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TIRE-PAVEMENT FRICTION AS A FUNCTION OF VEHICLE MANEUVERS

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Research Report No. 163-2F

Tire-Pavement Friction as a Function
of Vehicle Maneuvers

Research Study No. 2-10-72-163

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ABSTRACT

Limit maneuvers were performed on different wet pavements with disparate passenger vehicles, and the vehicle-available acceleration was compared with pavement friction indicators. Reasonably conservative estimates were made of vehicle cornering and/or stopping capability as a function of skid number measured at 40 mph. These estimates can be used to realistically evaluate pavement friction for expected maneuvers at individual roadway sites.

SUMMARY

Vehicle maneuverability tests on a wet surface indicated that it might be feasible to develop a relationship between limit vehicle-available acceleration and measurable pavement parameters, such as skid number, based on empirical data. From a previous study which compared the limit handling characteristics of a cross section of contemporary passenger vehicles, two cars were selected that represented this sample. They were instrumented to record the significant vehicle response parameters, and limit maneuvers were conducted on wet pavements with a range of friction and texture properties. The results of cornering, stopping, and combination maneuvers indicated that no simple relationship exists between measures of pavement friction and vehicle capability, but reasonably conservative estimates of the lower limit of vehicle-available acceleration were made based on skid number measured at 40 mph. Examples of the use of this information point up the fact that the maneuver itself partly determines the amount of vehicle-available friction and that, where appropriate, both cornering and stopping should be considered together rather than separately. The tests also indicate that low rear tire tread depths, which seem to be significantly associated with skidding accidents, do lessen vehicle cornering capability, and that the estimate of friction available becomes invalid for speeds and water depths which result in hydroplaning.

The results of this study can be used in conjunction with information from other studies to provide a comprehensive evaluation tool for assessing the potential of various courses of action in alleviating skidding accidents at problem sites.

IMPLEMENTATION STATEMENT

The developed relationship between minimum limit vehicle-available acceleration and SN_{40} can be used to evaluate the adequacy of friction at high accident-frequency sites, and also can be used to evaluate the effectiveness of a proposed modification in surface friction. Examples of the use of this model are given in the Appendix. It is important that the estimated cornering <u>and</u> stopping requirements be considered simultaneously and that other factors, such as visibility and the possibility of hydroplaning, be taken into account before deciding if a course of action available to highway engineers will produce the desired results.

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INTRODUCTION

The forces that enable a vehicle to travel the path prescribed by the driver are the result of tire-pavement friction. This friction is affected by pavement surface texture, tire characteristics, stresses on the tire-pavement interface, the relative speeds of the materials in contact, interfacial substances such as water or dirt, and other factors (1,2). The rapid increase in the last decade in the number of published reports concerning the effects of various parameters on available friction indicates a growing awareness of the seriousness of the skidding problem. A great deal of work, both theoretical and experimental, has been done to determine the forces developed on a single wheel under a given set of conditions. However, on a conventional automobile in an incipient skid configuration, the conditions existing at all tires are seldom if ever the same; and except for straight ahead, locked wheel skids, little work has been done in relating measured friction values to the ability of vehicles to perform controlled maneuvers.

In this study contemporary passenger vehicles were used as test devices to determine the limit accelerations available on wet pavements with a range of textures and skid numbers. Although the state-of-the-art does not permit accurate estimates to be made of vehicle maneuverability in all cases based on commonly used estimators of pavement friction, the data generated in the study are used to estimate the lower boundaries of vehicle-available acceleration from skid resistance measurements.

TEST PROGRAM

This study was divided into three phases: (a) a feasibility study using one passenger vehicle, (b) measurement of limit accelerations of two vehicles representing a population of vehicles, and (c) measurement of the deterioration in limit accelerations of these vehicles with some non-standard tire inflation and pressure conditions.

Vehicles and Tires

All vehicle suspensions were restored and maintained to manufacturer's specifications. Except for the tire variable portion, the tires were maintained at recommended inflation pressures and at least 5/32 inch tread depth. The effects of tire variables were investigated by using tires with 2/32 inch or less tread depth and inflation pressures of 4 psi below or 4 psi above recommended. No side-to-side asymmetry was attempted.

The first phase test vehicle was a 1964 Ford Custom sedan which had been used in a previous study of side friction factors used in the design of highway curves (3). It is similar to the vehicle which was mathematically modeled by Cornell Aeronautical Laboratory (4). (A computer simulation of this car has also been utilized by TTI researchers.) The vehicle, shown in Figure 1, was equipped with a bucket seat, shoulder harness, interior roll bar, and antirollover outriggers as were the other test vehicles. The tires were Sears Supertreads.

Based on an earlier study (5) which compared the open-loop response of a cross section of contemporary passenger vehicles in limit maneuvers, two representative automobiles were chosen for further testing. The ten vehicles previously compared included a wide range of geometry, weight

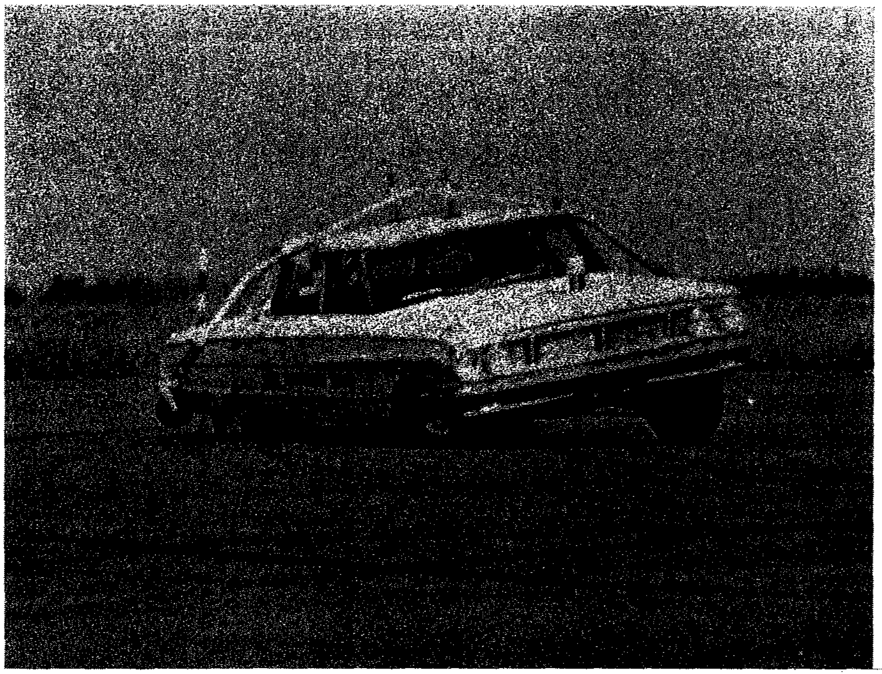

Figure 1. 1964 Ford Used in First Test Phase

distribution, power and suspension characteristics. Based on their observed responses to limit control inputs, these vehicles fell into two general categories -- those that had quick response but tended to experience an abrupt spinout in the limit and those that "plowed" out with no well-defined break in controllability. The former is represented in this study by a 1971 Volkswagen Superbeetle, Figure 2, and the latter by a 1971 Ford Custom sedan, Figure 3. The VW has a high center of mass to track width ratio, rearward weight bias and low rotational moment of inertia, while the Ford has a forward weight bias and is moderate in other respects.

In both the previous comparison and in this study, the vehicles were equipped with O.E. tires broken in by 200 miles of normal driving and a series of limit turns to produce the required shoulder wear necessary for consistent maximum cornering force. (It has been found that the limit cornering force of many tires increased up to a point with increasing shoulder wear (5).) The Ford tires were Uniroyal Fastrak H78-14 and the VW tires were 5.60 x 15 Continentals.

The results could be influenced by tire variations. However, comparisons between the Ford, VW, and the other vehicles included tire effects, i.e., the VW and Ford represent the cross section of vehicle-tire combinations of the previous study. In all cases tire tread depths of more than 5/32 inch were maintained except in the specific investigation of the effect of tire variables on vehicle maneuverability.

Measurement of Performance

Testing was semiopen loop, i.e., wherever possible the driver's inputs were controlled by steering and braking limiters. In tests in

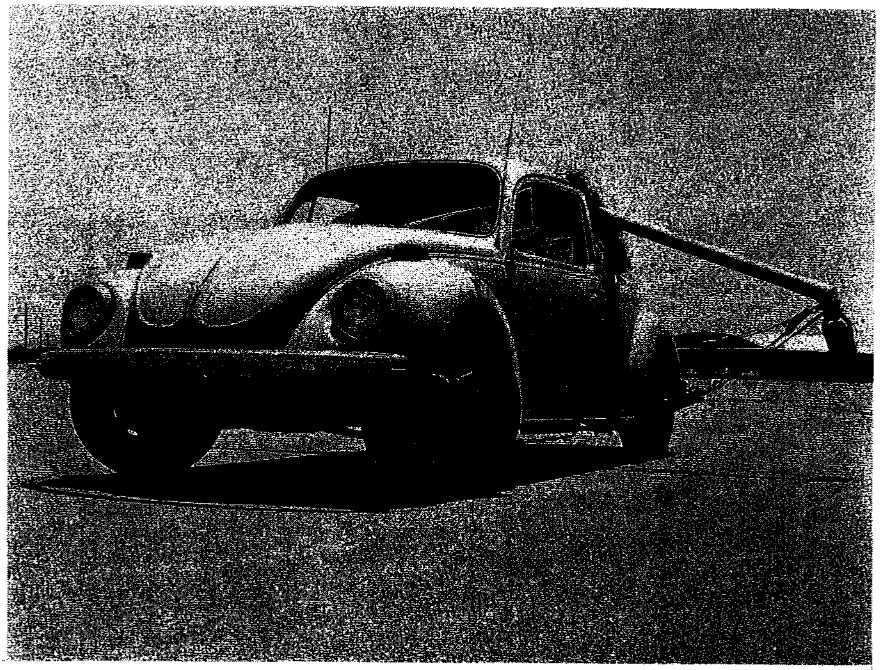

Figure 2. 1971 VW Superbeetle Used in Second Test Phase

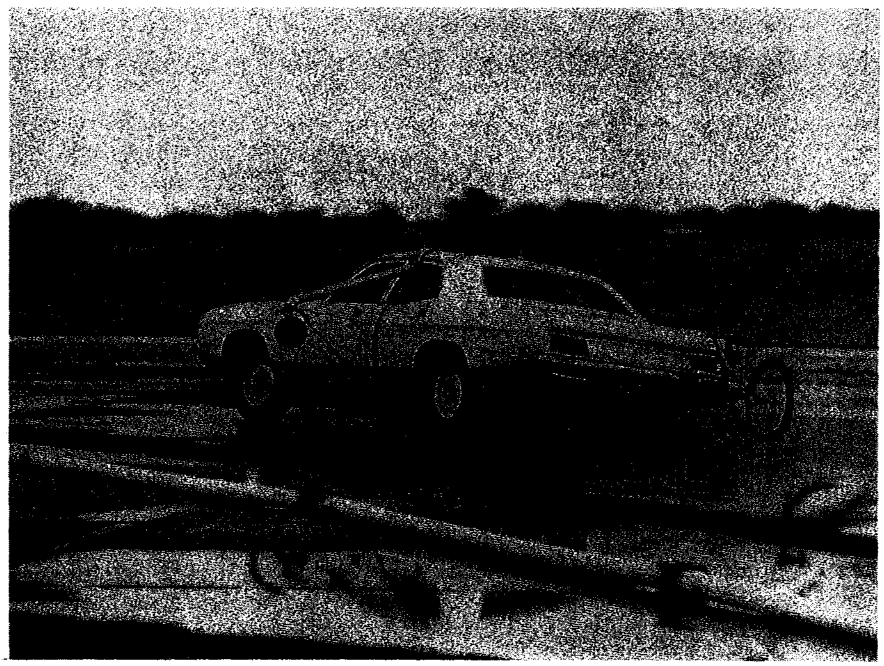

Figure 3. 1971 Ford Used in Second Test Phase
(shown traversing a 20° curve)

which inputs could not be predetermined, such as those on curves of fixed radius or limited geometry, the driver practiced to provide the required steer inputs during the maneuver. Repetitions indicated that consistency of vehicle response under these conditions was acceptable.

The electronic data were transmitted by telemetry and recorded on magnetic tape. All control valves and switches were located within easy reach of the test driver. A console adjacent to the driver's seat allowed data calibration steps and zeros to be obtained quickly and efficiently. Voice contact with the driver and telemetry base station was maintained through radio transceivers.

The following paragraphs briefly describe the vehicle instrumentation:

Accelerometers: Two accelerometers were mounted near the center of gravity (cg) to sense longitudinal and transverse accelerations. These were sensitive servo-type Larsen accelerometers with ranges of ±1 g.

Rate Gyros: Biaxial gyros were also mounted near the cg to sense yaw and roll rates. The yaw and roll rate outputs can be integrated to obtain yaw and roll angles. It was decided that to provide both angular displacements and rates, it is better to integrate rate rather than differentiate displacement because of the inherent "noise" in the latter process. The roll rate gyro had a range of ±25 deg/sec and the yaw rate gyro had a range of ±90 deg/sec.

Fifth Wheel: The fifth wheel used for sensing speed along the vehicle's path was modified by the inclusion of a lifting device which retracted the wheel at predetermined critical angles with the vehicle. This protected the fifth wheel during violent spinouts. The lifter could be actuated by the driver when backing the vehicle or when the fifth wheel was not in use between tests.

Steering Angle Limiter: This device was used to limit the steering angle for controlled turn inputs. A potentiometer was used to sense steering wheel angle (which was recorded) and counter-type dials could be set to the desired degree of left and/or right maximum steering angle at which mechanical pawls would be actuated by solenoids to prevent turning.

Wheel Rotation Sensors: Reed switches actuated by magnets on the wheel rims were installed on all four wheels. These allowed wheel rotations to be indicated every half rotation. This information is especially useful in braking tests to indicate wheel lockups.

Brake Pressure Limiter: This device was designed and fabricated to allow brake line pressure to be chosen and regulated in braking tests. In effect it is nothing more than a pressure reservoir against which the master cylinder works when the brake pedal is depressed. The driver could adjust the reservoir pressure and, since the reservoir had much greater volume than the master cylinder, no more brake line pressure could be obtained even though the brake pedal was depressed to the floorboard. A pressure transducer was installed in the master cylinder line to permit recording of brake line pressure. However, this is only necessary to measure onset rates or uncontrolled braking since the brake pressure in controlled braking could be set and read from the driver's seat.

Timing: A 100 Hz time signal was recorded with the electronic data to permit elapsed times to be determined. The electronic data channels were all recorded simultaneously to preserve their time relationships.

Much of the instrumentation can be seen in Figures 4 and 5.

Lateral and longitudinal vehicle accelerations were selected as parameters of primary significance since they result from forces which determine

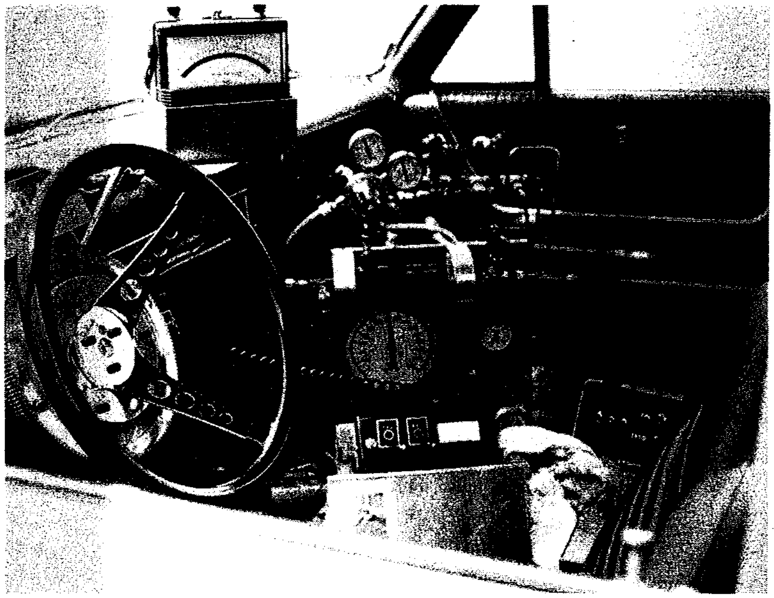

FIGURE 4. Vehicle Instrumentation
The steering wheel limiter on the steering column can be set with the two small dials in center foreground which are in front of the brake pressure limiter.

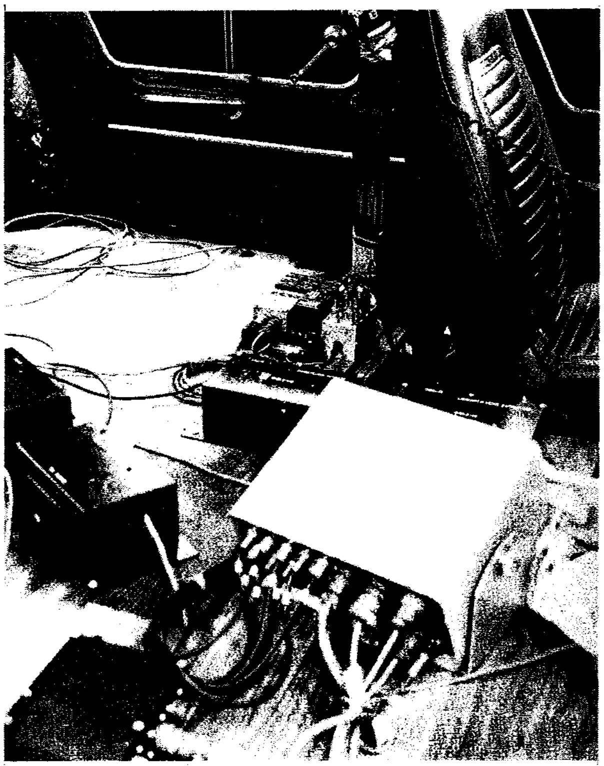

FIGURE 5. Vehicle Instrumentation
Foreground is back of instrumentation console. Telemetry transmitter is behind bucket seat.

vehicle motion. Maximum accelerations in steady-state maneuvers can be used to determine the stopping or cornering capability of the vehicle under those conditions. While yaw rate and other parameters may be of interest from a vehicle dynamics standpoint, for our purposes the achievable accelerations on a given pavement in a controlled maneuver (not in a state of spin or loss of control) are more meaningful and are used throughout this study. However, all data recorded are being retained on magnetic tape.

Maximum longitudinal deceleration for our purposes is defined as that resulting from a straight-ahead locked wheel skid with maximum braking. Somewhat higher deceleration may be obtained by controlling wheel slip to 10-20%, but this is not ordinarily achievable in contemporary cars driven by the hypothetical "ordinary" driver, and very likely cannot be achieved for any significant duration by highly trained drivers except under rare circumstances.

Maneuvers

The maneuvers included turning, braking, and combinations of these. No accelerating maneuvers were attempted, partly because of the difficulty of achieving and controlling reproducible increments of driving torque. Nonbraking maneuvers were performed throttle-off. More complete descriptions of the maneuvers are as follows:

1. Steady state turns - These are turns with fixed or near-fixed steering input. On the large test surface, runs were repeated with increasing steer input until lateral acceleration reached

a peak for that speed. On the J-curves (20° curves, 12 feet wide), the maximum lateral acceleration was determined by repeated trials at increasing speeds until the limit was bracketed. It was found that the maximum speed at which these curves could be negotiated was reproducible to about ±2 mph.

2. Straight line braking - The maximum (defined) deceleration was determined by full brake maneuvers with the steering wheel fixed at zero steer. This could be done on all surfaces due to the initial straight section of pavement at the beginning of the J-curves.

3. Braking in a turn - This maneuver was executed by determining the brake line pressure needed to produce medium deceleration without locking the wheels, then establishing a turn with fixed steer input and applying this brake pressure. On succeeding runs, steer input was increased until maximum lateral acceleration (for that degree of braking) was observed. This maneuver could only be performed on the large test pad due to limited geometry on the J-curves. The main purpose of this maneuver was to verify that the relationship between lateral and longitudinal acceleration could be approximated by an ellipse.

4. Avoidance maneuver - This maneuver can be thought of as a sudden lane change. It was a closed-loop maneuver in which the driver attempted to avoid a 6-foot-wide obstacle and remain in the adjacent lane. Limit conditions were established by repeating the runs with a fixed obstacle-distance and increasing speed until the maneuver consistently failed. Great emphasis was not placed

on this maneuver due to the unknown degree of dependence on driver skill.

Surface Characteristics

The surfaces utilized are listed in Table 1 along with the average texture depths (silicone putty method) and skid numbers (ASTM) at 40 mph. In most instances these pavements will be referred to by Surface Number for sake of brevity.

The water was applied to the surfaces by one of three means. On Surface 10 the water was supplied from a fire hydrant through a 4-inch diameter P.V.C. pipe with orifices drilled along its length. The pipe was oriented perpendicular to the slope of the pad and the water allowed to flow across the surface. Continuous flow resulted in water depths up to an average of 0.19 inch. By flooding the pad, stopping the flow and distributing the standing water with a sweeper, water depths less than 0.05 inch could be obtained in some instances. Due to surface, temperature and wind irregularities, the water depths were not always reproducible. However, average water depth was measured during testing when it exceeded the texture depth. This system in use is shown in Figure 6. Figure 7 shows the same system attached to a tank truck in use on the straight section of Surface 2. This section was used for the avoidance maneuvers with the 1964 Ford.

On the J-curves, spray nozzles were attached to the pipe which was supplied from a tank truck. These nozzles sprayed water onto the curved test surfaces. In this case the water flow was interrupted prior to the test vehicle approach. Due to high texture and limited water delivery

SURFACE NUMBER	DESCRIPTION	TEXTURE DEPTH (mils)	SN_{40}
2	Jennite Flush Seal (20° curve and straight pad)	14	18
4	Crushed Gravel Hot Mix (20° curve)	59	60
5	Rounded Gravel Hot Mix (20° curve)	37	50
7	Lightweight Aggregate Chip Seal (20° curve)	110	65
8	Lightweight Aggregate Hot Mix (20° curve)	38	54
10	Siliceous Rock Hot Mix (400 X 500 ft. test pad)	33	62

Table 1. Description of Test Surfaces

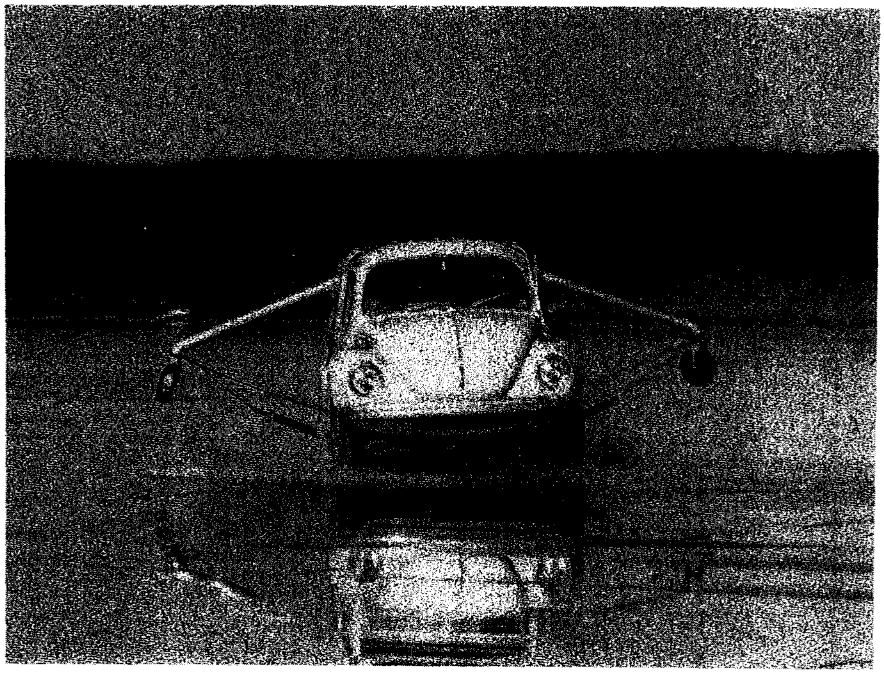

Figure 6. VW Maneuvering on Flooded Surface #10

FIGURE 7. Recovery Maneuver
on Jennite Skid Pad

rate, the water depth was measured on Surface 2 which has low macrotexture, after which it was applied on the other surfaces at the same rate although accurate depth measurements could not be made.

One reservation should be kept in mind when making predictions based on tests on these surfaces. That is, as indicated in Table 1, we have only one surface with a low Skid Number (Surface 2), and it also has low macrotexture. It would be very desirable to have data on other low friction surfaces as well as surfaces with a combination of low macrotexture, high microtexture and medium to high Skid Number.

RESULTS

Maximum Vehicle Accelerations (1964 Ford)

A complete description of the tests and results using the 1964 Ford was reported earlier (6). The results of the cornering, braking, and combination maneuvers with the vehicle on Surface 10 are illustrated by Figure 8.

It is interesting to look at the resultant of lateral and longitudinal accelerations in turning maneuvers with and without braking on dry and wet pavement. For the dry condition, as long as the turn radius allows full friction to be developed, the resultant maximum acceleration is not very sensitive to speed and averages approximately 0.85 g's for rolling wheels and about 0.7 g's for locked wheels. These are roughly equal to the cornering slip numbers and skid numbers (dry) obtained on that surface. However, in the wet condition the resultant acceleration is quite sensitive to speed. The interesting thing is that braking, either partial or full, and the two degrees of wetness seem to little effect the resultant, or total, acceleration for a given speed although it is speed sensitive. It appears that under these conditions for a given speed there is a friction value that is divided between lateral and longitudinal components based on the control inputs to the vehicle. That is, there is a fixed total acceleration possible, and an increase in one component is gained at the expense of the other although generally not on a one-to-one basis. Of course, more precisely reproducible data could very well discriminate between braking and nonbraking available friction.

At first glance the wet pavement resultant accelerations appear to contradict the fact that the maximum friction developed by a freely rolling

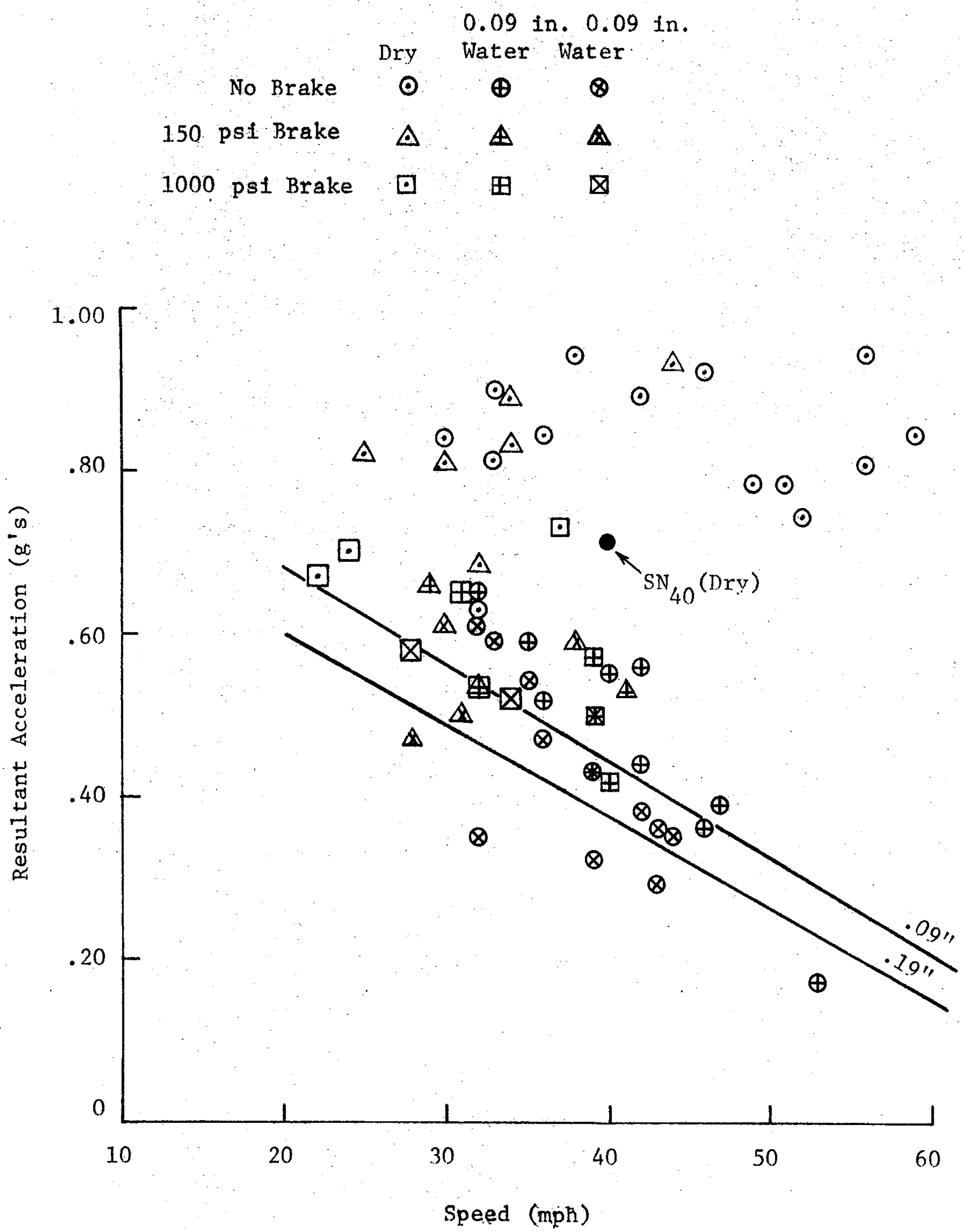

FIGURE 8. Resultant Accelerations, Asphalt Concrete, 12° Front Wheel Angle

wheel in the cornering mode is greater than that for a sliding wheel on this pavement. We must realize, though, that the resultant accelerations are the average result of four wheels with unequal loads and slip angles, that the vehicle is a much more dynamic and nonlinear device than a friction tester, that the water depths in these tests were much more than that used in most friction tests and, finally, that the data were gathered at the same steering angle in each test though not the same slip angles.

Some previous tests using the same test vehicle (but not the same tire) were run on dry portland cement concrete in which the steering angle was successively increased, at selected speeds, with the path and slip angle measured. With increased steering, the path radius of curvature decreased up to a given steer angle and then began to increase again. Figure 9 compares the path angle (referenced to the original path) in the "critical turn" runs with that predicted by the circular arc point-mass model using the measured dry coefficient of friction of 0.80. Also shown are the body slip angles which become relatively constant at 8 to 12°. At the "critical steer" angle for a given speed, the lateral acceleration saturates. The observed slip at minimum radius turn is approximately the slip angle at which maximum lateral force is observed in cornering slip number measurements on a single wheel. In this case the rear wheels are at this slip angle while the front have exceeded it. Past this, all wheels are at a high slip angle and the lateral component of acceleration obviously has reached saturation, preventing a smaller turn radius. Further steering causes a spin (or plow) condition which decreases the effectiveness of the turn. Figure 8 shows that the resultant acceleration on the dry asphalt surface saturates at about 30 mph for a 12° front wheel angle. It

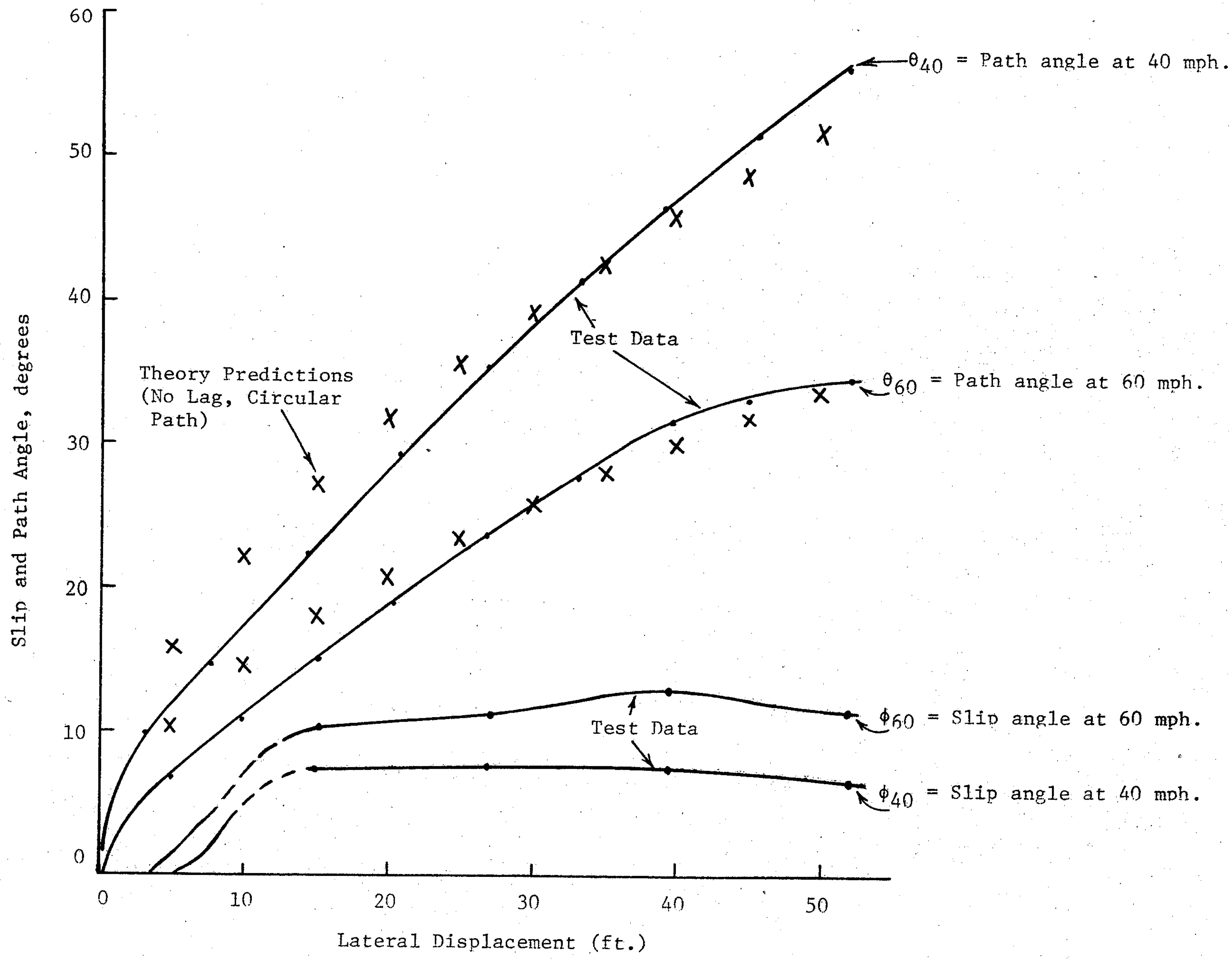

FIGURE 9. Slip and Path Angles in Sudden Turns on Portland Cement Concrete

is likely that the path radius would begin to increase at higher speeds for this amount of steer.

Hankins, in a study on factors affecting vehicle skids (7), developed a nomogram [based on data from Study 2-8-60-138 (8)] which permits a "modified friction factor" to be estimated from the ASTM skid number at 40 mph, speed, texture depth, and water depth. From the texture (putty impression method) of 0.033 inch and SN_{40} of 64 on the asphalt surface modified friction values for 0.09 and 0.19 inch water depth at three speeds were determined. These are indicated on Figure 8 as straight lines. The values are not very dependent on water depth, assuming minimal hydroplaning, and represent the measured values of resultant acceleration reasonably well. One point is also shown that represents the coefficient of friction measured with locked wheel skid trailer in the dry condition. It also compares favorably with the resultant accelerations observed in the dry condition.

The 1964 Ford was also used to investigate the lane change potential of the vehicle with a skilled driver at the controls.

Table 2 lists the data for the highest speeds that the lane change maneuvers could be performed without violating the obstruction zone or the outside of the adjacent lane. As expected, the speed at which the maneuver can be completed decreases with decreasing maneuvering distance. Figure 10 shows the maximum lateral accelerations obtained in the avoidance (initial) part of these maneuvers. It appears that this lateral acceleration peaks, for both surfaces, at about 0.5 to 0.6 g's. However, on the dry surface considerably more lateral acceleration was possible. This indicates that for constrained maneuvers of the lane change type the vehicles does not have sufficient time to develop the potential available friction as long as this friction is above a given amount. Comparing the two data traces

RUN NO.	V(mph)	AY(g's)	CONDITION
Asphalt			
13	56	.59	Dry, 60'
23	70	.51	Dry, 80'
28	35	.46	Wet, 60'
32	45	.37	Wet, 80'
Jennite			
53	51	.55	Dry, 60'
57	60	.57	Dry, 80'
61	36	.43	Wet, 60'
66	46	.41	Wet, 80'

V - Speed at maximum acceleration.

AY - Peak lateral acceleration in horizontal plane.

CONDITION - Wetting, obstruction distance.

Table 2. Data for Critical-Speed Lane Change Maneuvers

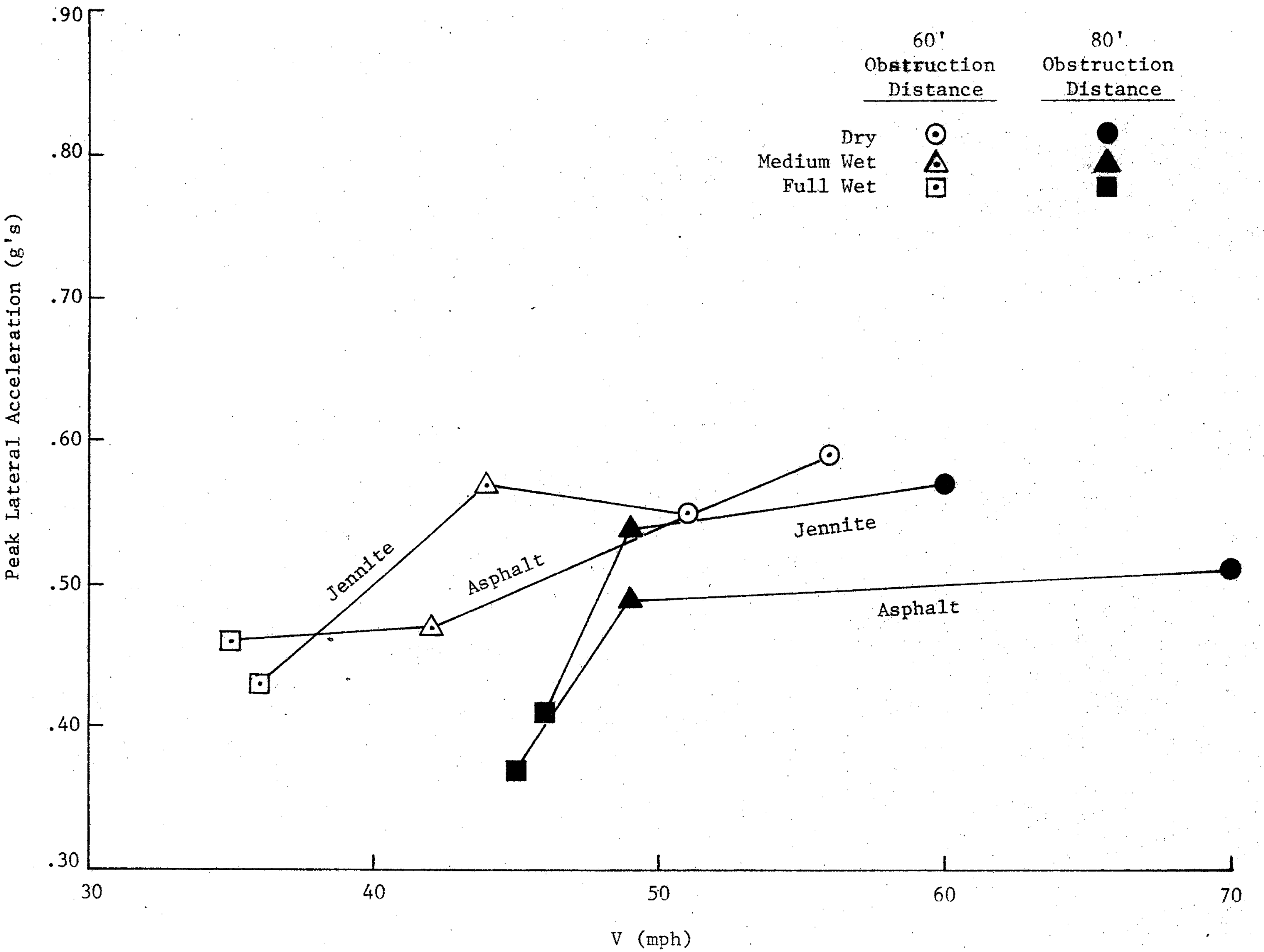

FIGURE 10. Peak Lateral Accelerations in First Phase of Critical Lane-Change Maneuvers

in Figure 11 illustrates this point. These two runs were chosen because the speeds (58 mph) at maximum acceleration and the maximum steer angles (about 230°) were the same. This gives a front wheel angle of about 9°. Both runs were made on dry asphalt concrete. Both maximum steer angles were reached in about the same time (0.6 second) and at this time both uncorrected lateral accelerations were about the same. In the step-steer maneuver, the steer angle was held constant while in the avoidance maneuver it began to reverse at this time. The lateral acceleration on the lane change maneuver peaked at 0.67 g's 0.4 second after maximum steer was reached and had been reversed. At this time the step-steer acceleration had reached 0.73 g's. From then on the lateral acceleration decreased in the lane change and increased in the step-steer to 0.95 g's 1.6 seconds after maximum steer angle was reached. So in the sudden lane change the time-lag phenomenon limits the maximum acceleration to about 70% of that possible. In any case the vehicle has at that time already passed the obstruction, and holding the steering input fixed would have been to no avail in the initial encounter. While the two test surfaces have widely differing friction values as measured by ASTM E-274, the ability to perform the lane change maneuver does not differ greatly from one to the other in the wet condition. It is also noted from the high-speed films that invariably the initial avoidance can be performed at higher speeds than can the recovery if successful recovery is judged by the criteria of staying within the adjacent lane. This appears to be due to the initial conditions of the two parts of the maneuver. In the initial avoidance, the vehicle is traveling straight and the vehicle must roll only one way in order to begin developing lateral force. In the recovery, the

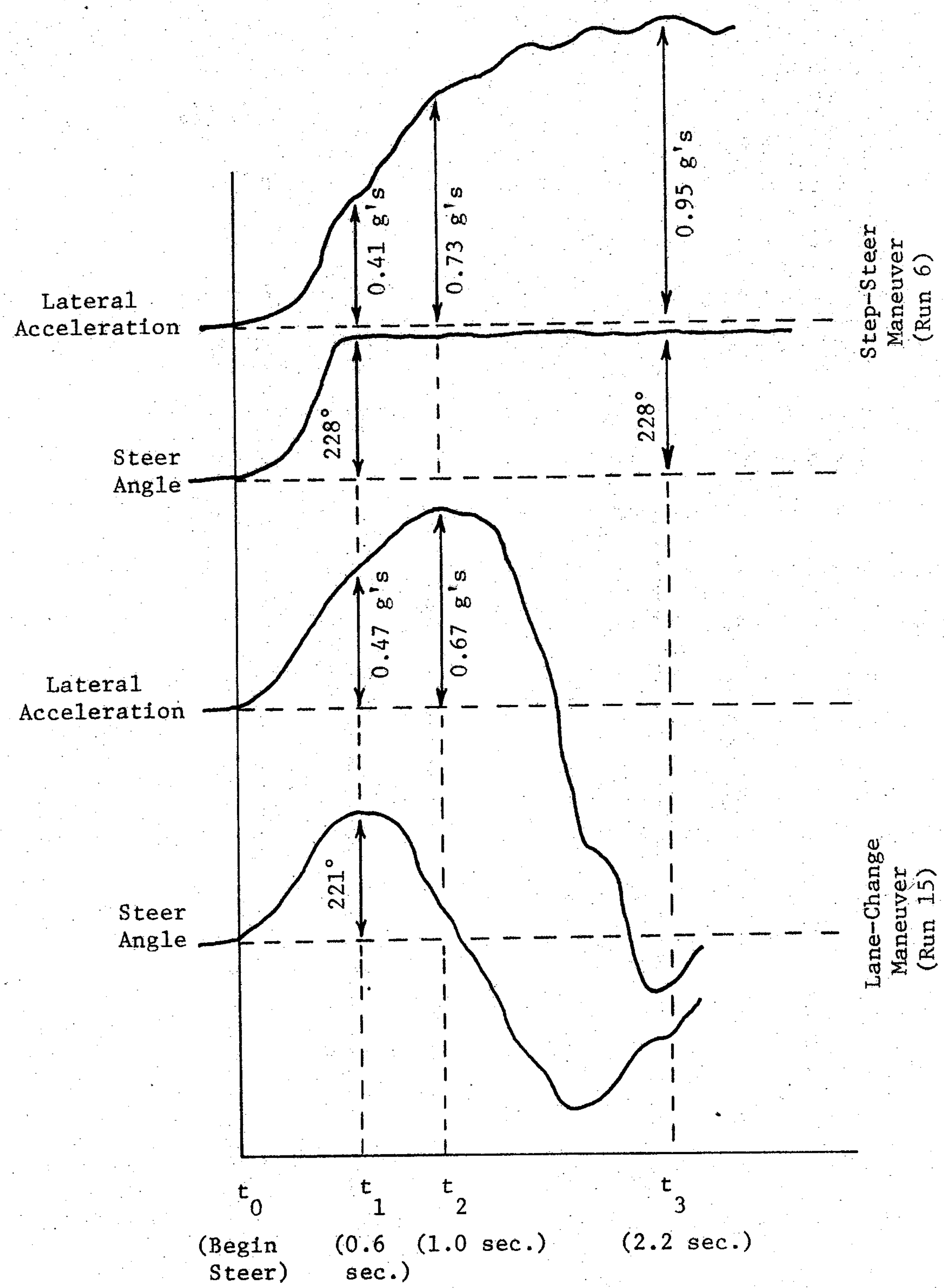

FIGURE 11. Steer Angle-Lateral Acceleration Comparison Between Steady Turn And Avoidance Maneuver Under Similar Conditions. (V = 58 mph)

turn is reversed, the vehicle must reverse the path curvature and perform a complete roll reversal. This not only requires more time (and distance) but the roll and yaw angular momenta reach higher peak values, which must be brought to zero in order to return to a straight path for an instant between the reversals. This seems to contribute to the tendency of the rear wheels to break traction causing a more severe spin condition. Another factor, the effect of which was not specifically investigated, was that all recovery maneuvers were made on slight reverse superelevations. This more closely simulates the condition in a lane change maneuver on two-lane roads. The test surface had no "roll-over" or crown, but had a cross-slope of 1/8 inch per foot to the left.

Both the electronic data and film analysis show a probable hydroplaning condition during two runs. In these runs, excessive initial steering inputs were accompanied by low yaw rates and lateral accelerations, which prevented missing the barrier. Data from another project (9) being conducted here indicate that in a straight ahead rolling condition 10% spin down of a similar tire under similar conditions would have occurred at about 50 mph. These runs were initiated at speeds of 57 and 53 mph. Runs at 46 and 47 mph did not result in comparable high steer-low response behavior. Although the lane change maneuver could be successfully performed at roughly the same speeds on wet hot-mix asphalt concrete and wet Jennite, this possible hydroplaning phenomenon, based on the previous criteria, was not as evident on the asphalt. This is probably due to the coarser texture of this surface.

Maximum Vehicle Accelerations (1971 Ford and Volkswagen)

In order to fully utilize the various pavements available at TTI for predicting maximum vehicle accelerations, some extrapolations must be made.

Since the various textures are contained in pads that have fixed radii of curvature (about 290 feet), there is only one stable limit condition. That is, there is only one speed at which that radius produces maximum lateral acceleration for each pad. However, because of the straight tangent sections, maximum stopping deceleration can be measured over the desired speed range.

Other researchers (11,12) have produced data indicating that the relationship between side force and longitudinal force is approximately elliptical, the degree of eccentricity depending on the surface, tires, and other factors. If this relationship is assumed, then for a given speed the maximum lateral and longitudinal accelerations define the eccentricity of the lateral-longitudinal acceleration curves. Then by defining the endpoints of the other ellipses from the stopping tests at other speeds, similar ellipses can be plotted giving a series of curves which estimate the lateral and longitudinal available acceleration for a range of speeds.

On Surface 10 the geometry does not restrict the vehicle to one curvature, and on this surface, measurement of limit accelerations was made at several speeds. Figures 12 and 13 are examples of the results.

The data for the Ford were obtained with an average water depth of 0.10 inch and those for the VW at 0.15 inch. (Water depth is partly dependent on wind and other factors and cannot be accurately reproduced over a large area.) The elliptical curves at 35 mph were fitted through the endpoints, then the intermediate points were plotted to get a feeling for the accuracy of the prediction based on endpoint alone. The points for each speed are actually taken at speeds within 2 mph of the indicated speed. (Limit conditions at a precise speed are extremely difficult to

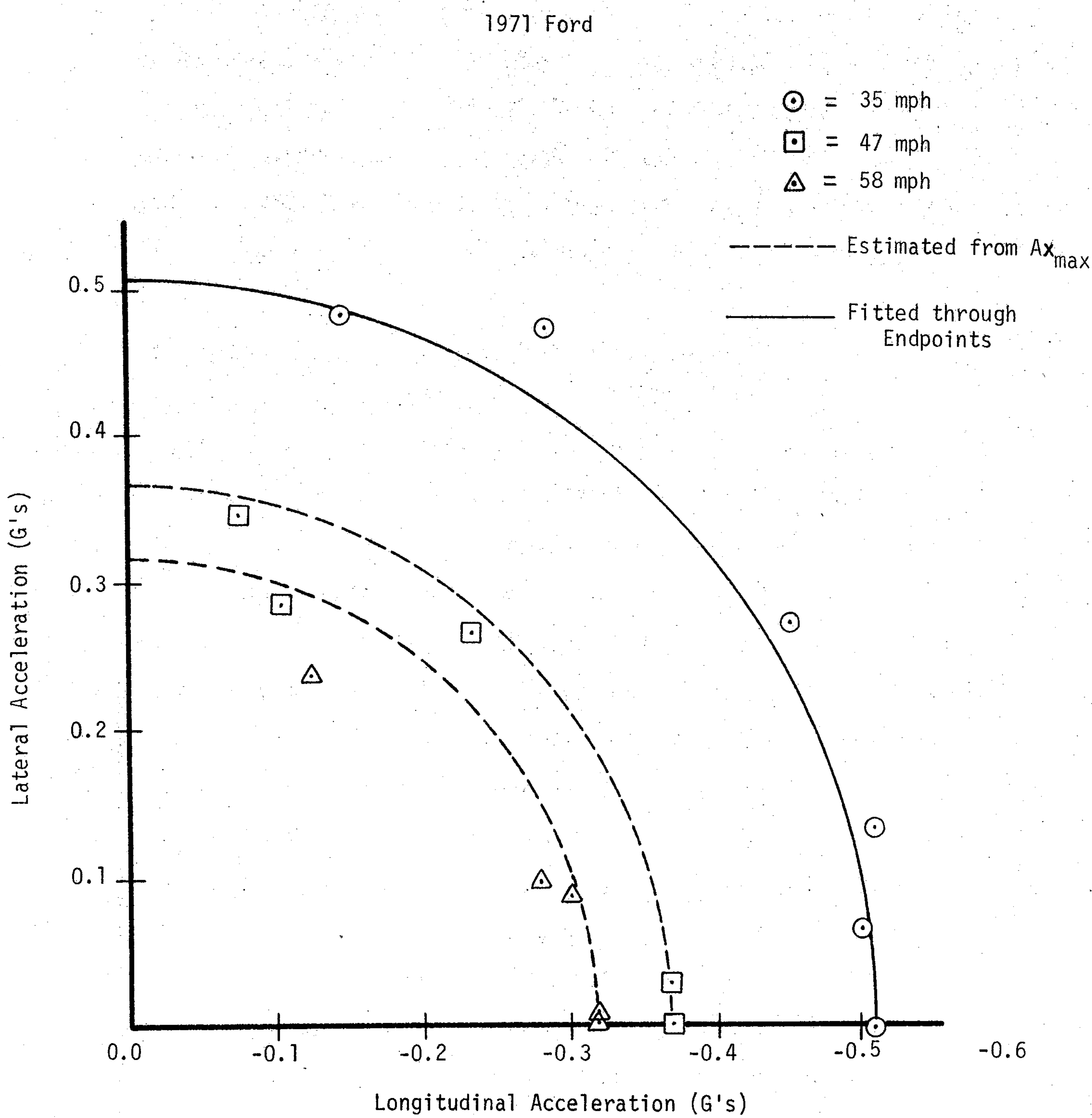

Figure 12. Longitudinal-Lateral Available Acceleration Using 1971 Ford on Surface No. 10.

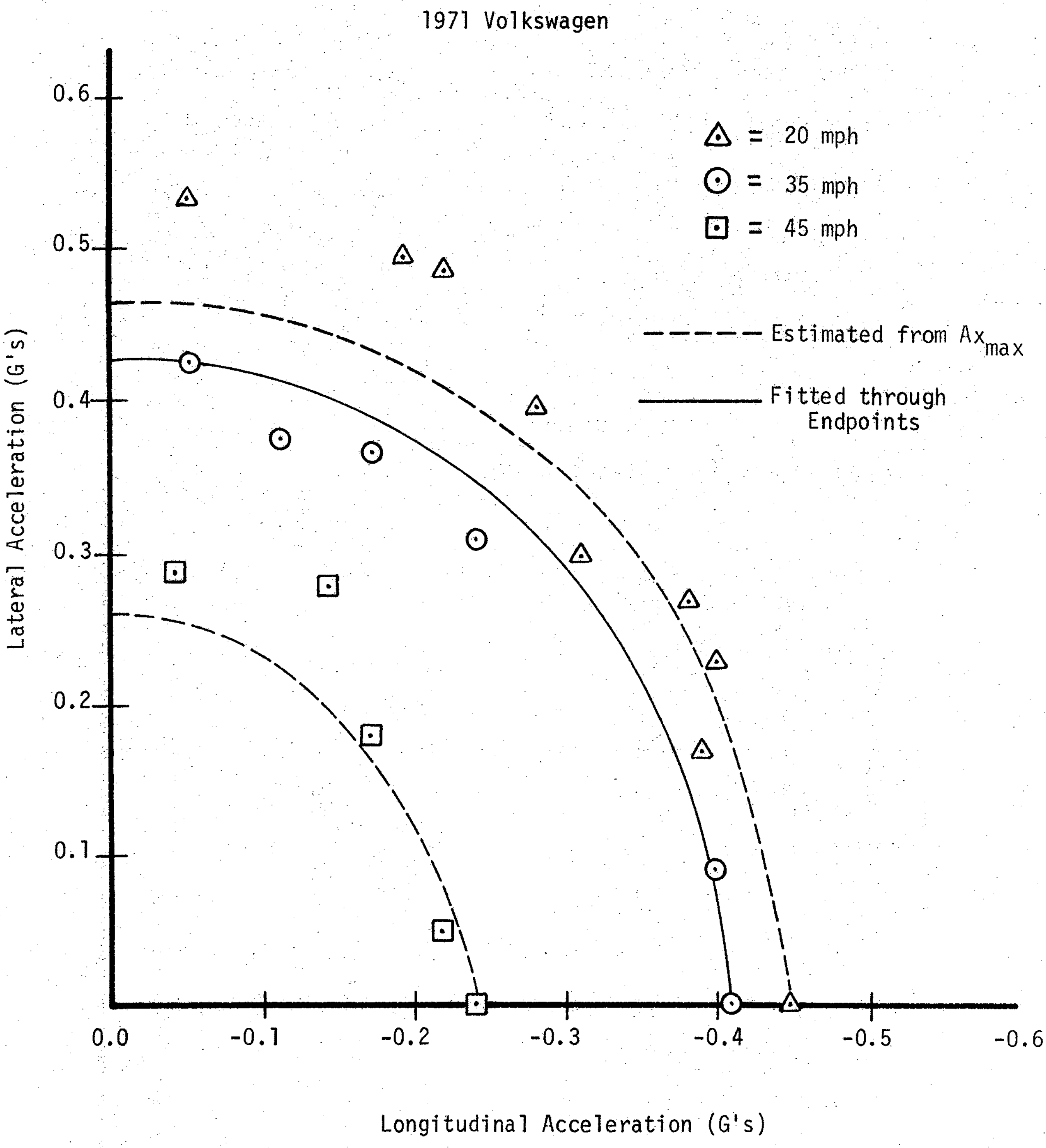

Figure 13. Longitudinal-Lateral Available Acceleration Using 1971 VW on Surface No. 10.

obtain.) The other two curves on each figure were obtained using the longitudinal limit accelerations and the same eccentricity as the 35 mph curves.

It is seen that extrapolations provide reasonable estimates of vehicle accelerations. In most cases the ellipses provide slightly conservative estimates of available friction forces.

By a process similar to the foregoing, the limit vehicle accelerations of the J-curves were estimated based on measurements made at a particular speed. The lateral-longitudinal acceleration curves are included in the Appendix, while the maximum values so obtained are presented in Tables 3 and 4. Stopping decelerations as a function of speed are also shown in the Appendix.

Acceleration as a Function of Skid Number

Using the data of this study only, there is no better correlation between vehicle-available acceleration and texture depth, British Pendulum Number, cornering slip number, or stereophoto analysis, than there is between vehicle acceleration and skid number. Since skid number is a common and convenient measure of friction and due to the emphasis placed on the accurate measurement of skid number at the FHWA Field Test and Evaluation Centers (13), this report will concentrate on the relationship of available acceleration to skid number. This does not preclude comparisons (using this data) with other parameters as the state-of-the-art advances.

Figure 14 compares the maximum vehicle accelerations at 40 mph with SN_{40} (skid number in accordance with ASTM 274-70). It appears that there is no simple relationship between skid number (and other parameters) and

SURFACE NUMBER	20 MPH		40 MPH		60 MPH	
	A_{x_m}	A_{y_m}	A_{x_m}	A_{y_m}	A_{x_m}	A_{y_m}
2	0.43	0.71	0.31	0.52	0.20	0.33
4	0.63	0.75	0.57	0.68	0.50	0.60
5	0.57	0.78	0.52	0.71	0.46	0.63
7	0.71	0.63	0.67	0.59	0.62	0.55
8	0.55	0.60	0.53	0.58	0.51	0.56

Table 3. Maximum Vehicle Accelerations, 1971 Ford Custom, in G's

SURFACE NUMBER	20 MPH		40 MPH		60 MPH	
	A_{x_m}	A_{y_m}	A_{x_m}	A_{y_m}	A_{x_m}	A_{y_m}
2	0.47	0.58	0.41	0.51	0.36	0.44
4	0.61	0.49	0.61	0.49	0.60	0.48
7	0.76	0.61	0.71	0.57	0.68	0.53
8	0.76	0.72	0.63	0.59	0.50	0.47

Table 4. Maximum Vehicle Accelerations,
1971 Volkswagen Superbeetle, in G's

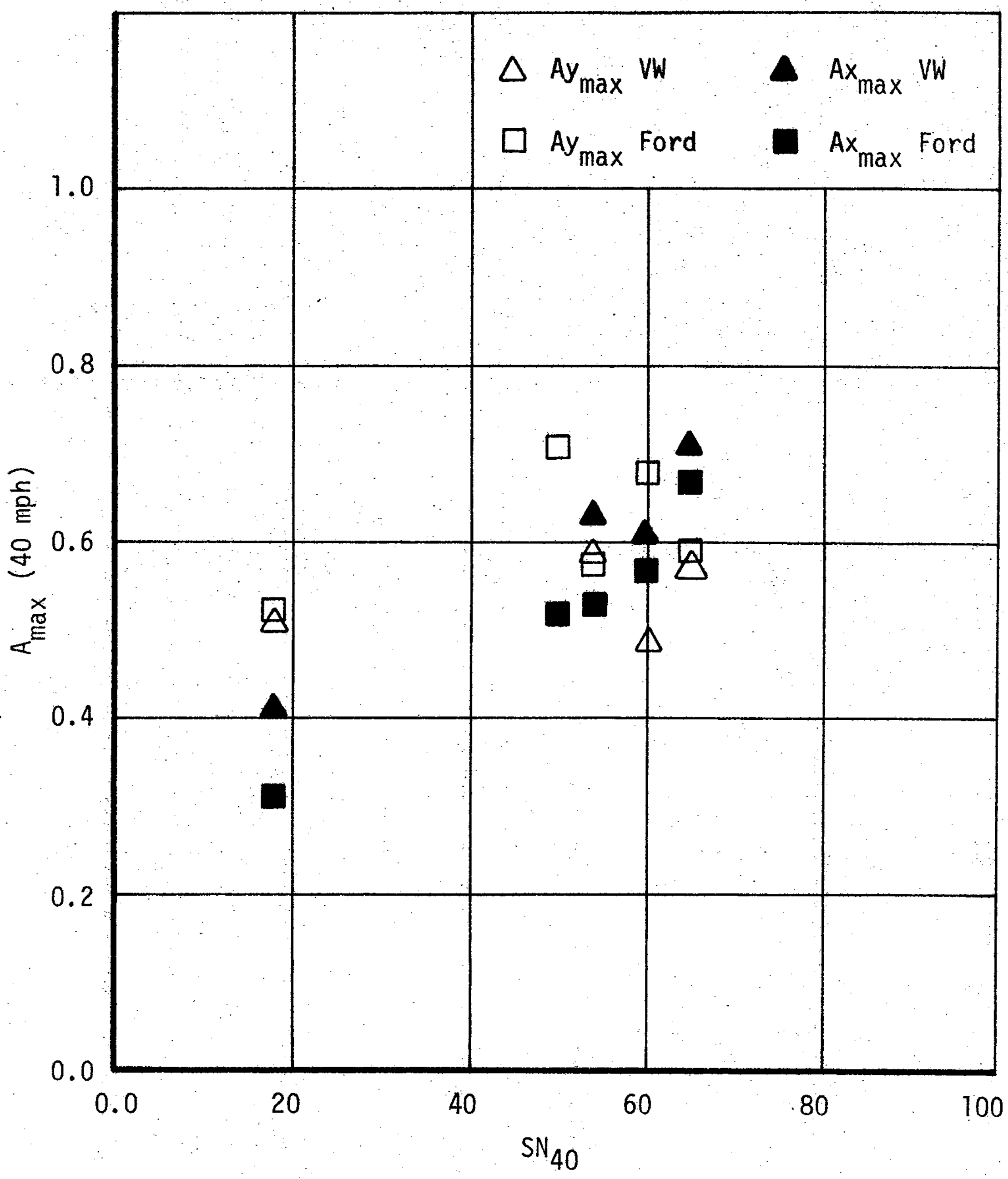

Figure 14. Vehicle Available Acceleration as a Function of Skid Number

vehicle available acceleration for a given pavement wetness. On some surfaces one vehicle can develop more friction than the other. On another surface this relationship reverses. Similarly, the relationship of Ax max and Ay max is not a constant, either for vehicles or surfaces. Therefore, it would be rash to make predictions at this time of available lateral and longitudinal acceleration separately. Let us pool the data and use mean values of available acceleration as an estimate of either longitudinal or lateral vehicle capability. Since this mean value, combining effects of cornering, stopping, vehicle and tire characteristics, will give a high estimate in approximately half the cases, we must make an adjustment to some lower value for use as a predictor. This "safety factor" may be arrived at in various ways. However, for our purposes, based on the range of responses on each pavement, the mean values are lowered one and two standard deviations (see Table 5) and these values are plotted in Figure 15. Also, the best-fit straight line through the lower points is shown. Figure 16 shows this estimator of lower limit vehicle acceleration for 20, 40, and 60 mph. Note that these curves diverge at lower SN's. Other than the fact that vehicle acceleration (and SN) measurement precision is poorer on low friction surfaces, these curves seem to indicate that high texture-high friction surfaces tend to minimize differences due to speed. One might expect this if the average water depth is less than the texture height, which it is in this case for the higher friction surfaces. Figure 17 shows that skid number also tends to become insensitive to texture on the high texture surfaces used in this study for the given water application rate. (The smoothness of this faired curve should not be interpreted to mean that texture alone is a good predictor of SN. Other surfaces not

SURFACE NUMBER	VELOCITY (MPH)	$\bar{A}$ (a)	S (b)	$\bar{A}$-2S (c)	SN_{40}
2	20	0.55	0.13	0.29	18
	40	0.44	0.10	0.24	
	60	0.33	0.10	0.13	
4	20	0.62	0.11	0.40	60
	40	0.59	0.08	0.43	
	60	0.55	0.06	0.43	
7	20	0.68	0.07	0.54	65
	40	0.64	0.07	0.50	
	60	0.60	0.07	0.56	
8	20	0.66	0.10	0.46	54
	40	0.58	0.04	0.50	
	60	0.51	0.04	0.43	

(a) Mean of maximum longitudinal and lateral accelerations for Ford and Volkswagen.

(b) Standard deviation about the mean.

(c) Mean available acceleration minus two standard deviations.

Table 5. Pooled Data Estimates of Available Acceleration as a Function of SN_{40}

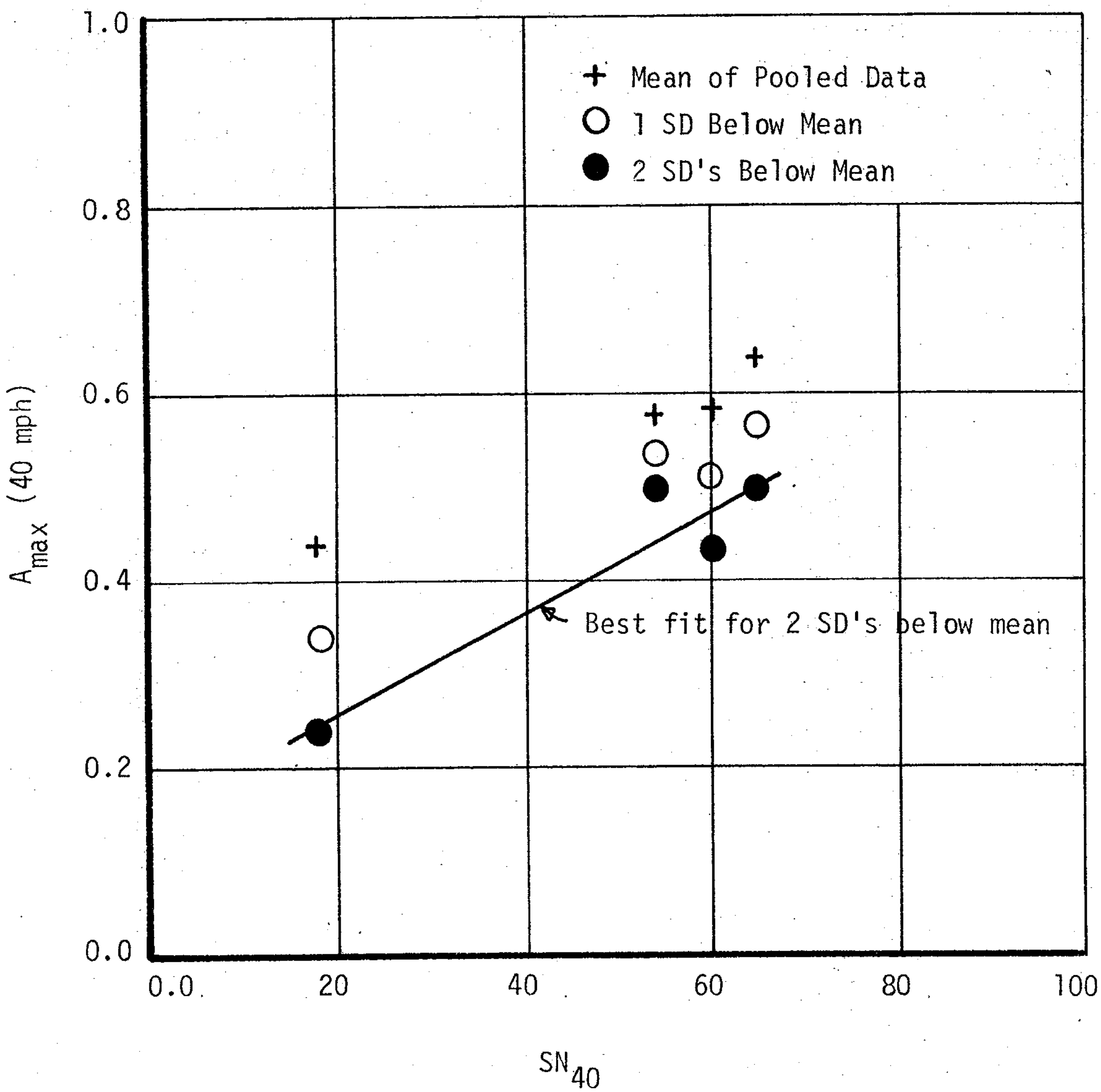

Figure 15. Estimation of Lower Limit Available Acceleration (40 mph) as a Function of Skid Number (40 mph)

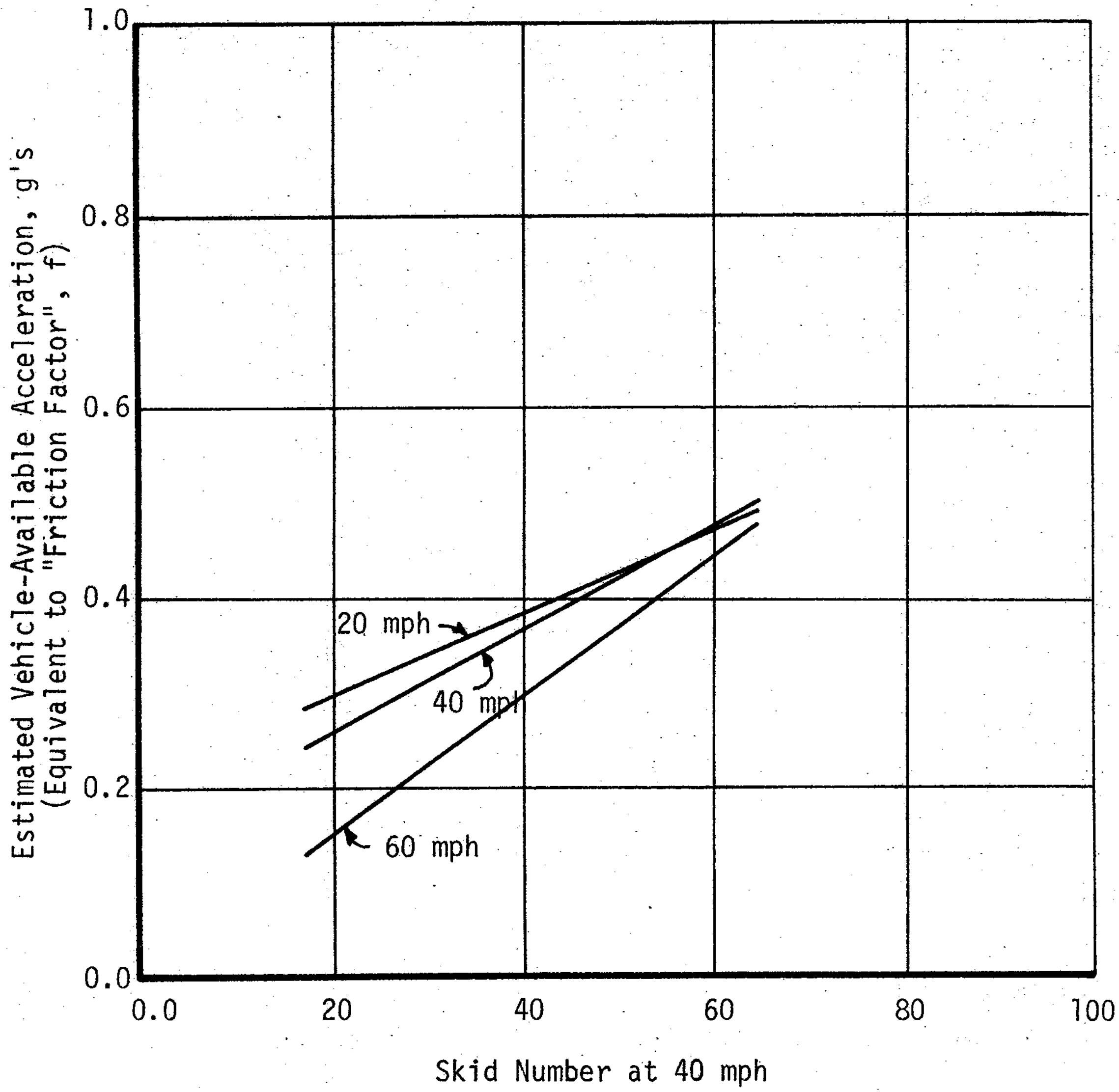

Figure 16. Estimated Acceleration Boundaries as a Function of SN_{40}

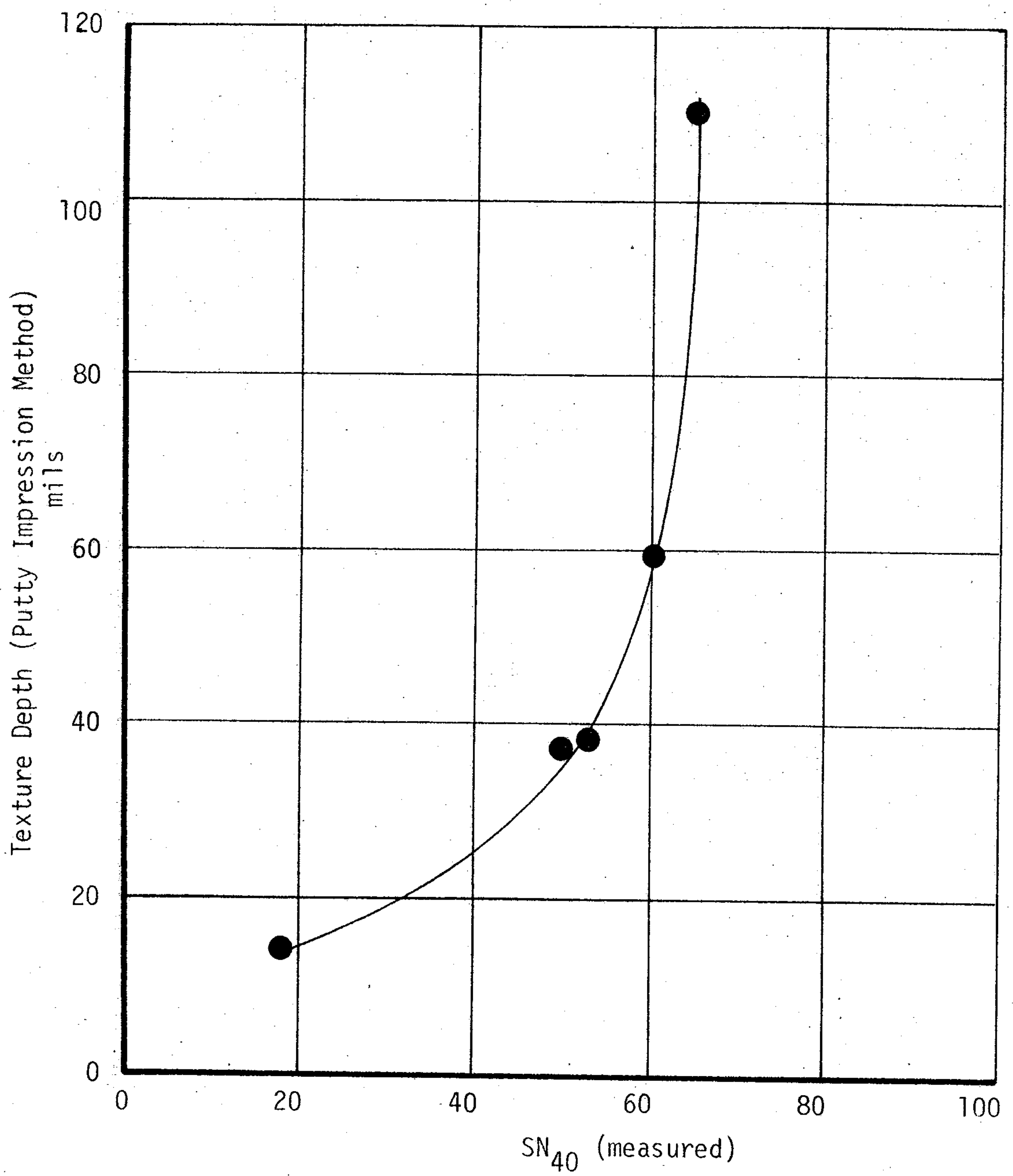

Figure 17. Texture vs. SN_{40} for 20° Curves

used in this study fall off this curve by varying amounts. However, they also indicate that SN does not always increase in proportion to texture.)

Several examples can be used to test our predictions for realistic water depths. (The effects of water depth will be discussed in more detail later in the report.)

In a previous study (3) using the 1964 Ford and a 1971 Pontiac on surfaces not used in our predictions, minimum limit accelerations of .38 g's and .30 g's were observed at 40 and 50 mph on a surface with an SN_{40} of 29.

Minimum limit accelerations of .43 g's and .40 g's were observed (again at 40 and 50 mph) on a surface with an SN_{40} of 50. Comparison with Figure 16 shows the predictions to be accurate to conservative.

Effect of Tire Variables

The data presented thus far were obtained with the tires at recommended inflation pressures and with 5/32 inch or more tread depth. Undoubtedly a vast number of vehicles in normal use are being operated with low tire tread depth, nonstandard distribution of inflation pressures, or both. In order to estimate the deterioration in limit acceleration due to these variables, tests were conducted using the 1971 Ford and 1971 Volkswagen with low tread depth and various tire pressure distributions. For the tread depth condition, 2/32 inch (minimum lawful depth in Texas) or less was selected. Pressures were chosen at 4 psi above and below the recommended pressures for the test vehicle loading. Various combinations of tread and inflation (including good tread and normal inflation) were tested. No left-right asymmetry was attempted. It became clear early that the combinations that produced the more obvious changes in vehicle behavior and limit acceleration were:

1. Normal tread and inflation front; worn tread and low inflation rear.
2. Worn tread and normal inflation front; normal tread and normal inflation rear. Where normal tread $\geq$ 5/32 inch; worn tread $\leq$ 2/32 inch; normal inflation = recommended and low inflation = 4 psi below recommended.

On every surface, with both vehicles, the worst case in cornering was produced by worn tread-low inflation in the rear and good tread-normal inflation in the front. In stopping, this same condition was frequently the worst case, with worn tread-normal inflation front and with good tread-normal inflation rear running second. However, the decrease in stopping ability due to tire conditions was not in general as pronounced as the decrease in cornering ability. For cornering, the decrease in radial acceleration as a percentage of the acceleration available with standard tire condition ranges from 13 to 35%.

Perhaps the most striking effect of low tread, low inflation in the rear is not evident from the acceleration data. That is, this condition caused the vehicles to spin when the limit was reached. At normal speeds and tire conditions, both vehicles remain relatively stable in the limit, tending to "plow" rather than spin. But with the poor rear tire conditions, exceeding the limit produced a sudden spin condition. From a stable "plowing out" condition the driver can regain directional control as soon as sufficient speed has been scrubbed off. However, the sudden, violent spin observed with low rear tread usually precludes resumption of control until the vehicle comes to a stop. Also, in the spin conditions, changes in surface friction or the presence of surface irregularities can cause large roll angles to be reached, though a full rollover would not have been produced in any of the tests.

In a report on wet-pavement accidents by Hankins, et al, (17), some interesting data are presented comparing frequency distributions of tread depths obtained from a non-accident random sample of vehicles and those from a sample of vehicles involved in single vehicle wet pavement accidents in one study area. The striking observation is made that the two distributions do not differ greatly for the front tire tread depths, but the frequency of low rear ($\leq$ 2/32 inch) tread depths from the accident sample is significantly greater than that from the nonaccident sample (see Figure 18). This may indicate that on other vehicles as well the low rear tread depth condition produces not only a reduced maneuvering capability but may indeed result in a type of skid (spin) from which the average driver would not be able to quickly regain control. In effect, these tire conditions can, in the limit, change the vehicle's handling characteristics from understeer to oversteer, which is considered an undesirable characteristic by automotive manufacturers. (Passenger cars are usually designed to understeer with normal loading and tire configurations.)

While we have been discussing the effects of variables of the individual tire, information pertaining to the problem of predicting vehicle maneuverability due to the effects of different tires is in order. In a study of tractional characteristics of a cross section of tires (14), A. H. Neill and P. H. Boyd conducted tests on wet surfaces using an instrumented vehicle. They found that 95% of the variation in friction between tests with tires of the same make and size would account for 87% of the variation in friction between all the different make and size tires. One conclusion that was drawn is that it was not feasible to grade tires of

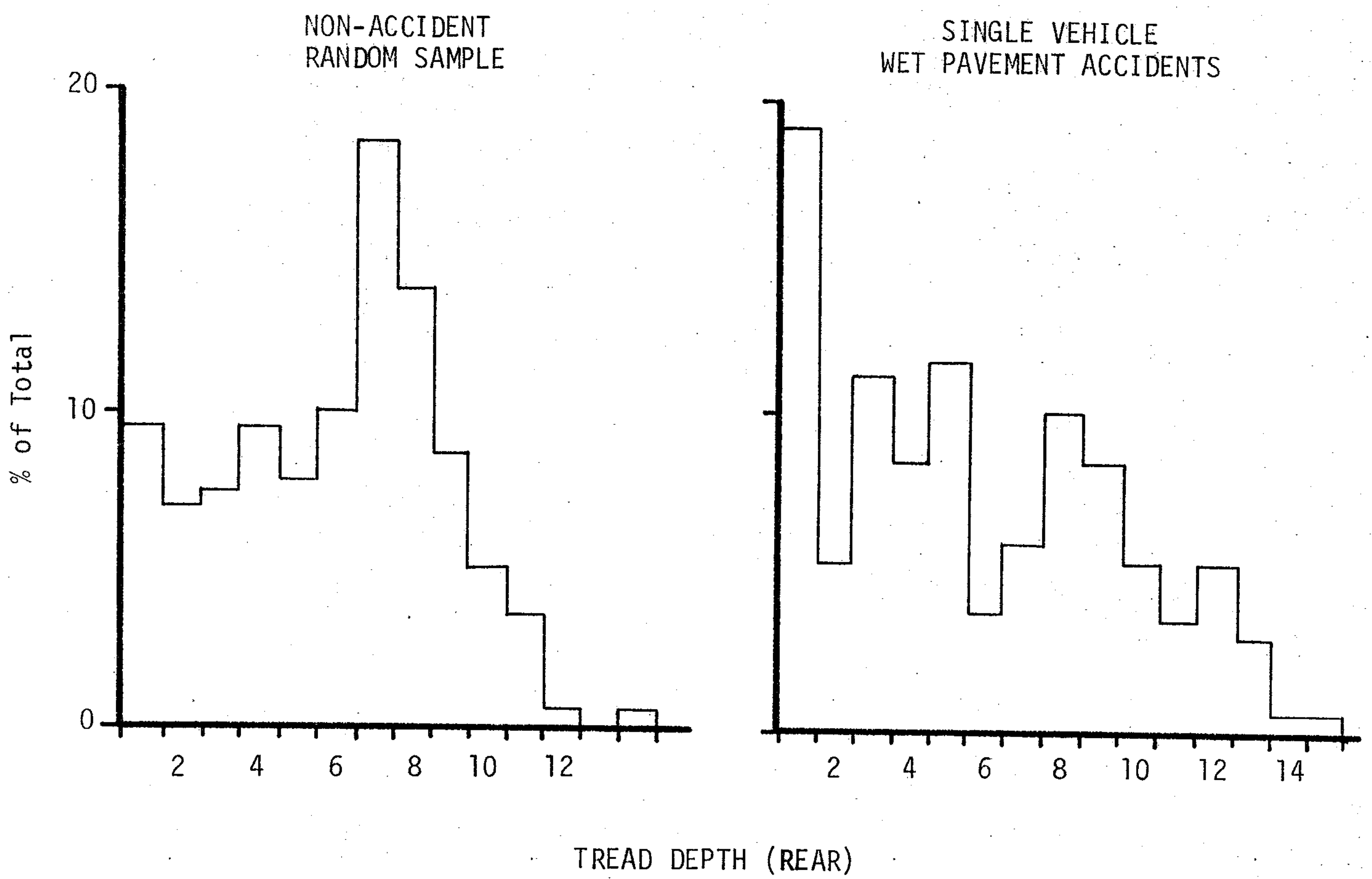

Figure 18. Distribution of Rear Tire Tread Depths for Accident Sample and Random Sample

different makes based on friction produced in vehicle tests. They also found that the various tires assumed different rankings on different surfaces.

Their results show that the available acceleration observed with tires that correspond to 90% of O.E. size tires has a range of about 0.2 g's. This means that an individual vehicle might be observed to have as much as 0.2 g's difference in available acceleration when using different tires. We observe a similar range for a given surface on Figure 14. Our study used cars selected to represent a range of responses and included the effect of tire type and size. The difference in response was of the order of that observed by Neill, and tire differences may be the dominant factor in the observed differences. We also observed that the ranking of the vehicles on different surfaces was not consistent. To accurately predict vehicle-available friction, it is clear that a knowledge of pavement parameters is insufficient. The effect of tires is significant, and a more complete understanding of the basic mechanism of tire-pavement interaction is needed. An ongoing study at TTI (15) is investigating this basic mechanism in order to simulate the interaction in mathematical models of vehicle handling. The data generated in our tests may be of value in validating such a model.

Water Depths

One of the major weaknesses of testing with external water sources is that water depth over a significant area is difficult to control and reproduce. Therefore the effects of water depth are difficult to separate from effects due to other parameters. Ordinarily, in full-scale vehicle tests we have had to some extent take what we could get in the way of water depth, and then measure the average value during testing. There are different schools of thought on the definition of different operational regimes due to water depth. For our purposes we will consider three different levels of operation based on water depth and speed.

First is "dry" pavement operation. This could be defined as the performance observed in which the effects of moisture are not discernible. Normally there is little variation in friction with speed, and since most pavements provide adequate friction in this condition, we have largely ignored it in this study.

Second and third are wet pavement operations which can be divided into two conditions -- that range of speed and water depth which produces an essentially linear decrease in friction with increasing speed and in which at least some maneuverability is observed, and the range above the point (or area) of depth and speed at which little or no maneuverability is observed. Our investigation was primarily centered in the middle range though "hydroplaning" conditions were encountered and will be discussed in another section.

For a given set of conditions, wet pavement friction has a speed gradient that is different on different surfaces. Holding other parameters constant, we also observe a decrease in friction with increasing water depth. However, as long as the pavement is not dry and hydroplaning conditions do not prevail, small changes in water depth were not observed to produce drastic changes in friction. The nomogram developed by Weaver, et al (7), also indicates that, within limits, friction is not very sensitive to water depth. The effect of water volume is also, in the middle regime, apparently (and not surprisingly) dependent on pavement texture depth. As long as the water does not approach the top of the asperities, it is assumed that lubrication of the pavement is the dominant factor. As the water depth becomes greater, hydrodynamic forces play an increasingly important role. It is felt that in the tests of this study these forces were significant on only two pavements, No.'s 2 and 10. On pavement 2, a very low texture is present, and on pavement 10 (large test pad) significant water depths above the asperities were observed. On the other surfaces it is estimated that a rainfall rate of about 8 inches/hour would produce the estimated water depths and that these rainfall rates would represent more than the 99.9th percentile rainfall rate in Central Texas. These estimates are based on a study by Gallaway (16) and on unpublished data from D. L. Ivey developed on another study (9).

Hydroplaning

Another study (9) terminating this year was aimed at identifying the conditions under which full hydroplaning occurs as indicated by spindown of a freely rolling wheel. While our vehicle measurements were concerned with maneuverability on wet pavement, they were not designed to investigate this phenomenon. Nevertheless, in some tests on two pavements on which the water depth was significantly above the asperities, we did observe vehicle behavior which indicated some degree of hydroplaning was occurring. This was indicated by high steer input and low vehicle response. Table 6 indicates the test conditions under which hydroplaning appeared to be occurring. An equation has been developed, though unpublished at this time, which relates speed to texture, tread depth, tire pressure, water depth, and percent spindown of a freely rolling wheel. This speed for the test conditions, and assuming a spindown of 20%, was computed for comparison. For the Ford, the speed for 20% spindown was computed to be

VEHICLE	SURFACE (No.)	TEXTURE DEPTH (in.)	AVERAGE WATER DEPTH (in.)	TREAD DEPTH (32nds in.)	TIRE PRESSURE (psi)	COMPUTED SPEED (mph)	OBSERVED SPEEDS (mph)
1964 Ford	2	0.014	0.10	8	26	53	53-57
1971 Ford	10	0.033	0.15	8	27	54	49-55
1971 VW	10	0.033	0.15	2	21	46	47-52

Table 6. Computed and Observed Hydroplaning Speeds

54 mph, and for the VW 46 mph. Table 6 also shows apparent hydroplaning conditions for the 1964 Ford on Surface 2. The computed speed for 20% spindown is 53 mph. (While 20% spindown was arbitrarily chosen for this comparison, lowering it to 10% or increasing it to 50% changes the predicted speeds by only about 3%. That is, based on this model, the speed producing detectable spindown is only a few mph lower than that producing full spindown.) The data from the vehicle tests can be searched further for evidence of hydroplaning that can be used to test the predictor.

EVALUATION OF DESIGN OR MAINTENANCE CRITERIA

Unfortunately we cannot at this time accurately predict vehicle capability in a given situation, partly because of the possible degrees of vehicle type, loading, tire type and condition, and other factors. Nevertheless, the data in this report were acquired using real but disparate vehicle-tire combinations. Let us assume, then, that the lower limits of Figure 16 are realistic, and look at the required friction for certain maneuvers.

It is desirable to reduce the accident frequency at certain sites. A high accident frequency can be the result of any number of factors, only one of which is the available friction. So, in making the decision to alter the skid resistance or not at such a site, we can utilize the results of this study.

First, a judgment must be made as to the type of maneuver which is being attempted, or the maneuver required for the particular location. The following subsections present the technique for utilizing the vehicle acceleration data, and examples of friction required as estimated by SN_{40} are computed for minimum recommended radius of curvature and stopping sight distance. These estimated values, since they correspond to the minimum recommended geometric factors, are indicative of maximum required friction. Most locations, of course, would not normally require friction factors of this magnitude. The example values for 40 and 60 mph are given in Table 7.

Cornering Only

For cornering only, the friction factor required may be estimated by the well-known formula,

$$f_c = \frac{V^2}{15R} - e \qquad \text{Eq. 1}$$

where V = speed in mph,

R = radius of curvature

and e = the superelevation in feet/foot.

We see from Table 7 that due to the large minimum recommended radius of curvature for design speed from the Operations and Procedures Manual (10) and assuming a superelevation of 0.06 feet/foot, the required skid numbers are too low to be meaningfully estimated from our data.

Stopping Only

The friction required to stop a vehicle from an initial speed V (mph) in a distance d (ft) may be approximated by

$$f_s = \frac{V^2}{30d} \qquad \text{Eq. 2}$$

"d" does not include the distance required for a driver to react.

If we use a perception-reaction time of 2.5 seconds, then the required stopping sight distance in feet is

$$S = d + (2.5 \text{ sec})(V \text{ ft/sec}) = d + (3.67)(V \text{ mph}) \qquad \text{Eq. 3}$$

"S" includes an allowance for driver perception-reaction time. Solving for d and substituting into Equation 2,

$$f_s = \frac{V^2}{30S - 110V} \qquad \text{Eq. 4}$$

The computed values of f and SN from Figure 16 are given in Table 7 for the recommended minimum stopping sight distances corresponding to design speeds of 40 and 60 mph.

MANEUVER	V (mph)	S (ft)	R (ft)	e (ft/ft)	F	SN_{40}
C	40	a	715	0.06	0.09	b
C	60	a	1910	0.06	0.07	b
S	40	300	c	d	0.35	37
S	60	600	c	d	0.32	43
CS	40	300	715	0.06	0.36	39
CS	60	600	1910	0.06	0.32	43

C = Cornering; S = Stopping; CS = Cornering + Stopping

V = Design speed, mph

S = <u>Minimum</u> recommended stopping sight distance, ft.

R = Radius of curvature, ft.

e = Superelevation, ft/ft

F = Resultant required friction factor

SN_{40} = Skid number at 40 mph

NOTES:

a. Stopping not considered. ($S = \infty$)

b. Values are too low to be estimated from Figure 16. Assume $SN_{40} < 20$.

c. Cornering not considered. ($R = \infty$)

d. e of 0.07 assumed for examples. This level of superelevation not expected to alter straight-line stopping performance significantly.

Table 7. Examples of Estimated Required SN_{40} for Minimum Sight Distance and Radius of Curvature

Stopping While Cornering

The Manual (10) does not differentiate between stopping friction on curves and tangent sections, and consequently recommends the same stopping sight distance in both cases. This could lead to improper estimates because it is known that an increase in limit cornering acceleration produces a decrease in limit available stopping acceleration, and vice versa (see Figures 12 and 13). Fortunately, the large minimum radii recommended in Texas require small cornering accelerations and therefore do not appreciably affect required stopping friction, as will be seen in Table 7. However, this fact should be kept in mind for curves such as off-ramps where sudden stops may be required and where the opportunity exists to exit at considerably more than design speed for the curvature.

Since the relationship between available stopping and cornering friction is approximated by an ellipse, the required friction is

$$F_{cs} = \sqrt{f_s^2 + f_c^2} \qquad \text{Eq. 5}$$

where f_s = required stopping friction

and f_c = required cornering friction

Squaring and adding Equations 1 and 4, we get

$$F_{cs} = [(\frac{V^2}{15R} - e)^2 + (\frac{V^2}{30S - 110V})^2]^{\frac{1}{2}} \qquad \text{Eq. 6}$$

For stopping distance only, not including perception reaction time, use

$$f_{cs} = [(\frac{V^2}{15R} - e)^2 + (\frac{V^2}{30d})^2]^{\frac{1}{2}} \qquad \text{Eq. 7}$$

We can see from Table 7 that, based on realistic estimates of vehicle capability under realistic conditions, the required SN_{40} for performing various maneuvers at 40 and 60 mph is close to 40. That is, for worst case conditions of minimum recommended stopping sight distance and radius of curvature, the estimated SN_{40} does not differ greatly with speed or maneuver type, and amounts to a value of about 40. While some factors such as unusual vehicle-tire conditions, excessive speed, or excessive water depths could make the estimate too low, we feel that under most conditions this value is a reasonable estimate and that problems arising on pavements with an SN_{40} of 40 might more effectively be solved by means other than simply providing more friction. However, high accident frequency sites should be evaluated individually in order to ascertain the nature of the problem. If it is found that drivers, for whatever reason, are attempting maneuvers which are not allowed for in the recommended design geometry (exceeding the design speed, for example), then it may be feasible from a cost-effective standpoint to provide more friction rather than redesign the geometry or make other alterations.

From Equation 6 it can be seen that the required friction for a given maneuver is most sensitive to speed which enters as the square. Table 8 shows the reduction in friction factor produced by a 10% change in each parameter for a selected set of initial conditions. It can be seen that in this case the reduction in SN for a 10% change of parameters is greatest for a reduction in speed and least for an increase in superelevation. This is because these initial conditions do not require a large percent of the friction to be spent in cornering. In Figures 12 and 13 it can be seen that when little cornering friction is required a small increase in

V (mph)	S (ft)	R (ft)	e (ft/ft)	PARAMETER CHANGED 10%	CHANGE IN SN_{40}
40	300	715	0.06	(initial conditions)	
36	300	715	0.06	V	-50%
40	330	715	0.06	S	-30%
40	300	785	0.06	R	- 5%
40	300	715	0.07	e	-<1%

Table 8. Effect of a 10% Change in Design Parameters on Required SN_{40} for a Selected Set of Initial Conditions

cornering friction demand does not significantly change the available stopping friction. However, in this case a small increase in demanded stopping friction reduces the friction available for cornering to almost zero. The converse is true for conditions in which almost all the friction is expended in cornering.

The Passing Maneuver

The passing maneuver tests show that, without braking, the speed at which a lane change can be made in a given distance is not very dependent on measured pavement friction, and that the maximum available friction is not in general used because of response time limitations in a single lane change. At 45 mph the lane change distance is about 80 feet, while at 35 it is 60 feet. This suggests that the distance required is approximately linear with speed, which also indicates that friction is not the only factor. If it were, we would expect the distance to be proportional to velocity squared. Since the lane change distance is a relatively small portion of the total passing distance, we will assume that each lane change occupies a longitudinal distance of 100 feet and that the relative movement between the passed and the passing vehicle, after the initial lane change and before the final lane change, is 100 feet. These distances provide an arbitrary safety margin. In order to complete a passing maneuver, the passing vehicle uses 100 feet for each lane change, or a total lane change distance of 200 feet. The time required to do this is $t_1 = \frac{200}{1.47V_1}$ where V_1 is the average speed of the passing vehicle in mph. (For simplicity we will consider all vehicles traveling at a constant speed though the passing vehicle will probably be acceleraring and an oncoming vehicle may be decelerating.)

The time spent in the passing lane will be $T_2 = \frac{100}{1.47(V_1 - V_2)}$ where V_2 is the speed of the passed vehicle in mph.

An oncoming vehicle traveling at speed V_3 will cause a closure rate of $(V_1 + V_3)$. If we let the speed of the passing and oncoming vehicles be equal to the design speed, V_d, the distance closed (assuming both vehicles' drivers see each other at the passing sight distance and the passing maneuver begins at this minimum distance) is, in feet,

$$S = 1.47\ (V_1 + V_3)(t_1 + t_2)$$

$$= 1.47\ (2V_d\ )\ \frac{200}{1.47V_d} + \frac{100}{1.47(V_d - V_2)}$$

$$= 400 + \frac{200V_d}{(V_d - V_2)}$$

Let $(V_d - V_2) = V_r$ = relative speed of the passed and passing vehicle. Then

$$S = 400 + \frac{200V_d}{V_r}$$

It is interesting to note that, based on this criterion, the minimum passing sight distances in the Operations and Procedures Manual require an average relative speed between the passed and the passing vehicle of about 7 mph for design speeds of 40 to 80 mph. A more exact model which eliminates some assumptions provided essentially the same result.

Suppose that the passing vehicle must brake down to the speed of the passed vehicle while either aborting a passing maneuver or re-entering the traffic stream at the end of the maneuver. An estimate of the increase in distance required to perform the lane change with sufficient deceleration to reach the passed vehicle's speed was made for a relative speed of 7 mph for several design speeds and friction factors. Only for higher speeds and very low friction does the distance required exceed our 100-foot estimate by 100 feet or more. And since 100 feet is probably within the error involved (due to assumptions) in estimating required passing sight distance, and is a relatively small percent of total sight distance, it does not appear that new estimates of required minimum sight distance need be made for the case of braking. While higher relative speeds between the passed and passing vehicle would require more distance for the maneuver to be completed with braking, the same higher relative speed would allow the overtaking to be completed sooner, thereby tending to offset this increase.

CONCLUSIONS

1. A more basic understanding of tire-pavement friction is required before vehicle-available friction for stopping and cornering can be separately predicted from nonvehicle measured parameters. However, lower limits of vehicle-available acceleration as a function of skid number at 40 mph have been established from full-scale test data. We feel that these lower limits are in the main conservative and that the relationship of SN_{40} to other design parameters can be estimated from these developed lower limits provided that hydroplaning conditions are not present.
2. Although the friction available on wet pavement decreases with increasing speed, it appears that a rather drastic reduction in maneuverability occurs within a few mph above some critical speed for a given set of conditions. We believe this is due to full hydroplaning, and the critical speed can be as low as 45 mph. The apparent drastic reduction may be due to going from some control to no control though the absolute reduction in available friction is relatively small.
3. In critical lane change maneuvers, increasing the skid number by a factor of three did not produce an appreciably greater capability. Several factors may be operative. Due to the phase lag between steer angle and vehicle response, the maximum available friction was not generated in a sudden transient maneuver. The time required to perform the lane change on a pavement with low SN is near the physical input rate limit of the driver, therefore the time required to perform the maneuver cannot be appreciably lowered by simply increasing friction. However, increased friction may reduce the tendency to lose control in the critical recovery phase of the maneuver.

4. The recommended practices of geometric design in the Operations and Procedures Manual (10) do not require a high skid number provided the driver is not exceeding the design speed, is alert to nonfixed obstructions such as other vehicles, and is not hydroplaning. The degree of driver error that should be accommodated is beyond the scope of this study. The increase in cornering or stopping capability resulting from an increase in skid number for a given site can be estimated from the relationships developed in this study. This increase might also be used to arrive at a decision on the more cost-effective action to be taken in treating high accident frequency sites. There are situations in which enough friction could not possibly have been achieved to prevent the accident, but it might reduce the accident severity.

5. In estimating the friction factor (and SN_{40}) required for vehicle maneuvers, stopping and cornering should be considered simultaneously rather than separately because one can affect the other.

6. Data from studies of water depth as a function of rainfall and pavement parameters, hydroplaning conditions, vehicle maneuverability, and driver behavior (vehicle path on curves, perception-reaction time) can now be combined to provide a more comprehensive model for the evaluation of pavement surfaces.

RECOMMENDATIONS

1. Combination of the findings of this and other studies should be made to produce a comprehensive pavement design and evaluation tool. The model should lend itself to continuous modification as new information becomes available.
2. New designs as well as high accident frequency sites should be evaluated for adequate surface friction using the estimates developed in this study. The effectiveness of a change in friction properties should likewise be estimated before the change is made.
3. An advanced accident reporting and investigating procedure should be developed for use at high accident frequency sites in order to more accurately determine the cost-effective treatment to reduce the frequency and/or severity of skidding accidents. The results of such investigations should be summarized in such a way that the more critical factors or combinations of factors in accident causation may eventually be ranked in order to minimize these factors in a cost-effective manner while in the design stage.
4. Attempts to inform and educate the driving public regarding the inherent danger in low tread depths and excessive speed on wet pavements should continue since these critical factors are beyond the control of highway engineers.

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APPENDIX

APPENDIX A

EXAMPLES OF USE OF ESTIMATED VEHICLE CAPABILITY

EXAMPLE I

<u>Hypothesis 1</u>: A certain curve seems to have a higher than average frequency of skidding accidents. This curve has a radius of 2000 feet and a sight distance of 1500 feet. The speed limit is 55 mph and the superelevation is 0.04 feet/foot.

Estimate of f from Equation 6, which includes an allowance for perception-reaction time:

$$f = [(\frac{(55)^2}{(15)(2000)} - 0.04)^2 + (\frac{(55)^2}{(30)(1500) - (110)(55)})^2]^{\frac{1}{2}}$$
$$= 0.10$$

From Figure 16 the estimated SN_{40} is about 10. If the measured SN_{40} significantly exceeds this value, other causes such as excessive water depths, excessive speed, traffic conflicts, confusing sight pictures, and poor visibility should be evaluated.

<u>Hypothesis 2</u>: After evaluation it is found that, while the sight distance is indeed 1500 feet or more, a road intersecting the highway provides a potential such that the drivers of the through vehicles may not have the full 1500 feet of stopping distance available, and that some are exceeding the design speed. A decision is made to provide a friction factor that will allow vehicles to stop from 60 mph in 380 feet. With a 2.5 second perception-reaction time, this is a total distance of 600 feet. Then,

$$f = [(\frac{(60)^2}{(15)(2000)} - 0.04)^2 + (\frac{(60)^2}{(30)(600) - (110)(60)})^2]^{\frac{1}{2}}$$

$$= (0.0064 + 0.0997)^{\frac{1}{2}} = 0.33$$

From Figure 16 the maximum SN_{40} required is about 45.

Hypothesis 3: It is also decided that drivers involved in accidents are attempting to travel paths that are substantially different from the curvature of the roadway. A limit path curvature of 1000 feet in the case of Hypothesis 2 would only require the SN_{40} to be raised from 45 to 50. This is a case where a slight increase (11%) in SN_{40} would permit a large decrease (50%) in the radius of curvature traveled. On the other hand, a similar decrease in the possible radius of curvature would be possible if the drivers would begin braking only 80 feet (less than one second) sooner. This is a case where braking and turning must be considered together rather than separately. Any method of inhibiting speeding on the part of drivers would pay handsome dividends in vehicle maneuverability.

EXAMPLE II

Hypothesis 1: At an interchange, a high accident frequency is observed. Referring to Figure A1, we see at this site that the following conditions exist:

$R = 300$ ft.

$e = 0.06$ ft/ft

$D = 1000$ ft.

The posted exit speed is 40 mph. From Equation 7 the required friction factor is

$$f = \left[\left(\frac{(40)^2}{(15)(300)} - 0.06\right)^2 + \left(\frac{(40)^2}{(30)(1000)}\right)^2\right]^{1/2}$$

$$= (0.0874 + 0.0028)^{1/2} = 0.30$$

for an SN_{40} of 28 from Figure 16.

Hypothesis 2: Assume that excessive water depths are not suspect, but that some vehicles may be exiting at speeds approaching the speed limit of the adjacent roadway, which is 55 mph. The computed friction factor for this speed, and assuming a full 1000 ft. of stopping distance, indicates an SN_{40} (>80) which at this time is not possible to achieve and maintain. Therefore the accidents due to this excessive exit speed cannot be effectively reduced by altering the friction, and this problem should be attacked by other means.

Hypothesis 3: The surface shows an SN_{40} of 30 which, assuming the proper exit speed,allows a stopping distance of 600 feet. If we desire to decrease the required distance to stop to 50% of 600, or 300 feet, the new friction factor is 0.34 giving an SN_{40} of 35. Therefore, only a small

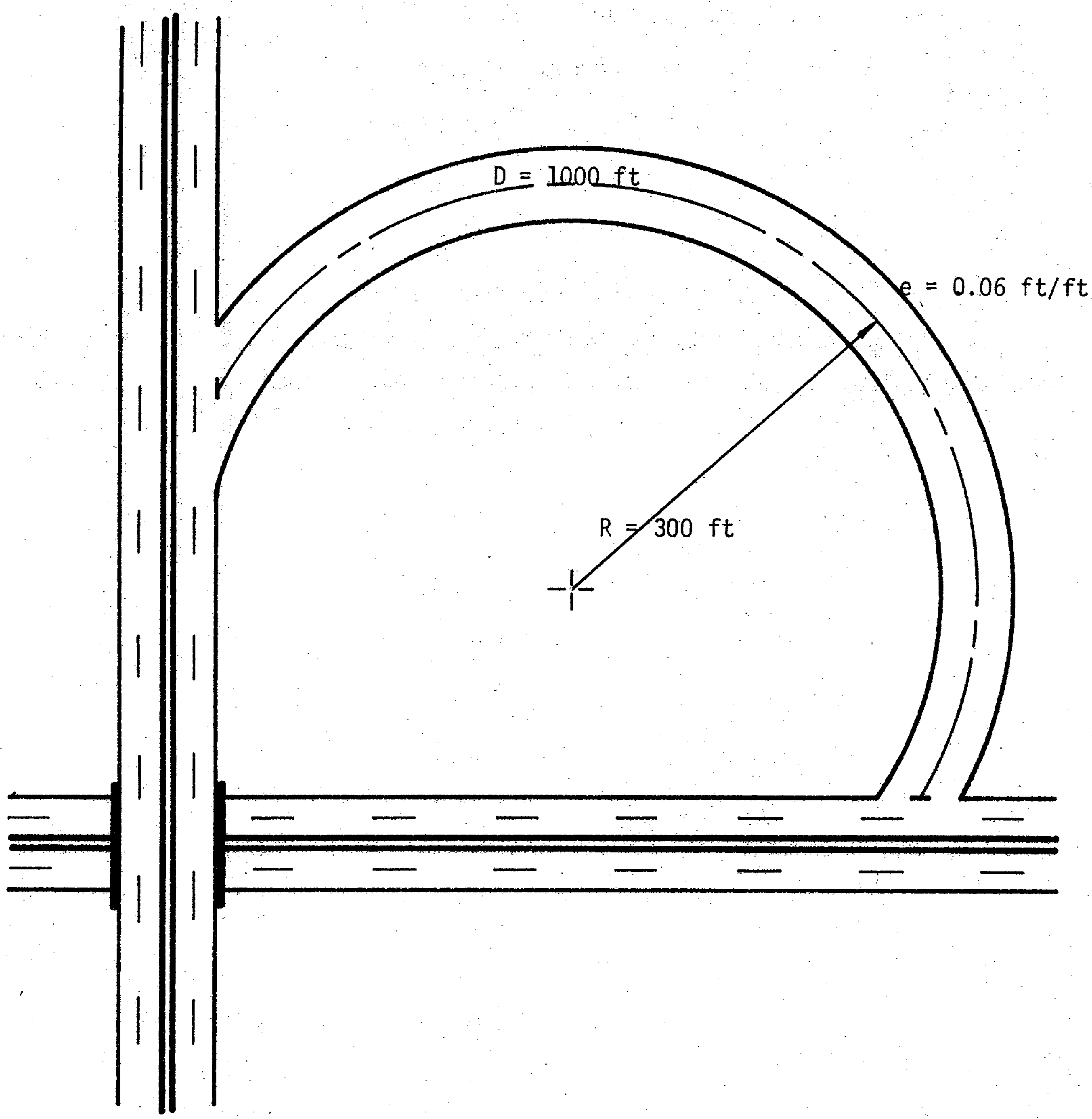
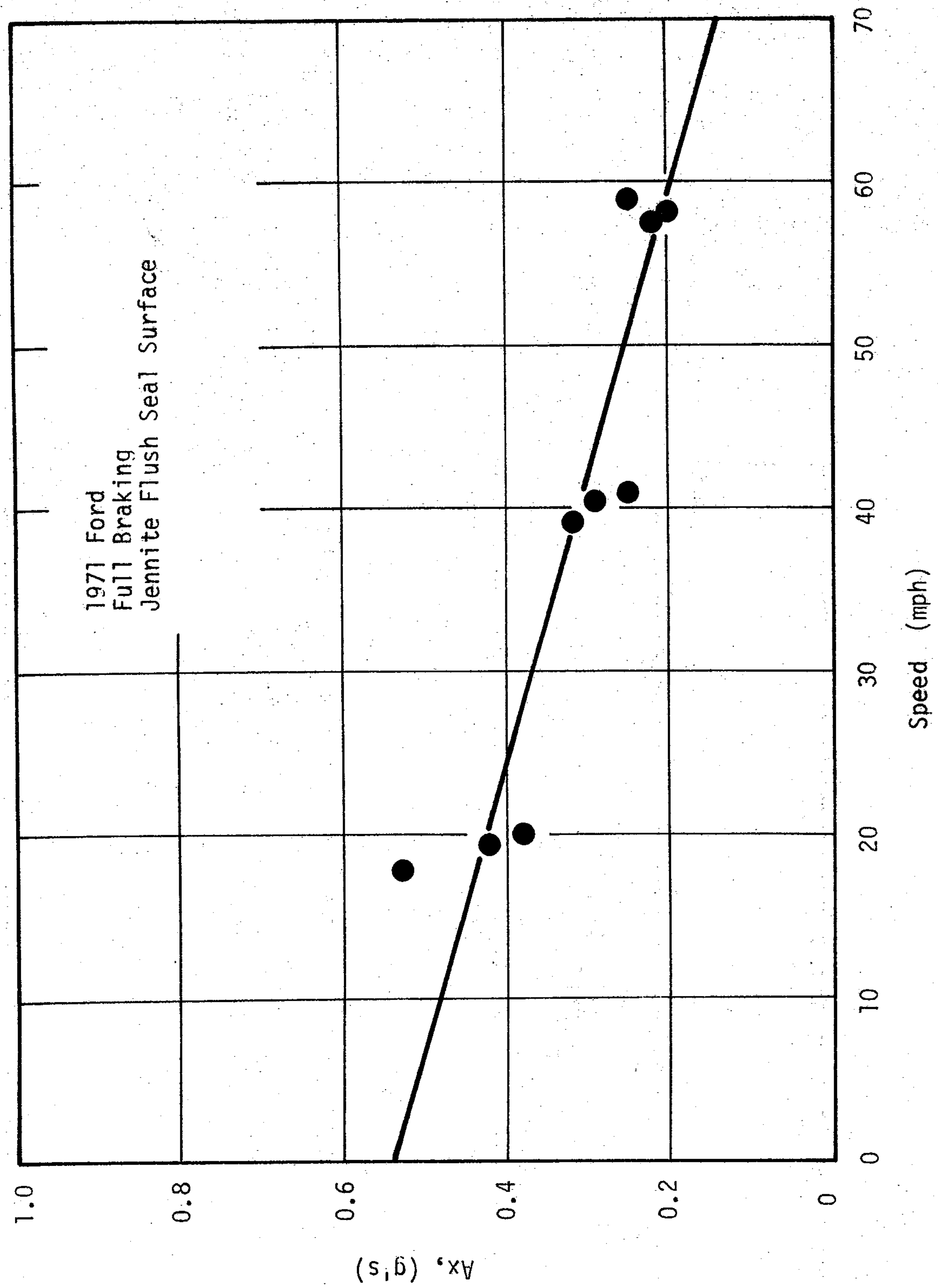
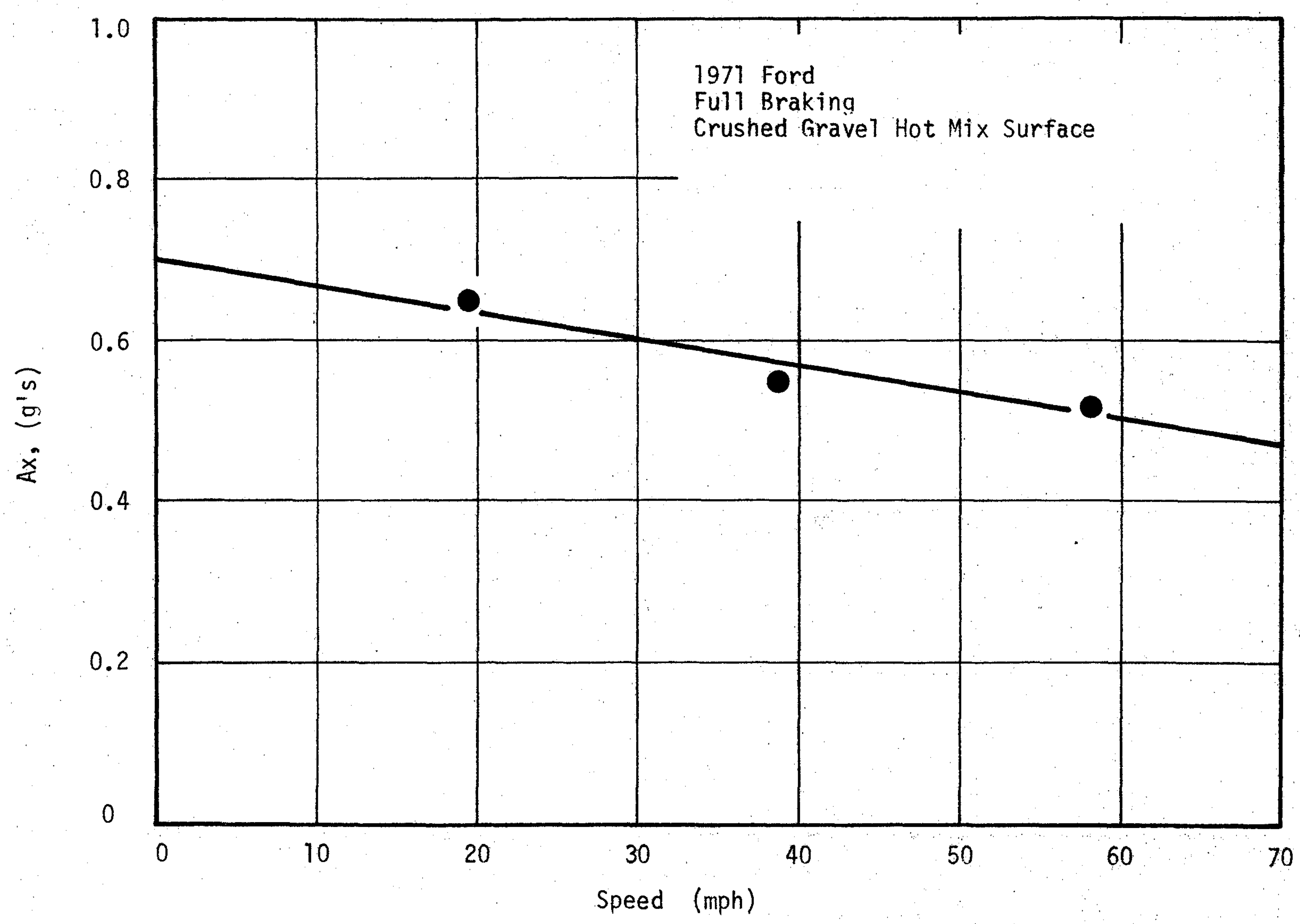


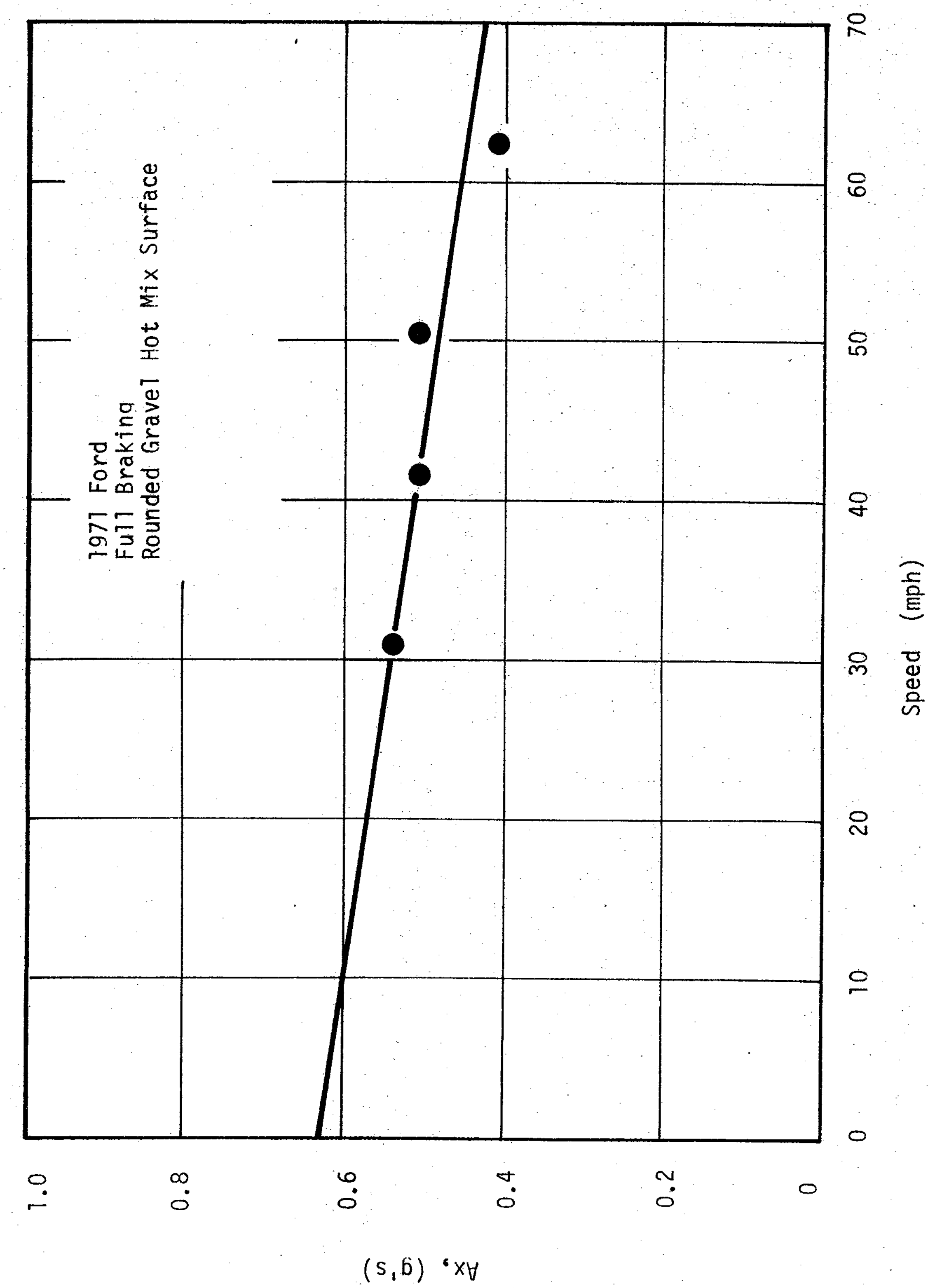
Figure A1. Hypothetical Interchange (Ex. II) increase (17%) in skid number produces, in this case, a large decrease (50%) in the distance required to come to a stop. This is because for these limit conditions the greater part of the available friction is being utilized for cornering, and any increase significantly increases the stopping capability. Conversely, at a site where only a small percent of the available friction is being utilized for cornering, if we keep the stopping demand constant, a small increase in friction will enhance cornering capability considerably. This points up the necessity to consider cornering and stopping demand simultaneously by using Equation 6 rather than as separate phenomena.

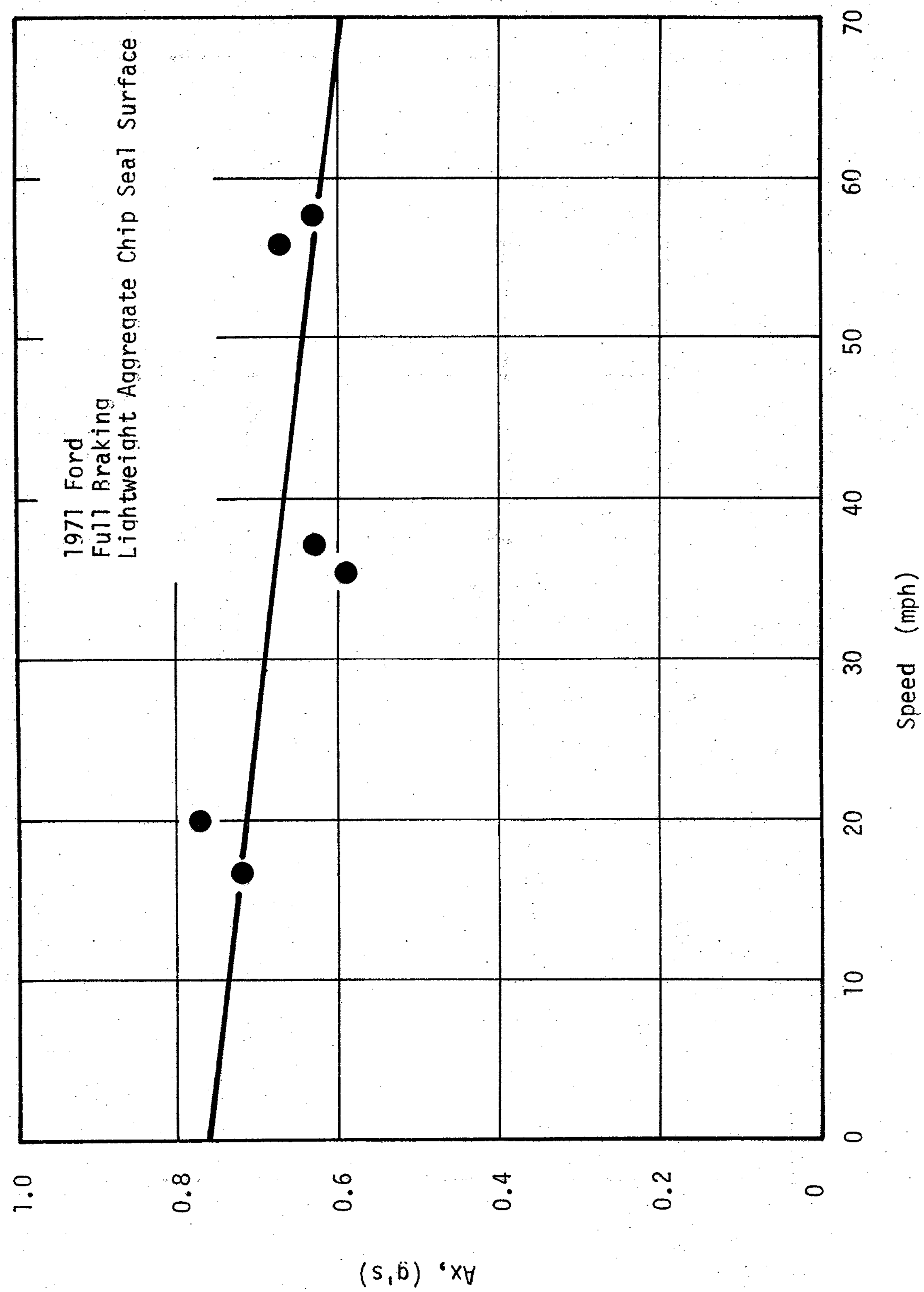
APPENDIX B

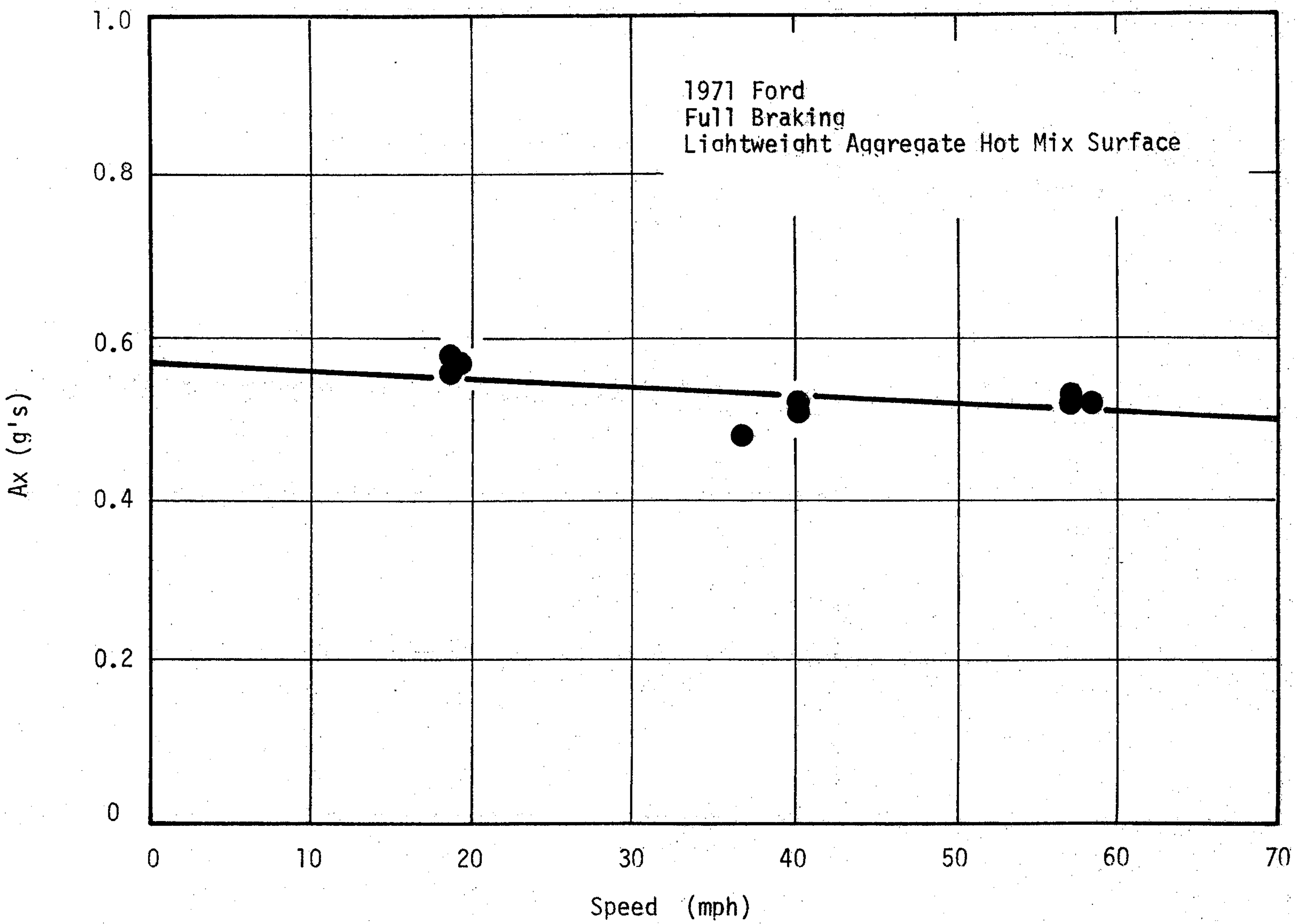
MAXIMUM VEHICLE ACCELERATIONS

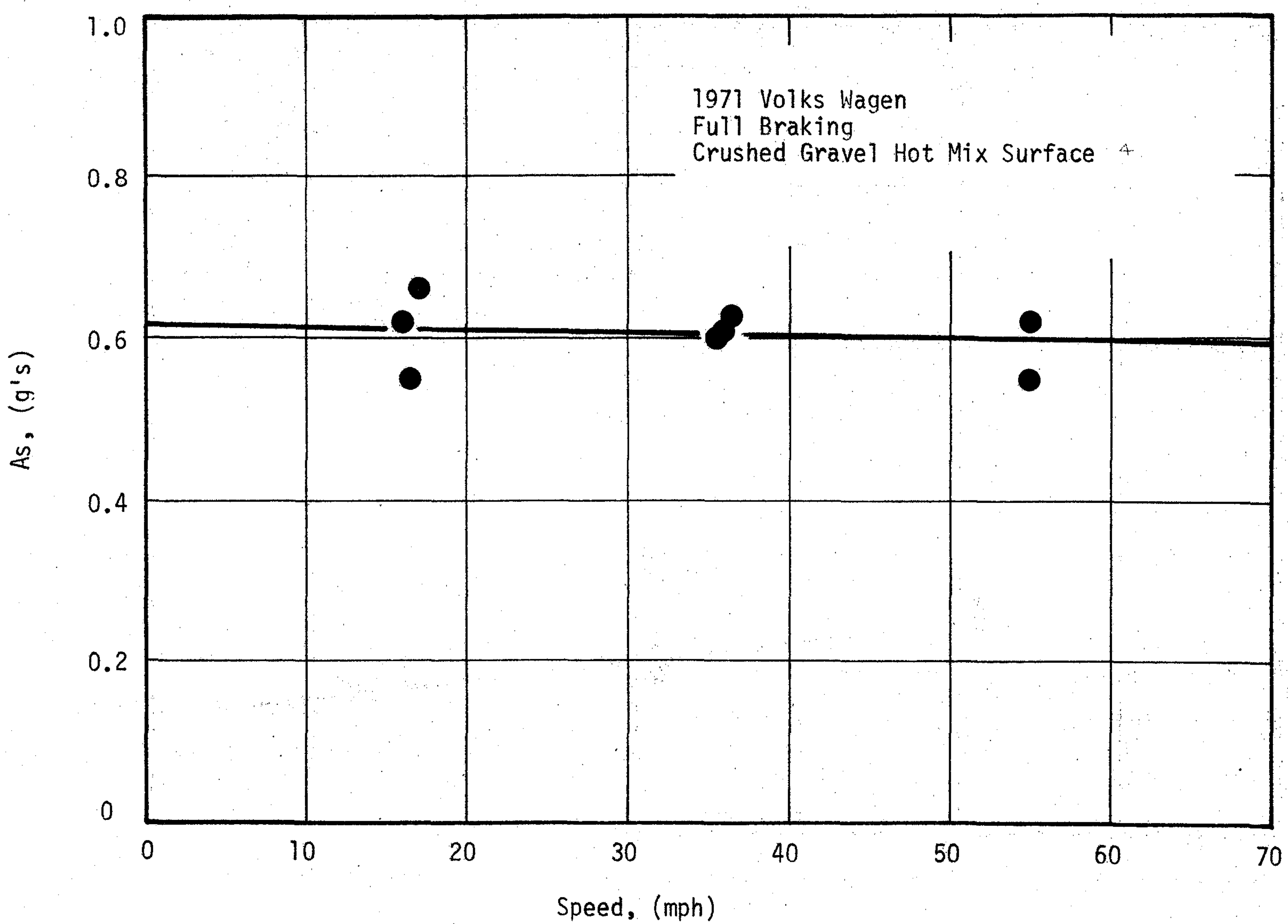

1971 Ford
Full Braking
Jennite Flush Seal Surface
Ax, (g's)
1.0
0.8
0.6
0.4
0.2
0
Speed (mph)
0
10
20
30
40
50
60
70

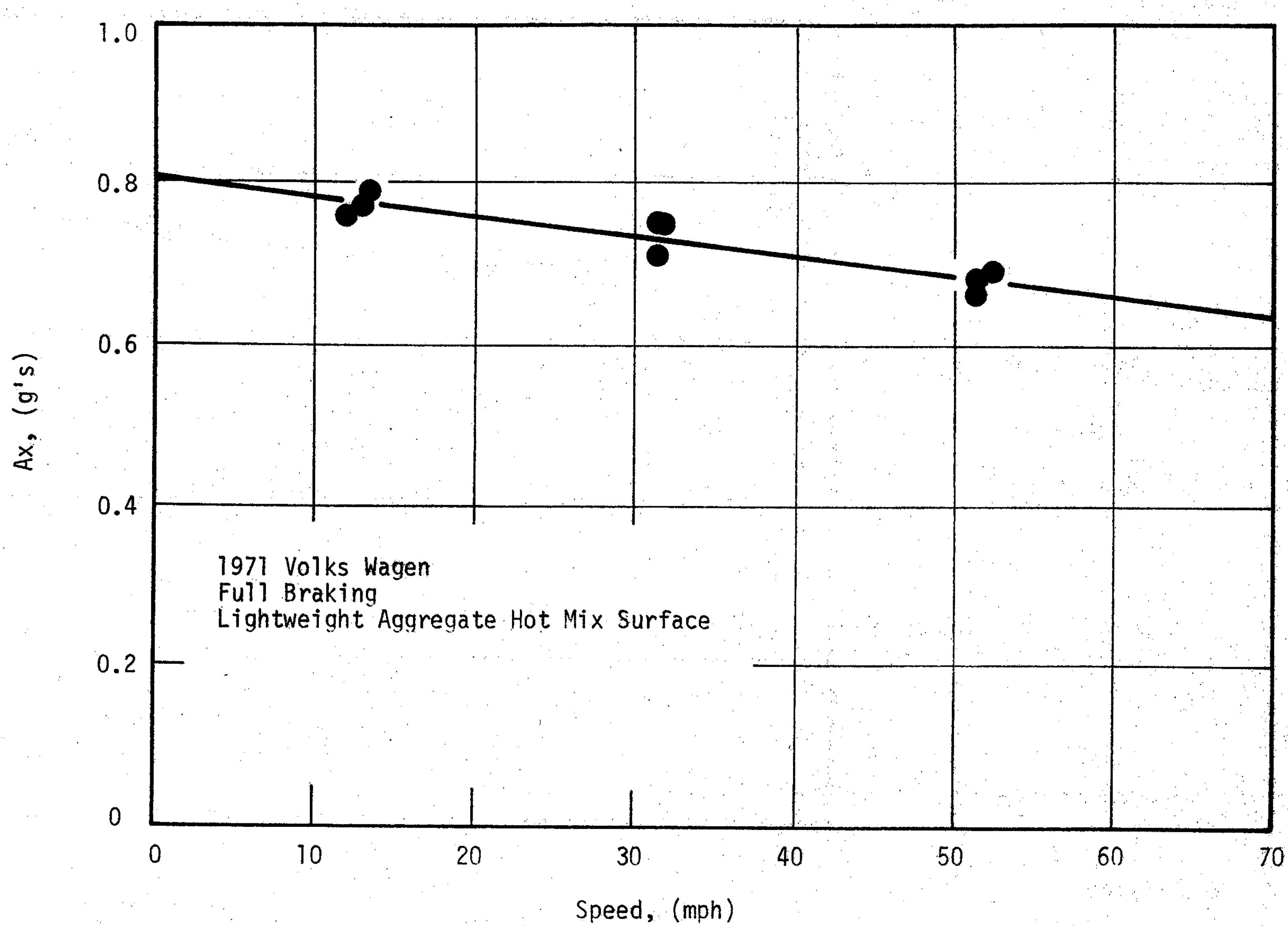

1971 Ford
Full Braking
Crushed Gravel Hot Mix Surface
1.0
0.8
0.6
0.4
0.2
0
Ax, (g's)
0
10
20
30
40
50
60
70
Speed (mph)

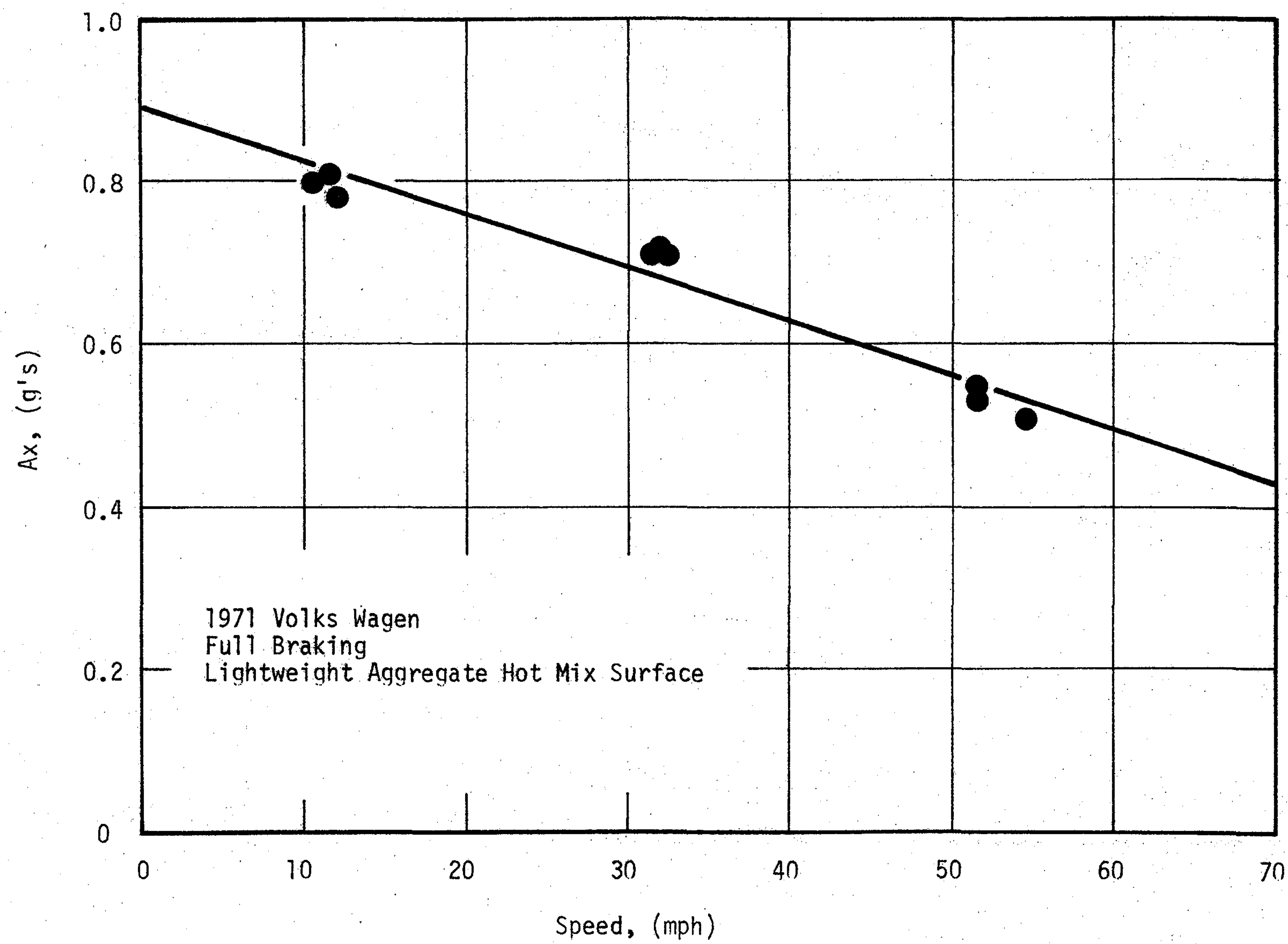

1971 Ford
Full Braking
Rounded Gravel Hot Mix Surface
Speed (mph)
Ax, (g's)
0
10
20
30
40
50
60
70
1.0
0.8
0.6
0.4
0.2
0

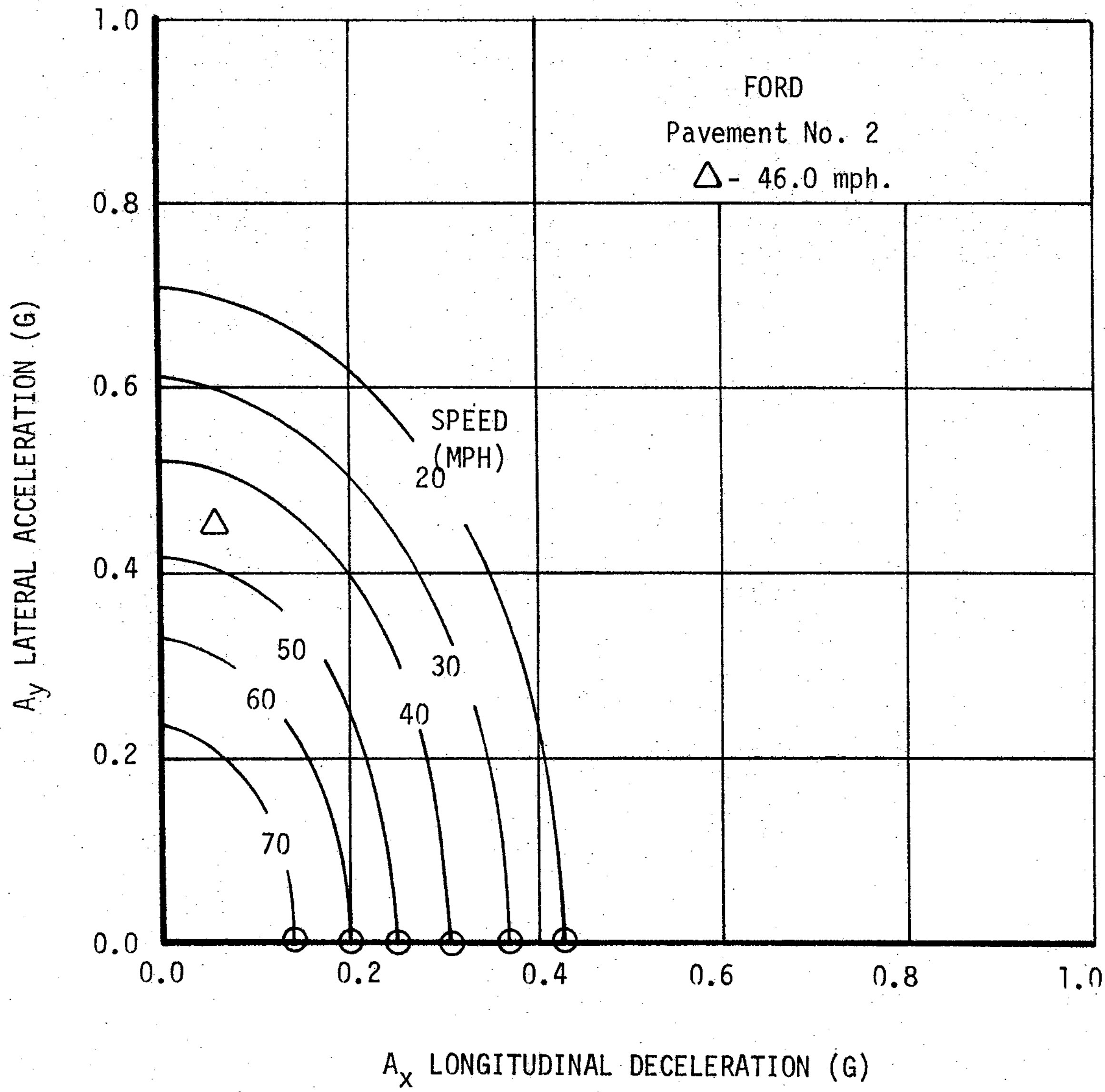

1971 Ford
Full Braking
Lightweight Aggregate Chip Seal Surface
Speed (mph)
Ax, (g's)
0
10
20
30
40
50
60
70
0
0.2
0.4
0.6
0.8
1.0

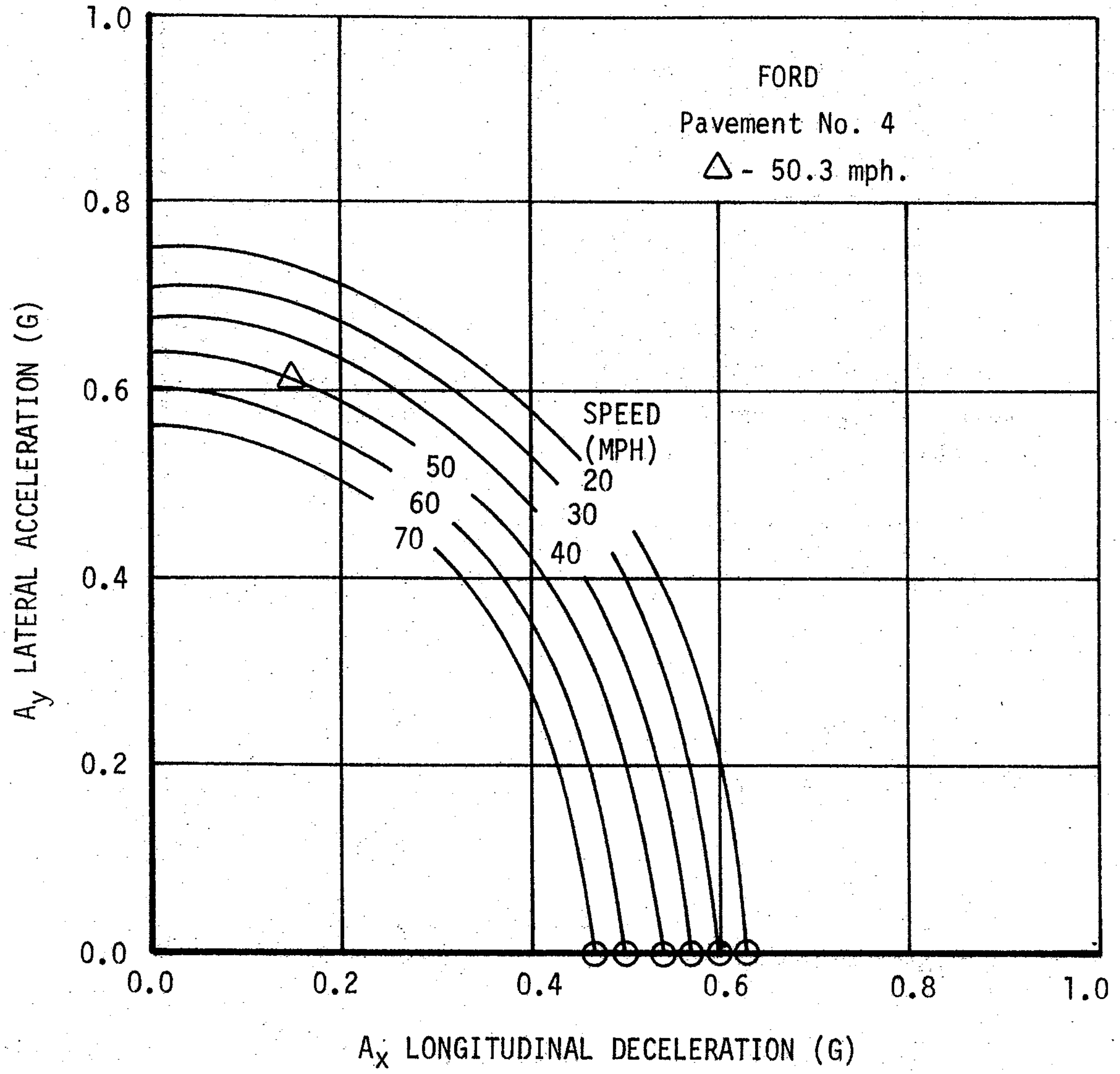

1971 Ford
Full Braking
Lightweight Aggregate Hot Mix Surface
Ax (g's)
1.0
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
Speed (mph)

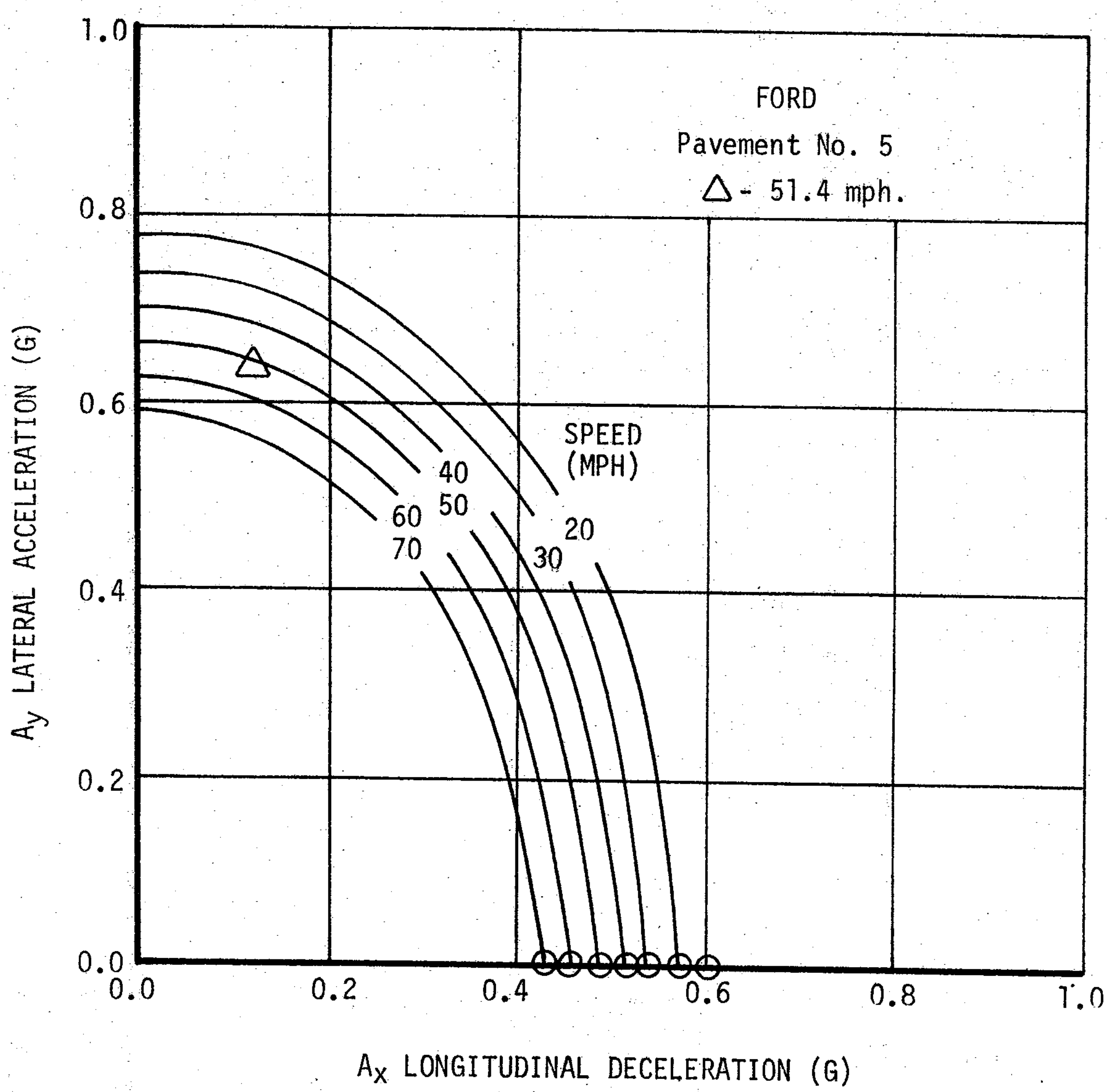

1971 Volks Wagen
Full Braking
Crushed Gravel Hot Mix Surface
1.0
0.8
0.6
0.4
0.2
0
As, (g's)
0
10
20
30
40
50
60
70
Speed, (mph)

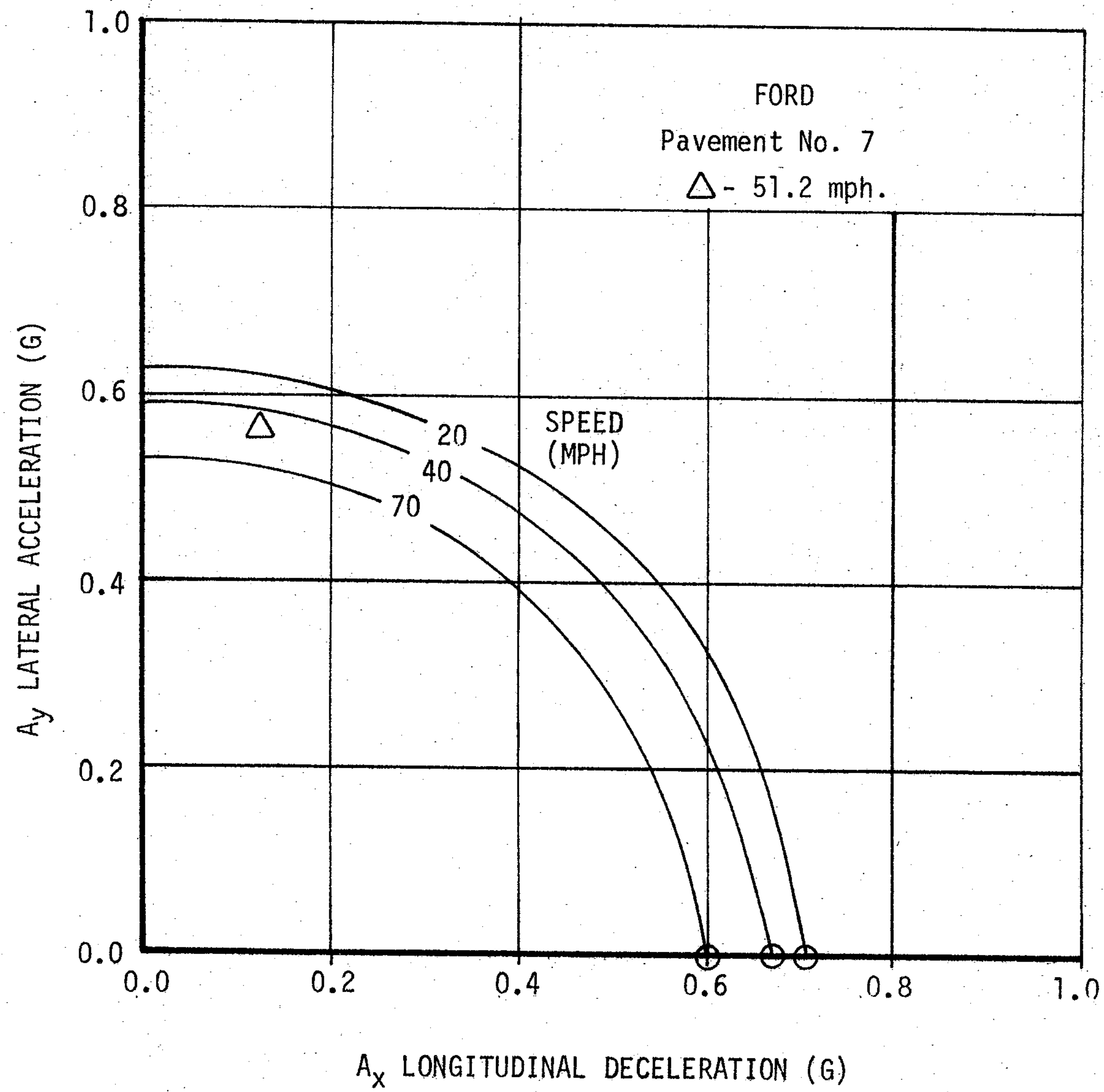

1.0
0.8
0.6
0.4
0.2
0
Ax, (g's)
0
10
20
30
40
50
60
70
Speed, (mph)
1971 Volks Wagen
Full Braking
Lightweight Aggregate Hot Mix Surface


1.0
0.8
0.6
0.4
0.2
0
Ax, (g's)
0
10
20
30
40
50
60
70
Speed, (mph)
1971 Volks Wagen
Full Braking
Lightweight Aggregate Hot Mix Surface

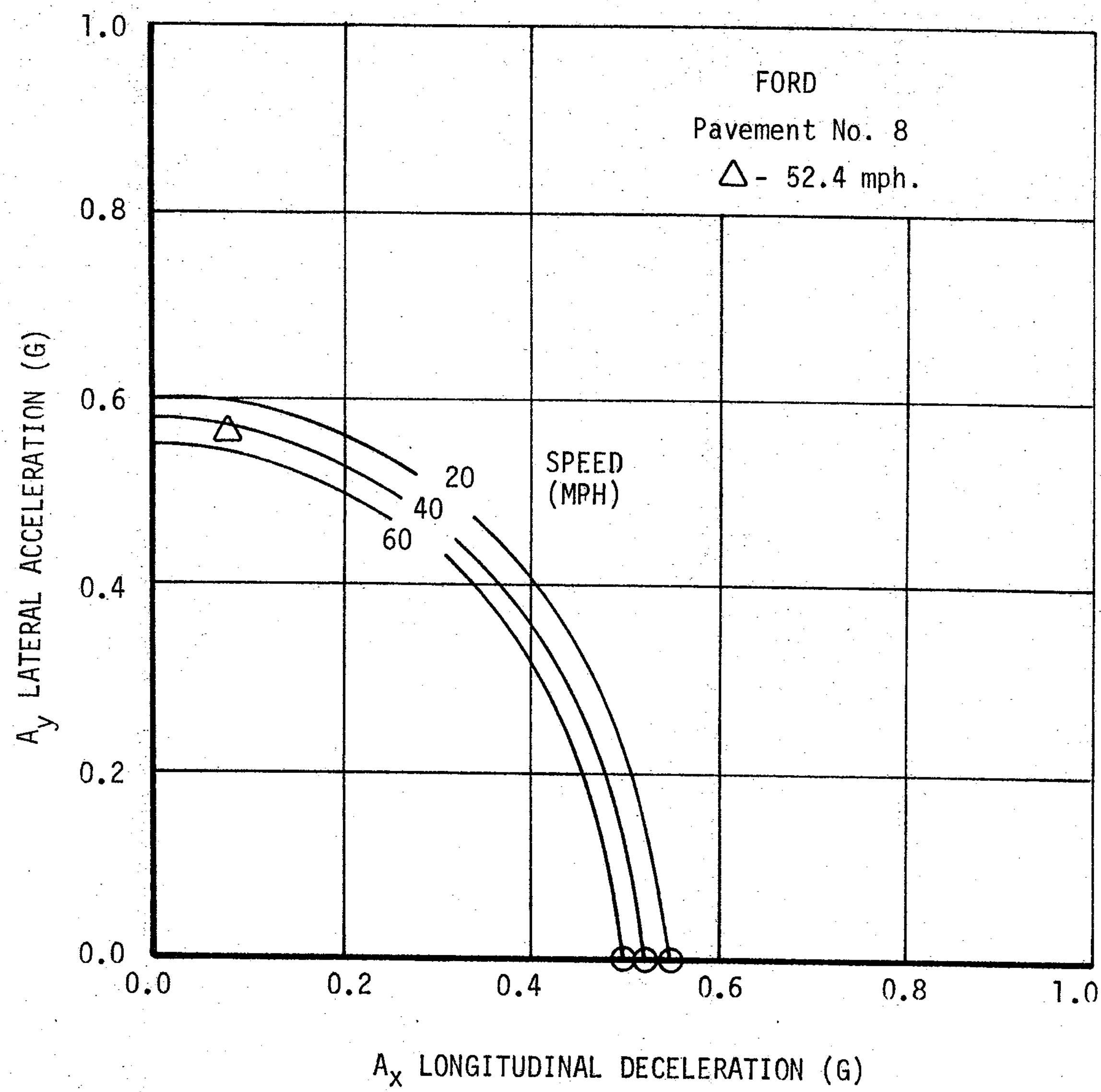

FORD
Pavement No. 2
△- 46.0 mph.
SPEED (MPH)
20
30
40
50
60
70
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
A_y LATERAL ACCELERATION (G)
A_x LONGITUDINAL DECELERATION (G)


FORD
Pavement No. 4
△ - 50.3 mph.
SPEED
(MPH)
20
30
40
50
60
70
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
A_y LATERAL ACCELERATION (G)
A_x LONGITUDINAL DECELERATION (G)

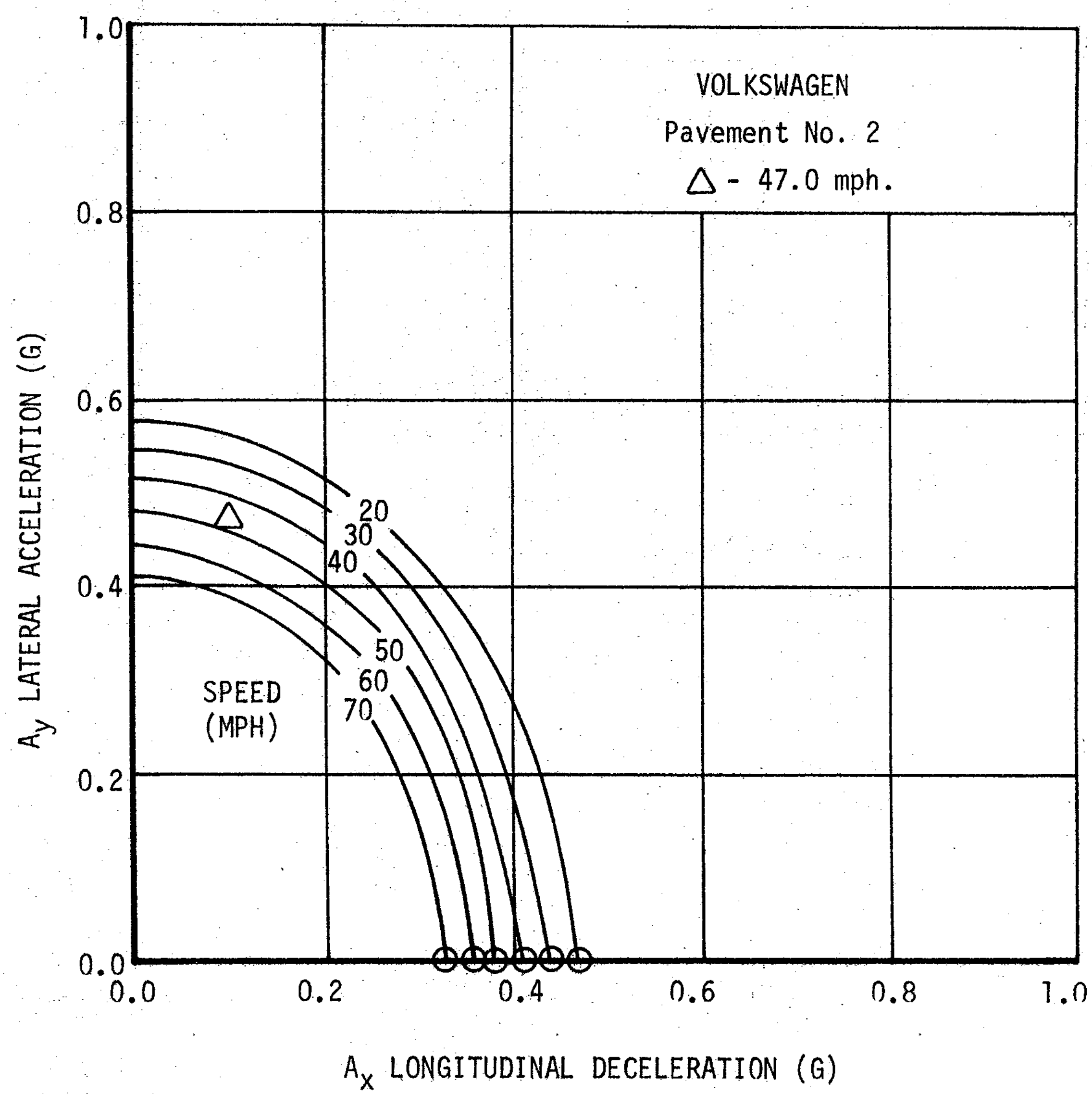

FORD
Pavement No. 5
△ - 51.4 mph.
SPEED (MPH)
20
30
40
50
60
70
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
A_y LATERAL ACCELERATION (G)
A_x LONGITUDINAL DECELERATION (G)



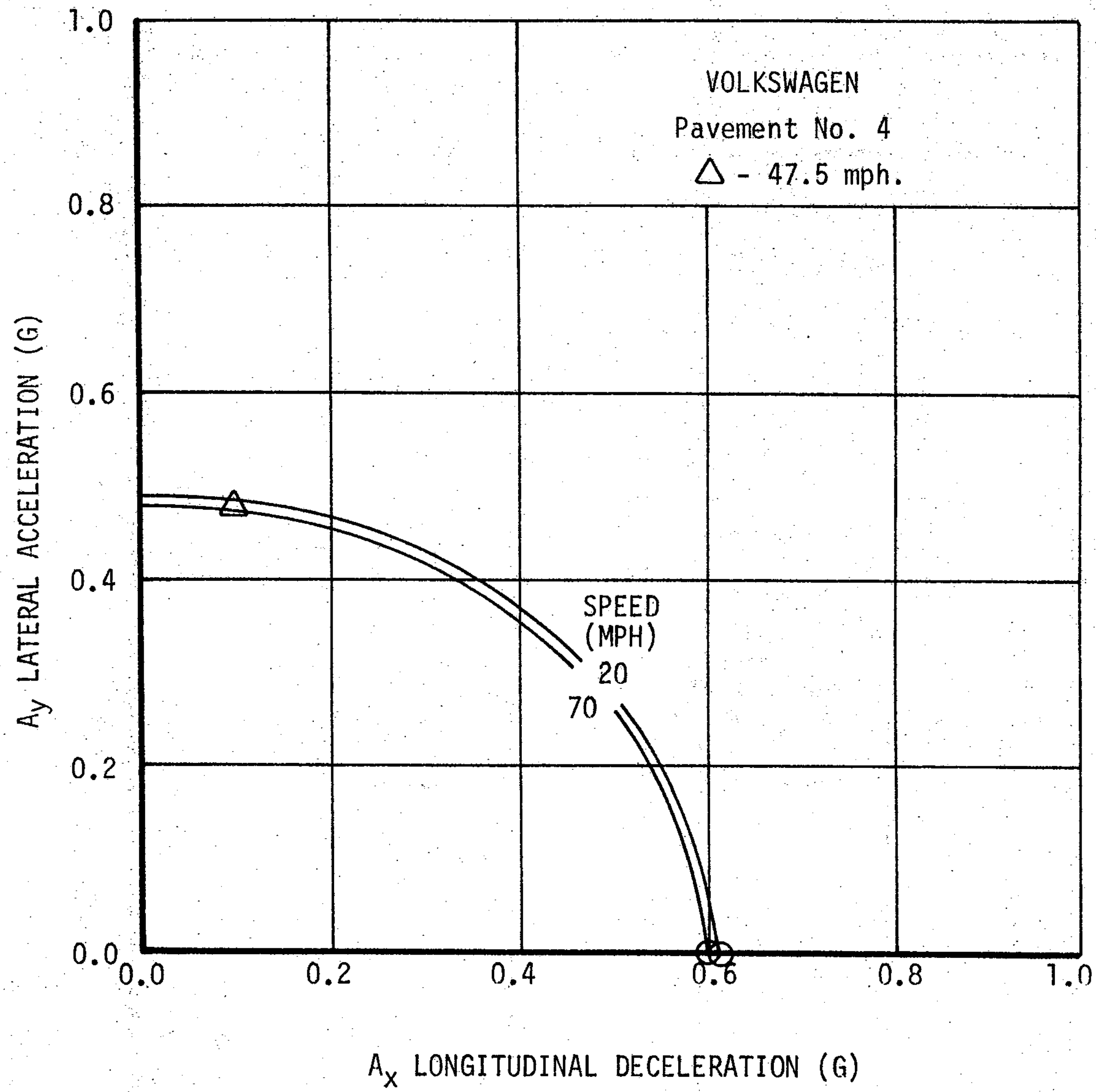
FORD
Pavement No. 7
△ - 51.2 mph.
SPEED
(MPH)
20
40
70
A_y LATERAL ACCELERATION (G)
A_x LONGITUDINAL DECELERATION (G)
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0

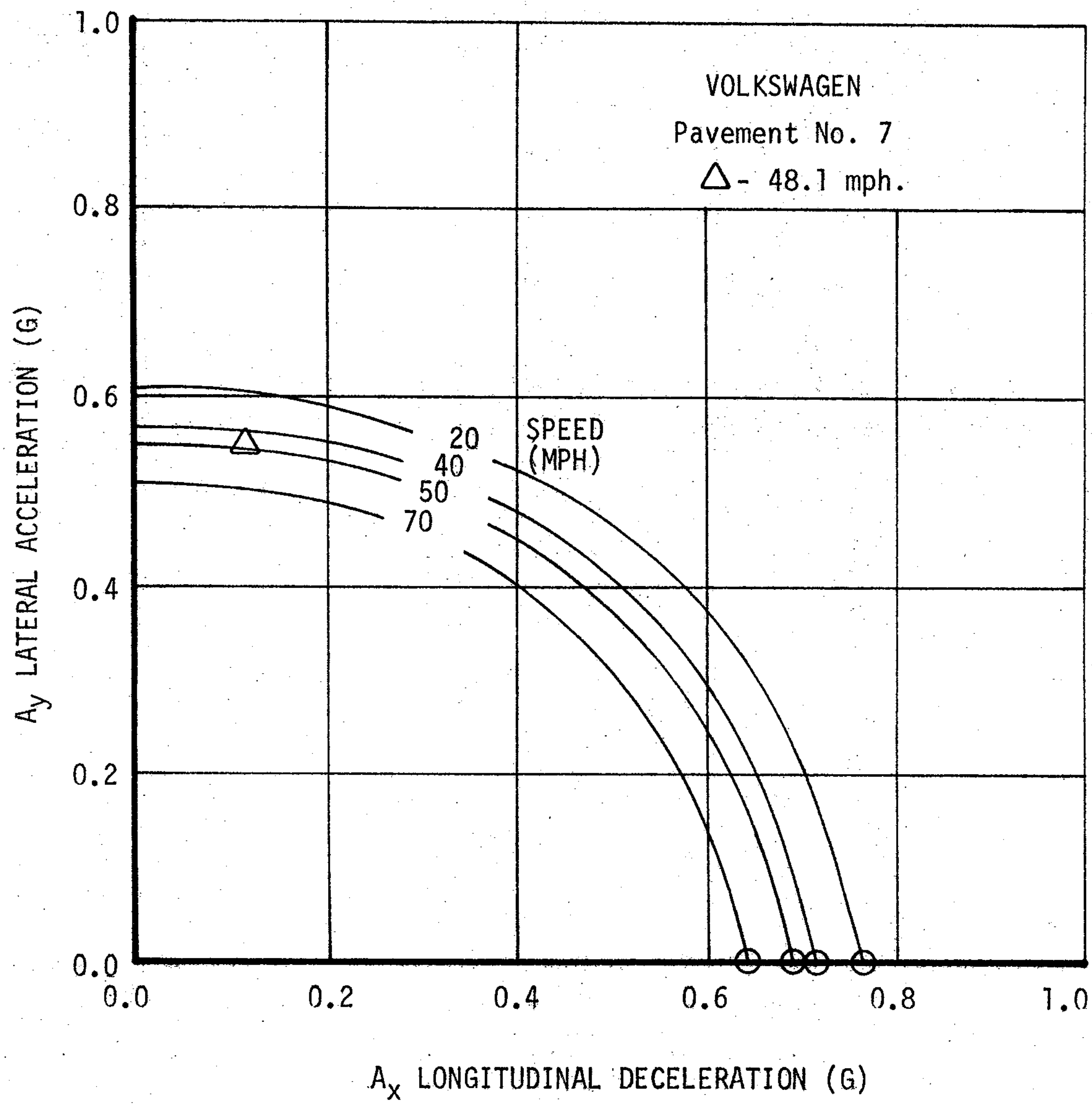


1.0
0.8
0.6
0.4
0.2
0.0
FORD
Pavement No. 8
△- 52.4 mph.
SPEED
(MPH)
20
40
60
A_y LATERAL ACCELERATION (G)
0.0
0.2
0.4
0.6
0.8
1.0
A_x LONGITUDINAL DECELERATION (G)

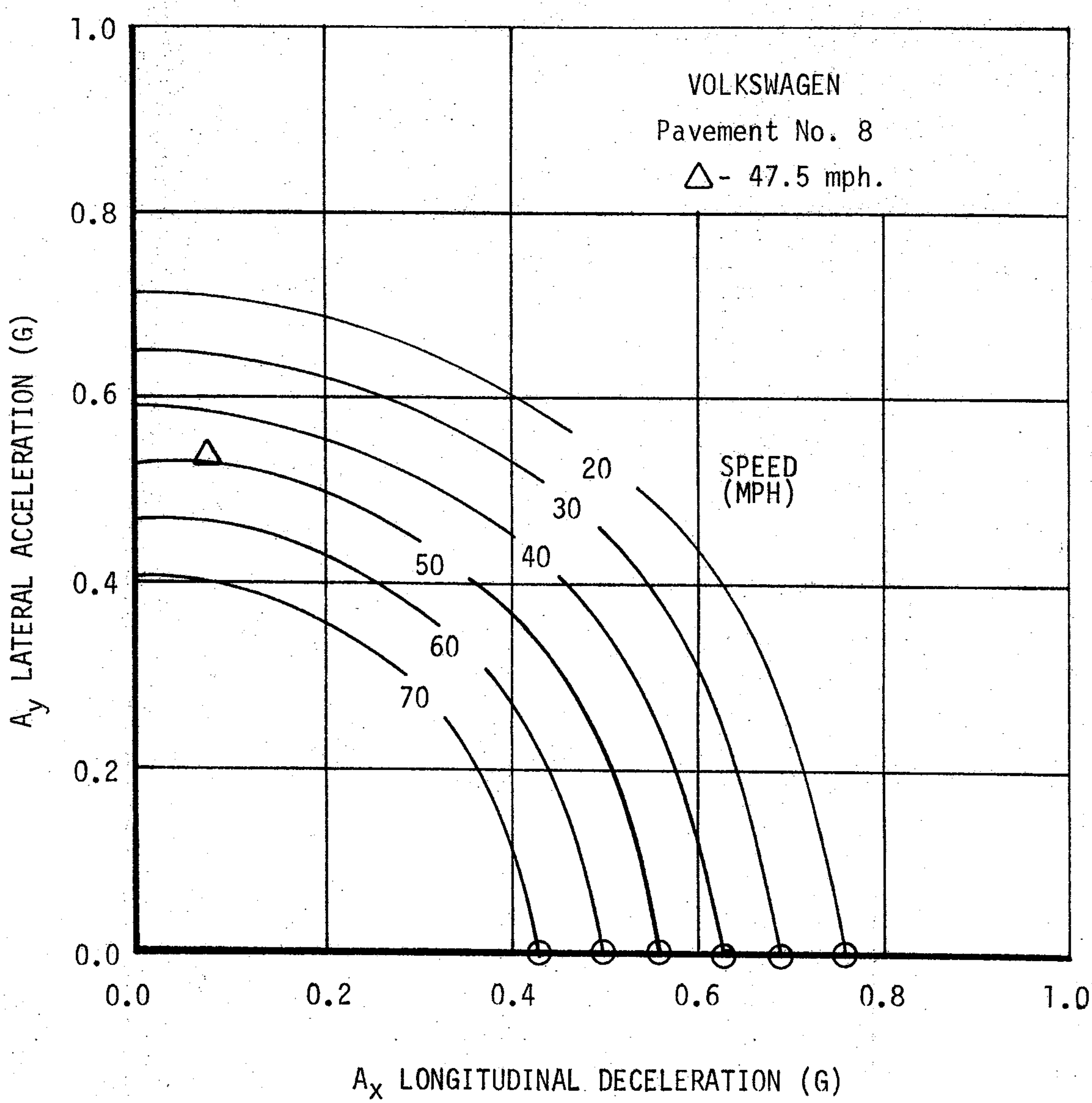


VOLKSWAGEN
Pavement No. 2
△ - 47.0 mph.
1.0
0.8
0.6
0.4
0.2
0.0
20
30
40
50
60
70
SPEED
(MPH)
0.0
0.2
0.4
0.6
0.8
1.0
A_y LATERAL ACCELERATION (G)
A_x LONGITUDINAL DECELERATION (G)


VOLKSWAGEN
Pavement No. 4
△ - 47.5 mph.
SPEED
(MPH)
20
70
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
A_y LATERAL ACCELERATION (G)
A_x LONGITUDINAL DECELERATION (G)



VOLKSWAGEN
Pavement No. 7
△- 48.1 mph.
SPEED
(MPH)
20
40
50
70
A_y LATERAL ACCELERATION (G)
A_x LONGITUDINAL DECELERATION (G)
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0


VOLKSWAGEN
Pavement No. 8
△- 47.5 mph.
SPEED (MPH)
20
30
40
50
60
70
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
A_y LATERAL ACCELERATION (G)
A_x LONGITUDINAL DECELERATION (G)