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FRICTIONAL PROPERTIES OF HIGHWAY SURFACES

Final Report

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The contents of this report reflect the views of the author, who is responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Arizona Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

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16. Abstract Purpose of study was to evaluate effects of differential friction; compare experimental & standard texturing techniques of PCCP; determine if Mu-Meter is capable of measuring frictional effects of grooving & develop wet pavement accident analysis system for use in Arizona. All phases of project were successfully completed.

Results of program have shown that differential friction can cause an extremely hazardous condition for a braking vehicle. As this problem can occur at high or low friction levels, & present maintenance & construction techniques can cause differential friction, it should be given major consideration in any pavement friction evaluation. Equations have been derived which will allow engineer to determine magnitude of problem.

There is a strong indication that differential friction may be as important in causation of wet pavement accidents as low friction levels. If so, a major re-evaluation of present friction evaluation & corrective techniques may be necessary.

All burlap drag textures tested produced poor, non-uniform finishes that were significantly less durable than other textures tested. For this reason, it is suggested that burlap drag texture not be used in the future. Nylon bristle broom texture produced best overall results, while magnesium fluted float produced unusual texture that definitely has merit.

The Mu-Meter is capable of measuring side-force effects of grooving PCCP. Benefits obtained from longitudinally grooving, however, are dependent on original friction level.

Through study, a viable system has been developed for predicting wet exposure accident rates & for realistically comparing wet-dry accident results.

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ABSTRACT

On May 1, 1973, the Arizona Department of Transportation initiated a research program entitled "Frictional Properties of Highway Surfaces" sponsored by the Federal Highway Administration. The specific aim of this program was to determine the effects of particular pavement friction properties on vehicular traffic. The program evaluated the following:

1. The effects of differential wheelpath friction.
2. Comparison of standard and experimental texturing of portland cement concrete pavement.
3. Frictional effects of grooving as measured by the Mu-Meter.
4. Development of a wet accident analysis system for the State of Arizona and other areas with arid climates.

This research has yielded results which are of significant importance and which indicate a major re-evaluation of present pavement friction evaluation and corrective techniques may be necessary.

Some of the major findings of this research are as follows:

1. Differential friction can cause an extremely hazardous condition for a braking vehicle. As this problem can occur at high as well as low friction levels, it should be given major consideration in any pavement friction evaluation.
2. Present construction and maintenance techniques can acutally create this problem.

3. There are numerous causes of differential friction and there is a strong indication that differential friction may be as important in the causation of wet pavement accidents as low friction level. If this is the case, a major re-evaluation of pavement friction evaluation, design, and corrective techniques may be necessary.
4. The Mu-Meter, unlike the ASTM locked wheel skid trailer, is capable of detecting the frictional effects of grooving.
5. Thru this study a viable system for predicting wet exposure accident rates has been developed for Arizona and other areas with arid climates.

As this study investigated several separate subjects, the final report has been broken into four separate parts. Each part will describe the work performed and the results for that phase of the research. At the end of the paper, the conclusions, recommendations and implementation for all four parts are discussed.

Parts 1, 3 and 4 of this study were accomplished with FHWA, HPR Funds, while Part 2 was performed under the FHWA Experimental Projects Program. Evaluation of pavement textures as described in Part 2 will be continued.

FRICTIONAL PROPERTIES OF HIGHWAY SURFACES

PART ONE

DIFFERENTIAL FRICTION RELATED TO SKIDDING

INTRODUCTION

As part of the Federally sponsored research project HPR 1-12 (146), Frictional Properties of Highway Surfaces, a thorough evaluation of the phenomena of differential friction was made. This portion of the paper describes the work that was performed which evaluated the effects differential friction has on a skidding car. It also describes the magnitude of the problem, as well as some of the causes and possible solutions.

DIFFERENTIAL FRICTION

Differential wheelpath friction is a term the author has derived to describe the condition that occurs when the individual wheelpaths on which a vehicle rides have different or unequal coefficients of friction. Although this phenomena is usually not considered in a pavement friction evaluation, it can have a significant effect on a braking vehicle.

Several years ago it was noted that, during stopping distance tests with a skidding car, some pavements caused a car to spin uncontrollably[1]. Under normal conditions, the car was designed to stop in a straight line and not rotate. It was found that this rotation was produced by different friction levels in each of the wheelpaths. As the tires on the left side of the car were exposed to a different friction level than those on the

right side, a turning movement was caused, with the vehicle rotating towards the higher friction side. As the car spun, the front wheels moved onto a higher friction level and the rear wheels onto the lower. Thus the car was still unstable and the spin continued until the vehicle stopped. An example of this is shown in Figure 1, where the right wheeltrack was beginning to flush (excessive asphalt on surface) and the left (on a different ribbon) was not. The wet stopping distance number (SDN) at 40 miles per hour (MPH), (SDN_{40}), was 50 for the right wheelpath and 60 for the left wheelpath. This is only a ten SDN, or 17% difference. In Picture A, the car skidded at 30 MPH and rotated 25° counterclockwise. In Picture B, the car skidded at 40 MPH and rotated 40° counterclockwise. In Picture C, the car skidded at 50 MPH and rotated 95° counterclockwise. When the direction of skidding was reversed, the similar values were recorded with the car turning clockwise. A more severe case is shown in Figure 2, in which the left wheeltrack was bleeding and the right wheeltrack had been chip sealed. The right wheelpath had a wet SDN_{40} of 67 and the left wheelpath had a wet SDN_{40} of 41, which is a 26 SDN, or 39 percent difference. In Picture A, the car skidded at 40 MPH and rotated 90° clockwise. In Picture B, the car skidded at 50 MPH and rotated 270° clockwise. Again the direction of skidding was reversed and the same values were recorded with the car rotating counterclockwise.

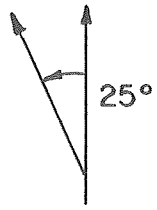
Figure 2 is an extreme case used to portray what might happen if one wheelpath was flushing and the other was not. The case shown in Figure 1 is common and although both wheelpaths have a satisfactory level of friction,

RIGHT WHEEL PATH = SDN_{40} 50

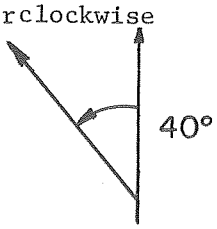
LEFT WHEEL PATH = SDN_{40} 60

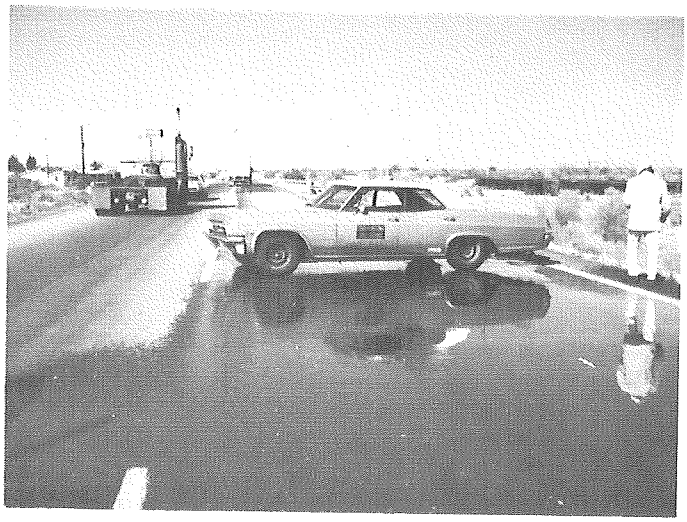
17% Difference

(A) Car skids at 30 MPH and rotates 25° counterclockwise



(B) Car skids at 40 MPH and rotates 40° counterclockwise





(C) Car skids at 50 MPH and rotates 95° counterclockwise

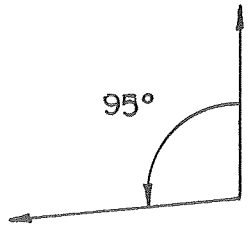


Figure 1

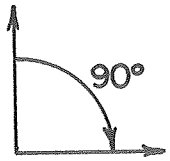
RIGHT WHEEL PATH = SDN_{40} 67

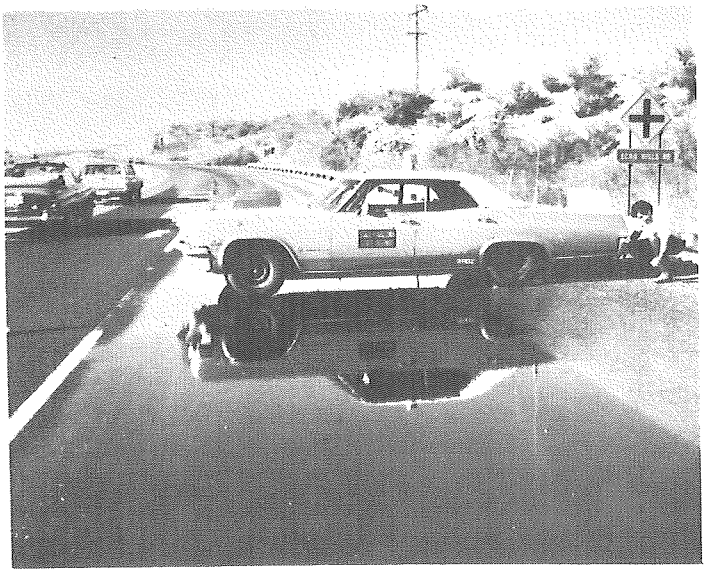
LEFT WHEEL PATH = SDN_{40} 41

39% Difference

(A)

Car skids at 40 MPH and rotates 90° clockwise





(B)

Car skids at 50 MPH and rotates at 270° clockwise

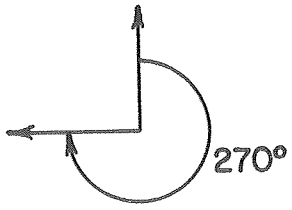


Figure 2

a hazardous condition occurs due to their difference. As the speed increases, the effects of differential friction increase dramatically. Under such conditions, the average driver tends to remove his foot from the brake as he begins to rotate. When he does, his car is propelled in the direction the vehicle is facing. This could be off the road or into oncoming traffic.

It was because of the potential hazard that this condition might cause, that a special research project was initiated to study this and other frictional problems. The project was HPR 1-12 (146) Frictional Properties of Highway Surfaces, which was begun in May 1973. The remainder of Part I will discuss the findings of this phase of the research program.

LOCKED WHEEL SKID TESTS

In order to fully evaluate the effects of differential friction, it was necessary to evaluate numerous locations to obtain test sites that would have a wide range of differential friction numbers and surface types. From thirty potential sites, sixteen were selected for detailed testing. The tests were performed using a 1969 Plymouth Fury and a 1973 AMC Matador.

Detailed testing included the following:

1. Measurement of the individual wet Stopping Distance Number[2] (SDN) for each side at 20 and 40 MPH with the locked wheel skid car. The value recorded for each side was used to represent an individual wheelpath when the surfaces were tested simultaneously.

2. Measurement of each individual side with the Mu-Meter at 20 and 40 MPH, after which the Mu Number (MuN) was recorded.
3. Measurement of the wet SDN on both surfaces simultaneously at 20, 30, 40 and 50 MPH. Besides measuring the stopping distance, the degree of rotation was also measured at each speed.
4. Skidding in the reverse direction to insure that the rotation was due to the differential friction and not due to the mechanics of the vehicle or any possible driver bias.

When the differential stopping distance tests were performed as described, special care was taken to keep the tests uniform. This was done in the following manner. When the desired test speed was reached, the driver would lock the brakes and hold the wheel from rotating, thus keeping the wheels pointed straight ahead with reference to the car. It was decided to use the straight wheel method because it was found that when all the brakes were locked, rotating the wheel had no effect (as expected) on reducing the spin of the car. The only effect it did have, was to possibly cause the driver to lose his concentration and not keep the brakes fully locked. If this had happened when the driver was in a spin, a major accident could have occurred.

When the car stopped, the rotation in degrees was measured. This was done in reference to a large protractor fastened to the trunk of the vehicle

and a fifteen-foot (4.57m) length of string, which was extended from the center of the protractor and aligned parallel to the centerline of the highway. This method proved very accurate and reliable.

LOCKED WHEEL SKID TEST RESULTS

The actual skid test results are shown in Appendix A. From these diagrams it can be seen that as the differential friction level increases, the amount of rotation in degrees per foot of skid also increases. This indicates that although a pavement has a good coefficient of friction in both its wheelpaths, if they are unequal it may cause a more hazardous condition than a low friction pavement with uniform friction. Similar findings were reported by Zuk at the University of Virginia[3]. In the bottom-right-hand corner of these figures is the skid number (actual stopping distance number) recorded for the individual wheelpaths at 20 and 40 MPH. The differential friction at 40 MPH is obtained by calculating the absolute difference between the SDN for each wheelpath recorded at 40 MPH. To calculate the rotation in degrees per foot, the actual rotation at a particular speed (shown in the center of the figure), is divided by the stopping distance (bottom left) recorded at that speed. The rotation in degrees per foot (3.28 deg. per meter), shown in the right corner, is that recorded for 40 MPH.

A complete listing of the test results recorded for all sixteen sites is shown in Figure 3. This data was used to derive equations relating the

rotation of a car to SDN, Differential Friction Number and vehicle speed. The Differential Friction Number (DFN) is defined by the author as the absolute difference between the wet SDN's of each wheelpath recorded at the same speed and subscripted by that speed if the test speed was other than 40 MPH.

Figures 4, 5 and 6 show the derived equations for 30, 40 and 50 MPH relating the degrees per foot rotation to the DFN recorded at 40 MPH. The correlation coefficients ranged between 0.93 and 0.94 and, as can be seen from the graphs, reliable equations were derived. Figure 7 shows all three equations plotted on the same graph. Site Number six was not used in the derivation of these equations, as it contained a portland cement concrete pavement (PCCP) and asphaltic concrete (AC) surface differential. The degree of rotation was high, but lower than expected. This may have been due to the longitudinal burlap drag texture on the PCCP pavement which would inpart a higher side force friction and thus inhibit rotation. If this is the case, grooving or grinding might be used to correct a differential friction problem.

From these three equations, a new equation was derived for use with any speed. The equation is as follows:

$$\text{Deg/Ft.} = 0.148 - .0049(V) + [.00263 + .009(V)]DFN$$

where:

Deg/Ft. = Degrees per foot rotation for given velocity (V)

FIGURE 3

DIFFERENTIAL WHEELPATH FRICTION TEST RESULTS

Separate Wheelpath Test Data					Differential Test Data					
Site Number	Speed MPH	Left Wheel Track Average SDN	Right Wheel Track Average SDN	Differential Friction Number	Test Speed MPH	Stopping Distance Feet	Stopping Distance Meters	Degrees* Rotation	Degrees Per Foot Rotation	Degrees Per Meter Rotation
1	20	64	70	6	22	25.5	7.8	---	---	
	40	57	62	5	30	48.5	14.8	---	---	
					40	96.5	29.4	16 cw	.166	.545
					50	149.5	45.6	12 cw	.080	.262
2	20	44	64	20	21	23.5	7.2	15 cw	.638	2.093
	40	36	57	21	31	55.5	16.9	27	.487	1.598
					42	122.0	37.2	95	.779	2.556
					48	190.5	58.1	142	.745	2.444
3	20	41	56	15	20	27.5	8.4	5 cw	.182	.597
	40	31	45	14	32	73.5	22.4	30	.408	1.338
					41	145.0	44.2	82	.566	1.857
					48	208.0	63.4	137	.659	2.162
4	20	56	62	6	20	27.5	8.4	10 cw	.364	1.194
	40	40	49	9	30	67.0	20.4	17	.254	.833
					40	120.0	36.6	57	.475	1.558
					49	205.0	62.5	129	.629	2.064
5	20	61	63	2	20	20.5	6.2	6 cw	.293	.961
	40	52	61	9	31	56.0	17.0	14	.250	.820
					40	97.5	29.7	25	.256	.840
					50	163.0	49.7	37	.227	.745
6	20	51	76	25	20	21.0	6.4	14 cw	.667	2.188
	40	47	73	26	31	51.5	15.7	34	.654	2.146
					40	92.5	28.2	57	.612	2.008
					51	157.0	47.9	119	.758	2.487
7	20	42	44	2	20	29.3	8.9	6 cw	.205	.672
	40	42	48	6	30	67.1	20.4	16	.238	.781
					40	117.5	35.8	27	.230	.754
					49	174.1	53.1	42	.241	.791
8	20	49	61	12	32	75.5	23.0	22 cw	.291	.955
	40	36	44	8	40	143.2	43.6	24	.168	.551
					45	157.2	47.9	28	.178	.584

FIGURE 3
Continued

DIFFERENTIAL WHEELPATH FRICTION TEST RESULTS

Separate Wheelpath Test Data					Differential Test Data					
Site Number	Speed MPH	Left Wheel Track Average SDN	Right Wheel Track Average SDN	Differential Friction Number	Test Speed MPH	Stopping Distance Feet	Stopping Distance Meters	Degrees* Rotation	Degrees Per Foot Rotation	Degrees Per Meter Rotation
9	20	60	38	22	21	24.5	7.5	6 ccw	.245	.804
	40	47	25	22	30	65.6	20.0	40	.611	2.004
					41	165.0	50.3	149	.903	2.963
					50	245.0	74.7	275	1.122	3.681
10	20	58	40	18	21	29.8	9.1	9 ccw	.302	.991
	40	49	32	17	32	82.2	25.1	50	.608	1.995
					41	150.4	45.8	139	.924	3.031
					50	244.6	74.6	209	.854	2.802
						152.1	46.4			
11	40	53	57	4	30	51.0	15.5	5 cw	.098	.322
					40	98.0	29.9	12	.122	.400
					50	185.0	56.4	35	.189	.620
12	20	58	56	2	21	31.4	9.6	1 cw	.032	.105
	40	45	49	4	30	66.3	20.2	4	.060	.197
					40	126.3	38.5	17	.135	.443
13	40	60	49	11	40	100.4	30.6	23 ccw	.229	.751
14	40	58	46	12	30	56.0	17.1	26 ccw	.464	1.522
					40	95.0	29.0	37	.389	1.276
					50	167.0	50.9	81	.485	1.591
15	40	57	38	19	31	60.0	18.3	30 ccw	.500	1.640
					41	120.0	36.6	98	.816	2.677
					51	206.7	63.0	173	.837	2.746
16	40	51	55	4	30	51.0	15.5	0 cw	.000	0.0
					40	95.0	29.0	6	.063	.207
					50	157.0	47.9	12	.076	.249

*cw = Clockwise
*ccw= Counter clockwise

V = Velocity of vehicle in MPH when the brakes are locked.

DFN = Differential Friction Number (Difference between wet Stopping Distance Numbers measured at 40 MPH in each wheelpath).

Deg/meter = 3.28 x Deg/Ft.

From this equation, it can be seen that the rotation in degrees per foot can be determined easily for any desired speed by simply knowing the SDN for each wheelpath.

When this value is multiplied by the stopping distance for the given surface, the total number of degrees that the vehicle will spin can be calculated. Our experiments have shown that the actual stopping distance on the differential surface is approximately equal to the average of the two stopping distances on the individual surfaces at the same speed. For example, if at 40 MPH a car stopped in 100 feet (30.48m) (SDN = 53) in the left wheelpath, and 200 feet (60.96m) (SDN = 27) in the right wheelpath, then when braking on both surfaces simultaneously, the vehicle would stop in 150 feet (45.72m) (SDN = 36, DFN = 26). If the degrees of rotation are desired, the 150 feet (45.72m) would be multiplied by the ^{o}/ft. rotation value, which at 40 MPH would be 1.1 (from the equation) for an estimated total of 165.5 degrees total rotation.

ROTATION (DEGREES/FOOT AT 30 MPH) VS SDN_{40} DIFFERENTIAL

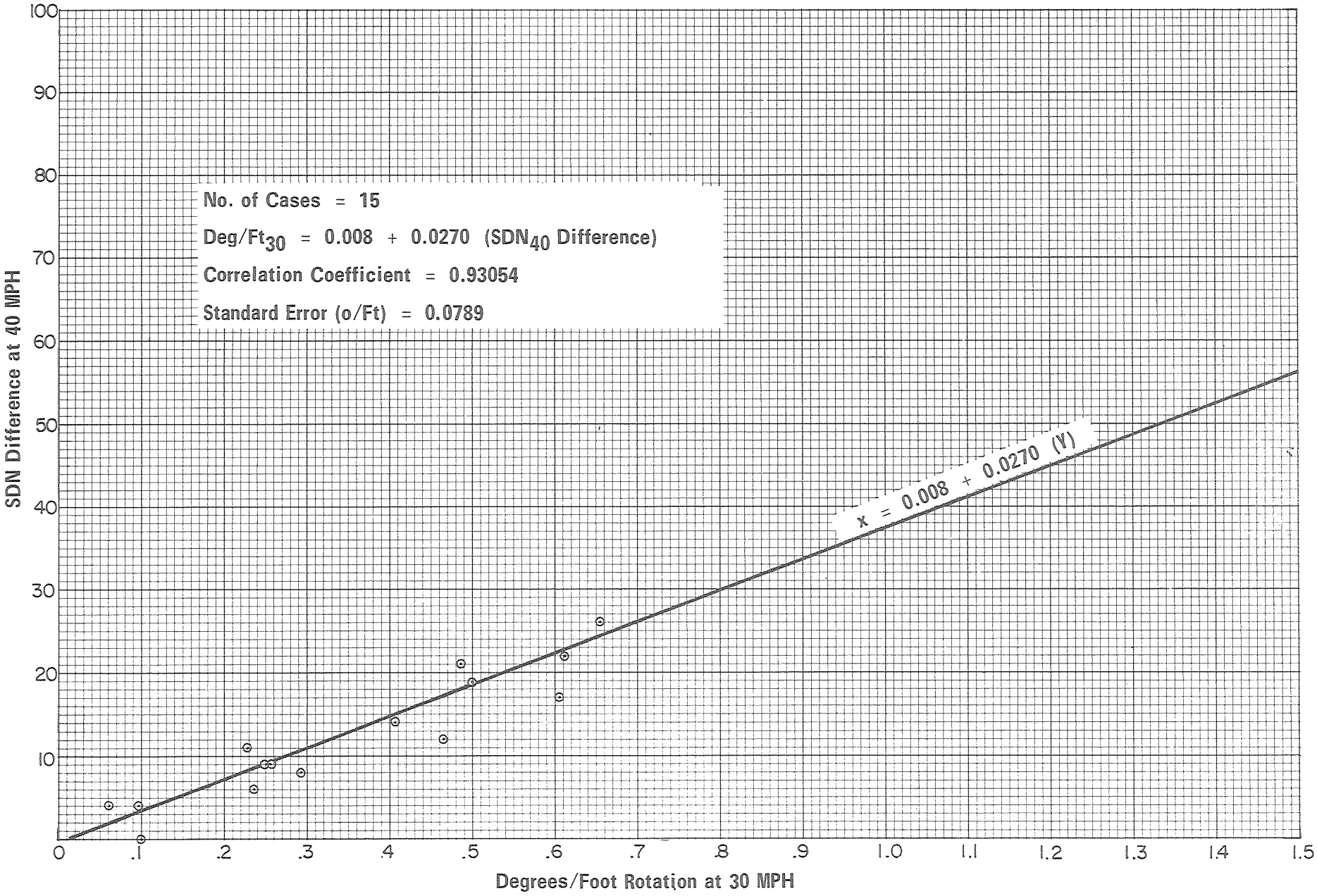


Figure 4

ROTATION (DEGREES/FOOT AT 40 MPH) VS SDN_{40} DIFFERENTIAL

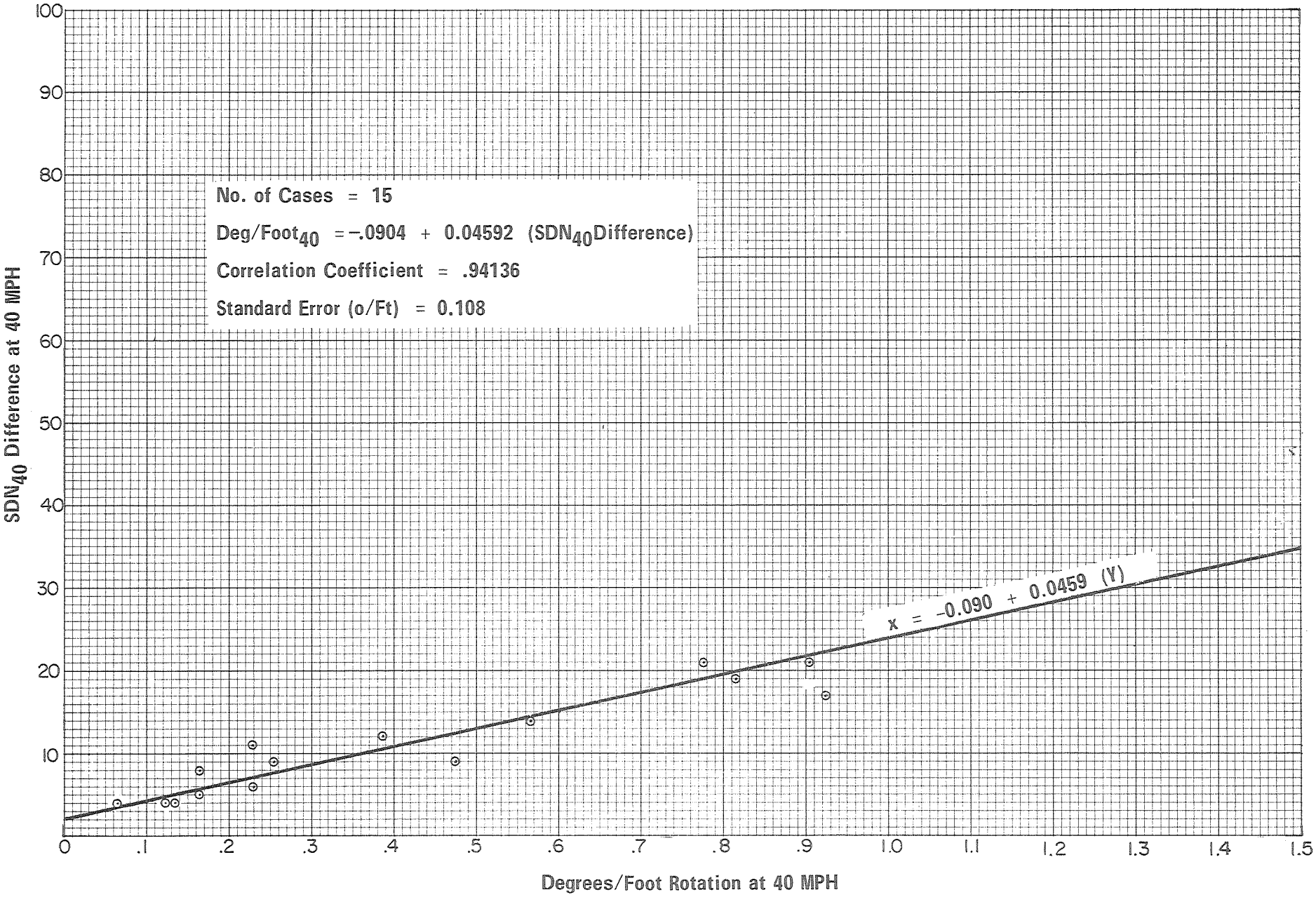
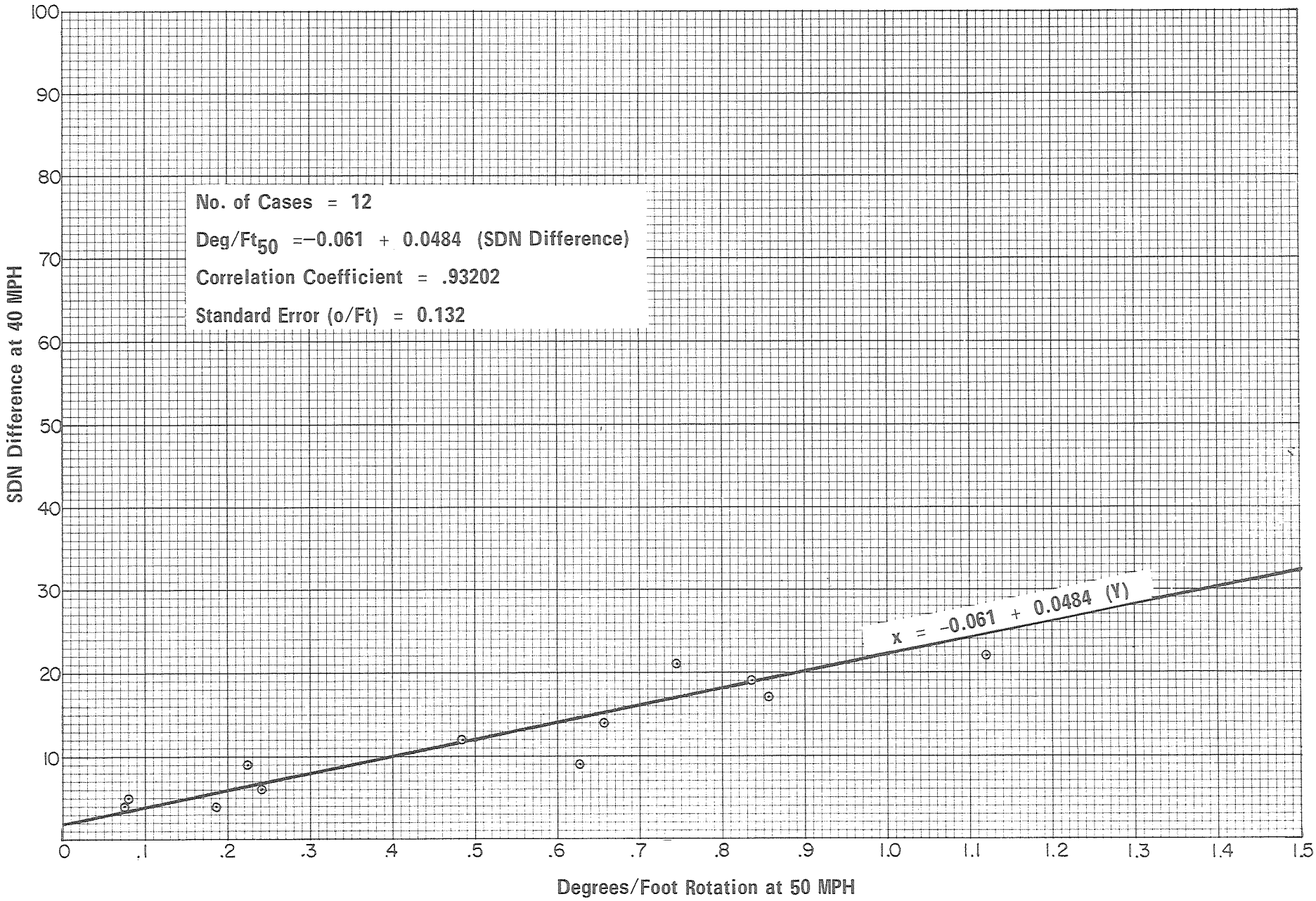


Figure 5

ROTATION (DEGREES/FOOT AT 50 MPH) VS SDN_{40} DIFFERENTIAL



Fi 6

ROTATION (DEGREES/FOOT) VS SDN_{40} DIFFERENTIAL

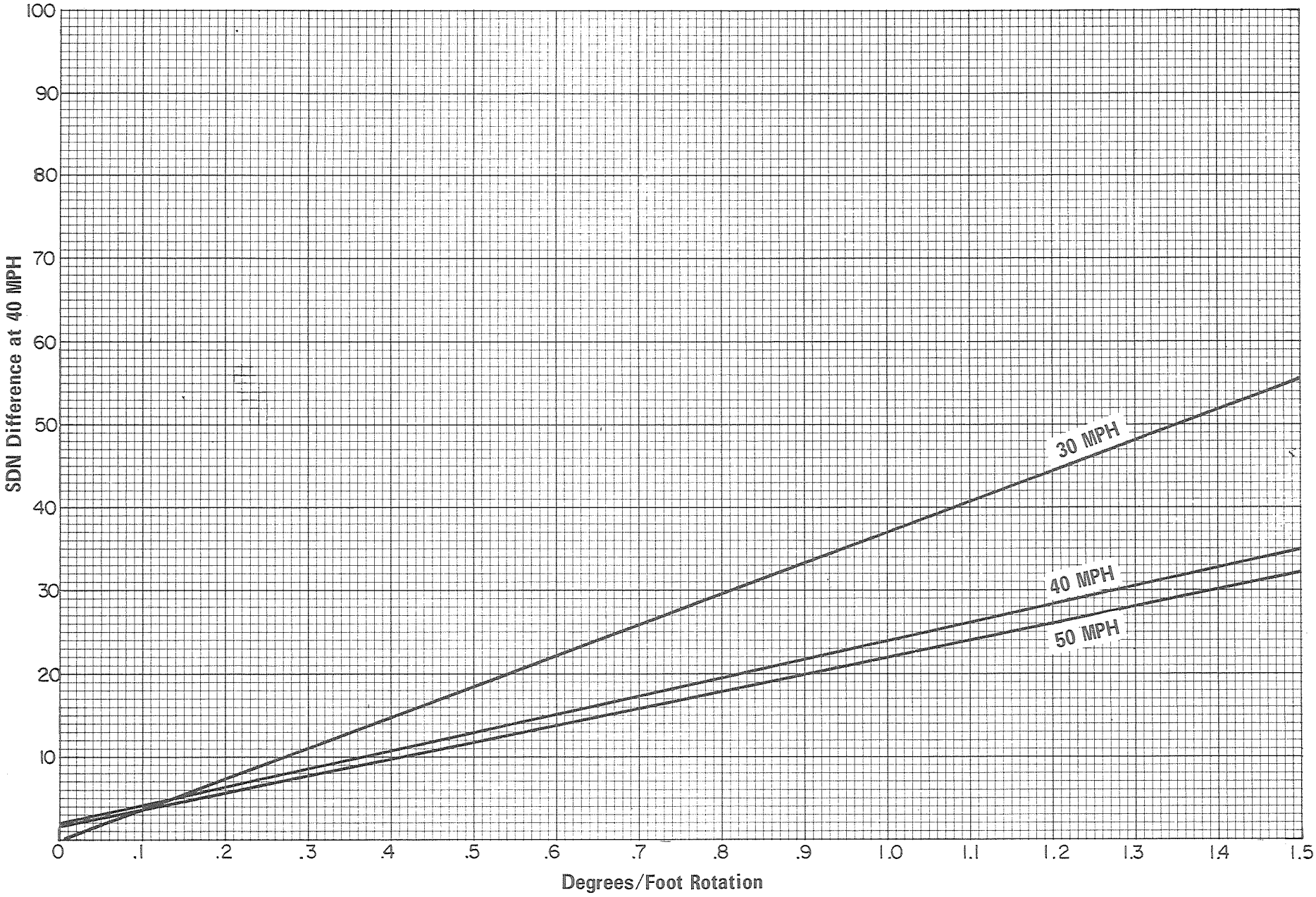


Figure 7

VEHICLE CONTROL TESTS

The second part of the evaluation was concerned with the maneuvering problems associated with the differential friction surface. The normal tendency for a driver is to release the brake after he begins to spin and to try simultaneously to regain control of his vehicle. For this reason we decided to reconstruct a similar condition. This was done in two phases. The first phase was an experiment to determine how many degrees a car could rotate before it could not be safely corrected by the driver. Figure 8 shows the schematic of the system that was used in the test. The premise of the test was that a vehicle would have a twelve-foot (3.66m) wide lane in which it could safely maneuver. If the vehicle moved out of its lane for a distance of up to six feet (1.83m) on either side, it was considered to be in another vehicle's lane and thus in a potential accident zone for oncoming or parallel traffic. The test vehicle was given additional maneuvering space as it was assumed that other traffic could move six feet (1.83m) over and avoid the spinning car. If the test car moved more than six feet (1.83m) into another lane, it was assumed that a theoretical collision with other traffic would occur, as an oncoming vehicle would not be able to avoid the spinning car. Traffic cones were placed along the imaginary collision zone, which allowed our vehicle a width of twenty-four feet (7.32m) in which to maneuver. During each test, the driver was instructed to avoid these cones, as they represented oncoming cars.

VEHICLE CONTROL TESTS

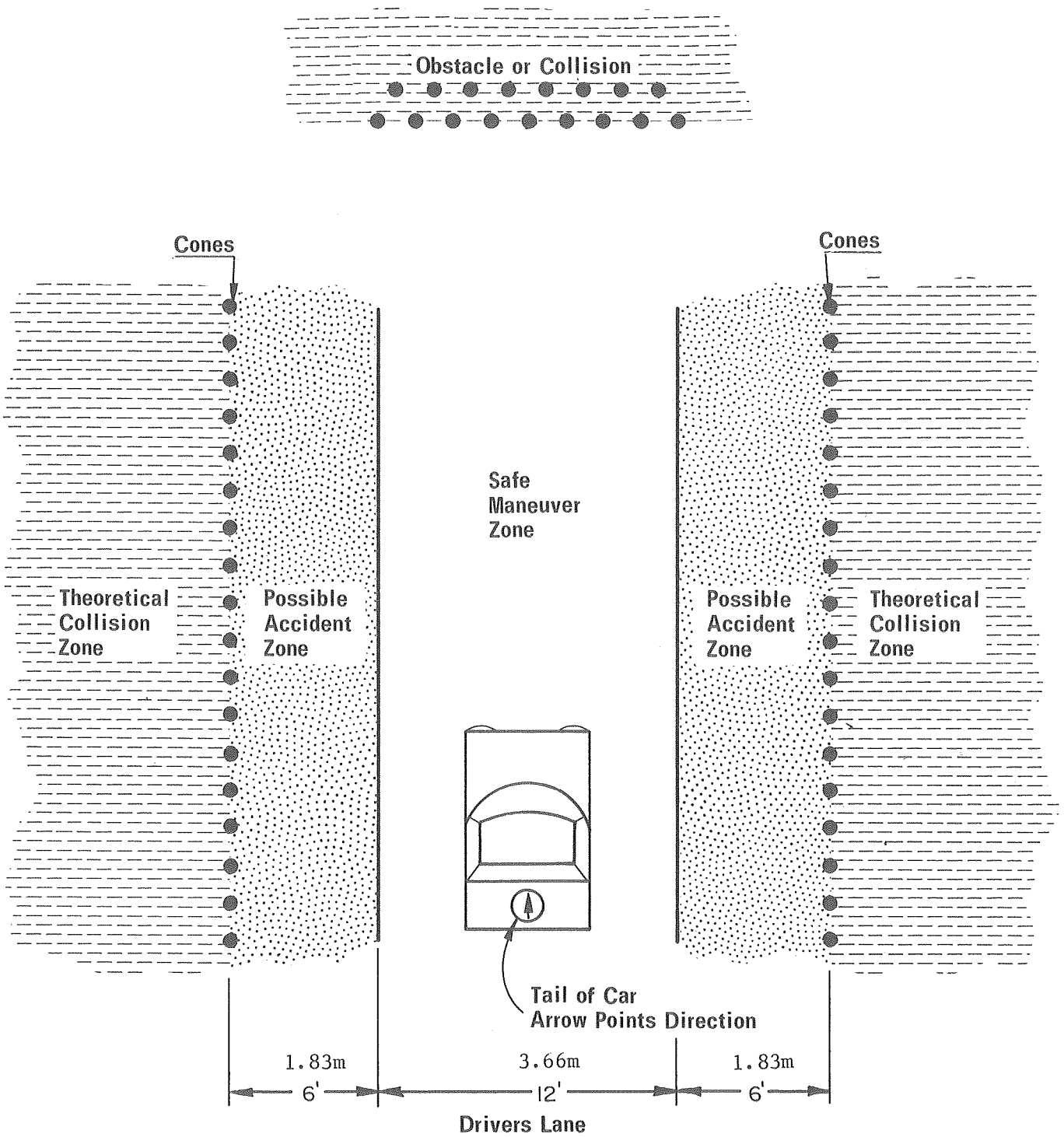


Figure 8

The second phase of the experiment evaluated the control problems associated with stopping when the brakes were not locked and the driver was allowed to freely maneuver his vehicle. In this case, cones were also set at various distances from a beginning braking point. This distance was ten feet (3.05m) further than the maximum braking distance recorded at any particular speed. The driver was then directed to stop in the given distance without hitting the side cones (theoretical collision) or hitting the cones at the end of the distance, which represented an obstacle.

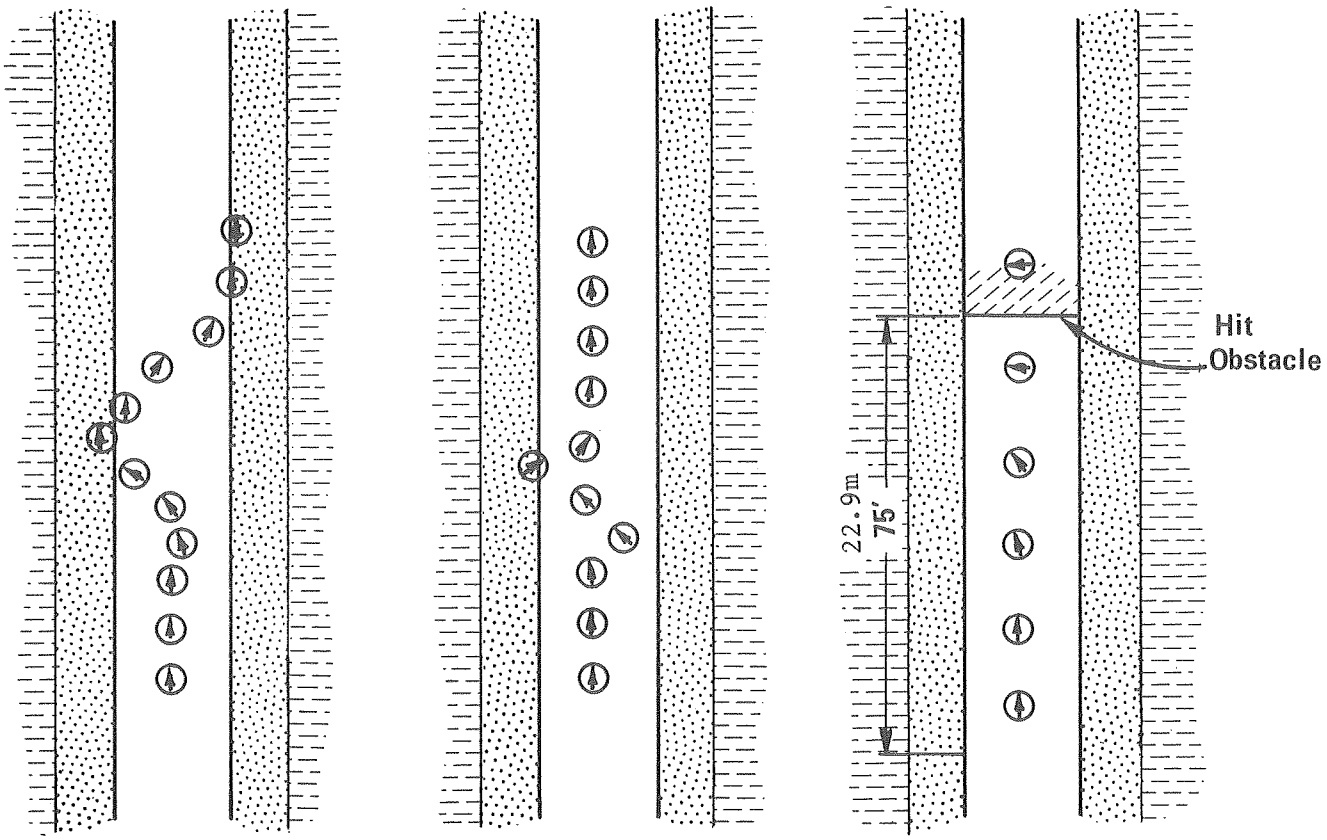
Motion pictures were made of all tests. Figures 9 thru 11 show the trajectory of the vehicle recorded on film for various test speeds. In these figures, a circle was used to represent the position of the rear end of the vehicle. The arrow inside the circle indicates the direction the front of the car was facing at that moment in time.

VEHICLE CONTROL TEST RESULTS

Figure 9 shows the trajectory of the vehicle during tests at 30 MPH. It can be seen that when the vehicle was allowed to rotate twenty degrees before releasing the brake, it moved into the possible accident zone, but did not enter the collision zone. In these tests, the vehicle had almost come to a complete halt before the brakes were released. When an obstacle was placed in the highway, the driver was able to stay in his lane, but unable to stop before reaching the object.

Figure 10 shows the results of the 40 MPH tests. The figure shows

VEHICLE CONTROL TESTS ON A DIFFERENTIAL FRICTION SURFACE ($DF_{40} = 17$)



20° Rotation Prior To Releasing Brake

30° Rotation Prior To Releasing Brake

Unlocked Brake Tests 91 Feet to Stop

30 MPH TESTS

Figure 9

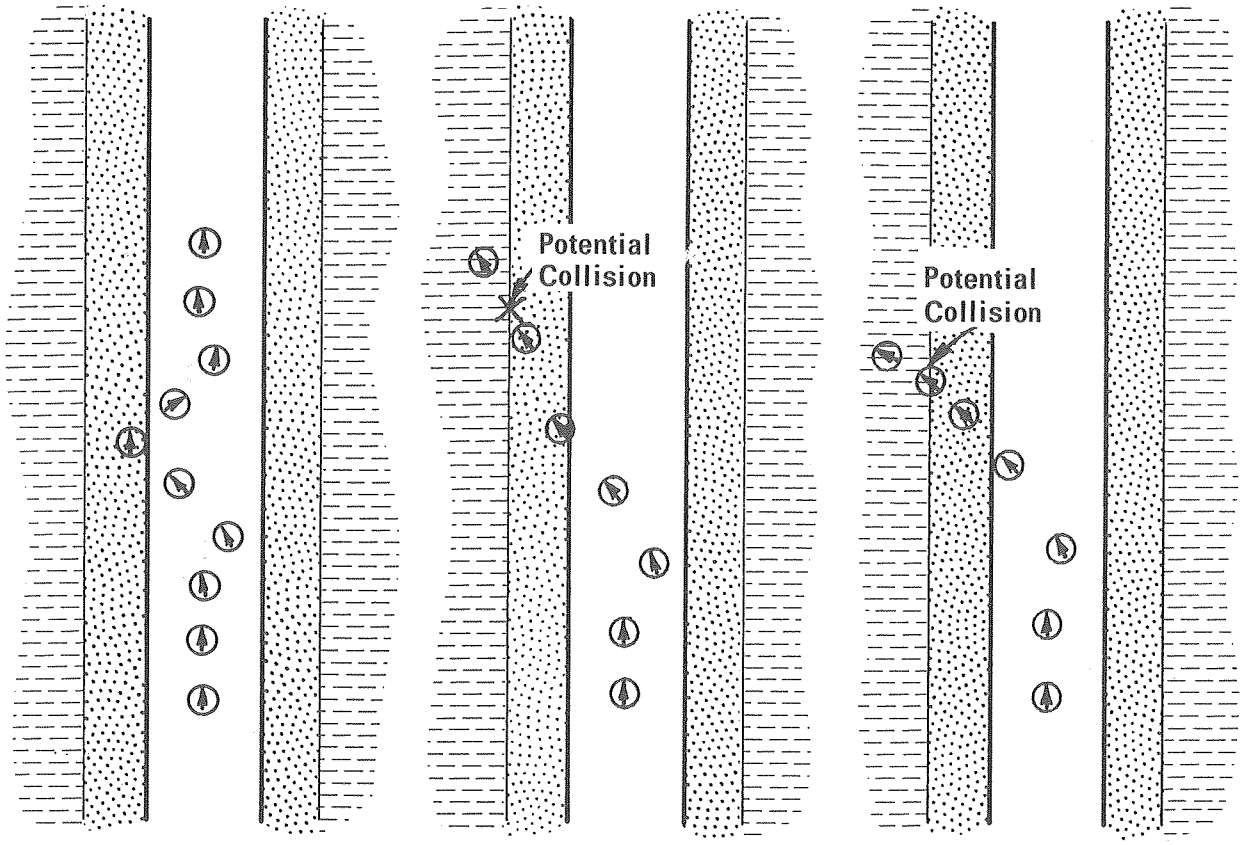
that the only case in which the vehicle did not move into the collision zone was for the 20° rotation test. In this case it moved only into the possible accident zone. The car was basically uncontrollable after rotating thirty degrees or more. When an obstacle was placed in the road, the driver did avoid it at 40 MPH; however, to do this, his car moved into the collision zone and spun out of control. When the obstacle was removed and the driver given unlimited stopping distance, he was still unable to prevent the car from spinning out of control and entering the collision zone.

Figure 11 shows the results of the 50 MPH tests. In this case the driver was unable to control the vehicle after ten degrees rotation and moved into the collision zone. When an obstacle was placed in the road, the vehicle not only moved into the collision zone, but also spun into the obstacle.

From the results of these speed tests, it is obvious that differential friction can significantly effect the control of a braking vehicle and produce a potentially hazardous condition which the driver may not be able to correct.

The greatest problem arises when the driver releases the brake after the car has begun to spin. When this is done, the vehicle is propelled in the direction it is facing, whether it be off the road or into oncoming traffic. The greater the rotation the more uncontrollable the vehicle. After passing ninety degrees, the car will actually be propelled rearward if the brake is released.

VEHICLE CONTROL TESTS ON A DIFFERENTIAL FRICTION SURFACE (DF_{40}=17



20° Rotation Prior To Releasing Brake

30° Rotation Prior To Releasing Brake

35° Rotation Prior To Releasing Brake

40 MPH TESTS

Figure 10