

Differential Friction: A Potential Skid Hazard

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Differential wheel-path friction, or differential friction, is a term derived to describe the condition that exists when the individual wheel paths on which a vehicle rides have different or unequal coefficients of friction. The problems associated with differential friction may be minor or extremely serious depending on the magnitude of the frictional difference and its relation to the average coefficient of friction. This problem may occur on surfaces with high as well as low coefficients of friction. For this reason, a frictional inventory made in only one wheel track may not detect such a problem. Although the coefficient of friction may be good to excellent in both wheel paths, the difference might cause a vehicle to spin out of control when braking if the wheel paths are unequal. Therefore, this concept should be given major consideration in any pavement friction evaluation. The paper describes the research performed to evaluate the effects of differential friction on a skidding car. It also describes the magnitude of the problem as well as some of the causes and possible solutions. The results of this research indicate that differential friction should be given major consideration in any pavement friction analysis. There are also strong indications that differential friction may be as important a cause of wet pavement accidents as low friction level. If this is the case, a major reevaluation of pavement friction evaluation, design, and corrective techniques may be necessary.

A thorough evaluation of the phenomenon of differential friction was made as part of the federally sponsored research project. This paper describes the work that was performed during this research, which evaluated the effects that 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. This subject is covered in greater detail in the final report (1).

DIFFERENTIAL FRICTION

Differential wheel-path friction is a term I have derived to describe the condition that occurs when the individual wheel paths on which a vehicle rides have different or unequal coefficients of friction. Although this phenomenon is usually not considered in a pavement friction evaluation, it can have a significant effect on a braking vehicle.

Several years ago, during stopping distance tests with a skidding car, some pavements caused the car to spin uncontrollably (2). Under normal conditions, the car was designed to stop in a straight line and not rotate. This rotation was found to be caused by unequal friction levels in each of the wheel paths. Because the tires on the left side of the car were exposed to a different pavement friction level than those on the right side were exposed to, a turning movement was caused, and the vehicle rotated toward the higher friction side. As the car spun, the front wheels moved onto the higher friction surface and the rear wheels moved onto the lower friction surface. 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 left wheel track was bleeding and the right wheel track had been chip sealed. The right wheel path had a wet stopping distance number (SDN₄₀) of 67 and the left wheel path had a wet SDN₄₀ of 41, which is a 26 SDN, or 39 percent, difference. In Figure 1a, the car skidded at 64.4 km/h (40 mph) and rotated 90 deg clockwise. In Figure 1b, the car skidded at 80.5 km/h (50 mph) and rotated 270 deg clockwise. Again the direction of skidding was reversed, and the same values were recorded with the car rotating counterclockwise.

Figure 1 is a case used to portray what might happen if one wheel path was flushing and the other was not. Although both wheel paths have a satisfactory level of friction, a hazardous condition exists because of their difference. As the speed increases, the effects of differential friction increase dramatically. The problem is serious because the average driver tends to remove his or her foot from the brake as the car begins to rotate. When this is done, the car is propelled in the direction that the vehicle is facing. This could be off the road or into oncoming traffic. Because of national concern about the potential hazard that this condition might cause, a special research project was initiated to study this and other frictional problems (1). The remainder of this paper will discuss some of the findings of the research project.

LOCKED-WHEEL SKID

Tests

To fully evaluate the effects of differential friction, numerous locations had to be evaluated to obtain test sites that would have a wide range of differential friction numbers and types of surfaces. From 30 potential sites, 16 were selected for detailed testing. The tests were performed with a 1969 Plymouth Fury and a 1973 AMC Matador. Detailed testing included

1. Measurement of the wet SDN by ASTM E 445-71T (3) for each individual side at 32.2 and 64.4 km/h (20 and 40 mph) with the locked-wheel skid car. The value recorded for each side was used to represent an individual wheel path when the surfaces were tested simultaneously.
2. Measurement of each individual side with the Mu-Meter at 32.2 and 64.4 km/h (20 and 40 mph) after which the mu number was recorded.
3. Measurement of the wet SDN on both surfaces simultaneously at 32.2, 48.3, 64.4, and 80.5 km/h (20, 30, 40, and 50 mph). In addition to stopping distance, degree of rotation was also measured at each speed.
4. Measurement of skidding in the reverse direction to ensure that rotation was due to differential friction and not the mechanics of the vehicle or any possible driver bias.

When the differential stopping distance tests were performed, special care was taken to keep the tests uniform. When the desired test speed was reached, the driver would lock the brakes and hold the steering wheel to prevent it from rotating. This kept the wheels pointed straight ahead in relation to the vehicle. 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 on reducing the spin of the car. The only effect it did have was to possibly cause the driver to lose his or her concentration and not keep the brakes fully locked. If this had happened when the driver was in a spin, a major accident might have occurred.

When the car stopped, the stopping distance and the rotation in degrees were measured. The rotation was measured in reference to a large protractor fastened to the trunk of the vehicle and a 4.57-m (15-ft) length of string that was extended from the center of the protractor and aligned parallel to the centerline of the highway. This method proved very accurate and reliable.

Results

Several of the actual test results are shown in Figures 2 through 5. From these diagrams, it can be seen that, as the differential friction level increases, the amount of rotation in degrees per meter of skid also increases. This indicates that good but unequal coefficients of friction in both wheel paths, may cause a more hazardous condition than low but uniform coefficients of friction. Similar findings were reported by Zuk (4). In the bottom right corner of these figures is the SDN recorded for the individual wheel paths at 32.2 and 64.4 km/h (20 and 40 mph). The differential friction at 64.4 km/h (40 mph) is obtained by calculating the absolute difference between the SDN for each wheel path recorded at 64.4 km/h (40 mph). To calculate the rotation in degrees per meter, divide the actual rotation at a particular speed (center of the figure) by the stopping distance (bottom left) recorded at that speed. The rotation shown in the right corner is for 64.4 km/h (40 mph).

A complete listing of the test results recorded for

all 16 sites is given in Table 1. These data were used to derive equations relating the rotation of a car to SDN, differential friction number (DFN), and vehicle speed. DFN is defined as the absolute difference between the wet SDNs of each wheel path recorded at the same speed and subscripted by that speed if other than 64.4 km/h (40 mph).

Equations for 48.3, 64.4, and 80.5 km/h (30, 40, and 50 mph) were obtained by relating the degrees per meter rotation to the DFN recorded at 64.4 km/h (40 mph). Correlation coefficients ranged between 0.93 and 0.94, and reliable equations were derived as can be seen in Figure 6. Figure 7 shows all three equations plotted on the same graph. Site 6 was not used in the derivation of these equations because it contained a portland cement concrete (PCC) and asphalt 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 PCC pavement, which would impart a higher side force 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:

$$\text{Deg/m} = \{0.148 - 0.0049(V) + [0.00263 + 0.0009(V)] \text{DFN}\} \times 3.28 \quad (1)$$

where

Deg/m = degrees per meter rotation for given velocity and

V = velocity of vehicle when the brakes are locked.

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

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 64.4 km/h (40 mph) a car stopped in 30.48 m (100 ft) (SDN = 53) in the left wheel path and 60.96 m (200 ft) (SDN = 27) in the right wheel path, then the vehicle would stop in 45.72 m (150 ft) (SDN = 36, DFN = 26) when braking on both surfaces simultaneously. If the degrees of rotation are desired, the 45.72 m (150 ft) would be multiplied by the deg/m rotation value. At 64.4 km/h (40 mph), this would be 3.61 deg/m (1.1 deg/ft) (from the equation) for an estimated total of 165.5-deg total rotation.

VEHICLE CONTROL

Tests

The second part of the evaluation was concerned with the maneuvering problems associated with the differential friction surface. A driver tends to release the brake after he or she begins to spin; at the same time, the driver tries to regain control of the vehicle. Therefore, a similar condition was reconstructed 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 3.7-m-wide (12-ft-wide) lane in which it could safely maneuver. If the vehicle moved out of its lane for a distance

Figure 1. Effects of differential friction.

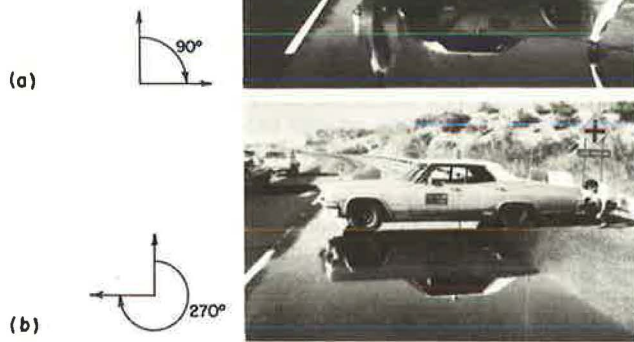


Figure 2. Rotation test, site 12.

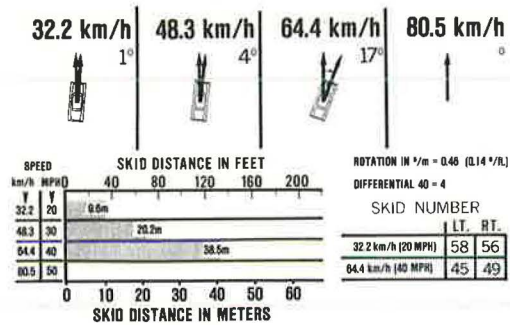


Figure 3. Rotation test, site 4.

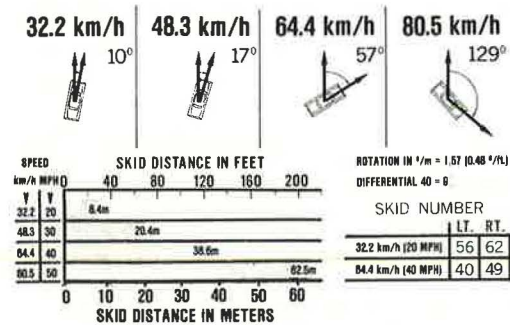


Figure 4. Rotation test, site 15.

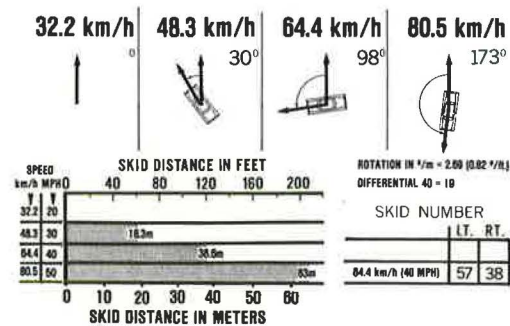


Figure 5. Rotation test, site 9.

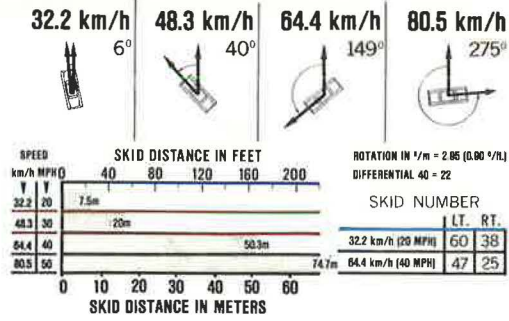
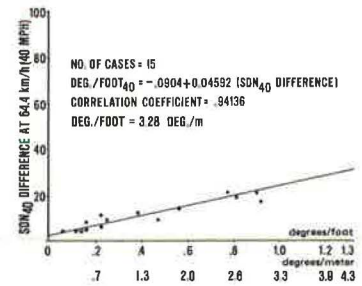
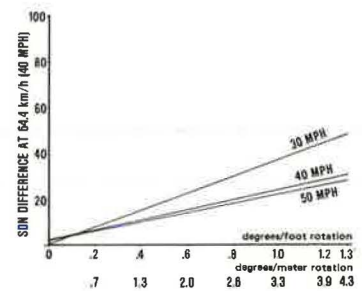
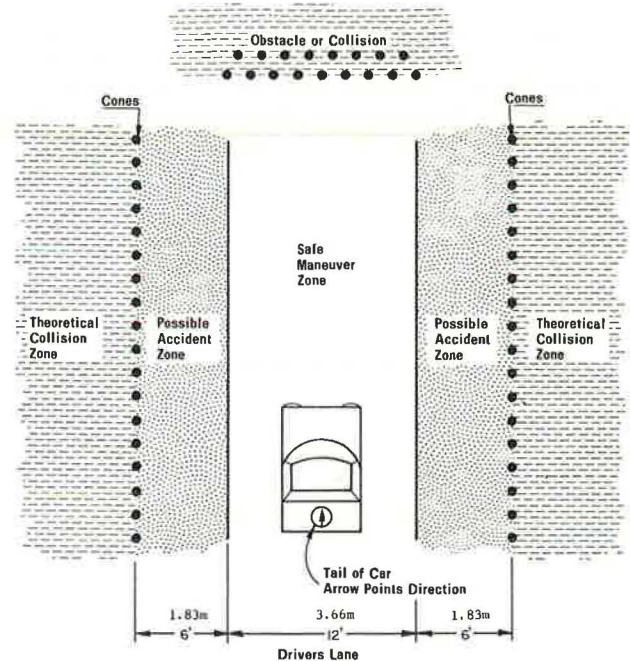
Figure 6. Rotation at 64.4 km/h (40 mph) versus SDN_{40} differential.Figure 7. Rotation versus SDN_{40} differential.

Figure 8. Vehicle control tests.



of up to 1.8 m (6 ft) on either side, it was considered to be in another lane and thus in a potential accident zone for oncoming or parallel traffic. The test vehicle was given additional maneuvering space because other traffic was assumed to be able to move 1.8 m (6 ft) and avoid the spinning car. If the car moved any further into another lane, a collision with other traffic was assumed to occur because 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 7.3 m (24 ft) in which to maneuver. During each test, the driver was instructed to avoid these cones because they represented oncoming cars.

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 the vehicle. In this case, cones were also set at various distances from a beginning braking point. The distance was 3.05 m (10 ft) 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 the cones at the end of the distance (obstacle).

Films were made of all tests. Figures 9 through 11 show the trajectory of the vehicle recorded on film for various test speeds. In these figures, a circle was used

Table 1. Differential wheel-path friction test results.

Site Number	Separate Wheel-Path Test Data				Differential Test Data			
	Test Speed (km/h)	Average SDN		DFN	Test Speed (km/h)	Stopping Distance (m)	Degrees Rotation	
		Left Wheel Track	Right Wheel Track				Clockwise	Counter-clockwise
1	32.2	64	70	6	35.4	7.8	—	—
	64.4	57	62	5	48.3	14.8	—	—
					64.4	29.4	16	0.545
					80.5	45.6	12	0.262
2	32.2	44	64	20	33.8	7.2	15	2.093
	64.4	36	57	21	49.9	16.9	27	1.598
					67.6	37.2	95	2.556
					77.2	58.1	142	2.444
3	32.2	41	56	15	32.2	8.4	5	0.597
	64.4	31	45	14	51.5	22.4	30	1.338
					66.0	44.2	82	1.857
					77.2	63.4	137	2.162
4	32.2	56	62	6	32.2	8.4	10	1.194
	64.4	40	49	9	48.3	20.4	17	0.833
					64.4	36.6	57	1.558
					78.8	62.5	129	2.064
5	32.2	61	63	2	32.2	6.2	6	0.961
	64.4	52	61	9	49.9	17.0	14	0.820
					64.4	29.7	25	0.840
					80.5	49.7	37	0.745
6	32.2	51	76	25	32.2	6.4	14	2.188
	64.4	47	73	26	49.9	15.7	34	2.146
					64.4	28.2	57	2.008
					82.1	47.9	119	2.487
7	32.2	42	44	2	32.2	8.9	6	0.672
	64.4	42	48	6	48.3	20.4	16	0.781
					64.4	35.8	27	0.754
					78.8	53.1	42	0.791
8	32.2	49	61	12	51.5	23.0	22	0.955
	64.4	36	44	8	64.4	43.6	24	0.551
					72.4	47.9	28	0.584
9	32.2	60	38	22	33.8	7.5	6	0.804
	64.4	47	25	22	48.3	20.0	40	2.004
					66.0	50.3	149	2.963
					80.5	74.7	275	3.681
10	32.2	58	40	18	33.8	9.1	9	0.991
	64.4	49	32	17	51.5	25.1	50	1.995
					66.0	45.8	139	3.031
					80.5	74.6	209	2.802
11	64.4	53	57	4	48.3	15.5	5	0.322
					64.4	29.9	12	0.400
					80.5	56.4	35	0.620
12	32.2	58	56	2	33.8	9.6	1	0.105
	64.2	45	49	4	48.3	20.2	4	0.197
					64.4	38.5	17	0.443
13	64.4	60	49	11	64.4	30.6	23	0.751
14	64.4	58	46	12	48.3	17.1	26	1.522
					64.4	29.0	37	1.276
					80.5	50.9	81	1.591
15	64.4	57	38	19	49.9	18.3	30	1.640
					66.0	36.6	98	2.677
					82.1	63.0	173	2.746
16	64.4	51	55	4	48.3	15.5	0	0
					64.4	29.0	6	0.207
					80.5	47.9	12	0.249

Note: 1 km/h = 0.621 mph. 1 m = 3.28 ft. 1 deg/m = 0.305 deg/ft.

to represent the position of the rear end of the vehicle. The arrow inside the circle indicates the direction that the front of the car was facing at that moment.

Results

Figure 9 shows the trajectory of the vehicle during tests

Figure 9. Vehicle control tests at 48.3 km/h (30 mph) where DFN = 17.

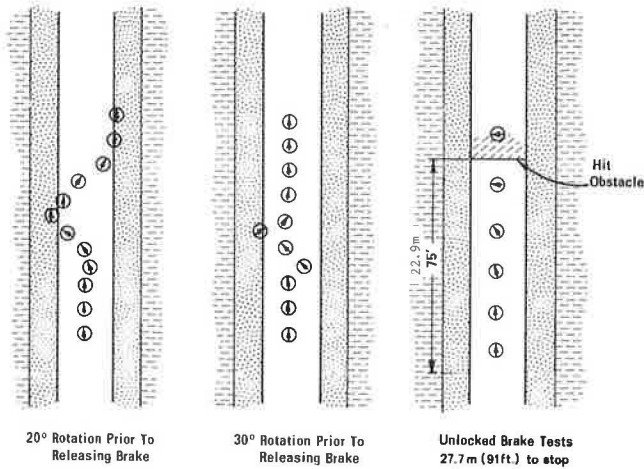
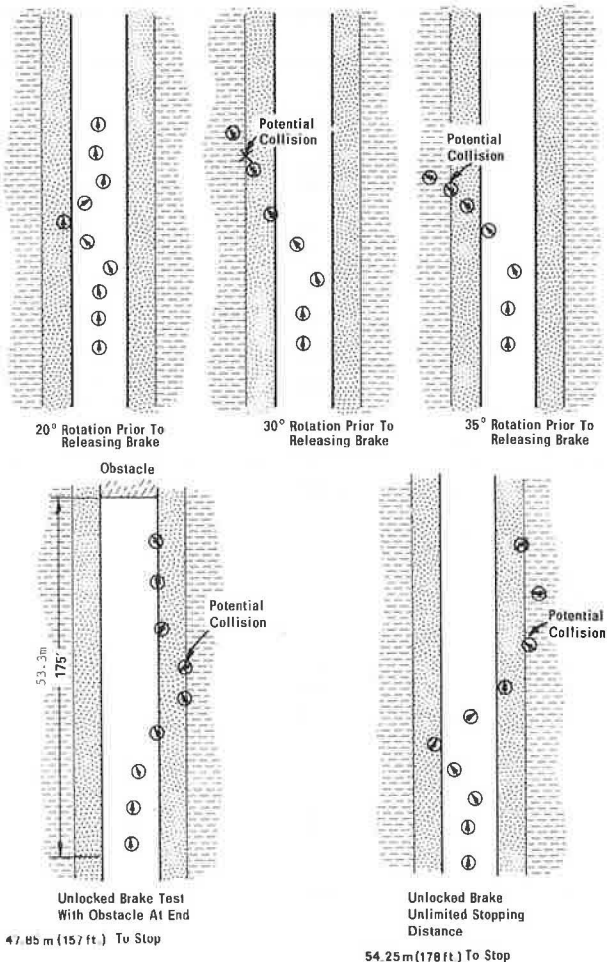


Figure 10. Vehicle control tests at 64.4 km/h (40 mph) where DFN = 17.



at 48.3 km/h (30 mph). When the vehicle was allowed to rotate 20 deg before releasing the brake, the vehicle 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 or her lane but unable to stop before reaching the object.

Figure 10 shows the results of the 64.4-km/h (40-mph) tests. The figure shows that the only case in which the vehicle did not move into the collision zone was the 20-deg rotation test. In this case it only moved into the

Figure 11. Vehicle control tests at 80.5 km/h (50 mph) where DFN = 17.

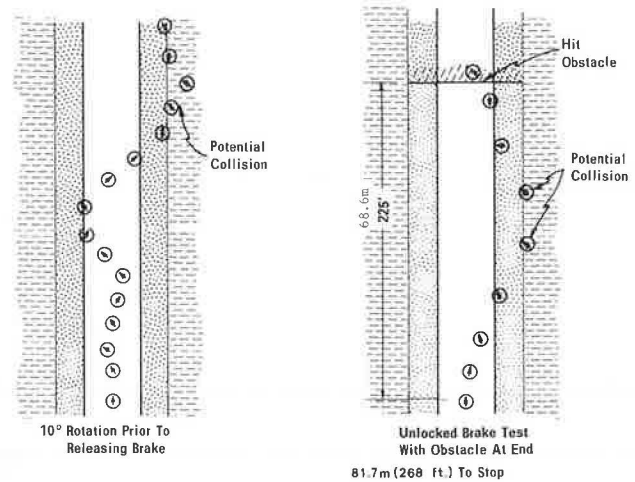


Figure 12. Differential flushing or bleeding.



Figure 13. Chip or slurry seal occupying only a portion of a lane.



possible accident zone. The car was basically uncontrollable after rotating 30 deg or more. When an obstacle was placed in the road, the driver avoided it at 64.4 km/h (40 mph); however, to do this, the car moved into the collision zone and spun out of control. When the obstacle was removed and the driver was given unlimited stopping distance, the driver was still unable to prevent the car from spinning out of control and entering the collision zone.

Figure 11 shows the results of the 80.5-km/h (50-mph) tests. In this case, the driver was unable to control the vehicle after 10-deg 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 affect the control of a braking vehicle and produce a potentially hazardous condition that 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 is, the more uncontrollable the vehicle is. After passing 90 deg, the car will actually be propelled rearward if the brakes are released.

If the driver keeps the brakes locked, the car will slide straight ahead and spin about its center of gravity or front wheels. Unfortunately, the average driver is not conditioned to do this. It is the tendency of the average driver to be confused by the rotation and possibly release the brake after spinning approximately 30 deg. If the vehicle is still moving, this is an extremely dangerous thing to do.

From our tests, it can be generally concluded that, if the differential friction causes a vehicle to rotate more than approximately 25 deg while it is still sliding at a speed greater than 24.14 km/h (15 mph), the driver may not be able to prevent the vehicle from entering the collision zone if the brakes are unlocked. Because there are numerous combinations of speeds and differential friction levels that will produce this condition, it is evident that differential friction can indeed be a potential hazard to the driving public. It is estimated that, when braking, a major loss of control may occur if the differential friction surface produces total rotations greater than those listed in the following tabulation (1 km/h = 0.621 mph):

Speed at Which Wheels Are Locked (km/h)	Total Rotation After Car Has Stopped (deg)
48.3	30
64.4	50
80.5	70

As the total rotation increases above these values, the potential loss of control is drastically increased.

Our tests were performed under theoretically controlled conditions in which the driver was familiar with the surface. Even under these conditions, the tests were hazardous at speeds in excess of 48.3 km/h (30 mph), and thus only one site was thoroughly investigated. Spot testing at other locations confirmed that this site was representative of the results that could be expected. It is unfortunate that at some locations the driving public may be faced with such conditions at speeds of 88.5 km/h (55 mph) or more. There is a strong indication that differential friction may be as important as low friction level in causing wet pavement accidents. If so, a major reevaluation of current pavement friction evaluation, design, and corrective techniques may be necessary.

CAUSES OF DIFFERENTIAL FRICTION

There are numerous causes of differential friction. Some are created or induced by construction practices, others by maintenance techniques. Most are initiated or compounded by exposure to traffic.

It should be remembered that friction is a force generated at the tire-pavement interface. For this reason, both the pavement and the tires, as well as the vehicle dynamics, greatly affect the coefficient of friction. It follows that vehicle dynamics and tires may cause differential friction even though the pavement may have a uniform friction level. Because this report is primarily interested in the effects of highway surfaces, only differential friction caused by the pavement surface will be considered here.

The following sections give information on the most commonly found differential wheel-path friction conditions. There are numerous other causes of differential friction that will not be mentioned here. Most of the causes of differential friction need not occur and can be avoided if proper consideration is given to this phenomenon.

Differential Flushing or Bleeding

Differential flushing or bleeding (Figure 12) is created when a portion of the lane is flushing or bleeding while the rest is not. Such a condition can also occur when full-lane-width repairs are not made.

Unequal Wear or Flushing

Unequal wear or flushing, like differential flushing or bleeding, may be caused when the contact of two asphalt ribbons falls inside one travel lane. Unlike the cause of differential flushing or bleeding, however, the main contributor to the condition is traffic. If the two ribbons are not alike or are polished at different rates, vehicles riding in the lane will experience differential friction. An unequal transverse distribution of traffic in very wide lanes can also cause this problem because truck and passenger car traffic may ride on different portions of the lane and cause differential wear.

Chip or Slurry Seals

When a chip or slurry seal is placed across only a portion of the lane width (Figure 13) a major differential friction condition may exist. Maintenance forces may create such a problem while attempting to reduce costs; however, it only creates a more expensive and hazardous condition. This problem is greatly magnified if the seal bleeds.

Dissimilar Shoulder Surfacing

When a distress or shoulder lane has a dissimilar surface texture different from the travel lane (Figure 14), a differential friction condition may exist. An example of this may be the use of a chip seal shoulder and an AC travel lane or an AC shoulder and a concrete travel lane. A recent preliminary report (5) has shown that 65 percent of truck traffic may ride with one wheel on the shoulder. This indicates that differential friction should be of concern.

Maintenance Crack Patching

Maintenance crack patching can be a major problem when the rate of crack patching in one wheel track is much greater than in the other (Figure 15). When this problem

exists, it is almost impossible to cure without major corrective action.

Unequal Drainage Properties

When surface drainage characteristics are different, a differential friction condition may exist (Figure 16). An example of this might be a chip seal in combination with an AC surface.

Unequal Water Layer Thickness

Unequal water layer thickness or ponding can be caused by improper geometrics or low spots in a highway. Because this situation may cause only one side of a car to hydroplane, an extreme differential friction may be created even though there is uniformity in the surface. This condition can also occur when only a portion of the pavement is wet, as in the case of roadside sprinklers

Figure 14. PCC pavement travel lane with AC distress lane.



Figure 15. Maintenance crack patching.



Figure 16. Unequal drainage properties.



that spray onto the highway.

PREVENTION OF DIFFERENTIAL FRICTION

Differential friction can be avoided if the problem is considered during construction and maintenance operations.

During construction, ribbons should be placed so that all longitudinal joints fall on the outside of the lane at or very near the location of the lane stripe. The shoulder and distress lanes should also be of the same type of surface as that used for the travel lanes. The use of a chip seal shoulder with an AC travel lane or an AC shoulder with PCC pavement travel lane may cause differential friction and should be avoided if possible.

During maintenance operations, it is imperative that most operations be uniform across the full width of the lane. The application of any corrective action for only a portion of the lane width should be avoided when possible. Heavy crack patching or maintenance operations in only one wheel track will cause a differential friction condition that is not easily corrected.

The problem of differential friction is corrected when both wheel paths have similar coefficients of friction. This is not difficult to achieve if the underlying variables are understood. If they are not, then there is little hope for correcting or eliminating the differential friction problem. In fact, there is a good chance that such problems will be inadvertently created by many highway operations.

CONCLUSIONS AND RECOMMENDATIONS

Differential friction can cause an extremely hazardous condition for a braking vehicle. Because the problem can occur at high as well as low friction levels, it should be given major consideration in any pavement friction evaluation.

There is a strong indication that differential friction may be as important as low friction in causing wet pavement accidents. If this is the case, a major reevaluation of current pavement friction evaluation, design, and corrective techniques may be necessary.

For any particular combination of differential friction number and speed, the number of degrees of rotation can be calculated by equations given in this paper. Thus the magnitude of the problem can be predicted by means of normal skid testing techniques without the hazards of actual vehicle rotation tests.

When riding on a differential friction surface, the greatest problem arises when the driver releases the brakes after the car has begun to spin. When this is done, the vehicle is propelled in the direction that it is facing. This could be off the road or into oncoming traffic. The greater the degree of rotation is, the more uncontrollable the vehicle is.

Surface friction inventories made in only one wheel track may not detect this problem unless visual observations are recorded. Although one or both wheel paths may have a high friction level, a hazardous condition for a braking vehicle may be caused if they are unequal.

There are numerous causes of differential friction, most of which can be avoided during construction, design, and maintenance operations. Because maintenance operations may be the largest contributor to this problem, it is hoped that, in the future, the maintenance engineer as well as other highway engineers will give more consideration to this problem and its correction. This paper outlines some of the major causes and corrective techniques that need to be considered with this problem.

ACKNOWLEDGMENT

The contents of this paper reflect my views. I am 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.

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