wheels of the car so as to keep its revolutions per minute as low as possible.

The design of American cars over the past years has been toward improvement in economy and performance, which requires powerful engines; in the package with this comes some increase in top speed.

In the future we can expect further improvements in economy by wider use of the new high-compression engines and further improvement in fuels. Some improvement in performance will probably be made, although at the lower speeds, especially with modern high-compression engines and automatic transmissions, the ultimate has been about reached. This ultimate, of course, is the point at which the coefficient of friction between the drive wheels and a dry pavement is insufficient to keep the wheels from spinning under full acceleration.

Braking Distances of Vehicles from High Speeds

O. K. Normann, *Chief*

Traffic Operations Section, Bureau of Public Roads

Braking distances were measured for 53 passenger cars making stops from speeds ranging from 20 to 90 mph. on a concrete surface. The average distances traveled after the brakes had been applied were 22 ft. from a speed of 20 mph., 130 ft. from 50 mph., and 585 ft. from 90 mph. Some of the passenger cars required more than 600 ft. to stop from 75 mph.

During the tests, information was obtained on the acceleration rates of passenger cars, the reaction time of drivers, and the effect of brake fade or the temporary reduction of brake effectiveness resulting from heat.

In an effort to relate the braking distances of the vehicles to the coefficient of friction between the tires and the road surface, equipment was developed to measure coefficients of friction of road surfaces. Comparisons were obtained for different types of road surfaces when dry and wet and for different tires. It was found, for example, that some surfaces which had the highest friction coefficients when dry had the lowest coefficients when wet. It was also found that two sets of tires which had identical tread patterns and consisted of the same rubber compound could cause a difference of 30 percent in braking distances.

● IN December 1940, the late Ernest E. Wilson, who was at that time director of the General Motors Proving Ground, reported the results of tests to determine deceleration distances for high-speed vehicles. He used 15 passenger cars in perfect condition and eight highly experienced test drivers to obtain braking distances for speeds ranging from 50 to 70 mph. Since 1940, about 35 million passenger cars have been built in the United States, but few if any results of tests to determine braking distances from high speeds have been reported. There have been numerous reports for tests made from speeds of 20 to 40 mph., but passenger cars are now being operated at an average speed of about 52 mph. on our main rural highways, with about 12 percent exceeding 60 mph., and an occasional vehicle traveling in excess of 80 mph.

One possible reason that more high-speed tests have not been conducted is the common assumption that any passenger car with brakes in good condition can lock all four wheels and that shorter stopping distances can be realized only through improving the texture of road surfaces to obtain higher coefficients of friction, especially for wet surfaces, and by avoiding the use of tires that have worn smooth.

Although a more critical skidding condition usually exists when a surface is wet than when dry, about three out of four fatal accidents and two out of three of all accidents occur on dry surfaces. Many of these, no doubt, could have been avoided if the drivers had been able to stop a little sooner.

STOPS FROM 90 MPH.

To obtain current information on braking distances from high speeds, the Bureau of Public Roads conducted a series of tests on 53 vehicles including 10 of the most common makes. Twelve of the cars were government vehicles owned by the Bureau of Public Roads. The other 41 were private cars owned by employees of the Bureau of Public Roads who

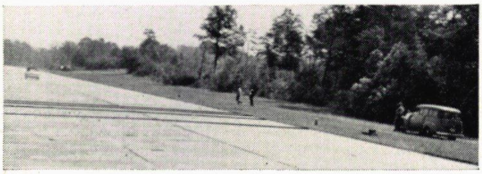

Figure 1. Brake-test location.

volunteered to participate in the tests. Each vehicle was driven during the test by the person who normally operated the vehicle.

Stops similar to those that would have been made in an emergency were made by all the drivers from speeds of 20 and 40 mph. Most drivers also made emergency stops from 60 mph., and the drivers of the government vehicles and some of the private cars made stops from the highest attainable speed, which was generally over 70 mph. Data were obtained for a total of 214 stops, including 14 at speeds exceeding 75 mph. and 7 at 90 mph.

The tests were conducted on a concrete taxiway 6,500 ft. long and 50 ft. wide at Andrews Air Force Base (Fig. 1). The surface had a broomed finish and was free of oil drippings since it had been used very little. About 2,000 ft. from the end of the taxiway, a rubber tube with an air-switch on one end was stretched across the surface. As the front wheels of a vehicle passed over this tube, a solenoid was actuated which turned on a brilliant light 700 ft. away on the right-hand side of the surface. This light acted as a signal to inform the driver to apply his brakes as quickly as possible. Immediately ahead of the tube which actuated the light were three other tubes connected to a recording speedmeter located in a panel truck parked at one side of the surface. Accurate speeds could thus be obtained immediately prior to the brake application for vehicles traveling within the range of 15 to 100 mph.

Figure 2. Mounting detonator on vehicle.

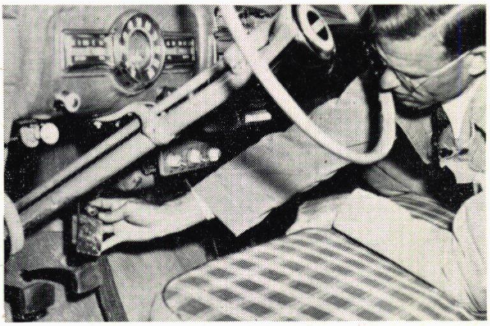

Figure 3. Installing switch on brake pedal.

Each vehicle to be tested was equipped with a detonator mounted on the front bumper (Fig. 2) and actuated electrically through a switch on the brake pedal (Fig. 3). When the brake pedal was touched, the detonator fired a .22-cal. cartridge, and a capsule filled with yellow pigment left a yellow mark 5 in. in diameter on the pavement to indicate the point at which the brakes were first applied. The distance between the tube which actuated the light and the yellow mark was the distance

traveled during the driver's reaction time, whereas the distance between the yellow mark and the point where the vehicle came to a stop was the braking distance. Measurements were made by use of a scale marked directly on the concrete surface.

Prior to testing each vehicle, the following information was recorded: (1) year model and make of vehicle, (2) present mileage on vehicle, (3) mileage when brakes were last relined or adjusted, (4) distance between floor boards and brake pedal when depressed, (5) condition of tires, and (6) name and age of driver.

During each brake test, observers stationed along the taxiway noted whether any wheels skidded and, if so, which wheels locked. The

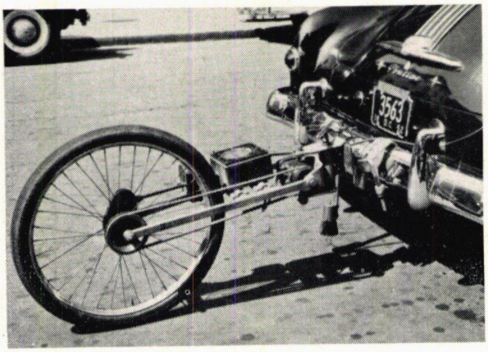

Figure 4. Fifth wheel used to obtain time-distance curves.

drivers were requested to have their vehicles in high gear before reaching 20 mph., to accelerate as fast as possible to the predetermined braking speed, to continue at that speed until they saw the spotlight illuminated, and then to come to a stop as quickly as possible. No instructions were given the drivers regarding use of the clutch pedal and no observations were made as to when the clutch pedal was depressed during the stops.

An observer in the vehicle noted the time required to accelerate to various speeds and the speedometer reading immediately before the brakes were applied. The recorded speedometer readings were later adjusted to conform with actual speeds. The observer also kept the driver informed of the speedometer reading so that the driver could keep his eyes trained on the road and spotlight. After the test, the observer questioned the driver as to whether he considered the stop a comfortable one, whether he thought the stop could have been made in a shorter distance, and whether he applied his maximum force to the brake pedal during the stop. The observer also measured the distance between the floor board and the depressed brake pedal.

PERFORMANCE OF TEST VEHICLES

The 53 vehicles used for the high-speed brake tests were not all new vehicles. There were 12 that were new and 3 that were 10 years old. The average age of the 53 test vehicles was 3.4 years, compared with an average age of 7 years for all passenger cars

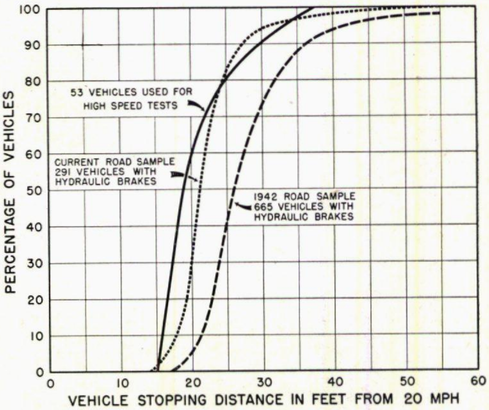

Figure 5. Stopping distances for various groups of vehicles sampled.

registered in the United States during 1951. All of the drivers participating in the test considered their brakes in good condition, and it will be shown that the vehicles participating in the brake tests could be stopped from a speed of 20 mph. in shorter distances than the average vehicle being operated on public highways.

Comparisons of stopping distances from a speed of 20 mph. for the 53 vehicles used in the high-speed tests with corresponding values for vehicles included in other comprehensive studies are shown by Figure 5. The results for the 1942 road sample and the current road sample were obtained by conducting brake tests on vehicles selected at random from everyday traffic on main rural highways. Each vehicle selected at random was subjected to

three or more emergency stops from 20 mph. on dry concrete pavements.

It may be noted from Figure 5 that there has been a substantial improvement since 1942 in the brake performance of vehicles in operation on our highways. In 1942, only 40 percent could be stopped in less than 25 ft. and 13 percent required more than 35 ft. Today, 83 percent can be stopped in 25 ft. and only 3 percent require more than 35 ft. There are still, however, some vehicles being operated on our highways while the brakes are in such a poor condition that they cannot be stopped from 20 mph. in 60 ft., more than four times the distance required for some vehicles.

None of the vehicles used for the high-speed tests required more than 37 ft. to stop from 20 mph. On an average, they showed somewhat better brake performance from 20 mph. than those selected for the current road sample. This was to be expected, since most of the drivers who volunteered for the high-speed tests thought, no doubt, that they and their vehicles would perform as well or better than average. Most of the drivers undoubtedly volunteered because they were willing to spend some time and money in helping to obtain useful facts relating to one of the most necessary elements of highway safety—the ability of vehicles to stop from high speeds. It is doubtful, however, that any one of the drivers would have participated in the test had he known that his performance would have been the worst of the lot.

ACCELERATION RATES

Before discussing the more involved results of the brake-performance tests, it seems desirable to dispose of a few of the results of these tests that may be termed "byproducts." These relate to the acceleration rates of passenger cars, reaction times of drivers, and accuracy of speedometers. Figures 6, 7, and 8 relate to the acceleration rates of passenger cars. In these figures, the passenger cars have been classified into three groups. The first group, or Group A, includes all of the vehicles tested. Group B includes only the vehicles that reached a top speed of about 80 mph. on the test course, and Group C includes only the vehicles that reached a top speed of 90 mph. on the test course.

Figure 6 shows the total time to accelerate to any given speed from a speed of 20 mph. in high gear. It is also possible to determine by subtraction the time to accelerate from a given speed to any higher speed within the range of the chart. The vehicles capable of a 90 mph. speed could accelerate from 20 to nearly 70 mph. in approximately the same time as they required to accelerate from 70 to 90 mph. They

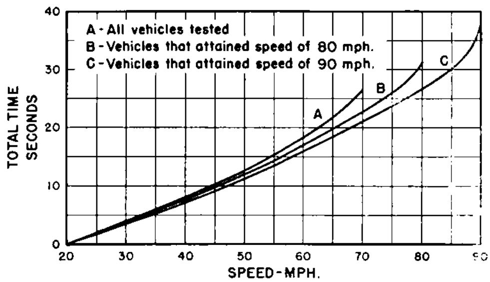

Figure 6. Time to accelerate from 20 mph. in high gear.

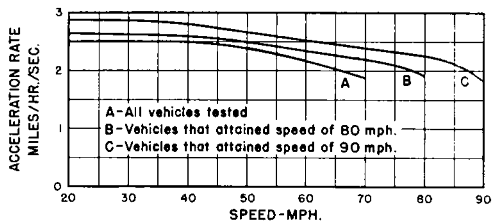

Figure 7. Average acceleration rate from 20 mph.

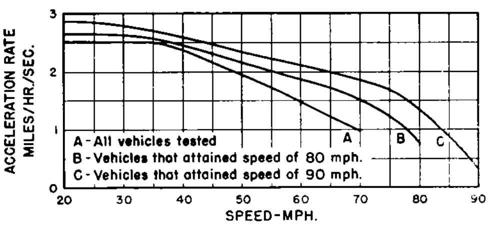

Figure 8. Instantaneous acceleration rates at various speeds.

traveled an average of 1,450 ft. in going from 20 to 70 mph., and 1,850 ft. in going from 70 to 90 mph.

The average acceleration rates while increasing from a speed of 20 mph. to a higher speed are shown by Figure 7. The average rate of acceleration decreases as the speed increases, although the difference is slight between 20 and 40 mph.

The instantaneous acceleration rates at various speeds are shown by Figure 8. The

average vehicle had an acceleration rate of 2.5 mph. per sec. at speeds between 20 and 35 mph., whereas the vehicles that could reach 90 mph. had a maximum instantaneous acceleration rate of 2.8 mph. per sec. at a speed of 20 mph. Rates of 2.5 and 2.8 mph. per sec. are equivalent to 3.7 and 4.1 ft. per sec. per sec., respectively. As the speed approaches the top speed of a car, the acceleration rate approaches zero. From the curves of Figure 8 it appears that the cars which reached a speed of 90 mph. could have eventually reached about 92 mph., and those that reached a speed of 80 mph. could eventually have increased their speeds to 85 mph.

Information regarding the acceleration rates of passenger cars is used in connection with many highway-design problems relating to traffic operations. In recent years the principal source of such information has been the results obtained for six passenger cars tested in 1938. The results for the 53 cars in current use indicate that acceleration rates at the present time are 20 to 30 percent higher than for the six cars tested in 1938.

REACTION TIME OF DRIVERS

The measurements of driver-reaction time and distance that were made during the braking-distance tests from high speeds may be considered as absolute minimums. Each driver was aware of the approximate time that the stop was to be made and was poised for the occasion. Only the reaction time for the initial test run of each driver has been used for this analysis. During subsequent tests, several of the drivers anticipated the time that the signal light would be illuminated and had removed their foot from the accelerator prior to reaching the road tube that actuated the light.

Figure 9 shows the distribution of reaction times for the 53 drivers. Some drivers reacted and moved their right feet from the accelerator to the brake pedal in 0.4 sec. One driver required 1.7 sec. Repeated tests on the drivers who had the longer reaction times gave consistent results which eliminated the possibility that these drivers misinterpreted the instructions. All except the one driver had a reaction time of less than 1 sec. for the conditions of these tests. The average reaction time was 0.73 sec. and 95 percent of the drivers reacted in less than 0.9 sec., which is consistent with the results of other studies.

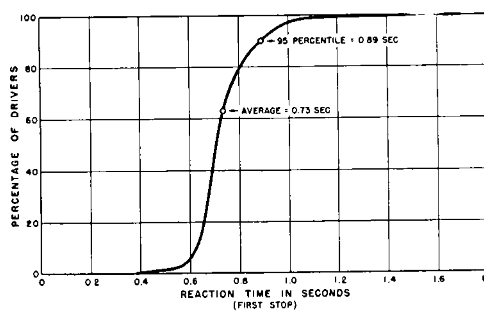

Figure 9. Reaction times during high-speed tests.

SPEEDOMETER INACCURACY

It was interesting to find that more of the speedometers were low than high when compared with the actual speeds of the vehicles. This is contrary to the common belief that speedometers have a tendency to indicate higher speeds than the actual speeds. If it is considered that a speedometer is correct when it registers within 2 mph. of the actual speed, which is as close as the readings on many of the present models can be determined, the following were the results for the 53 vehicles: (1) 19 speedometers correct to within 2 mph. at all speeds tested; (2) 6 speedometers more than 2 mph. high; and (3) 28 speedometers more than 2 mph. low.

The average error for the six speedometers that were high was 6.7 percent for speeds below 50 mph. and 6.1 percent for speeds above 50 mph. At no speed did any of these speedometers have an error of more than 10 percent.

The average error for the 28 speedometers that were low was 12.1 percent for speeds under 50 and 10.1 percent for speeds over 50 mph. Four of the speedometers were between 20 and 24 percent low at all speeds. The speedometers indicated 57 to 60 mph. when the vehicles were actually traveling 75 mph. The methods used for conducting the test eliminated the possibility that these errors resulted from a lag in the speedometers.

APPLICATION TIME AND FADING

Most of the brake tests were run without the use of a fifth wheel by merely measuring

the distance between the chalk mark on the pavement indicating the point where the operator touched the brake pedal to the point where the car came to rest. In a few of the tests, however, a fifth wheel and chronograph were mounted on the test vehicle to obtain a time–distance record during each stop. From the time–distance record, deceleration rates were determined. Figure 10 shows a curve representing the average rates of deceleration during two stops from 30 mph. by one vehicle. In the one case, the stopping distance was 48 ft., and in the other it was 50 ft.

Figure 10 shows that the deceleration rate reached 22 ft. per sec. per sec. within 0.6 of a second after the operator touched the brake pedal. It is not known whether there was any deceleration within the first 0.1 sec., but after 0.2 sec. had elapsed, the vehicle was decelerating at a rate of 15 ft. per sec. per sec. After 0.6 sec. there was only a very slight increase in the deceleration rate until the vehicle came to a stop.

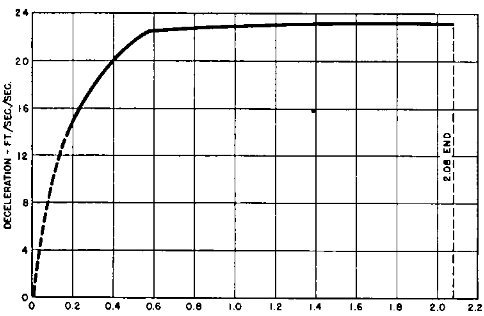

Figure 10. Deceleration rates during stop from 30 mph. (average of two tests).

During several of the stops from high speeds, the brakes seemed to fade shortly after being applied, making it appear as though the vehicle had very poor brakes. Brake fade may be defined as a temporary reduction in brake effectiveness resulting from heat. In such a case, the distance traveled to bring the vehicle to a stop after its speed had been reduced to 30 mph. seemed exceptionally long. In fact, one driver thought his brakes were not functioning during the latter part of a stop from 60 mph. Fading usually did not appear to be pronounced during stops below 70 mph., except when several stops were made within a few minutes without giving the brake drums time to cool between the brake applications. The general procedure for these tests was to allow the brakes time to cool between successive applications.

The distances required to bring a particular vehicle to a stop from a speed of 30 mph. when the initial speed was 30 mph. in one case and 80 mph. in two other cases are shown by Figure 11. The one stop from an initial speed of 80 mph. was made in 400 ft., the shortest distance in five tries, whereas the other stop from 80 mph. was made in 564 ft., the longest distance in five tries. None of the wheels locked during any of the three stops illustrated by Figure 11, although the operator applied the maximum force possible to the brake pedal in each instance.

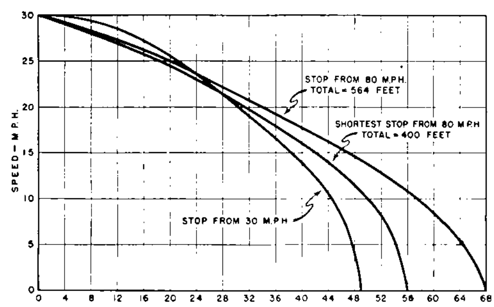

Figure 11. Braking distance from 30 mph.; initial speed 30 and 80 mph.

The speed-distance curve of Figure 11 for the stop from an initial speed of 30 mph. is the average data for the same stops as those illustrated by Figure 10. The curve shows that at the beginning of these stops, there was a decrease in speed of only 1 mph. during the first 8 ft. of travel. Shortly thereafter, the vehicle's speed decreased about 1 mph. for each 1.6 ft. of travel, and immediately before coming to a stop the speed decreased 4 mph. while the vehicle traveled about 1 ft.

With an initial speed of 80 mph., the vehicle was decelerating a little less than 1 mph. for each 4 ft. of travel while going 30 mph. During the remainder of the two stops, the speed decreased at a much lower rate for the same travel distance than during the stop made from an initial speed of 30 mph.

One of the stops made from an initial

speed of 80 mph. required 68 ft. to bring the vehicle to a stop after the speed was reduced to 30 mph., while in the other case the corresponding distance was 56 ft. The difference between these two distances and the 49 ft. required for an initial speed of 30 mph. may be attributed to brake fade. In the one case the difference was 19 ft., or 39 percent of the normal stopping distance for this vehicle from 30 mph.

The tests on which the information in Figure 11 was based were by no means the worst examples of fade that occurred during the series of tests. They were the only high-speed tests for which this type of data were obtained and have been presented to illustrate one reason that stopping distances do not vary exactly as the square of the speed.

VARIATION IN BRAKE PERFORMANCE

Under identical conditions, brake performance at high speeds was not always the same. The variation in braking distances for one vehicle with the same driver on the same surface is illustrated by the data shown in Figure 12 and Table 1. The figure shows the stopping distances from various speeds for this one vehicle as small circles and the average stopping distances for all vehicles as a dashed curve.

It may be seen from Figure 12 that the results for this one vehicle, which was subjected to more tests than any other vehicle, compare favorably with the average values. Fading of the brakes was especially pronounced during the three stops above the average line for speeds in the neighborhood of 80 mph. and during the two stops above the line at 90 mph. These stops required considerably longer distances than other stops made by the same vehicle at corresponding speeds.

Table 1 contains the same information as Figure 12 with a record of the skid marks made by the vehicle. It must be remembered that during all of these tests, except Nos. 9 and 19, the driver applied the maximum possible pressure to the brake pedal over the entire stopping distance. In some instances the wheels locked, leaving skid marks for all four wheels. In other instances none of the wheels locked. During some of the stops when the wheels did not lock, they were evidently not turning as fast as the car was traveling because light skid marks or tire traces were plainly visible, generally outlining the edges of the tire tread.

During the nine tests from speeds above 75 mph., it was possible to lock the wheels only twice (Tests 10 and 19). During Test 9, an attempt was made to eliminate brake fade by fanning the brakes (removing all pressure from the brake pedal occasionally), but this apparently was not effective in reducing the total braking distance.

The results for Tests 18 and 19 (Table 1) are especially significant. For both of these stops which were made from approximately the same speed, the braking distance was 400 ft. Test 18 was a very comfortable stop, whereas the stop made during Test 19 was the most dangerous one of the entire series.

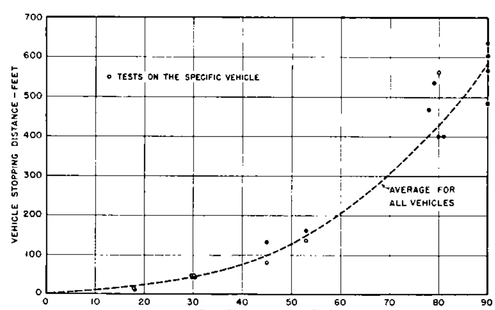

Figure 12. Results of brake tests made on one specific vehicle as compared to all vehicles.

During Test 19, all four wheels locked 31 ft. beyond the point where the brakes were applied, the vehicle skidded for 151 ft., where it struck a construction joint in the pavement and dived to the adjacent lane, at which time the brakes were released sufficiently to allow the wheels to turn. The vehicle then traveled 118 ft. with the wheels turning and then skidded 100 ft. to a stop. The tires were so badly worn on one side as a result of this one stop that all four had to be replaced to eliminate a pronounced bumping as the vehicle was driven over a smooth surface.

The braking characteristics experienced during the 19 tests on this one vehicle indicate that if the wheels do not lock immediately after full pressure is applied, they cannot be locked at all.

There evidently is enough heat developed with full brake pressure and the wheels turning that fading soon takes place, especially at the higher speeds, and much longer stopping dis-

TABLE 1
RESULTS OF BRAKING-DISTANCE TESTS

Test No.	Initial Speed	Braking Distance	Skid Marks	Run No.	Initial Speed	Braking Distance	Skid Marks
	mph.	*ft.*			*mph.*	*ft.*	
1	18	14	4 wheels	13	79	540	None
6	19	14	4 wheels	14[a]	78	468	None
				15[a]	80	564	None
16	30	48	None	18[a]	80	400	Light[c]
12	30	45	4 wheels	19[a]	81	400	4 wheels[d]
11	30	46	Light				
17[a]	30	50	Light	4	90	608	None
				5	90	569	None
2	45	80	4 wheels	10	90	482	4 wheels[b]
3	45	133	None	9	90	640	None[e]
7	53	137	4 wheels[b]				
8	53	162	None				

[a] Different brake lining than in rest of tests.
[b] Vehicle made a sharp dive.
[c] Very smooth stop.
[d] Four wheels locked for 251 ft.
[e] Attempt made to fan brakes.

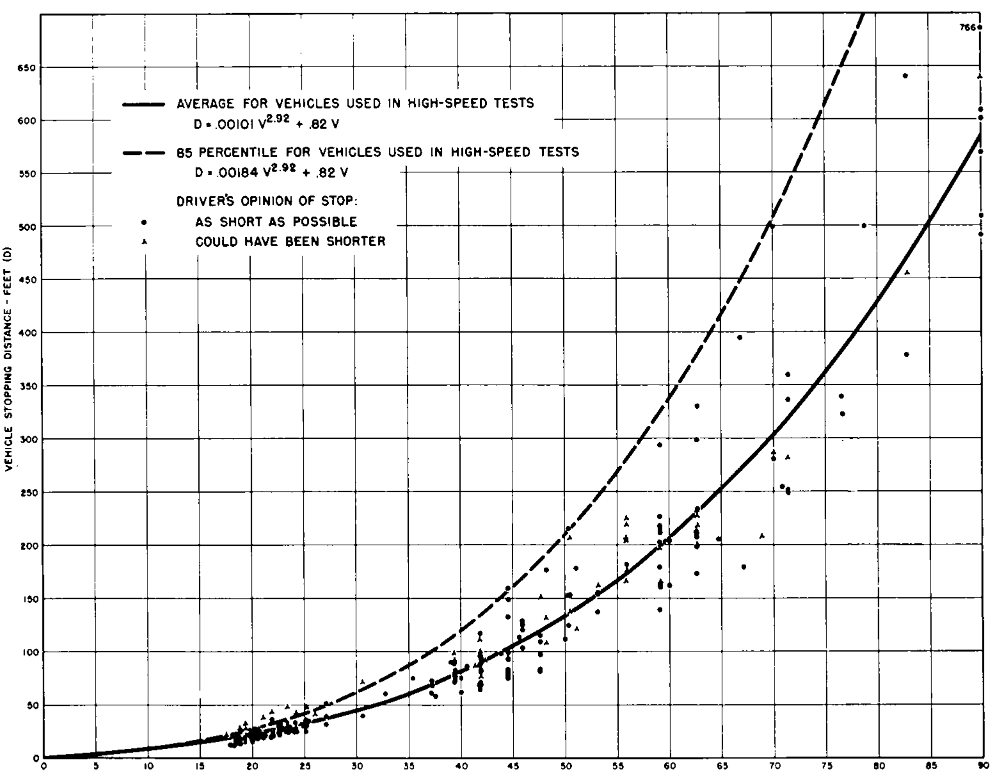

Figure 13. Braking distances during high-speed tests.

tances result than when the wheels lock. Whether or not it will be possible to lock the wheels at high speeds is unpredictable on a dry concrete surface of the type where these tests were conducted. Stops from high speeds with the wheels locked are, of course, dangerous

from a viewpoint of maintaining control of the path of the vehicle. In an emergency, however, bringing the vehicle to a stop in the shortest distance possible may be more important than the exact path of the vehicle. Even with the most careful and experienced drivers, such situations do arise.

The braking distance and initial speed recorded for each test conducted on all the vehicles are shown by Figure 13. In an attempt to determine the reason for the comparatively wide scatter of the points, the tests for which the drivers stated that they made the stop as fast as possible have been shown as dots, whereas, the small triangular points represent tests for which the driver stated that he thought the stop could have been made in a shorter distance.

TABLE 2
STOPPING DISTANCE RELATED TO DRIVER OPINION OF PERFORMANCE

Initial Speed	Stopping Distance	
	Stop made as fast as possible	Stop *not* made as fast as possible
mph.	*ft.*	*ft.*
22	25	34
40	86	90
50	126	146
60	210	206
70	311	259
80	464	357

It should be noted that Figure 13 shows a fairly even distribution of both types of points on both sides of the average curve. In fact, when the stopping distances that the drivers thought were not as short as possible were compared with those they thought were the shortest possible, it becomes evident that the driver's opinion is of little value (see Table 2).

LOCKING OF WHEELS

For speeds of 50 mph. or less, the braking distances for the stops made as fast as possible are slightly shorter than for the stops not made as fast as possible. For speeds above 50 mph., the reverse is true, and the difference is more pronounced.

It is also interesting to compare the drivers' opinions as to whether or not the stops could be considered comfortable with the actual braking distances. Invariably the more-comfortable stops were made in the shorter distances, even when stops by the same driver-vehicle combination were compared. Within the range of these studies, it is evident that other factors have a greater influence than the average deceleration rate on the comfort characteristics of the stop. Based on the opinion of the observer who rode with the driver on each test, the most uncomfortable stops, or those most likely to throw an occupant against the windshield or dashboard, were the stops made from the lowest speed of 20 mph. At high speeds, the brakes are evidently not capable of overcoming the angular momentum of the wheels and other revolving parts of the vehicle at a fast enough rate to cause a sudden and great change in the speed of a vehicle.

Using data for the tests in which the drivers applied the maximum brake pressures they could develop, it was found that no wheels locked in 42 percent of the tests, all wheels locked in 30 percent, and one or two wheels, generally the rear wheels, locked in 28 percent of the tests. Wheels were more apt to lock at the lower speeds than at the higher speeds. At speeds of 20 mph., all four wheels locked in 35 percent of the tests, whereas at speeds exceeding 60 mph. the corresponding figure was only 19 percent. The common assumption that any passenger car with brakes in good condition is capable of locking all four wheels may be questioned. This may hold true for certain drivers on all types of surfaces or for all drivers on certain surfaces, but not for all drivers on all surfaces. The concrete surface on the taxiway had a higher coefficient of friction than the surface of any highway on which tests were made in connection with this investigation. A dangerous condition would exist, however, if manufacturers provided brakes that would grab or lock the wheels too easily.

BRAKING DISTANCE INCREASES FASTER THAN SQUARE OF SPEED

The braking distance does not vary as the square of the speed. For example, the average stop from 30 mph. was made in 40 ft. With the braking distance varying as the square of the speed, a stop from 90 mph. would require only 360 ft., whereas the average stop from 90 mph. actually required 580 ft. Not one of the stops from 90 mph. was made in 360 ft. The shortest distance was 490 ft.

There are several reasons that the braking distances do not vary as the square of the

speed. The effects of brake fade have already been discussed. Likewise, it has been shown that full deceleration does not start immediately when the brake pedal is touched. It takes some time to depress the pedal as far as it will go and some additional time for the brake fluid to expand the brake shoes through the wheel cylinders. Other factors also affect the brake distance. While it is true that the kinetic energy of the vehicle in the direction it is traveling varies as the square of the speed, the rate at which brakes can absorb this energy and the additional angular kinetic energy in the wheels and other rotating parts is apparently limited.

The relation between speed and braking distance as obtained by these tests is shown by Figure 13. The upper curve shows the 85-percentile stopping distances. The equation for the lower curve is

$$D = 0.00101V^{2.92} + 0.82V$$

where D is the average stopping distance in feet and V is the speed in miles per hour.

The numbers in this equation were obtained by assuming that the equation should have the form $D = aV^b + cV$. They were determined so as to minimize the sum of the squared deviations of the plotted points from the curve. The second term on the right-hand side of the equation represents the distance traveled during actions taking a constant length of time, such as the time to depress the brake pedal and the time required for the brake cylinders to expand the brake shoes. This equation fits the data better than any other type of equation investigated and far better than one based on the assumption that braking distances vary as the square of the speed.

The 85-percentile curve shows that the distance within which 85 stops out of 100 can be made and not the distance within which 85 percent of the vehicles can always stop. It has been based on observed data up to a speed of 40 mph. Above 40 mph. there were so few tests that the 85-percentile curve has been based on sound statistical procedures assuming that the second term, $0.82V$, which consists largely of brake-application distance, and the exponent in the first term would be the same as for the average curve. It was also known that most of the vehicles with poor brake performance at the lower speeds were not tested at the higher speeds. In fact, only 3 of the 11 vehicles that required more than the 85-percentile distance to stop from a speed of 20 mph. participated in the tests at speeds above 40 mph. Also, an analysis of the stopping distances of the vehicles that did participate at the high speeds shows a marked tendency for those having the longer stopping distances at the lower speeds to have also the longer stopping distances at higher speeds. The portion of the 85-percentile curve above 40 mph. therefore represents the best estimate that can be made on a basis of these tests, even though few of the points represent stopping distances longer than the 85-percentile values.

Equations that are somewhat easier to solve and give approximately the same results as the equations shown in Figure 13 are as follows for the average and 85-percentile curves, respectively, with D and V being in the same units as for the exact equations:

$$D = 0.00069V^3 + V$$
$$D = 0.00126V^3 + V$$

An appreciation of the effect of speed on the distance required to stop a passenger car may be obtained from Figure 14. The 1-sec. perception time and the other second for reaction time are certainly minimum values for drivers under actual operating conditions, except under congested traffic conditions when the time required by a driver to perceive the illumination of the stop light on a preceding vehicle might possibly be somewhat less than 1 sec. Considering the conditions under which these data were obtained, the driver stopping distances shown in Figure 14 can be considered as absolute minimums for use in determining standards of design for safe highways. If any safety factor is applied, longer driver stopping distances must be used. For certain elements of design, the average values might be applicable, but generally safe conditions will not be attained unless driver stopping distances at least as high as the 85-percentile values are used.

Some surfaces when dry do not have as high a coefficient of friction as a concrete surface, and no road surface included in these tests had as high a coefficient of friction when wet as a dry concrete surface. The 85-percentile values for the stopping distance as shown by Figure 14 are applicable to all road

surfaces, however, where the coefficient of friction that can be developed between the tires and the road surface is equal to or greater than the lowest equivalent coefficient of friction utilized in these tests by the vehicles in making 85 percent of the stops.

The average coefficients of friction utilized by the vehicles over their entire braking distances on the dry concrete surface are shown by Figure 15. These averages were calculated by use of the equation $d = V^2/30f$ where d is the braking distance in feet, V is the initial speed in miles per hour, and f is the average coefficient of friction developed between the tires and the road surface over the entire braking distance. Since the braking distance

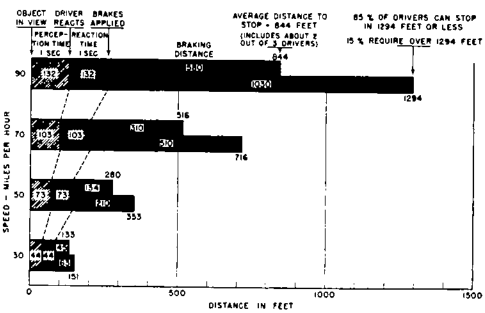

Figure 14. Driver stopping distance on dry concrete.

includes the distance traveled during the brake application time, the average utilized coefficient of friction increases as the speed increases from 20 to 30 mph. because the brake application distance becomes an increasingly smaller portion of the total braking distance.

While making stops from 20 mph., there was at least one vehicle that utilized an average coefficient of friction of 0.88 over its braking distance. The average coefficient of friction utilized by the average vehicle was 0.65, and the vehicles that required the 85-percentile braking distance utilized an average coefficient of 0.48. Likewise, the corresponding coefficients of friction that were utilized for the stops from 90 mph. were 0.57, 0.46, and 0.26, respectively. The maximum friction coefficient during any one stop is always greater than the average for the entire braking distance. For example, during the stop from 30 mph., as shown in Figure 11, the vehicle could have stopped in the 49 ft. if a coefficient of friction of 0.61 had been utilized over the entire distance, calculated on the same basis as the curves of Figure 15. Actually, however, the maximum coefficient of friction developed during this same stop was 0.72, since the maximum deceleration rate was 23.2 ft. per sec. per sec. as shown by Figure 10. It is evident, therefore, that coefficients of friction greater than the average values shown in Figure 15 were developed between the tires and the road surface during the braking-distance tests.

In an effort to determine the actual coefficient of friction of the taxiway surface and to compare this value with the coefficients utilized by the vehicles in braking, equipment was developed to measure friction coefficients of road surfaces. This equipment and other

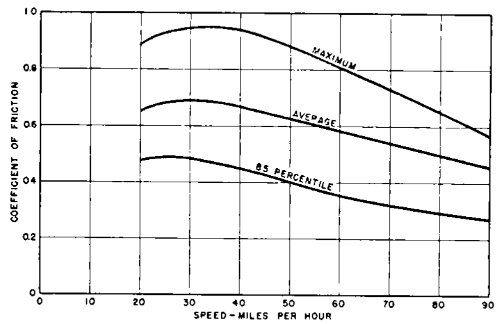

Figure 15. Average utilized friction coefficient while braking.

tests for which it was used will be described after the results of friction tests on the taxiway surface have been discussed.

TIRES HAVE MAJOR EFFECT ON FRICTION FACTOR AND BRAKING DISTANCE

Coefficients of friction between the taxiway surface and one particular set of tires under dry conditions were found to be as shown in the first column of Table 3. It was evident that if these were the correct coefficients of friction for the taxiway surface, it would have been impossible to make many of the stops within the distances recorded during the brake tests. Average coefficients of friction at least as high as those shown by Figure 15 were necessary to stop the vehicles within the recorded distances, excluding the braking effect of air resistance.

The only explanation for the wide discrepancy seemed to be that the tires on the

vehicle used to measure the friction coefficients were not as resistant to skidding as the tires on some of the vehicles used for the brake tests. This was confirmed by interchanging the tires on the friction-test vehicle with the tires on one of the vehicles for which short stopping distances were recorded. The coefficients of friction for the surface on the taxiway were then found to be from 23 to 33 percent higher than with the original tires. This is shown by Table 3. The coefficients were then of sufficient magnitude to account for the braking distances recorded during the high-speed tests in which high coefficients of friction were utilized.

TABLE 3
EFFECT OF TIRES ON FRICTION COEFFICIENTS

Type of Test	Coefficient of Friction	
	First set of tires	Second set of tires
Concrete surface on taxiway		
Impending slide from stopped position	0.77	0.95
Impending slide with wheels turning at slow speed	.69	.92
Sliding at slow speed	.67	.86
Impending slide at 25 mph	.57	
Sliding at 25 mph	.46	
Bituminous-concrete surface		
Impending slide at slow speed	.56	.70
Sliding at slow speed	.53	.68

Similar differences in friction coefficients between the two sets of tires were found for a bituminous surface, the results for which are included in Table 3. It was surprising to find that the tires made such a great difference, especially since both sets of tires had the same tread pattern and were fabricated from the same rubber compound (based on the manufacturers' records of the serial numbers).

The hardness to which the rubber had been cured appeared to be the only measurable difference between the physical characteristics of the two sets of tires. Had an attempt been made to find the tires that would result in the highest and lowest friction factors, the difference undoubtedly would have been much greater than the difference between the two sets that were used.

A few tests were also made on a third set of tires by towing a light pickup truck with a large, 10-wheeled wrecker. The resulting coefficients of friction were 53 percent higher than for the first set of tires and 25 percent higher than for the second set of tires. The third set of tires was one size larger and had a different tread pattern than the other two sets of tires. The rubber used in their fabrication may also have been of a different compound and cured to a different hardness than either of the other two sets of tires.

In view of these results, further study should be made to obtain conclusive answers to a number of questions directly related to highway safety. How many drivers realize when they buy a new set of tires that their stopping distances in emergencies may be 30 percent greater with one set of tires than with another set? For safety reasons, would it be equally desirable to reduce nonuniformity in tires and nonuniformity in the texture of road surfaces to improve coefficients of friction between tires and road surfaces? Also, in brake-performance tests, to what extent are coefficients of friction between the road surface and the particular set of tires being measured rather than brake performance?

The studies on the taxiway surface were to obtain some idea of the relation between friction coefficients and stopping distances. While the equipment for measuring friction coefficients was available, it appeared desirable to extend the studies to other surfaces, principally to obtain a better idea of the problems involved in programing a comprehensive study of the relation between friction coefficients and braking distances.

SPECIAL APPARATUS

To measure friction coefficients of road surfaces, a four-wheeled vehicle was towed with a cable and the towing force measured with a resistance strain-gage dynamometer. This method was selected as the most suitable one available after other methods reported for previous investigations were reviewed.

The towed vehicle used for these tests was an army jeep with a four-wheel drive, new brakes, and passenger-car tires. Two hydraulic shock absorbers were mounted on the front bumper in such a manner that they served as the front support for the tension-bar dynamometer used in conjunction with an electronic strain recorder. The shock absorbers also served to dampen vibrations and variations in the towing force imparted to the dynamometer by the cable when on rough

surfaces. The other end of the dynamometer was fastened to the bumper of the jeep with a connection that permitted the same flexibility as a universal joint. The towing force was kept parallel with the road surface at all times by a 25-ft. steel cable attached to the differential of the tow truck at the same height as the mounting on the bumper of the jeep. Figures 16 through 20 show the equipment used to measure the friction coefficients of road surfaces.

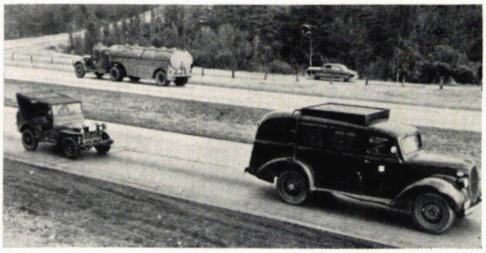

Figure 16. Towing jeep with panel truck during coefficient-of-friction tests.

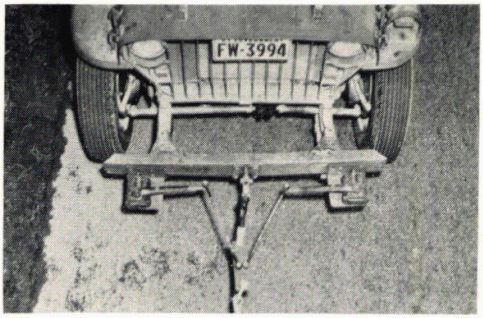

Figure 17. Dynamometer connection to towed vehicle.

A resistance strain-gage dynamometer and an electronic recorder furnished by the Naval Gun Factory were used throughout these tests. Gages were placed on the four sides of the ½-in.-square aluminum bar with a temperature control element. The unit was waterproofed to permit operation in any type of weather. The SR-4 strain recorder was fastened to shock mountings in the tow truck and connected with the dynamometer bar by insulated wires fastened to the tow cable. The calibration of the dynamometer was checked before starting and after completing the friction tests.

The three following types of friction coefficients were measured at each test location: (1) the maximum starting coefficient of friction from a stopped position; (2) the maximum

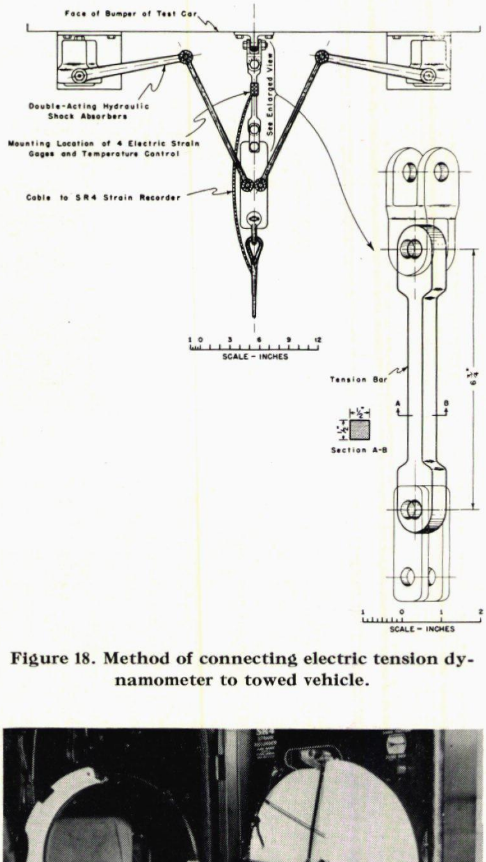

Figure 18. Method of connecting electric tension dynamometer to towed vehicle.

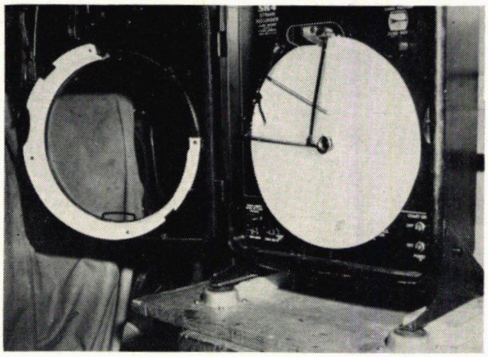

Figure 19. SR-4 recorder used to register strain on dynamometer.

impending coefficient of friction with the wheels turning and a skid impending; and (3) the sliding coefficient of friction with the wheels locked.

A standard procedure was followed for each

test which involved the following steps repeated at least once at each location to obtain a check on the initial readings:

1. The brakes of the jeep were fully applied with the motor stopped and the transmission in low gear.

2. The tow truck moved ahead in low-low gear engaging the clutch slowly until the

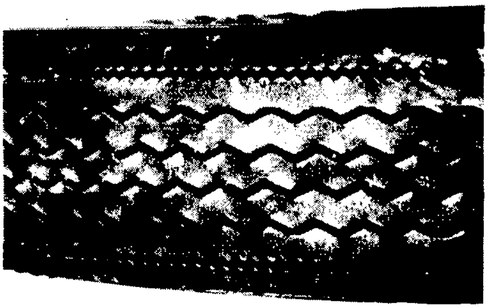

Figure 20. Tread pattern of tires used in friction tests.

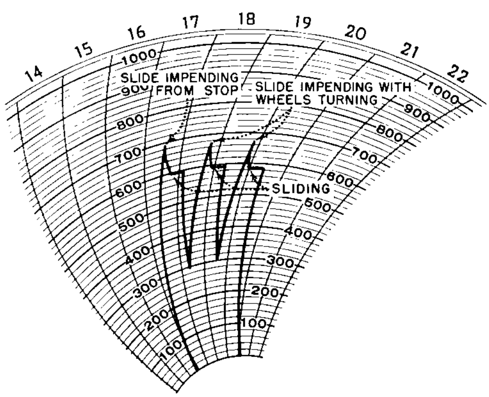

Figure 21. Typical dynamometer recording.

towed vehicle started to slide. The vehicle then continued at a slow speed until the entire test had been completed.

3. After the jeep had moved about 10 ft. with its wheels locked, the operator disengaged the clutch and released the brakes on the towed vehicle until the wheels started to turn. He then applied the brakes slowly to obtain the maximum braking force without locking the wheels and then released the clutch slowly. This caused all wheels to start sliding simultaneously.

4. After sliding ahead about 10 ft. with the wheels locked, Operation 3 was repeated.

RANGE OF SURFACE-FRICTION FACTORS

In addition to the friction tests conducted on the taxiway at Andrews Air Force Base, 108 tests were conducted on that section of concrete on US 40 where brake tests had been conducted on vehicles selected at random. Friction tests were also conducted at 25 locations selected at random around Washington, D. C., to obtain some idea of the various conditions encountered by drivers in the normal operation of their vehicles. One of

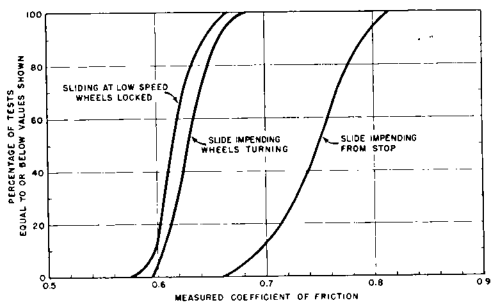

Figure 22. Range in coefficients of friction on 1-mi. section of concrete pavement where random brake performance tests were conducted.

these locations was on Memorial Bridge where rear-end collisions frequently have caused long delays to traffic crossing the bridge during morning and evening rush hours, especially on days when the surface was wet. The measurements were repeated at 11 of the test locations during a rainy period or between intermittent showers while the surfaces were wet.

The results of these tests show that the taxiway on which the brake tests from high speeds were conducted had a higher coefficient of friction when dry than any of the road surfaces on which tests were made. The taxiway had an average coefficient of friction 5 percent higher than the surface in Maryland where the random brake-performance tests were conducted.

The range in friction coefficients on a 1-mi. section of highway on and in the vicinity of the ½-mi. section where the random brake-performance tests were conducted is shown by Figure 22. These were obtained with the set of tires that resulted in the lower coefficients.

The range as shown by Figure 22 is, nevertheless, significant.

With a range of more than 10 percent in the coefficient of friction of the surface, depending on the exact location of the test, and a possible variation of at least 30 percent due to the tires, it is evident that these variations had some effect on the results of the brake-performance tests. Was brake performance or was the coefficient of friction between the road surface and the tires being measured? It is evident that the results for one must be considered in combination with the other.

The relative coefficients of friction at low speeds for seven different types of surfaces

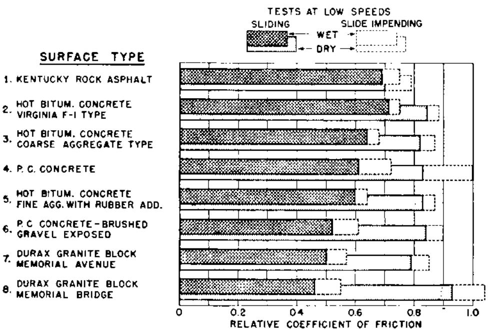

Figure 23. Relative coefficients of friction impending coefficient for portland-cement concrete used as unity.

when dry and when wet are shown in Figure 23. The term "relative" is used because the values are based on one particular set of tires. With other sets of tires the values might be considerably higher or lower, and there is no positive assurance that the relative magnitude of the coefficients between different surfaces would be the same as shown by Figure 23. In fact, the results of a limited number of tests on different surfaces with different tires indicate the possibility that one surface with a relatively high coefficient of friction as compared with other surfaces when measured with one set of tires may have relatively a much lower coefficient of friction when the measurements are made with another set of tires. It can be hoped, however, that the data shown by Figure 23 do represent about average conditions on a relative basis. They should not be used without this qualification and without the additional qualification that construction methods and other factors can result in a wide variation in friction coefficients, even for the same general type of surface.

Figure 23 shows that the impending coefficients of friction immediately before the wheels start sliding are higher for all types of surfaces, both dry and wet, than the coefficients after the wheels start to slide. Also, all surfaces when wet have lower friction coefficients than when dry.

A most interesting comparison exists between the Durax granite-block surface on Memorial Bridge where heavy traffic volumes had worn the peaks on the blocks smooth and the same type of surface on Memorial Avenue where traffic volumes since construction had been much lower than on the bridge. When dry, the worn surface on the bridge had a higher coefficient of friction than any of the road surfaces, but when wet it had the lowest coefficient of friction. Both the impending and sliding values for the wet condition were only about 50 percent of the values for the dry condition. This was undoubtedly an important contributing factor to the large number of rear-end collisions and at least two head-on collisions that occurred while the surface was wet.

When Memorial Bridge was resurfaced with a rock-asphalt mixture, the coefficient of friction for the dry condition was reduced about 25 percent. During the more critical condition, however, when the surface was wet, resurfacing the bridge increased the impending coefficient of friction 36 percent and the sliding coefficient of friction 53 percent.

It is also interesting to note that all of the surface materials, except Kentucky rock asphalt and the granite blocks, have about the same coefficients when dry and a wide range in the coefficients when wet. At one intersection, the intersection area and the approaches for a short distance from the intersection had been resurfaced with a hot bituminous concrete containing a fine aggregate and a rubber addition as an experiment. The resurfaced areas (Type 5, Figure 23) actually had a lower friction coefficient than the sections on the approaches that had not been resurfaced (Type 2, Figure 23).

The effect of temperature on friction coefficients was studied at 12 locations by conducting tests while the air temperature was 36 F. on one day and repeating the tests on another day when the temperature was 53 F.

It was cloudy on both days, and there had been a change in air temperature of only 2 deg. during the 24 hr. prior to the tests.

The difference in temperature apparently had no effect at five locations with concrete surfaces. At three locations, the coefficients of friction were slightly higher, and at two locations they were slightly lower at 53 F. than at 36 F. At the seven locations with various types of bituminous surfaces, the friction coefficients were consistently higher at the lower temperature than at the higher temperature. The average difference was 10 percent for the impending coefficients of friction with the wheels turning and 8 percent with the wheels sliding in a locked position.

SUMMARY

The tests to determine braking distances of vehicles from high speeds and the tests of friction coefficients may be regarded as pilot studies pointing to the need for more-extensive studies that should involve the coöperation of the automotive and tire industries. The brake-performance tests may seem to be of limited number but, as far as is known, have not been made elsewhere in larger numbers.

The tests were of sufficient scope to throw serious doubt on some of the beliefs and opinions accepted in the past and to suggest the need for research broad enough in scope to give conclusive answers to the following questions:

1. What is the braking force or deceleration rate that drivers should be expected to attain on a dry surface? The tests showed that drivers of passenger cars with brakes in good condition were not always capable of obtaining a braking force sufficient to lock the wheels on dry surfaces with high coefficients of friction, especially at high speeds.

2. Are not distances within which most vehicles can be stopped from high speeds most of the time on surfaces with high coefficients of friction considerably longer than those generally accepted to be correct in the past? In these limited tests vehicle-braking distances on dry surfaces increased with increased speed at a rate greater than the square of the speed.

3. What causes the large variation in the braking distances of different vehicles and of the same vehicle during successive stops? During these tests there was a wide variation in the braking action of the same vehicle and in the braking action of different vehicles, especially at high speeds.

4. To what extent do brakes and road conditions cause vehicles to dive to one side and the drivers to lose control of their vehicles? In these tests deceleration rates attained by vehicles in making stops from high speeds were not uncomfortable unless the wheels locked or the driver was unable to control the path of the vehicle due to improperly adjusted brakes or nonuniformity of the road surface.

5. What is the exact extent to which brake fade and other factors affect stopping distances of vehicles under normal operating conditions? In these tests brake fade appeared to be one of the most serious deficiencies of the cars tested.

The results of the friction coefficient measurements are useful principally as a pilot study to illustrate the necessary magnitude of any investigation designed to obtain exact information on the interrelation of stopping distances and friction coefficients between tires and road surfaces. Much is being done by highway departments to improve the nonskid qualities of roadway surfaces and to eliminate types that are exceedingly slippery when wet. Is it not also necessary to consider the variation in tires concurrently with the road surfaces to improve friction coefficients? Improvement in operating safety can be expected from continued attention to better road surface design and from continued improvement in the construction of tires. Would it not be advisable to establish minimum standards for both road surfaces and tires to avoid having drivers confronted with unexpectedly hazardous friction factors on both wet and dry surfaces?