DECELERATION DISTANCES FOR HIGH SPEED VEHICLES

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A series of tests was run to determine average deceleration rates under several types of decelerating conditions The first series were made to determine the maximum average deceleration rates obtainable Test speeds were 50, 60 and 70 miles per hour The average deceleration rates were between 19 and 22 ft per sec ^{2} The second series of tests was made to determine deceleration rates with only engine braking, air and rolling resistance supplying the decelerating forces Decelerations on the order of 3 2 ft per sec ^{2} were obtained at 70 miles per hour but the values dropped to 0 8 ft per sec ^{2} at 10 miles per hour The third series evaluated the decelerating effects of air and rolling resistance alone About 1 75 ft per sec ^{2} deceleration at 70 miles per hour and about 0 37 ft per sec ^{2} at 10 miles per hour were obtained under these test conditions A fourth series was made to evaluate comfort factors for passengers and driver The reactions of the observers were that about 8 55 ft per sec ^{2} average deceleration produced a comfortable stop Average deceleration of 11 05 ft per sec ^{2} was undesirable and somewhat uncomfortable The driver would rather not use this rate of deceleration Rates of 13 90 ft per sec ^{2} were considered very undesirable by the passengers and any loose articles resting on the seats were thrown off on the floor This rate becomes dangerous to the passengers The average deceleration figures were determined from distances and initial velocities This calculation must be emphasized since the maximum rate of deceleration obtained during the test is considerably greater Furthermore, often-times figures from maximum reading decelerometers have been used for computation purposes The distances calculated from such data would require much too severe stops for comfort or safety

It was concluded that highway design should be based on the comfort figure wherever possible, for example, sight distances should be calculated for average deceleration rates of 8 50–9 00 ft per sec ^{2} rather than, say, the maximum capability figure of 19–22 ft per sec ^{2}

The function of the Highway Designer is to build roads which will provide the greatest return to the using public This return should be interpreted in terms of the fastest possible movement of traffic with safety and comfort If a road is to be made safe and comfortable and at the same time permit fast movement of vehicles, it is necessary to consider both vehicle limitations and human limitations

The distances and deceleration rates required to bring a vehicle to a safe stop are of essential importance in highway design The limiting values of stopping distance and deceleration rates should not be determined by the vehicle itself, but by passenger reaction Most vehicles could be stopped in much shorter distances and with higher deceleration rates than is now the practice without harm to the vehicle, providing sufficient traction were available Deceleration rates greater than those now available are very probably not desirable because of human limitations and responses. The build up of passenger resistance to acceleration is sufficiently slow that a high deceleration suddenly applied, while not harmful to the vehicle, could cause serious injuries to the passengers and even the driver The limitation is in the time required by an individual to adjust himself to externally applied forces High uniform accelerations can be compensated for providing that these accelerations are reached very gradually. It is believed that about 10 ft per sec^2 is the limiting value for comfort if maintained for any length of time and that at least one half second should be used to change from 0 acceleration to 10 ft. per sec^2.

A series of tests was run to determine the vehicle capabilities under several decelerating conditions and in addition some tests were made to determine passenger and driver reaction. The distances, times, and average deceleration rates observed during this series of stopping tests are shown in the accompanying curves and tables. These data are representative of the average of a number of vehicles of different makes where only vehicle capabilities are considered Where driver and passenger characteristics are considered, the averages of eight experienced observers were used. These men were Proving Ground Department Heads or their Assistants.

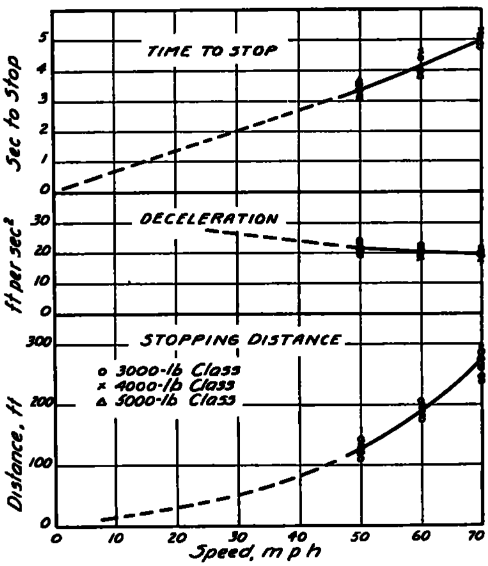

Figure 1. Maximum Deceleration Tests. Level Grade

The tests were all run on level straightaways and, except for those tests involving passenger reaction, the road surfaces were of concrete. Speeds were observed by a fifth wheel speedometer and distances measured from a counter attached to the fifth wheel. The counter is accurate to 5 ft. in a mile and the speed to within 0.5 of a mile per hour.

The deceleration rates for all of the stopping tests were calculated from the initial velocities and stopping distances. No reaction time or distance was involved.

The first data obtained were for the extreme emergency condition where the shortest safe stopping distance was required. The specification for this test was that the driver must bring the car to a stop from 70 miles per hour as quickly

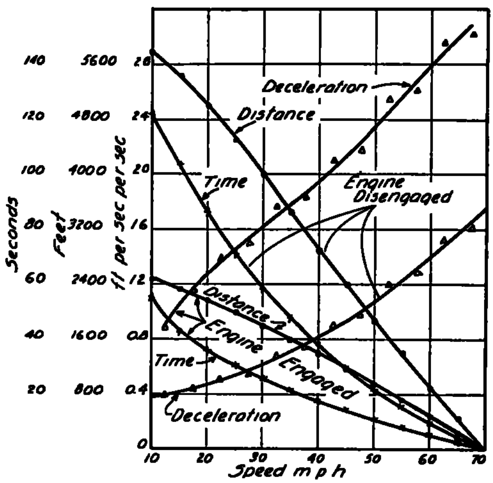

Figure 2. Deceleration Time, Distance and Deceleration from 70 m.p.h. Level Grade, Deceleration Without Use of Brakes. Average weight of 15 (1940) cars 4004 lb.

as possible and still keep the car within the boundaries of a 12-ft. concrete lane. This specification was made to rule out the sliding stop, since a vehicle is not in good control with the wheels sliding. All passenger cars have brakes adequate to slide all wheels, and all cars are subject to the difficulties encountered if the driver locks the wheels with the brakes. The results of these tests are shown in Figure 1. The average deceleration rate, distance, and time are shown by the curves and the points show the variation for the several cars.

The second set of tests covers that type of deceleration where only the engine braking is used This braking practice is used by most drivers whenever slowing down for turns, or when watching a changing situation ahead which, as it develops further, may require some further maneuver such as changing course or changing speed Results for this type of deceleration are shown in Figure 2 The distance curves indicate the distances required to decelerate from 70 miles per hour to any desired speed For example, it takes 2170 feet to slow down from 70 miles per hour to 20 miles per hour with the engine supplying the braking effort The time curve shows that it takes 36 sec to accomplish this speed reduction by such means These distance and time curves apply only when deceleration starts from 70 m p h The deceleration curve shows that the deceleration rate varies with speed where the engine is used as a brake These deceleration rates will be the same regardless of the speed from which the deceleration starts That is, if the test had been started at 50 or 60 miles per hour instead of 70, the deceleration rate at 30 miles per hour would still be 1 62 ft per sec² Therefore, these values may be used to compute distances or times from any initial condition It will be noted that the deceleration rates obtained are more than are useable for most icy conditions at moderate and high speeds where the road friction coefficient may be on the order of 0 07 With this coefficient, the road friction obtained from the two rear tires can provide traction for approximately 1 125 ft per sec² deceleration

The third set of tests shows the results of coasting tests where the only decelerating forces are those exerted by air resistance and rolling resistances The data for these tests are shown as part of Figure 2 Here again the distance and time curves are shown which apply only for the deceleration starting at a speed of 70 miles per hour In this case, it takes 5000 ft and 86 sec to coast from 70 miles per hour to 20 miles per hour The rates of deceleration shown in the deceleration curve apply regardless of the speed at which deceleration was started and may be used to calculate time and distance curves for any speed at which deceleration starts These deceleration rate data are again shown in Figure 3 An equation of the type $F = K_1 W + K_2AV^2$ was found to fit the observed data very well where F = force in lb, W = car weight in lb, A = frontal area in sq ft, V = m p.h; and K_1 and K_2 = constant (F was plotted as ft per sec² in these curves, since the mass of the car was known) In this case, $K_1 = 0\,0115$ and $K_2 = 0\,00125$ K_2AV^2 is the air resistance component in this equation The above equation is the typical two-term air and rolling resistance equation worked out from studies of a considerable amount of data on both air resistance and rolling resistance

The air resistance forces are of considerable interest because these are forces additive to those obtained through the friction between the tire and the road and are a function of the speed of the vehicle The maximum obtainable decelerations for any condition of road surface must be the sum of that which may be obtained from road friction and that obtained from air resistance Of course, under accelerating conditions, the air resistance becomes a subtractive portion

The effects of air and rolling resistance are shown in Figure 3 by a curve plotted for values of K_2AV^2, the air resistance, and a curve for the sum of the road frictional forces and air resistance This curve indicates that a car could be stopped and held on a grade of approximately 7 per cent in icy weather A curve of accelerating capability is also shown in Figure 3 This curve shows that on ice, assuming a 0.07 coefficient, the maximum obtainable speed is about 58.5 miles per hour and is determined by the air and rolling resistance.

In Figure 4, the same effects are shown by comparisons between deceleration distances calculated by the use of a friction coefficient of 0.07 (which is about that to be expected for ordinary icy conditions bordering on the wet side), and those distances calculated from the sum of the road friction and air resistance

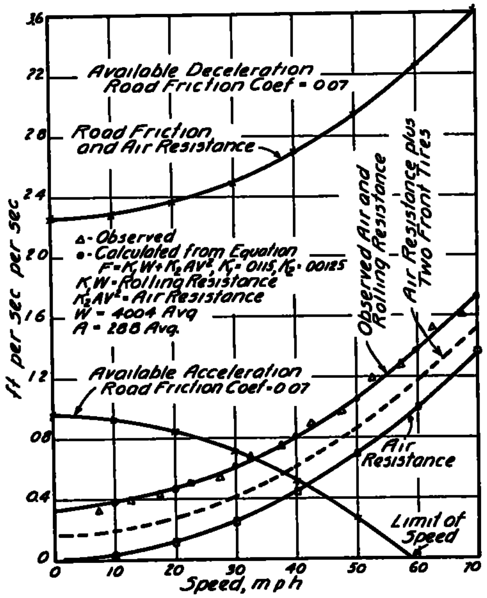

Figure 3. Air and Rolling Resistance Effects Added to Available Road and Tire Tractive Force For Icy Road Conditions.

decelerating forces. A grade climbing ability curve based on the friction coefficient of 0.07 and the air resistance is also shown in Figure 4 This curve is calculated from the tractive ability of the two rear tires less the air resistance of the vehicle and the rolling resistance of the two front tires. This curve indicates that if the gradients on a road do not exceed 3 per cent, very little difficulty should be experienced with cars becoming stalled on hills because of lack of traction. Since there is more deceleration capability on ice than acceleration capability as shown by the curves in Figure 3, it is obvious that there is a desirable safety feature in limiting grades to 3 per cent, both from a climbing ability and stopping ability standpoint.

A further series of tests involving passenger and driver reactions were run to determine comfortable braking distances from 70 miles per hour The results of these tests are shown in Table 1. The decelerations shown are, as stated before, average decelerations calculated

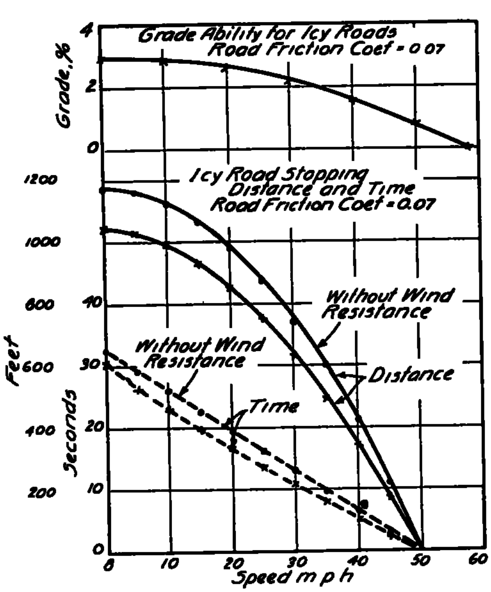

Figure 4

from the initial speed and stopping distance. The maximum decelerations obtained during the test naturally are above this average. Emphasis has been placed on the fact that the results are shown in terms of average deceleration rates. Oftentimes readings for this type of test are taken from indicating decelerometers. Then when calculations are made, the stopping distances arrived at are of such an order that if a driver were to keep within these distance requirements the stop required would be much too severe. It appears from the

TABLE 1

STOPS FROM 70 MILES PER HOUR

Comfortable to Passengers Preferred by Driver	619 ft	= 8 55 ft per sec ^{2} average
Undesirable but Not Alarming to Passengers Driver Would Rather Not Use	479 ft	= 11.05 ft. per sec ^{2} average
Severe and Uncomfortable to Passengers Slides Packages and Objects Off Seats Driver Classes as Emergency Stop	380 ft	= 13 90 ft per sec ^{2} average

12 9 ft per sec ^{2} Used in Designing Sight Distances

TABLE 2

DISTANCES FOR DIFFERENT TYPES OF STOPS FROM 70 MILES PER HOUR—INCLUDING A 2-SEC DAYTIME AND A 3-SEC NIGHT TIME PERCEPTION-REACTION TIME

	Day	Night	Dec ft per sec ^{2}
Comfortable to Passenger Preferred by Driver	835	927	8 55
Undesirable, but Not Alarming to Passengers Driver Would Rather Not Use	685	787	11 05
Design Distances for Pennsylvania Turnpike	616	718	12 9
Severe and Uncomfortable to Passengers Slides Objects off Seats Driver Classes as an Emergency Stop	586	688	13 9
Maximum Stop Car Must Stay in a 12-Foot Lane Brakes in Best Condition	476	578	19 5

test results in this table that the average deceleration rate for comfort should not exceed 8 50–9 00 ft per sec^2 An average deceleration rate of 13 9 ft per sec^2 is excessive and if used without warning may result in passenger injury

A summary of tests is shown in Table 2 This table shows that the capability of the car to stop is beyond the comfort and safe range for the passengers It is believed that where it is at all possible, the designers should use the deceleration rates which do not exceed the normal comfortable range since, even on straight, level roads with unlimited visibility, emergency conditions demanding high deceleration rates sometimes occur The most desirable road should be the one where the greatest margins of safety are provided by allowing the driver the maximum possible time to make a response to any situation which may occur. In other words, we believe it may be stated that the best and safest road with a given number of traffic lanes is the one which will handle most rapidly a given volume of traffic with the maximum comfort to the driver and passengers

DISCUSSION ON DECELERATION DISTANCES

PROF R A. MOYER, *Iowa State College* I would like to support the general conclusions in regard to the comfortable rates of deceleration given by Mr Wilson which he proposes should be used by designers of highways At Iowa State College we have for the past two years been operating four test cars daily as a part of a project on the study of motor vehicle operating costs. The speeds ranged from 25 m p.h. to 65 m.p h. Each of these cars is equipped with a Tapley decelerometer I agree with Mr Wilson that this device gives the maximum stopping rate and not the average rate. However, we have found that the difference between the maximum and the average rate is very small if the brakes are in good condition and if a reasonably uniform pressure on the brake pedal is provided. In driving these cars in normal cross-country type of operation for a distance of more than a quarter million miles, our drivers rarely have found it necessary to stop at the maximum rate established by test by Mr Wilson to be about 19 to 20 ft. per sec per sec. In the ordinary emergency stop the rate was more likely 12 to 13 ft per sec per sec. than 19 to 20 ft. per sec. per sec. and even for this lower rate considerable pressure on the brake pedal was necessary to develop this braking force. Our experience has indicated that if the higher rate is developed on dry pavements, skid marks will show up as a result of locking the wheels. While skid marks are commonly observed on pavements, my observations lead me to say that considering the volume of traffic and the number of stops made, the percentage of stops involving skid marks is very low indeed.

I heartily agree with Mr. Wilson that the comfortable rate of stopping of 8 to 9 ft. per sec per sec. is the one preferred by drivers and is the one which designers should use. In approaching intersections, sharp curves, or any other point along the road where deceleration may be necessary, our experience indicates that the drivers prefer to use the motor compression to reduce the speed of the car to about 30 m p.h. At speeds below 30 m.p.h. the deceleration rate provided by engine compression is so slow that brakes are necessary and it is in this range of speed that the stopping rate of 8 to 9 ft. per sec. per sec. should be used for all normal driving operations. It is possible that on high speed express type highways such as the Pennsylvania Turnpike, the initial speeds are so high that braking in the deceleration lanes will start at speeds above 30 m.p.h. and that the deceleration rates during braking will be greater than 8 to 9 ft. per sec. per sec. This is a point which should be investigated by speed surveys on the Turnpike. But even if the rates in the surveys were found to be greater than 8 to 9 ft per sec. per sec., I would still favor the lower rate for design purposes to provide a greater margin of safety and to encourage drivers to stop at this safer lower rate.

MR. JOSEPH BARNETT, *Public Roads Administration:* I should like to record appreciation to Mr. Wilson and the General Motors Proving Grounds for these tests of stopping distances from speeds of 60 and 70 miles per hour Very few tests of stopping distances at high speeds were available About 40 m.p.h. was about the highest speed used in observations of stopping distances heretofore. The American Association of State Highway Officials adopted the practice of designing sight distance based on stopping distances resulting from the use of a friction factor of 0.4, making allowance for perception and reaction time There has been considerable criticism that a friction factor of 0.4 was too low, that it should be higher and the stopping distances should be shorter These tests should quiet such criticism for they indicate that 0.4 is none too low.