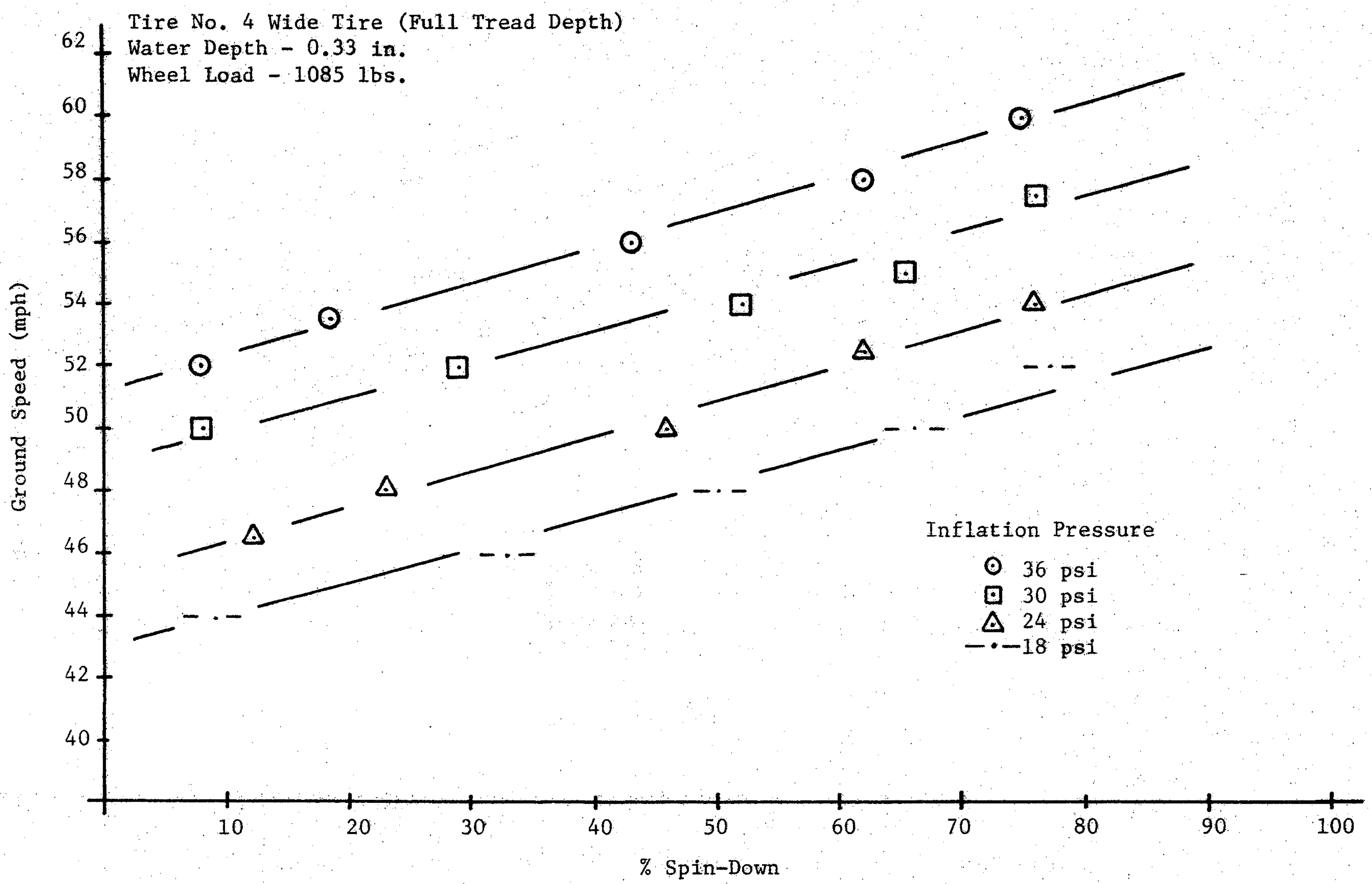


FIGURE 16. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR JENNITE PAVEMENT.

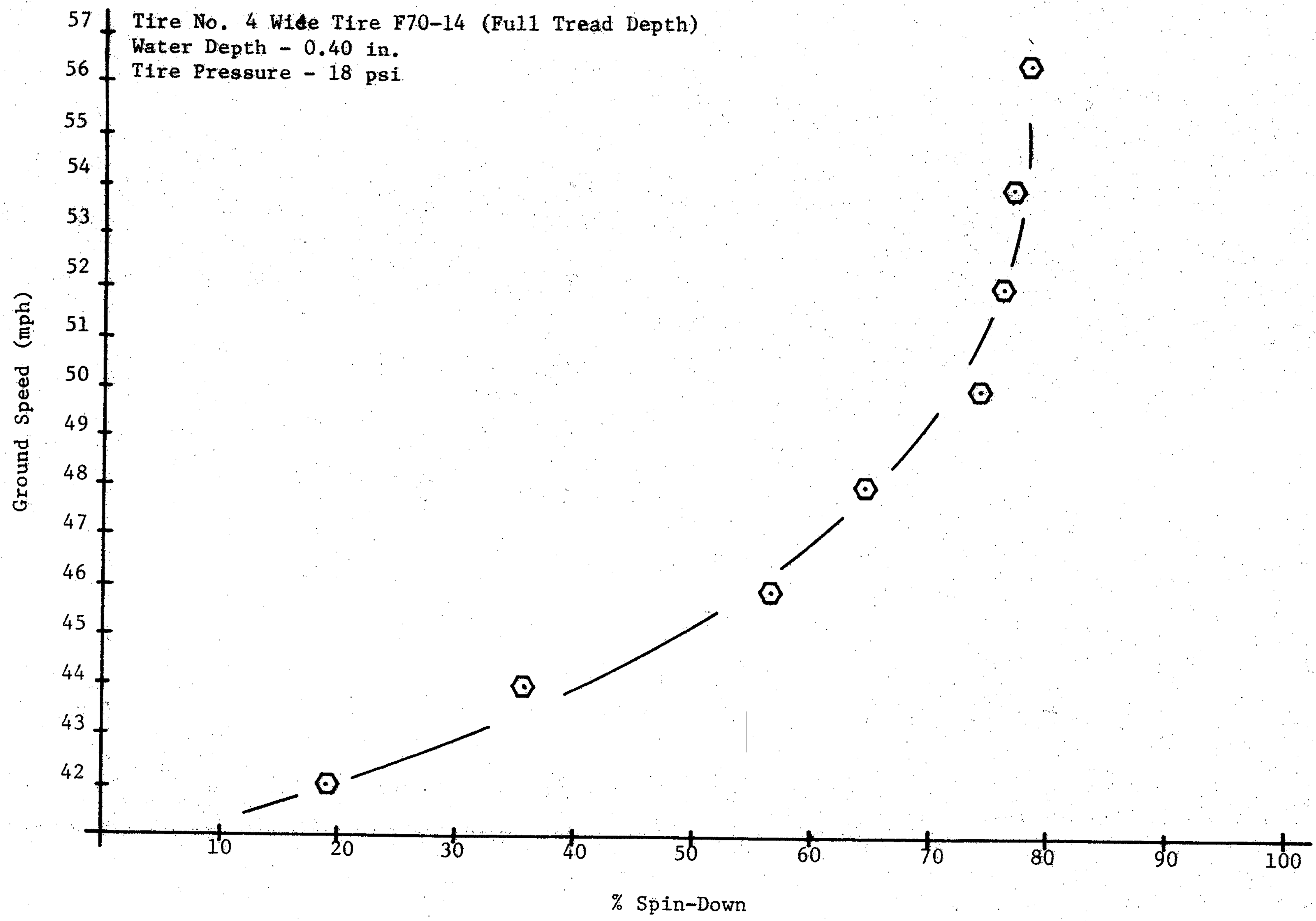


FIGURE 17. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR JENNITE PAVEMENT.

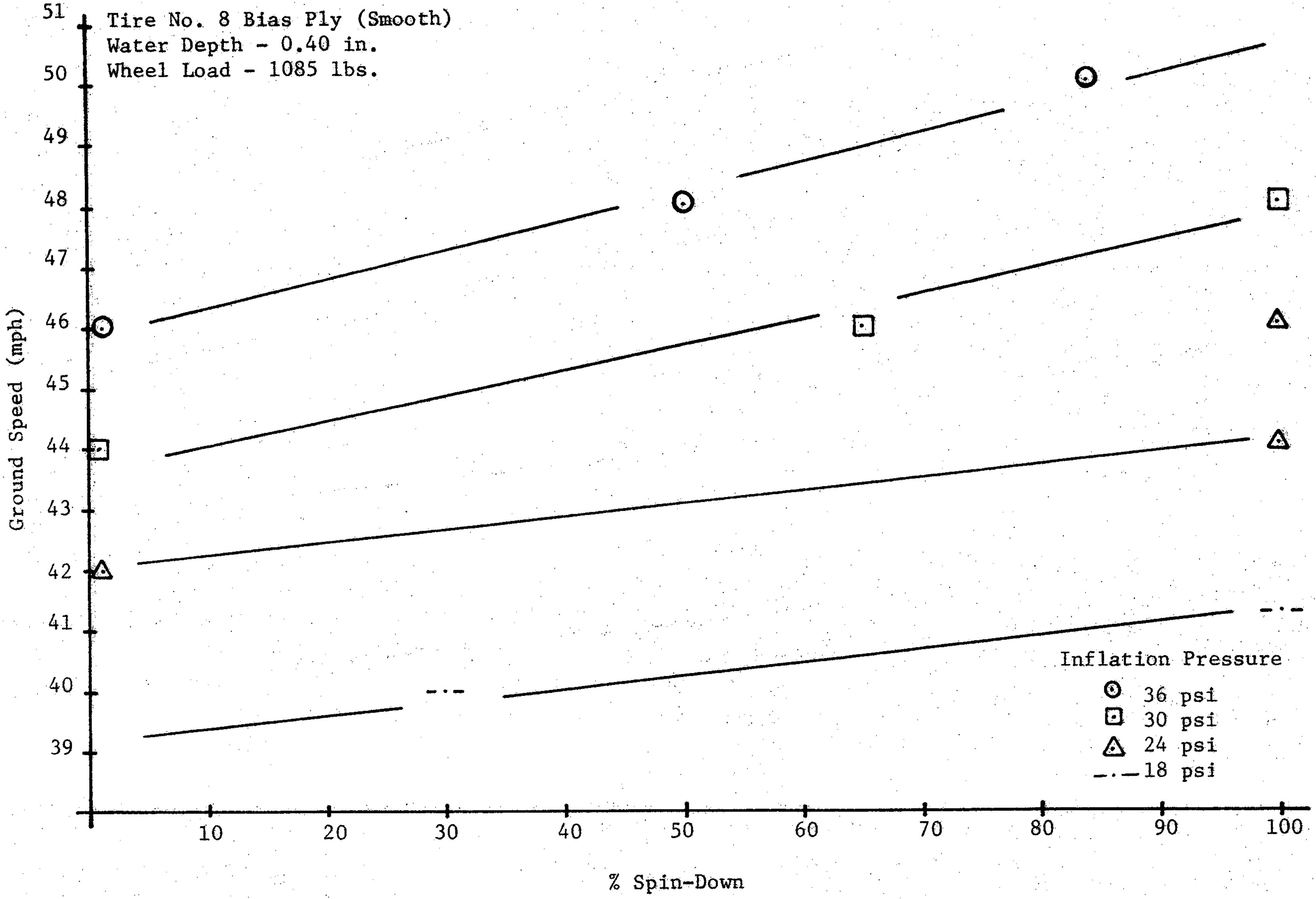


FIGURE 18. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR JENNITE PAVEMENT.

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

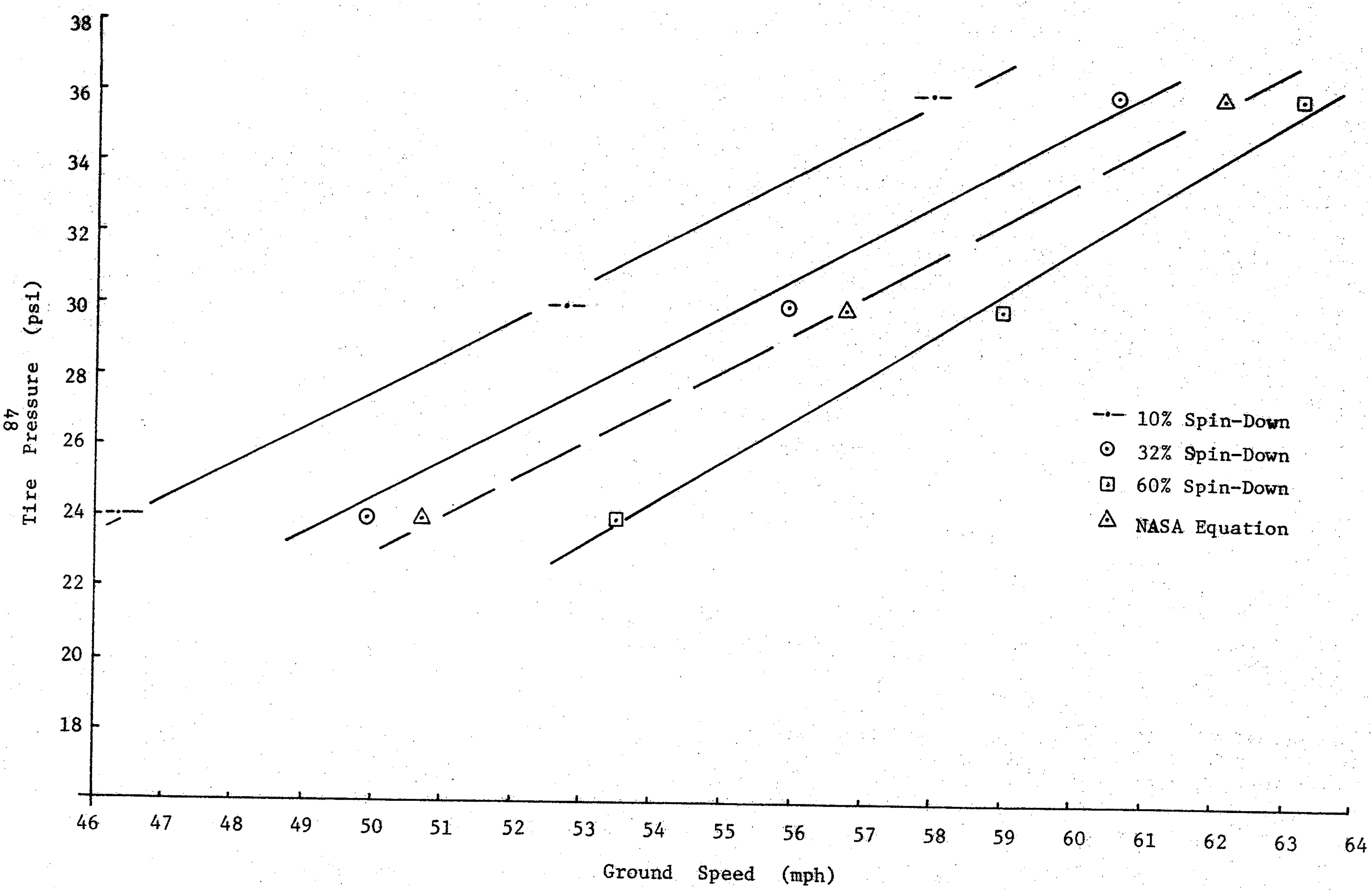


FIGURE 19. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR CONCRETE PAVEMENT.

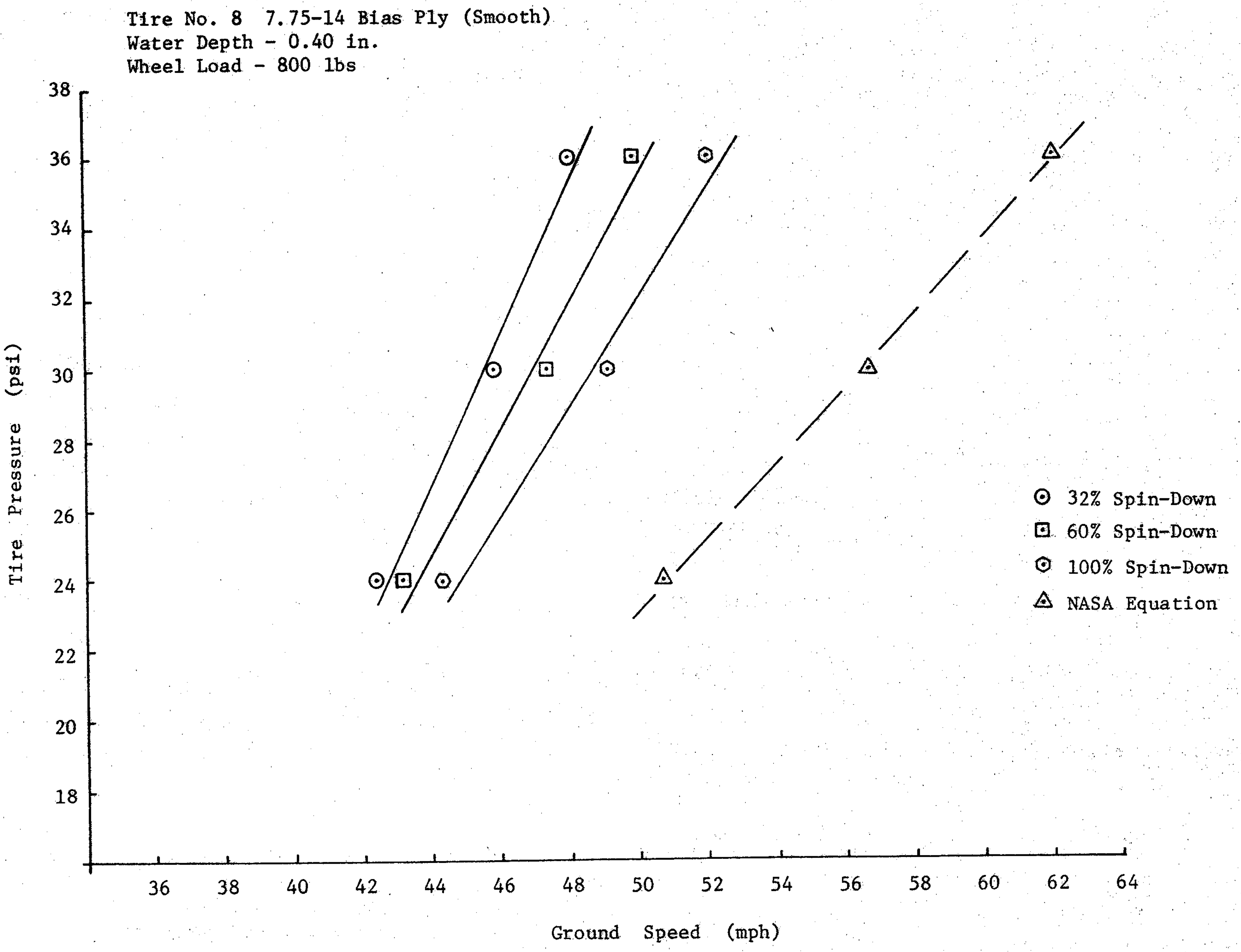


FIGURE 20. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR CONCRETE PAVEMENT.

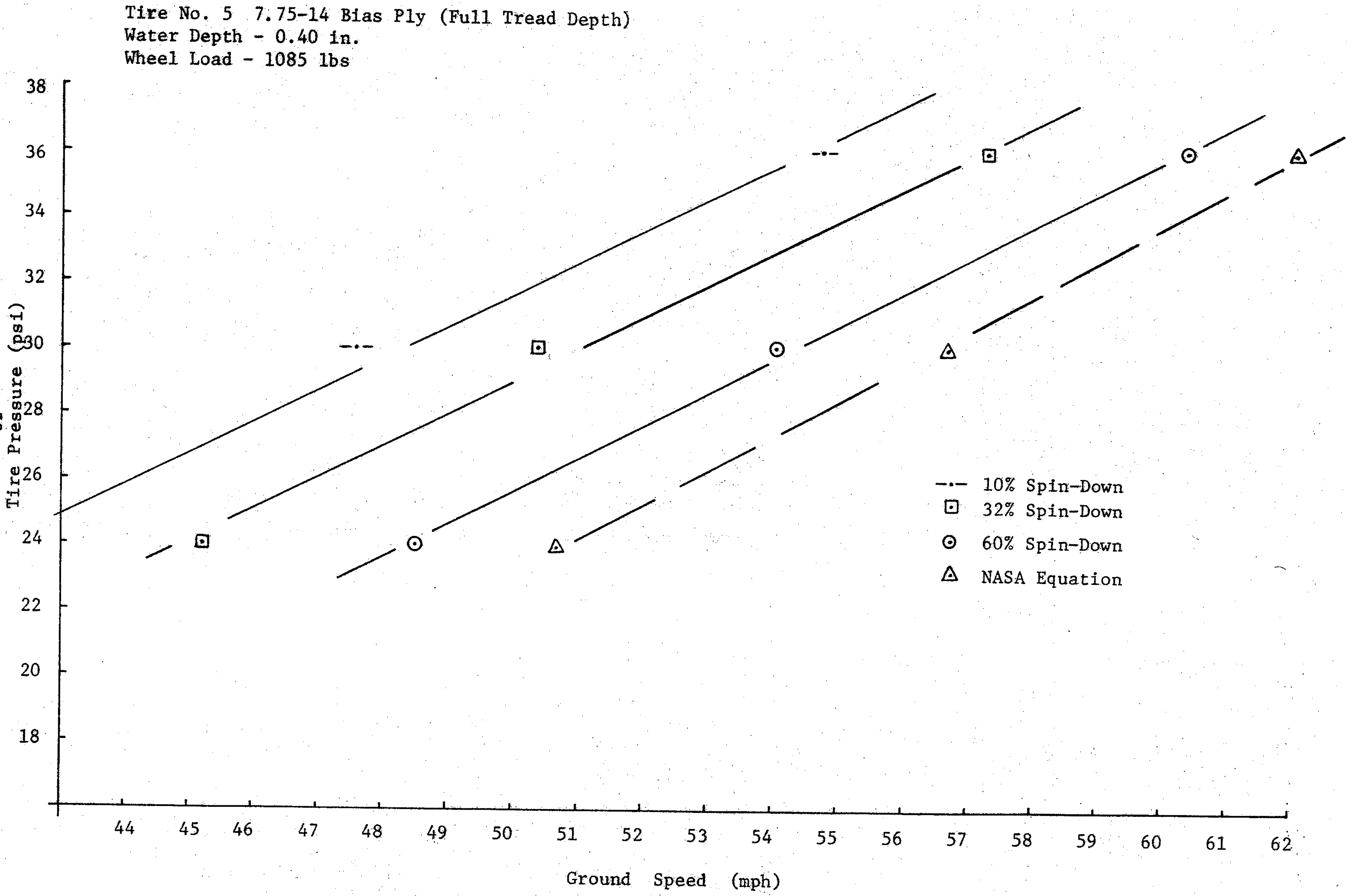


FIGURE 21. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR CONCRETE PAVEMENT.

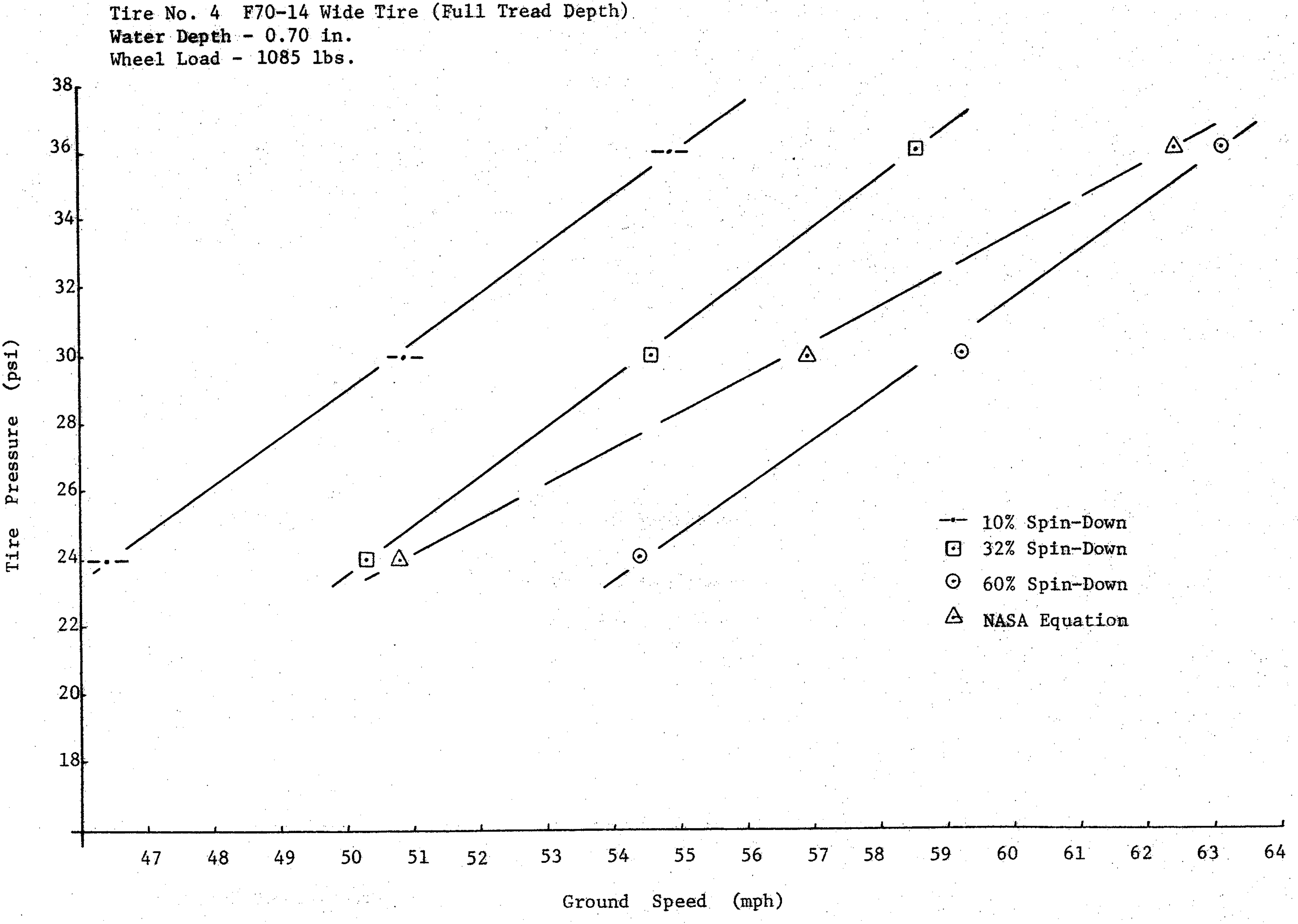


FIGURE 22. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR BITUMINOUS SURFACE TREATMENT.

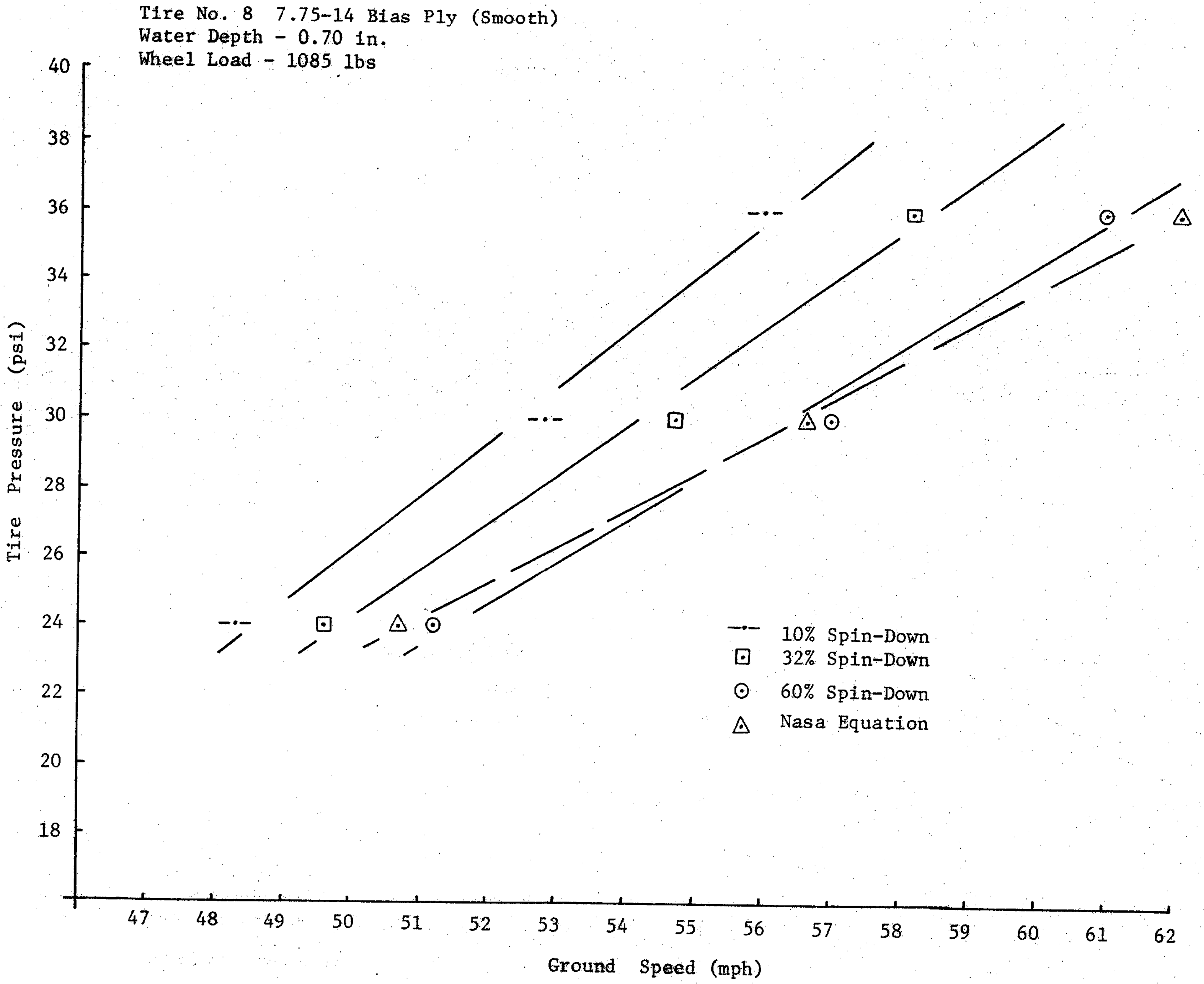


FIGURE 23.COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR BITUMINOUS SURFACE TREATMENT.

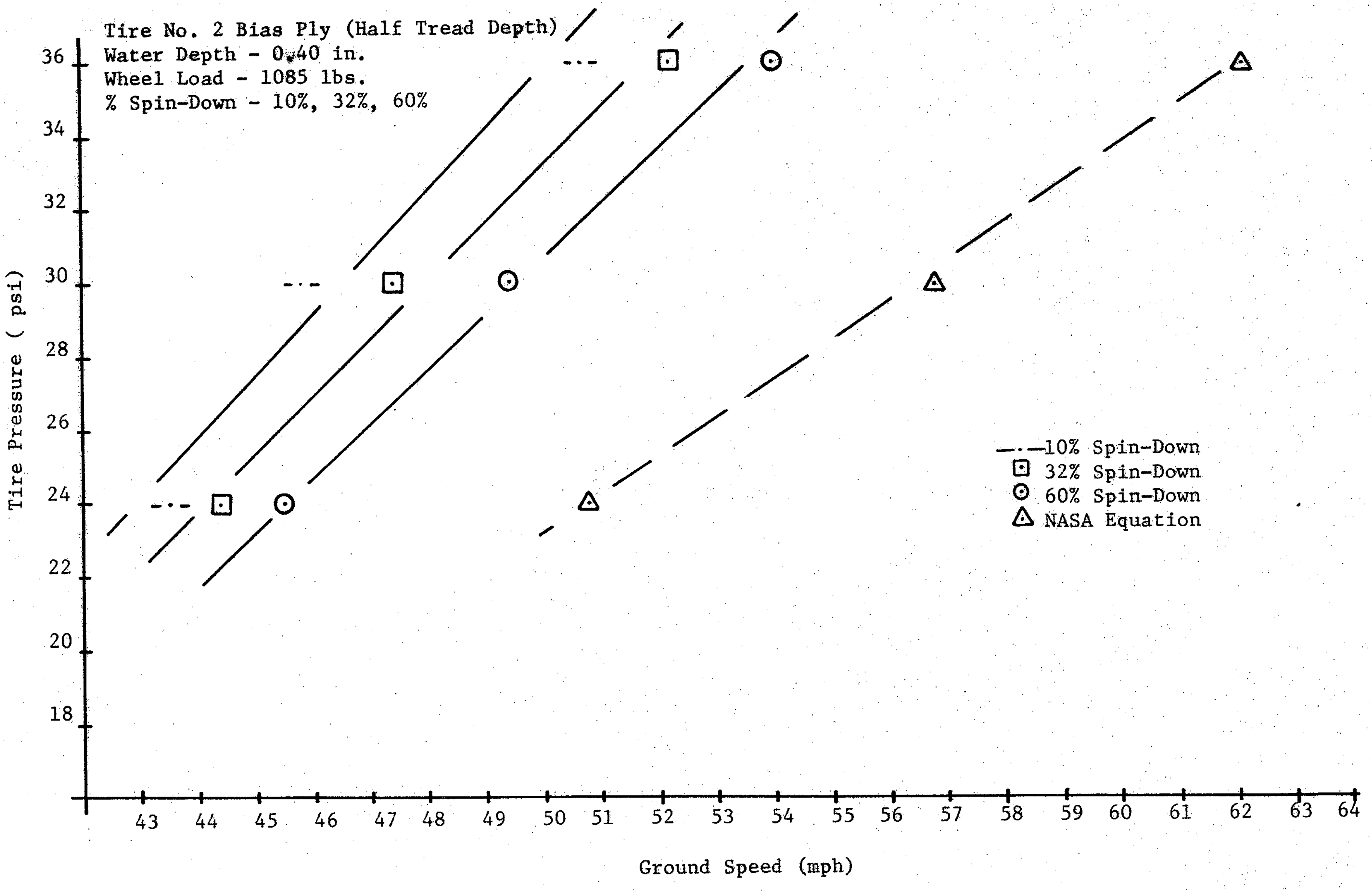


FIGURE 24. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR ASPHALT PAVEMENT.

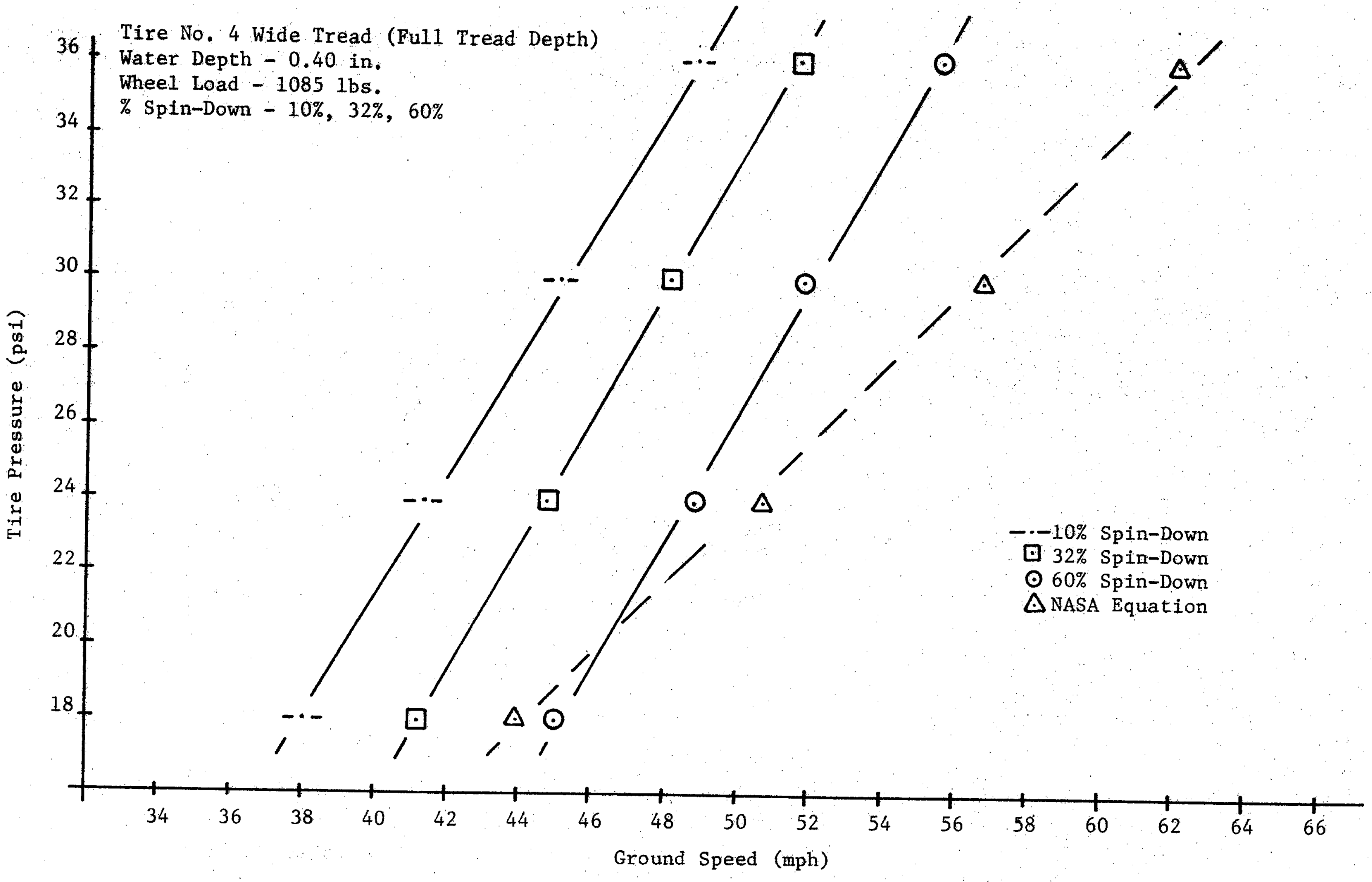


FIGURE 25. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR ASPHALT PAVEMENT.

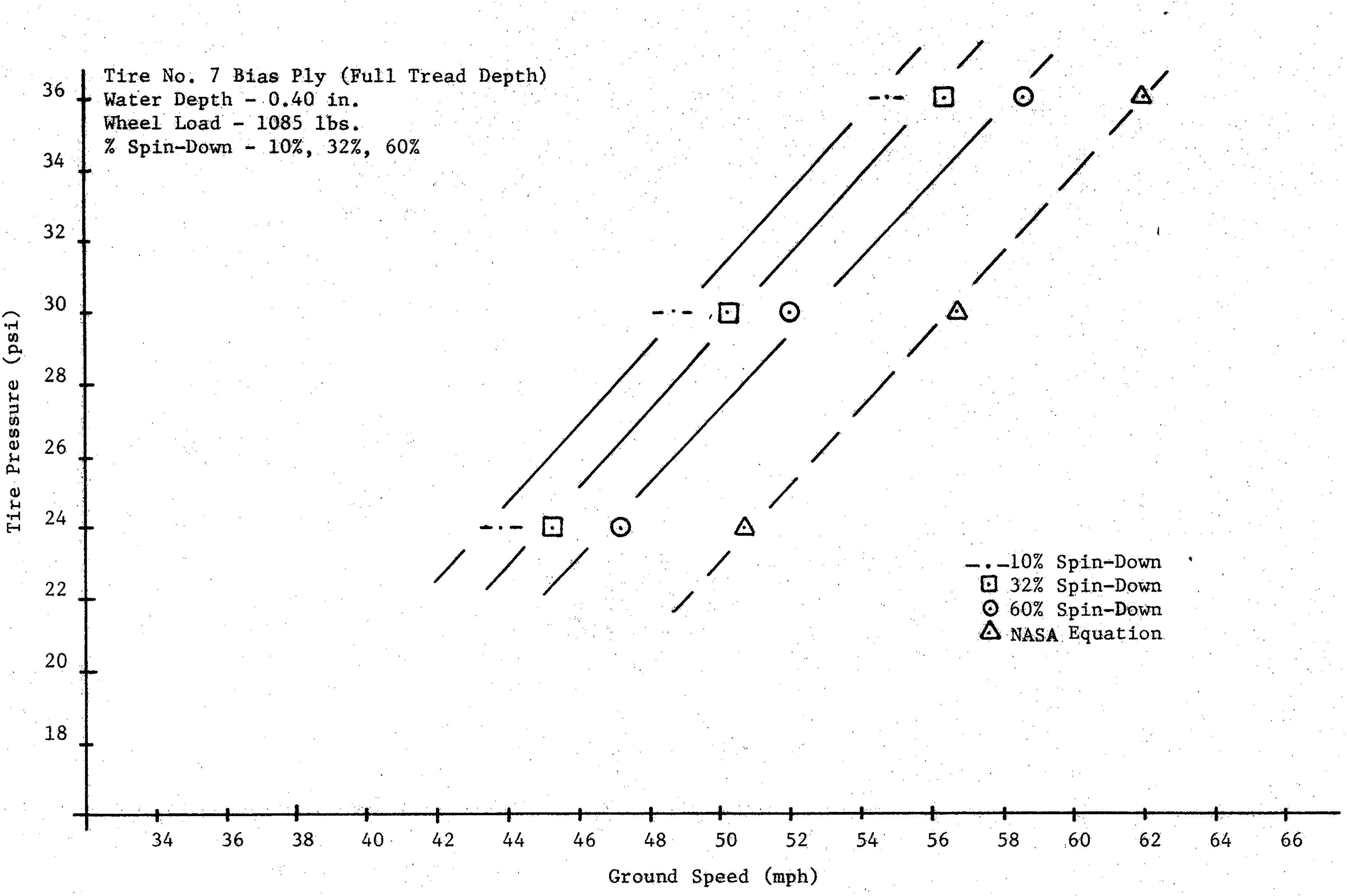


FIGURE 26. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR ASPHALT PAVEMENT.

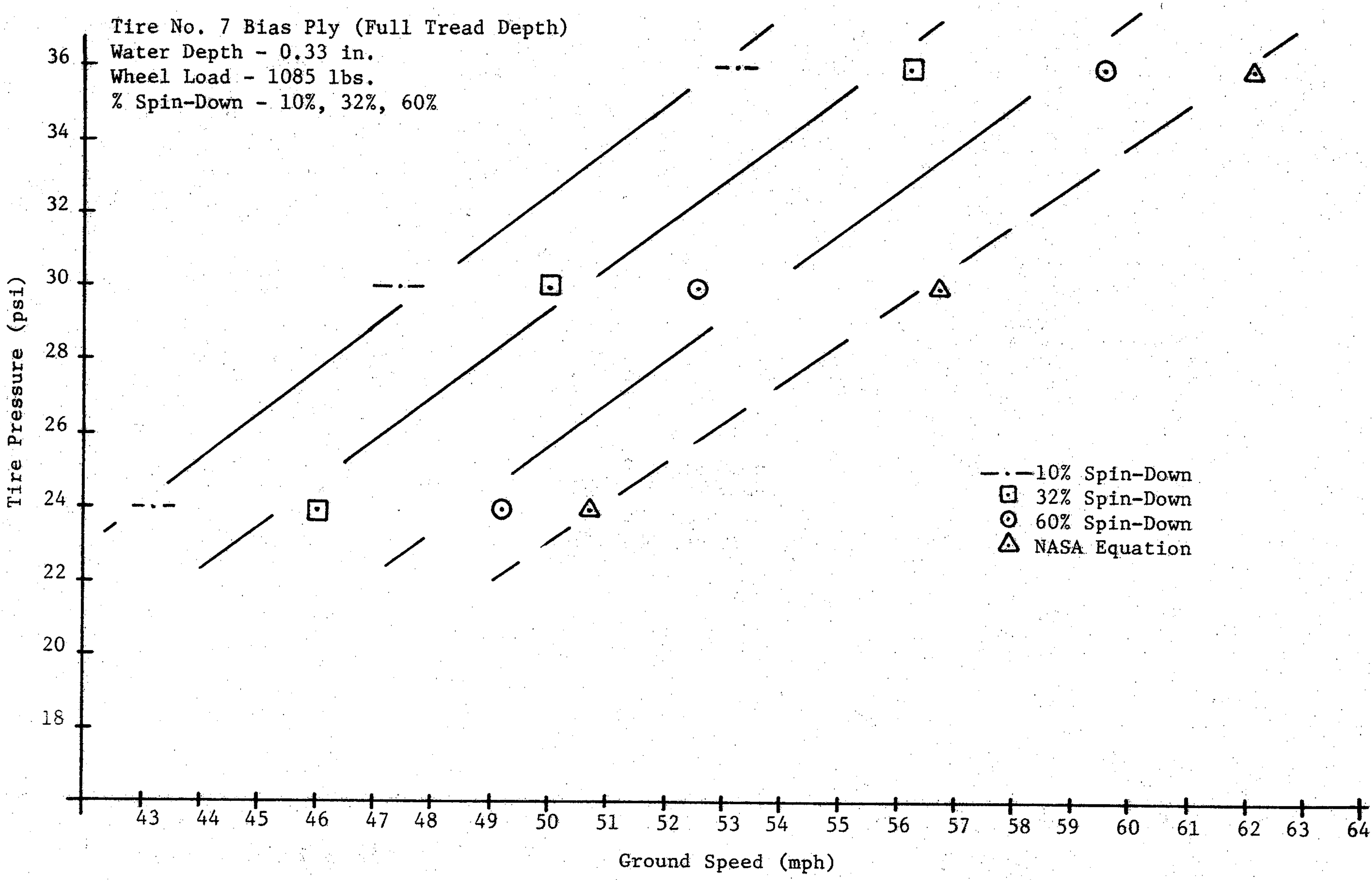


FIGURE 27. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR ASPHALT PAVEMENT.

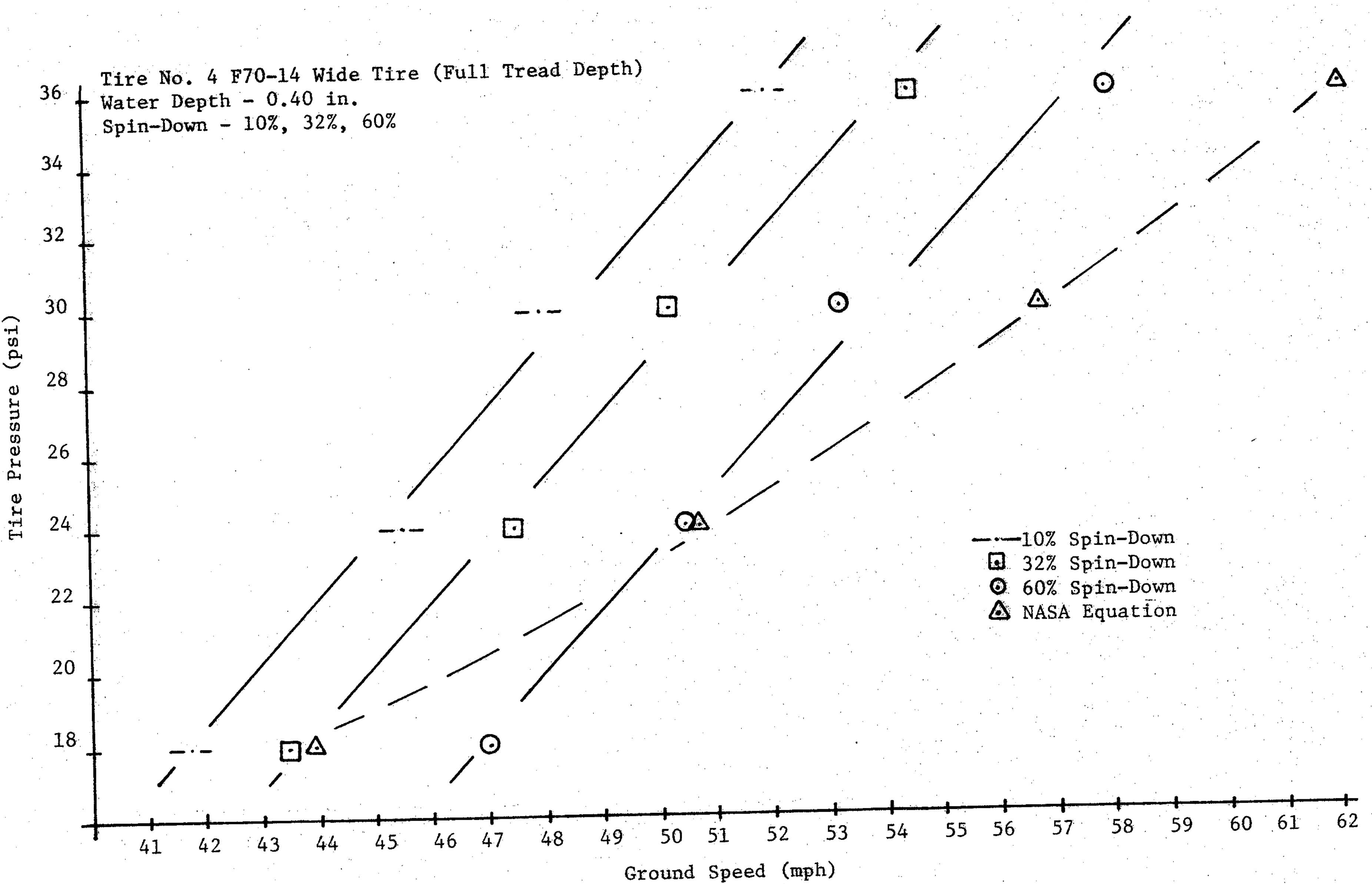


FIGURE 28. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR JENNITE PAVEMENT.

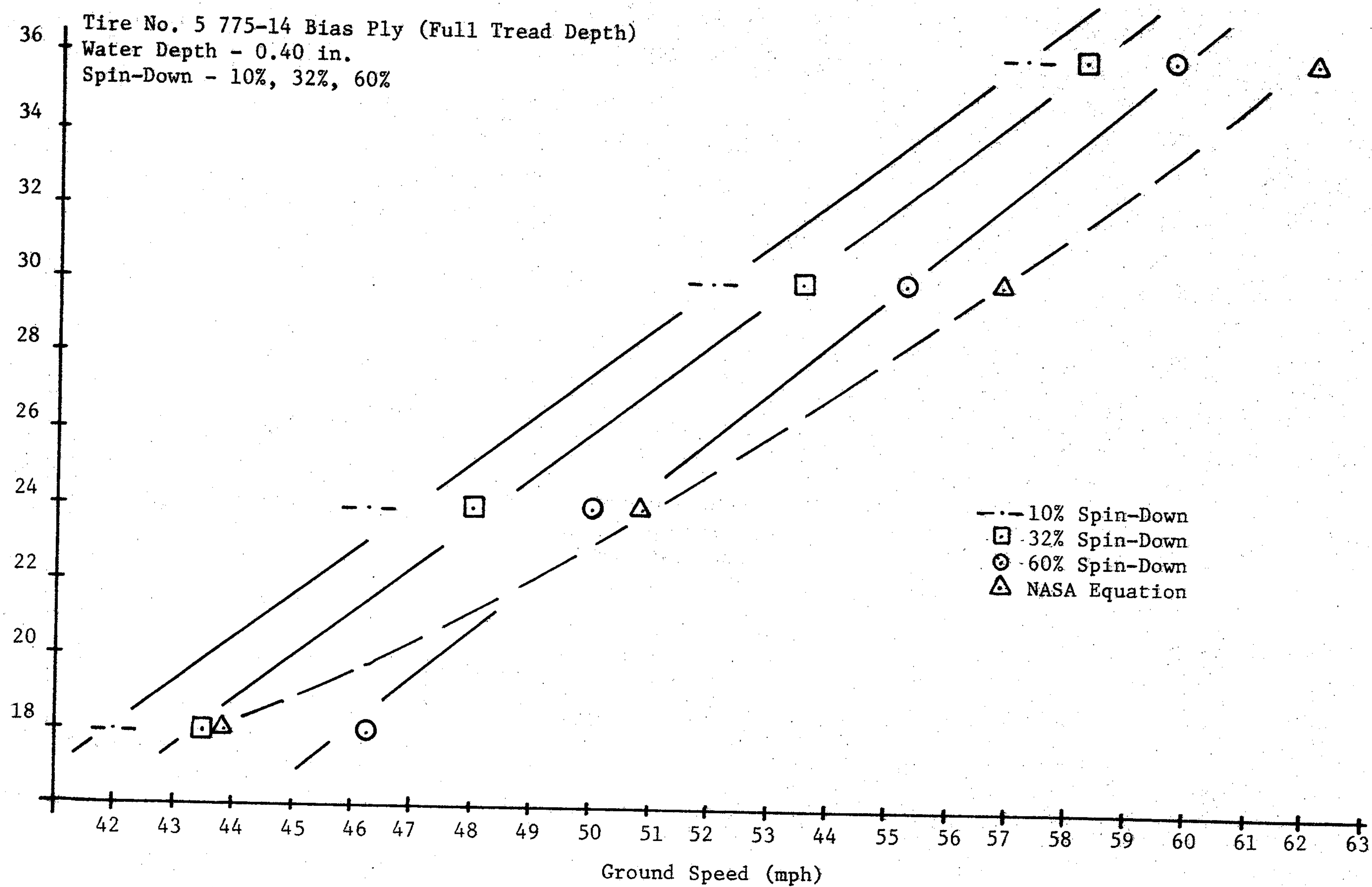


FIGURE 29. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR JENNITE PAVEMENT.

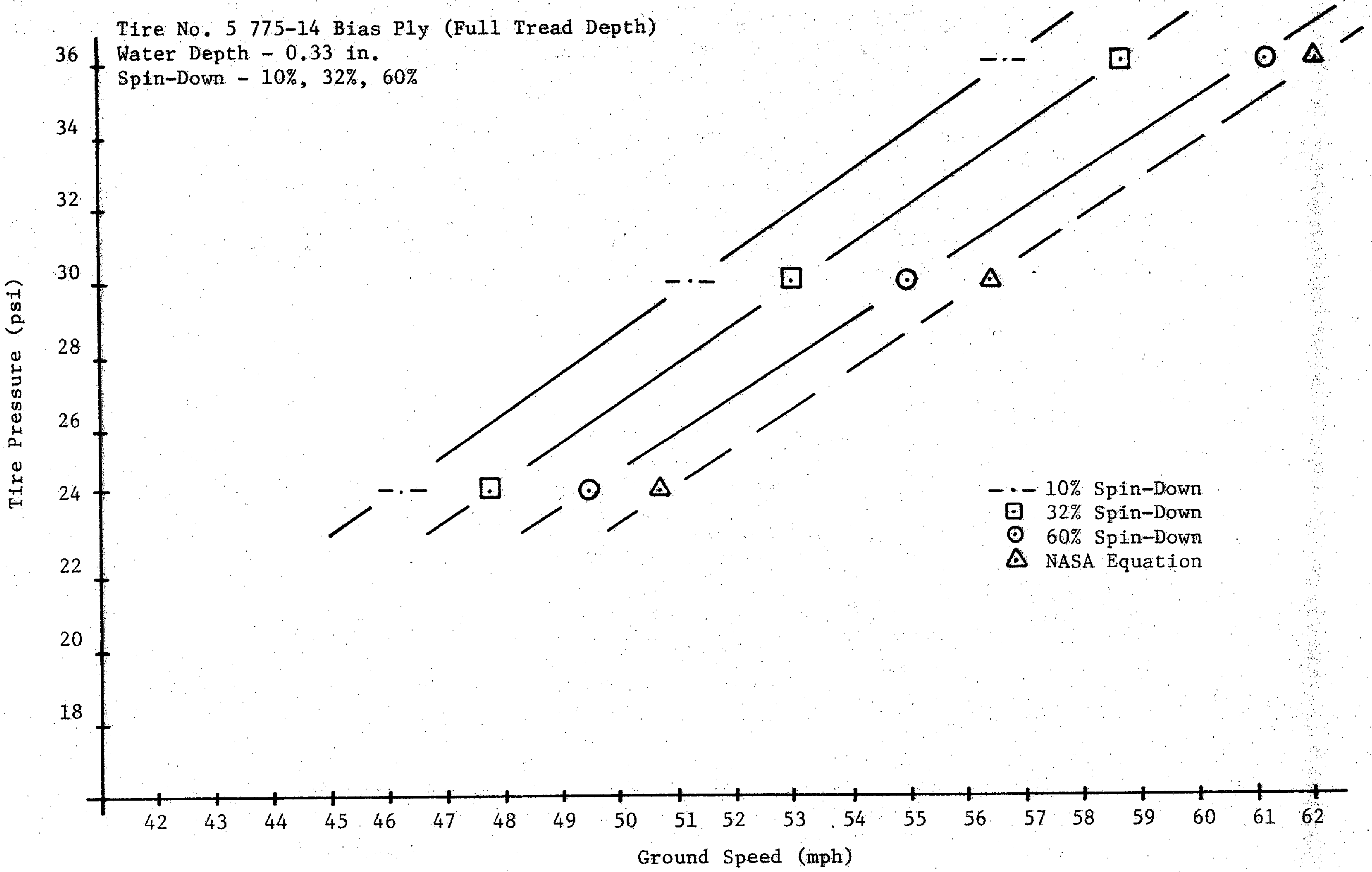


FIGURE 30. COMPARISON OF EXPERIMENTAL RESULTS WITH NASA EQUATION FOR JENNITE PAVEMENT.

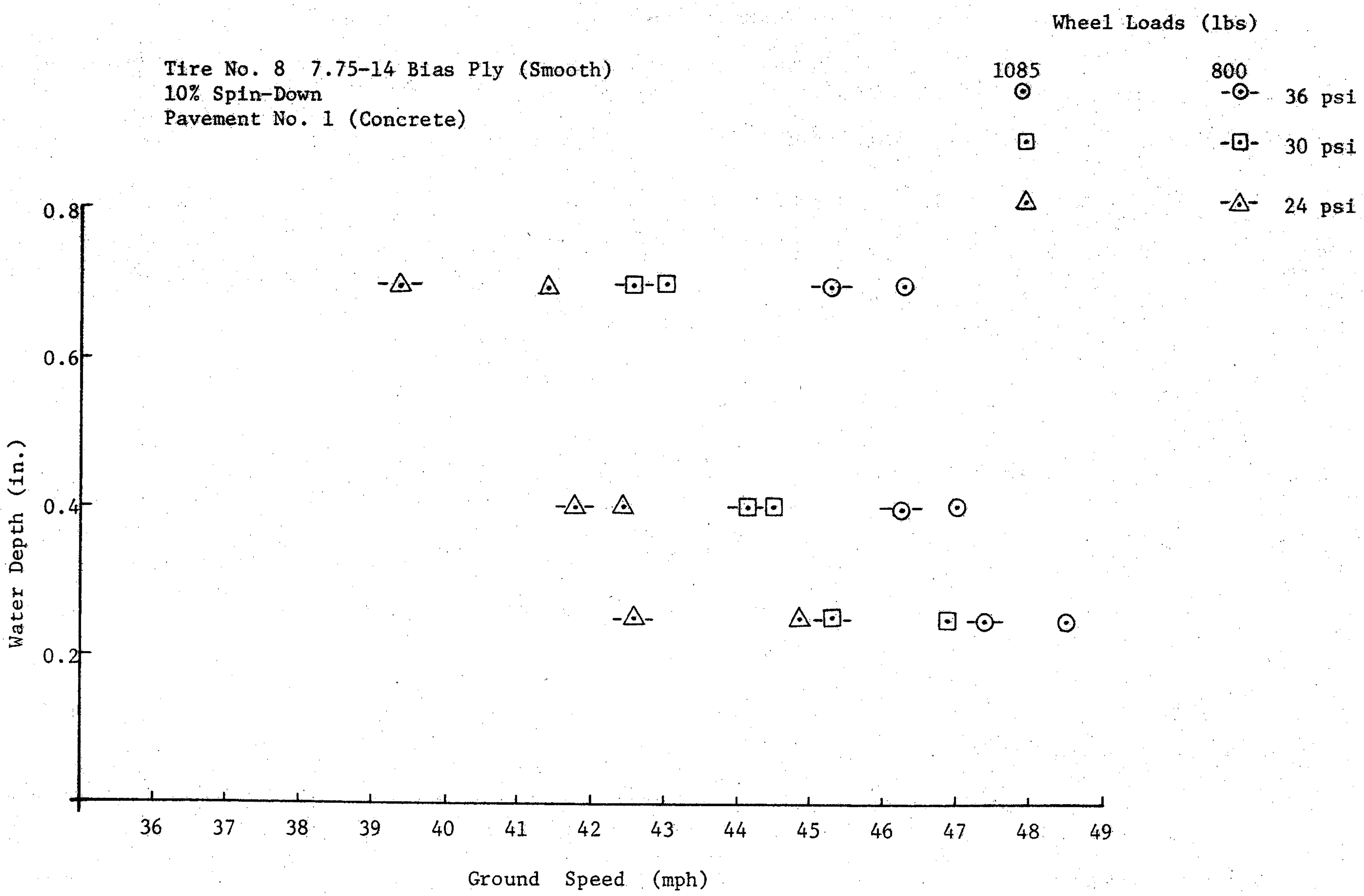


FIGURE 31. EFFECT OF WATER DEPTH AND WHEEL LOAD ON GROUND SPEED TO CAUSE 10% SPIN-DOWN.

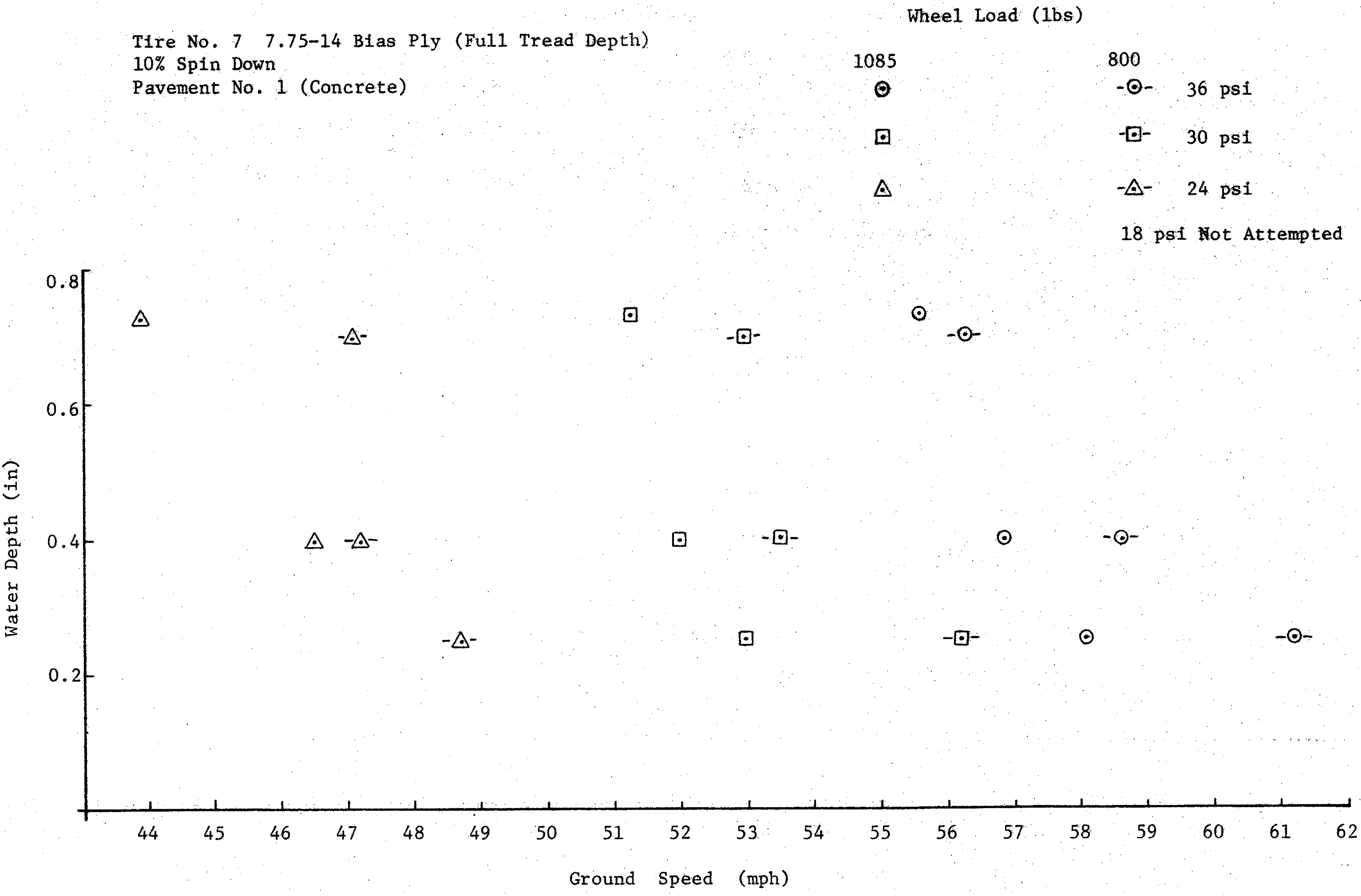


FIGURE 32. EFFECT OF WATER DEPTH AND WHEEL LOAD ON GROUND SPEED TO CAUSE 10% SPIN-DOWN.

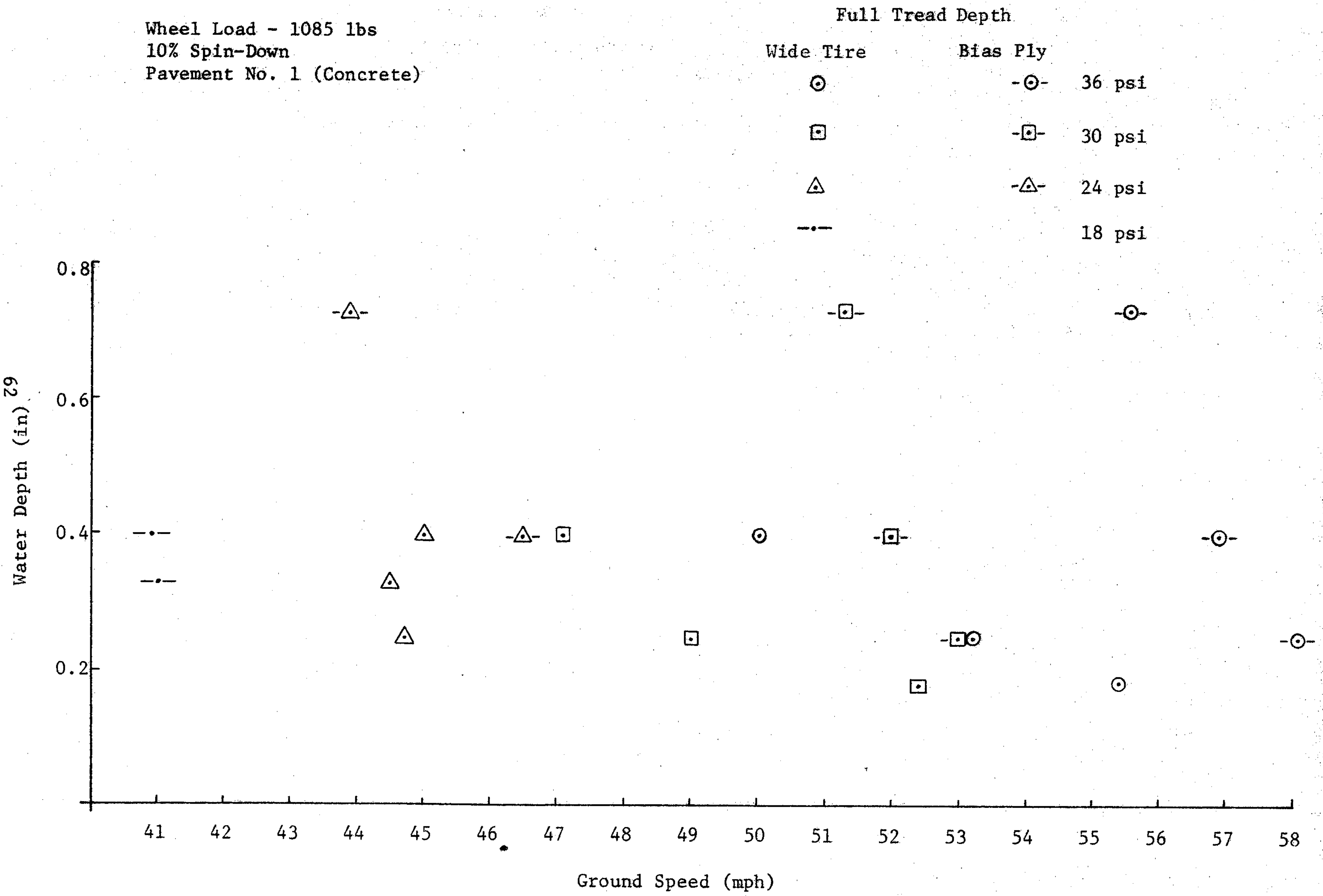


FIGURE 33. EFFECT OF WATER DEPTH AND TIRE ASPECT RATIO ON SPEED TO CAUSE 10% SPIN-DOWN.

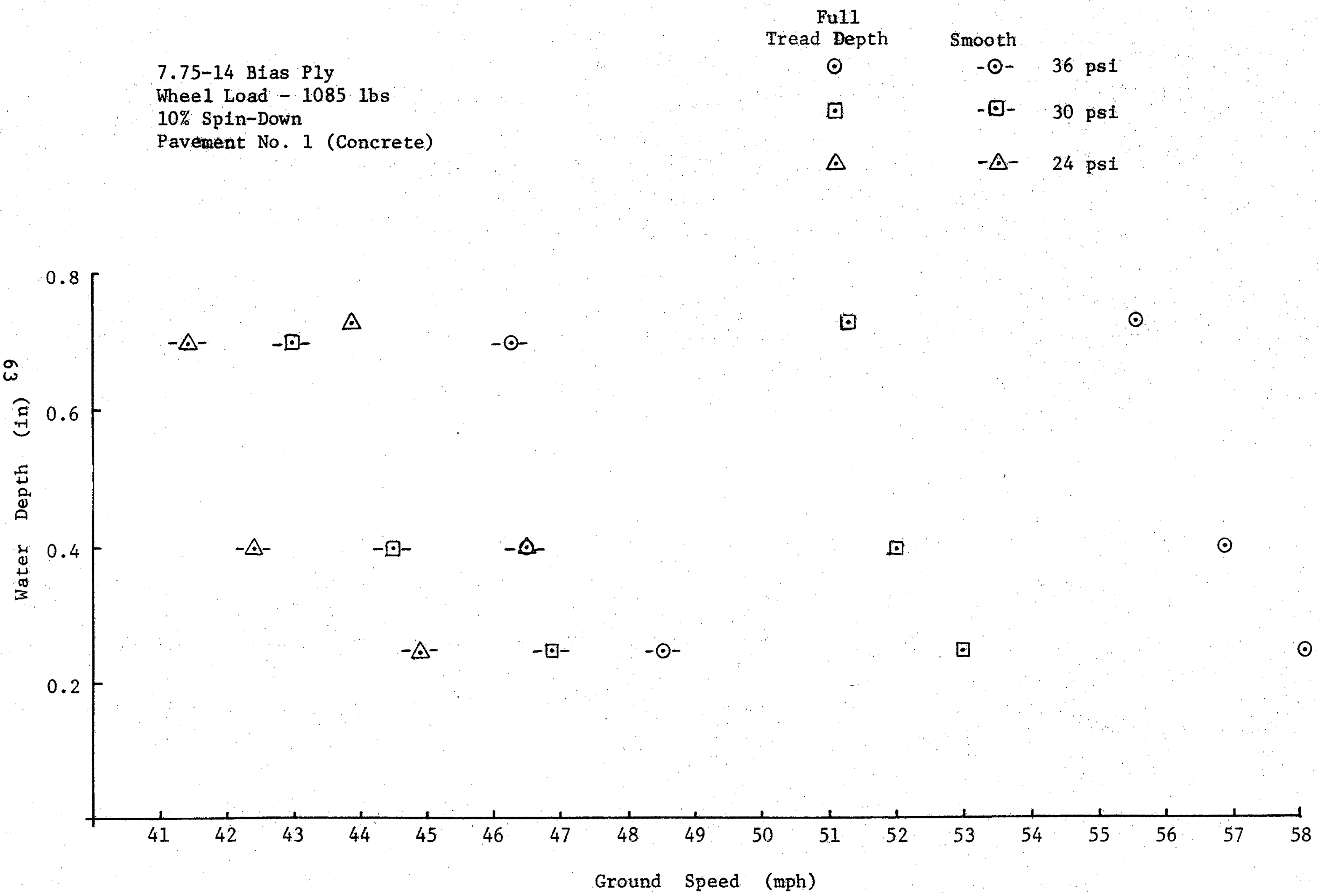


FIGURE 34. EFFECT OF WATER DEPTH AND TREAD DEPTH ON SPEED TO CAUSE 10% SPIN-DOWN.

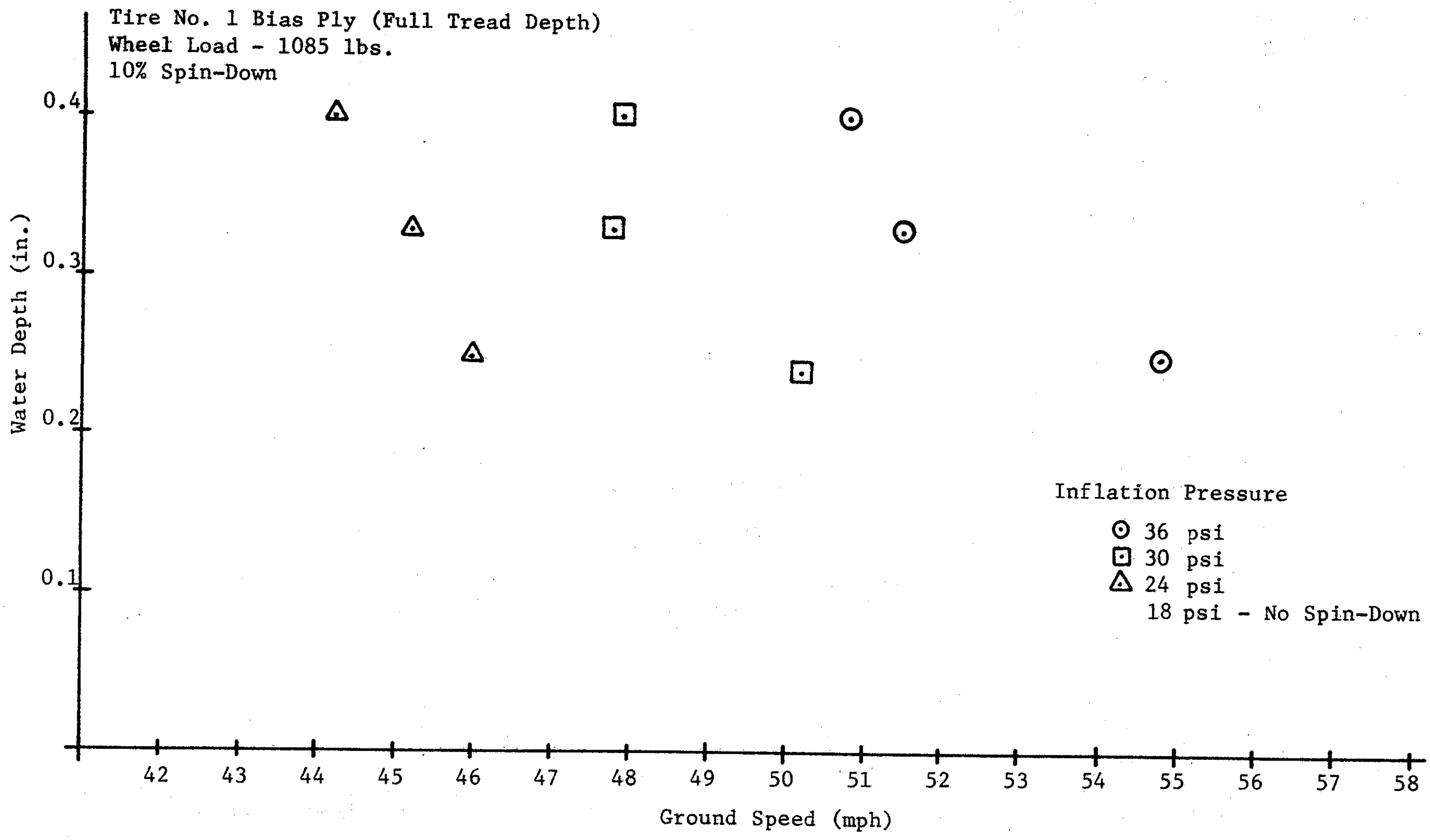


FIGURE 35. EFFECT OF WATER DEPTH ON SPEED TO CAUSE 10% SPIN-DOWN - ASPHALT PAVEMENT.

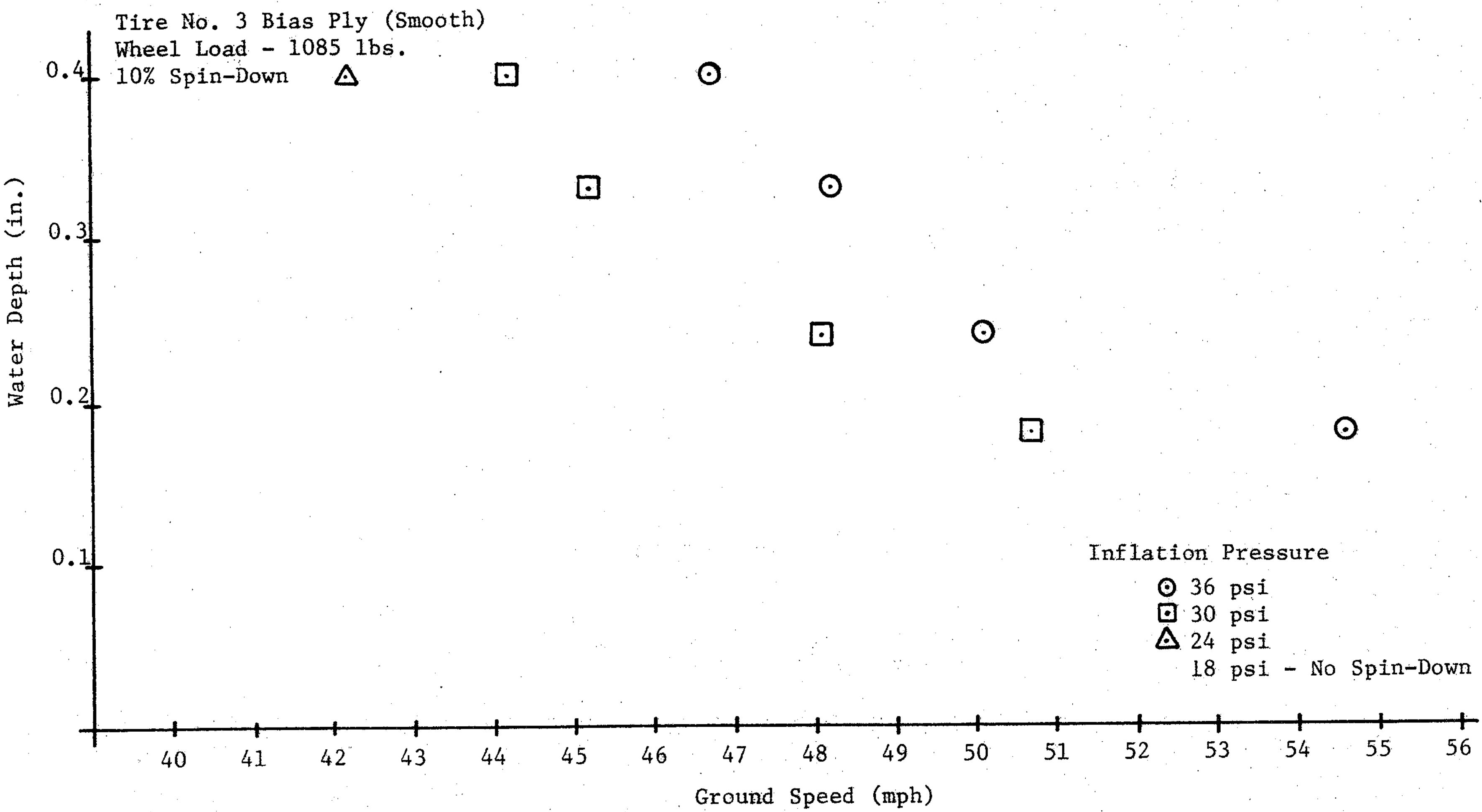


FIGURE 36. EFFECT OF WATER DEPTH ON SPEED TO CAUSE 10% SPIN-DOWN - ASPHALT PAVEMENT.

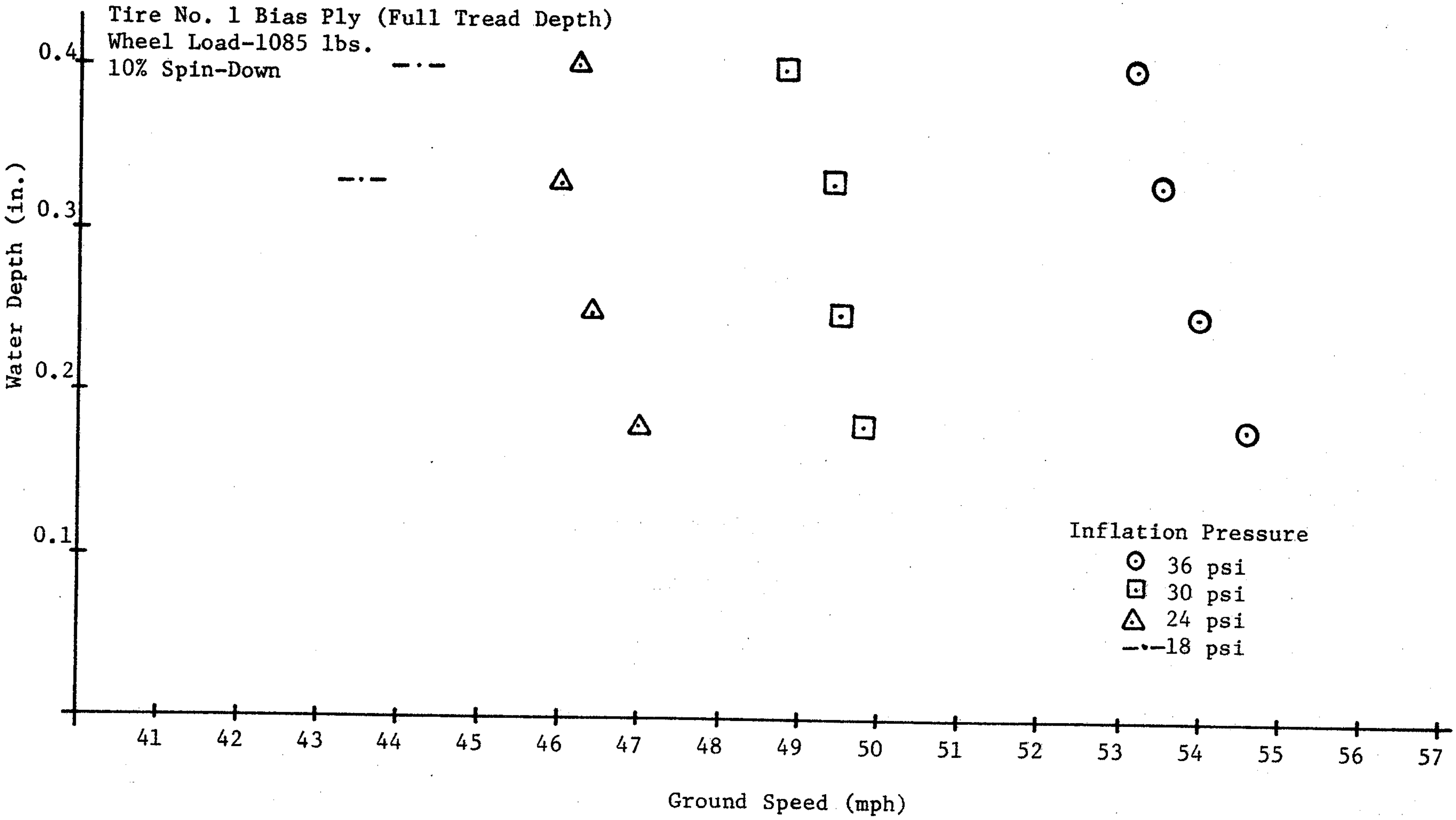


FIGURE 37. EFFECT OF WATER DEPTH ON SPEED TO CAUSE 10% SPIN-DOWN - JENNITE PAVEMENT.

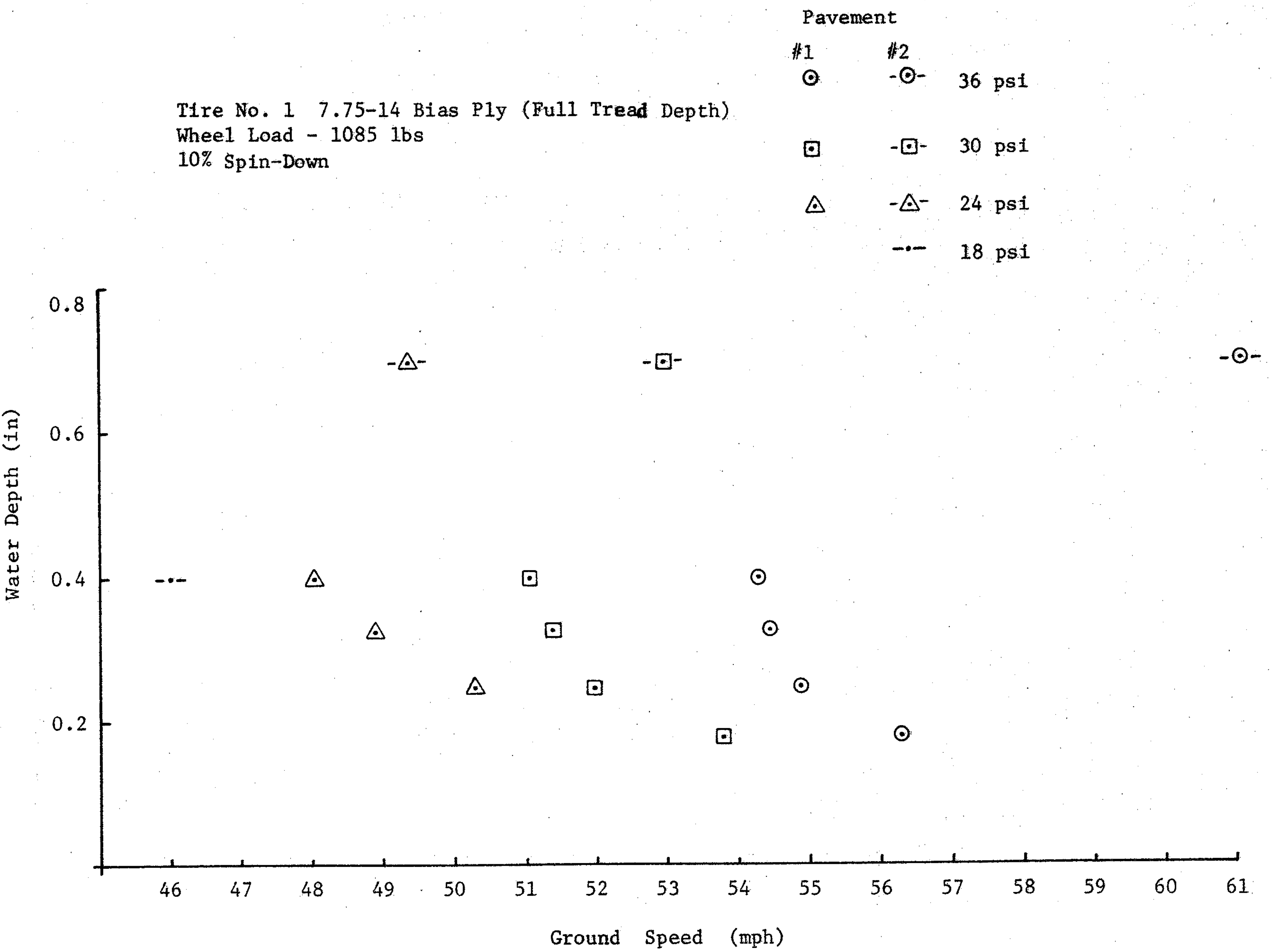


FIGURE 38. COMPARISON OF CONCRETE AND BITUMINOUS SURFACE TREATMENT.

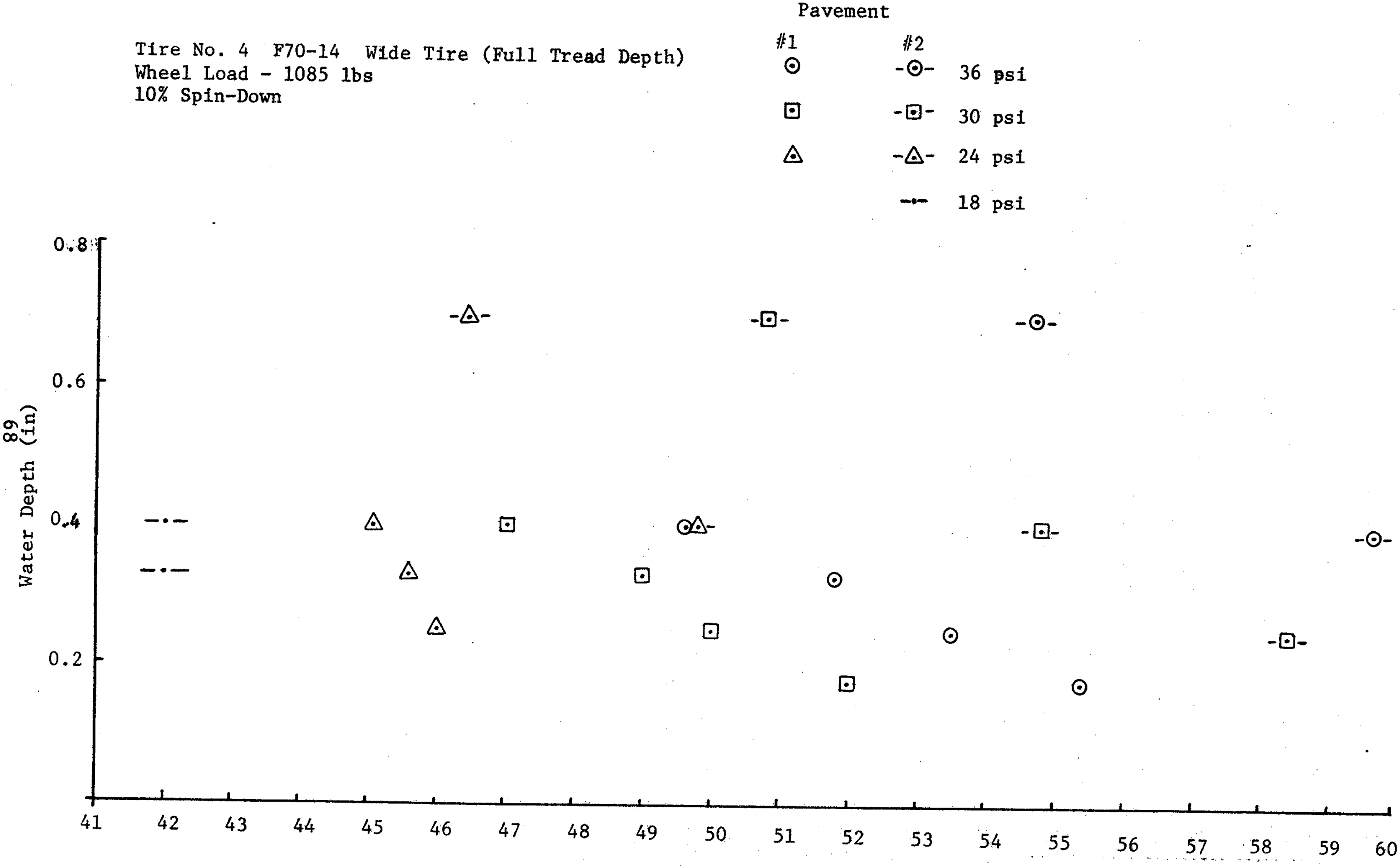


FIGURE 39. COMPARISON OF CONCRETE AND BITUMINOUS SURFACE TREATMENT.

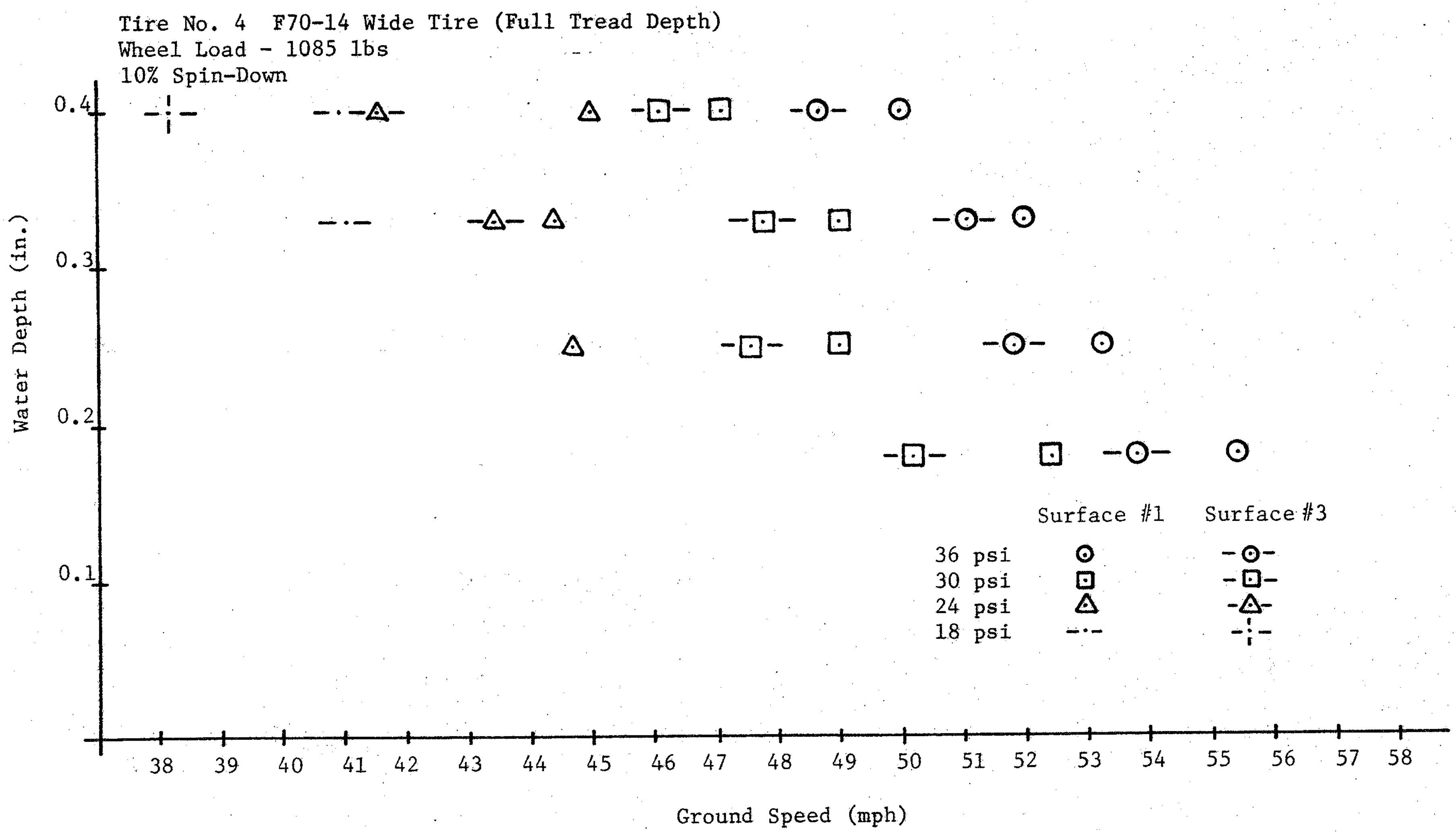

Tire No. 4 F70-14 Wide Tire (Full Tread Depth)
Wheel Load - 1085 lbs
10% Spin-Down

FIGURE 40. COMPARISON OF CONCRETE AND ASPHALT PAVEMENTS.

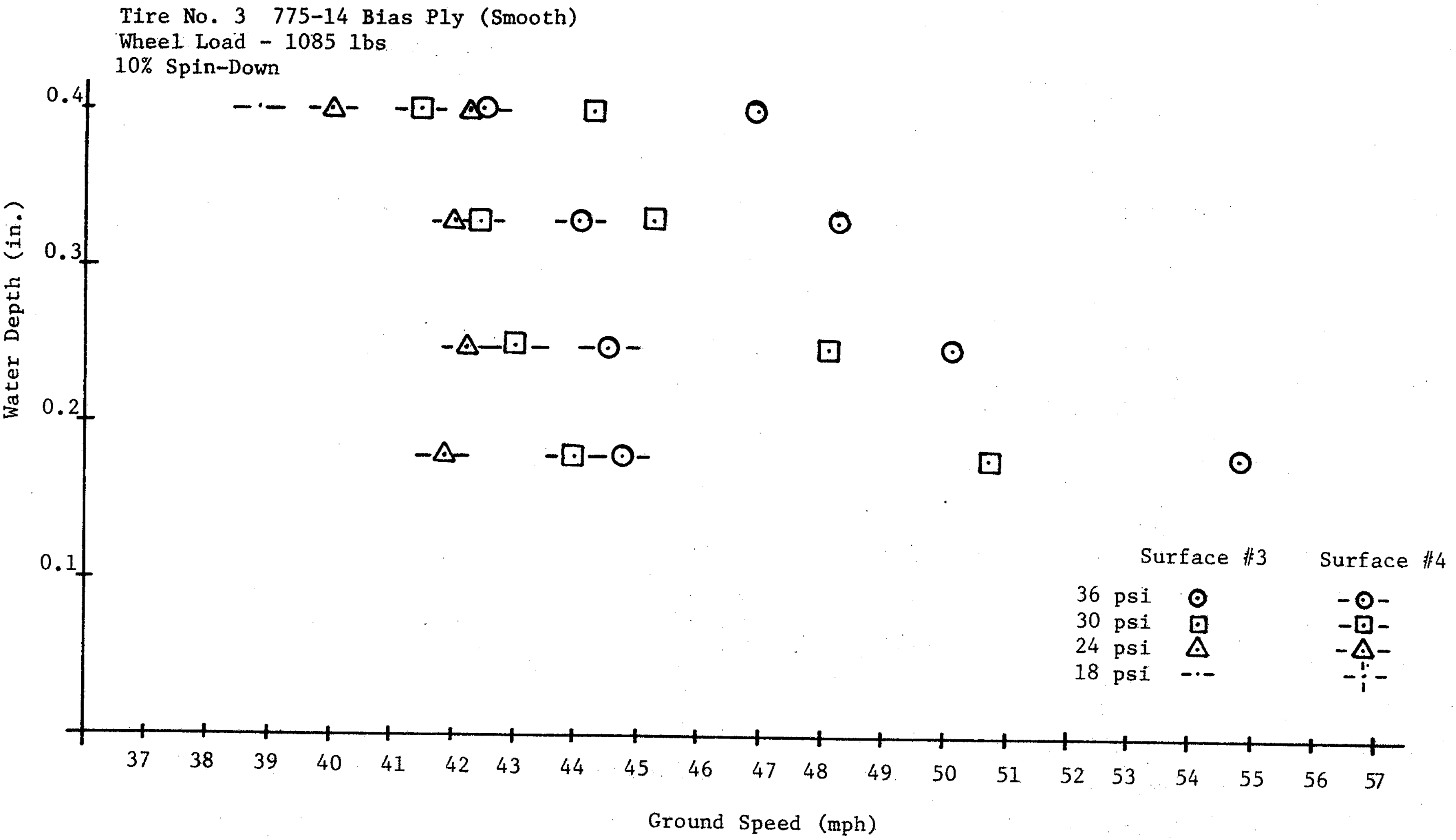


FIGURE 41. COMPARISON OF ASPHALT AND JENNITE PAVEMENTS.

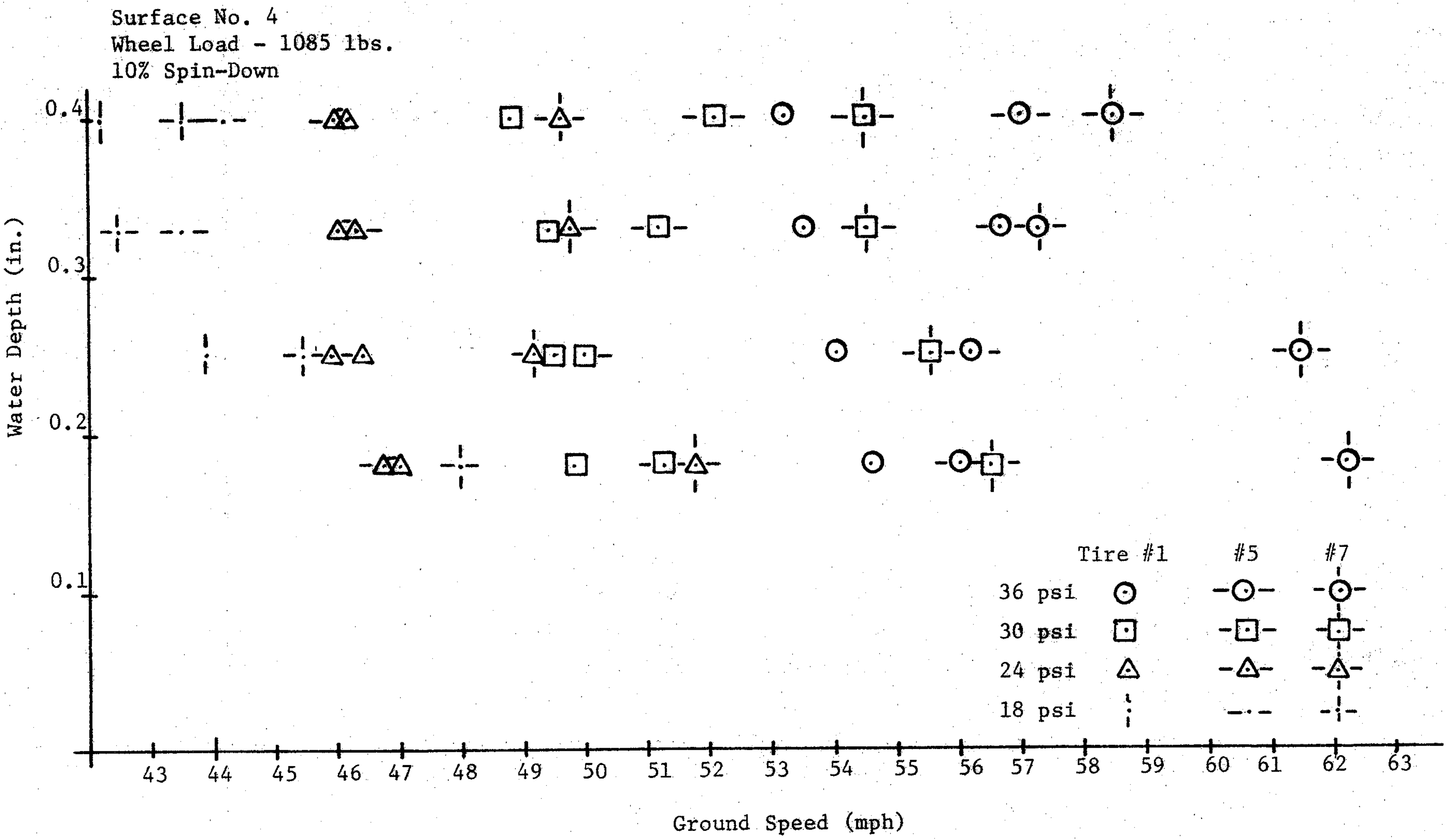


FIGURE 42. COMPARISON OF BIAS PLY TIRES TESTED (1, 5, 7).

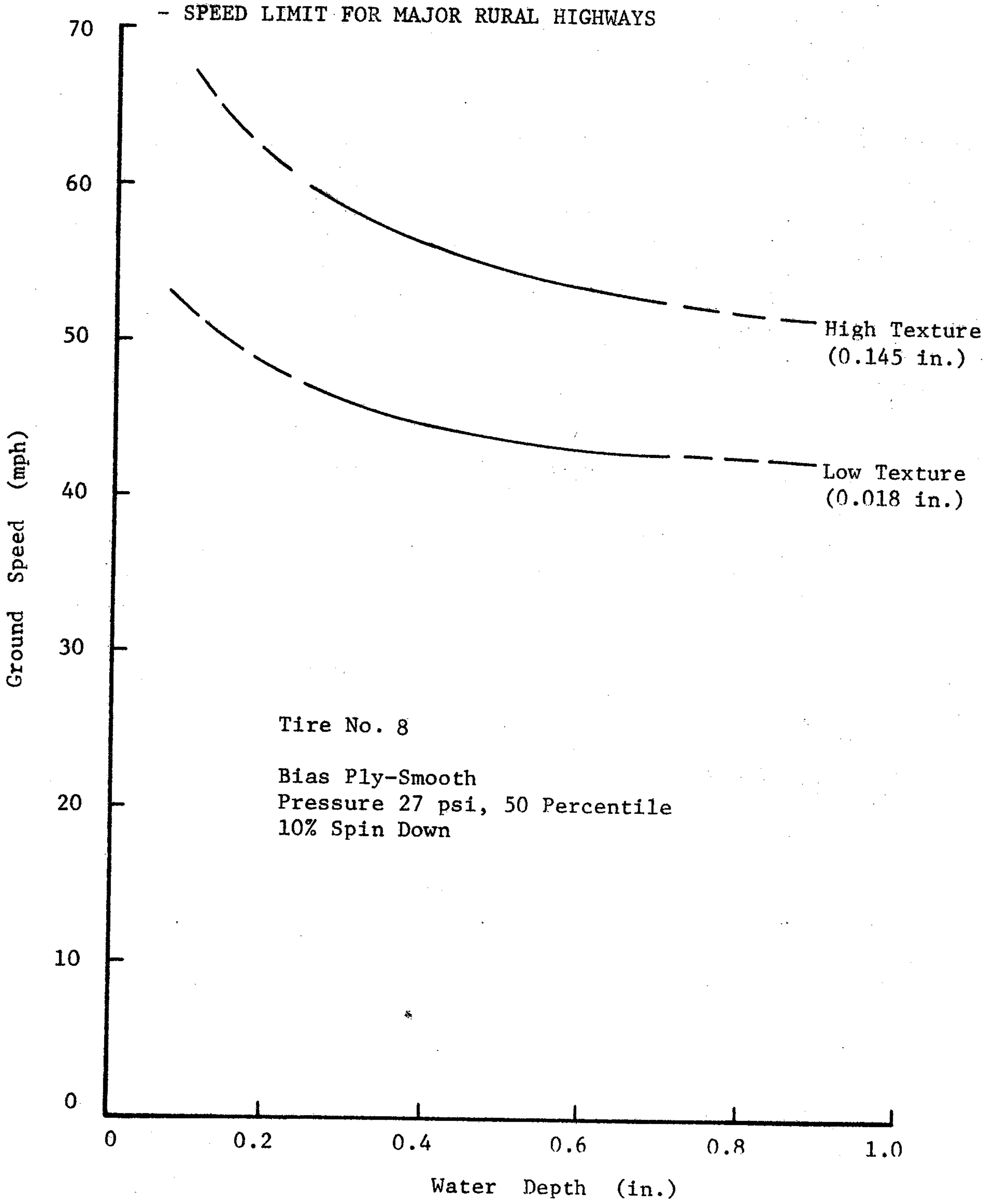


FIGURE 43. EFFECT OF TEXTURE ON HYDROPLANING.

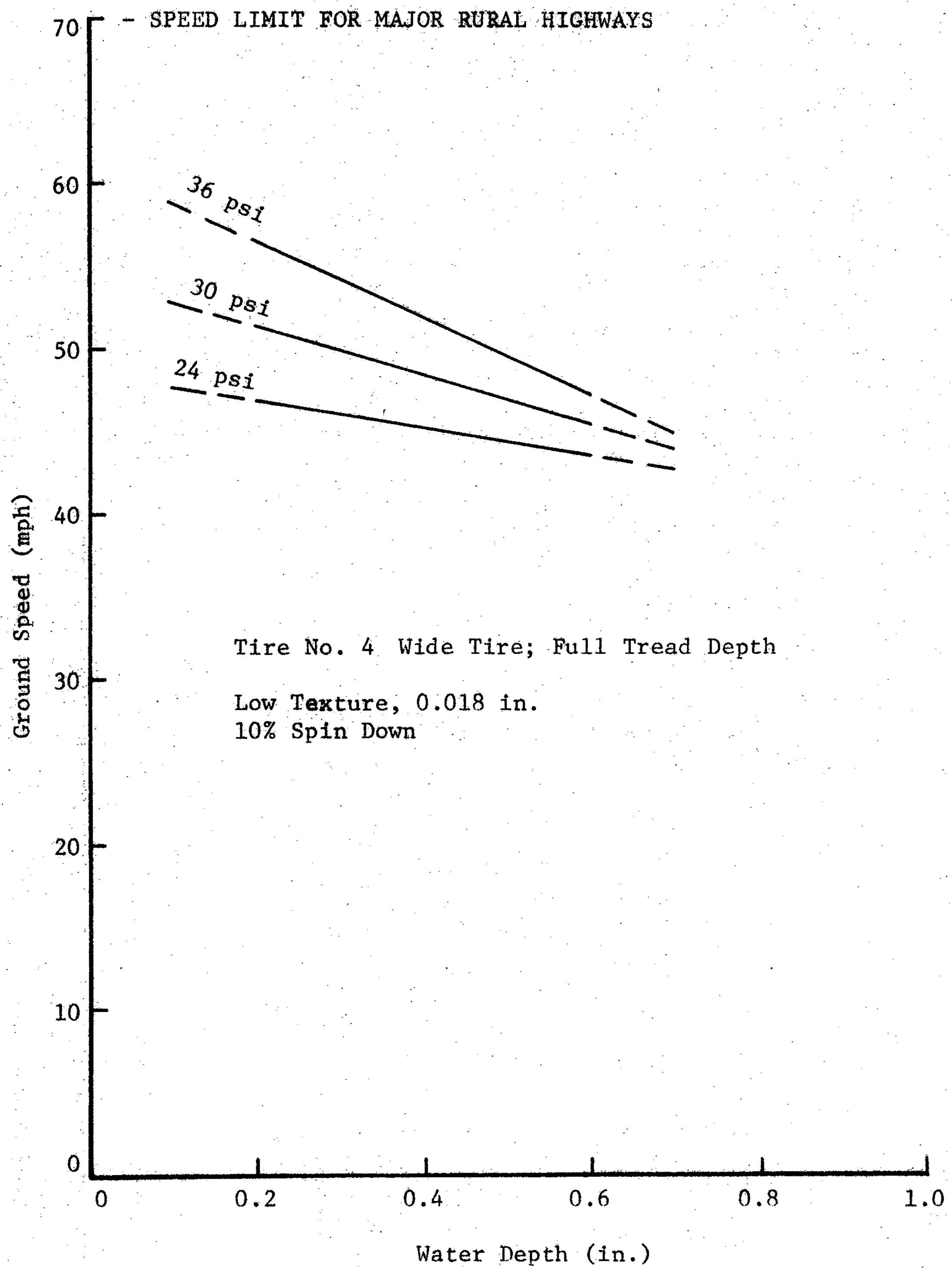


FIGURE 44. EFFECT OF PRESSURE ON HYDROPLANING.

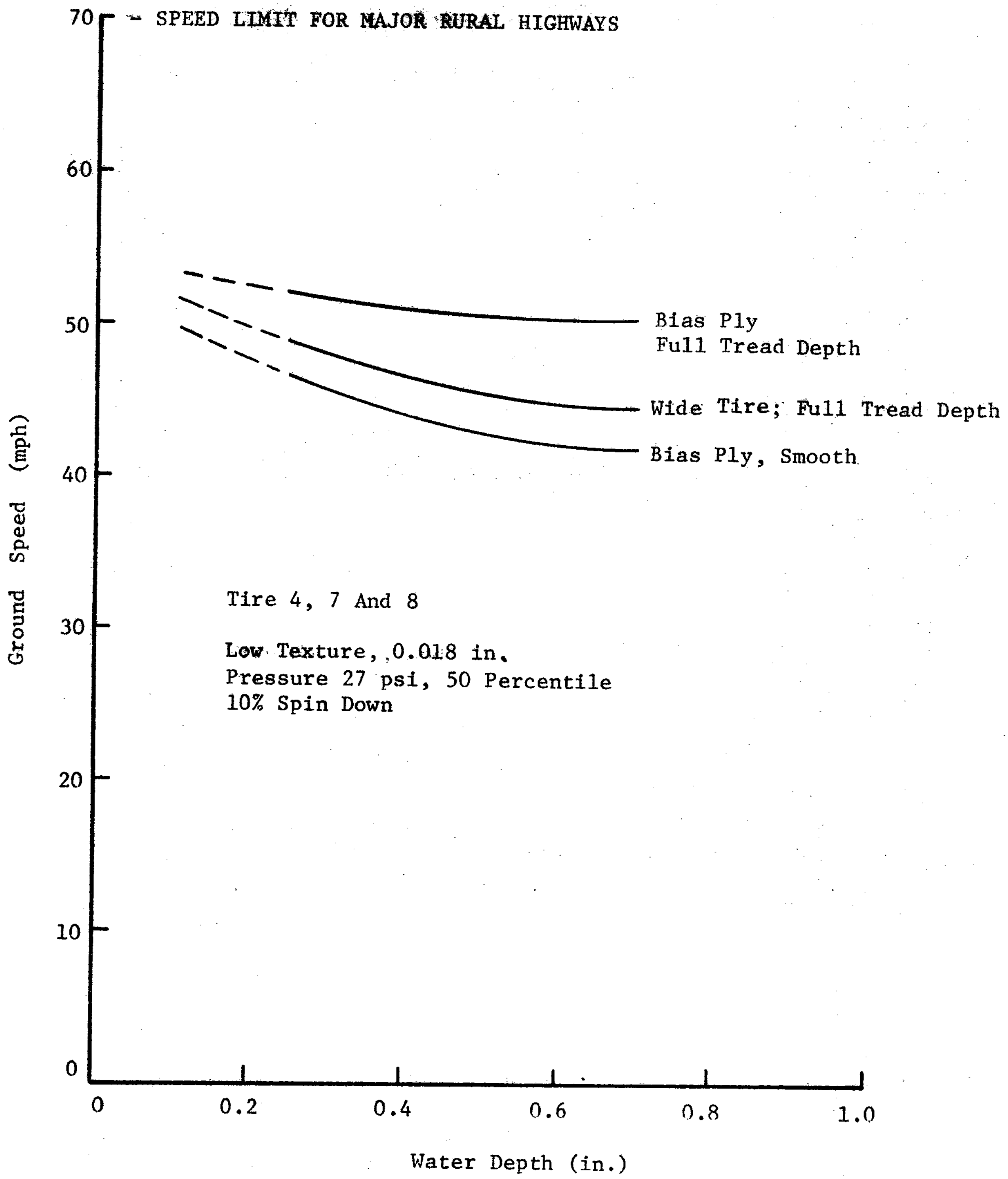


FIGURE 45. EFFECT OF TIRE ON HYDROPLANING.

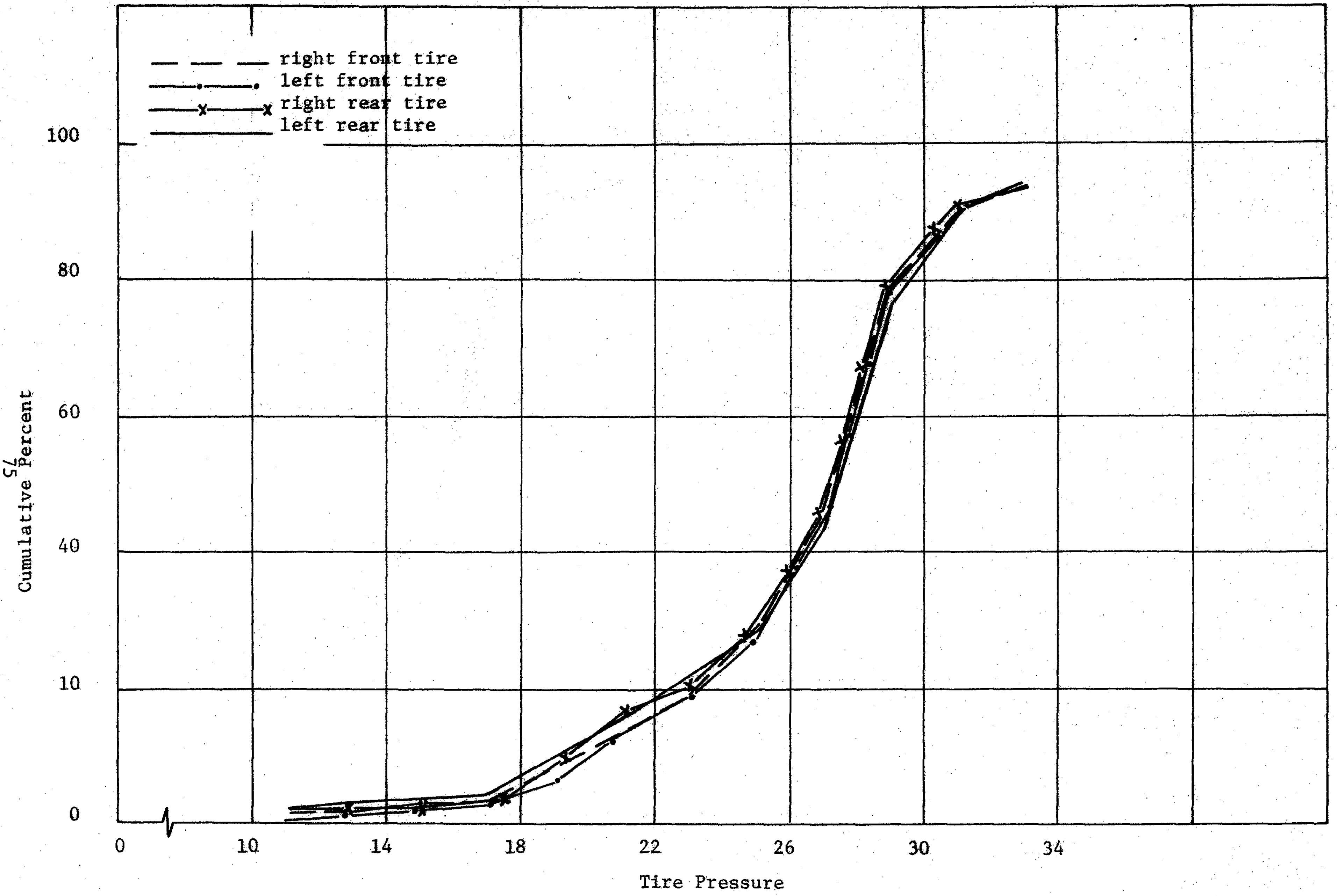


FIGURE 46. COMPARISON OF TIRE PRESSURES - ACCIDENT SAMPLE.