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BUREAU OF PUBLIC ROADS

VOL. 19, NO. 12 ▽ FEBRUARY 1939

FIELD PARTY OBTAINING HIGHWAY CAPACITY DATA ON AN ILLINOIS HIGHWAY

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D. M. BEACH, *Editor*

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The reports of research published in this magazine are necessarily qualified by the conditions of the tests from which the data are obtained. Whenever it is deemed possible to do so, generalizations are drawn from the results of the tests; and, unless this is done, the conclusions formulated must be considered as specifically pertinent only to described conditions.

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PRELIMINARY RESULTS OF HIGHWAY CAPACITY STUDIES

Reported by O. K. NORMANN, Associate Highway Economist, Bureau of Public Roads

DURING the last few years many miles of highway have been reconstructed or replaced, not because they failed structurally, but because they became obsolete through inability to permit the present volumes of traffic to move at reasonable speeds and with freedom from interference between vehicles. State-wide highway planning surveys now being conducted in 46 States will furnish highway engineers with more accurate traffic volume figures and future traffic estimates than they have had in the past, but to make the best possible use of this information the capacity of various surface widths and types of design and alinement must be known.

Many attempts have been made to determine highway capacities by both theoretical formulas and field observations. In general the theoretical derivations, obtained by assuming that all vehicles travel at the same speed, have resulted in extremely high and impractical volumes. The field observations have either been too limited or lacking in essential data, such as the speeds at which the individual vehicles were traveling, to yield accurate and conclusive results.

Realizing that a large quantity of detailed data would be required before the relative capacities of highways of various widths and alinements could be determined, the Bureau of Public Roads conducted a number of capacity studies on some of the most heavily traveled rural highways in New York and New England during the summers of 1934 and 1935, and cooperated with the Illinois Division of Highways in a similar study in Illinois during 1937.

At all study locations the time that each vehicle entered and left a section of highway ⅕ mile long was entered on a graphic time-recorder (see fig. 1) and each vehicle was classified as a passenger car, bus, or truck. Each truck was further classified as a light, medium, or heavy truck, truck and full trailer, or truck and semi-trailer. It was possible to obtain from these basic data the speed of each vehicle, its time or distance spacings, from other vehicles, and the exact volume of traffic in each direction during any desired time period. The studies were conducted for approximately 8 hours each day, starting while traffic was light and continuing through the heaviest volumes. This gave a range in traffic density at each location.

Data for a total of over 300,000 vehicles with volumes as high as 3,400 per hour in one direction on a four-lane road were recorded during the studies. The majority of the sections were level tangents on rural highways. Although 300,000 vehicles may seem to be a large sample, it is not to be expected that the data will yield answers to all highway capacity problems. However, a few significant traffic characteristics have been developed by the analyses thus far completed. The purpose of this report is to present a few typical results.

Figure 2 shows the tabulating machine card used for the Illinois study and illustrates the data that are obtained for each vehicle passing through the study sections. Entries in the columns headed "time at center" enable the cards to be sorted into any time period group desired.

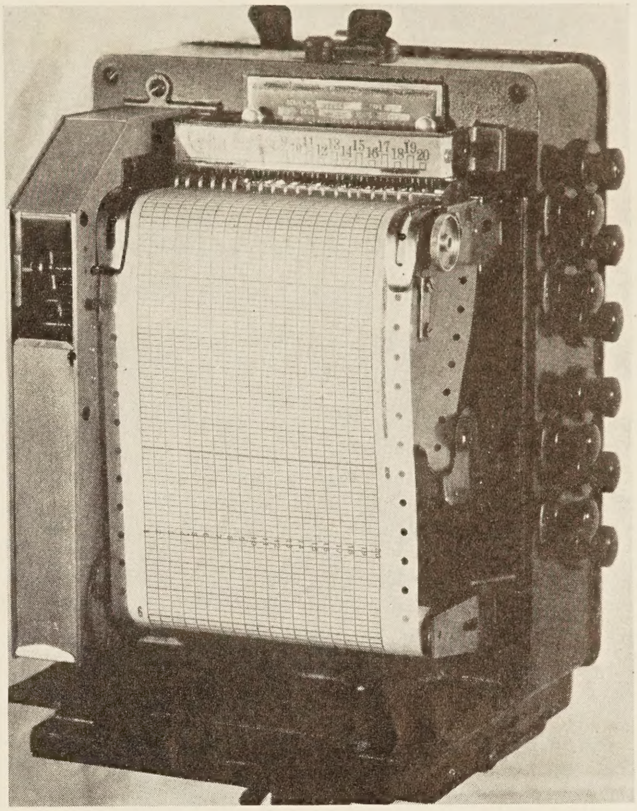


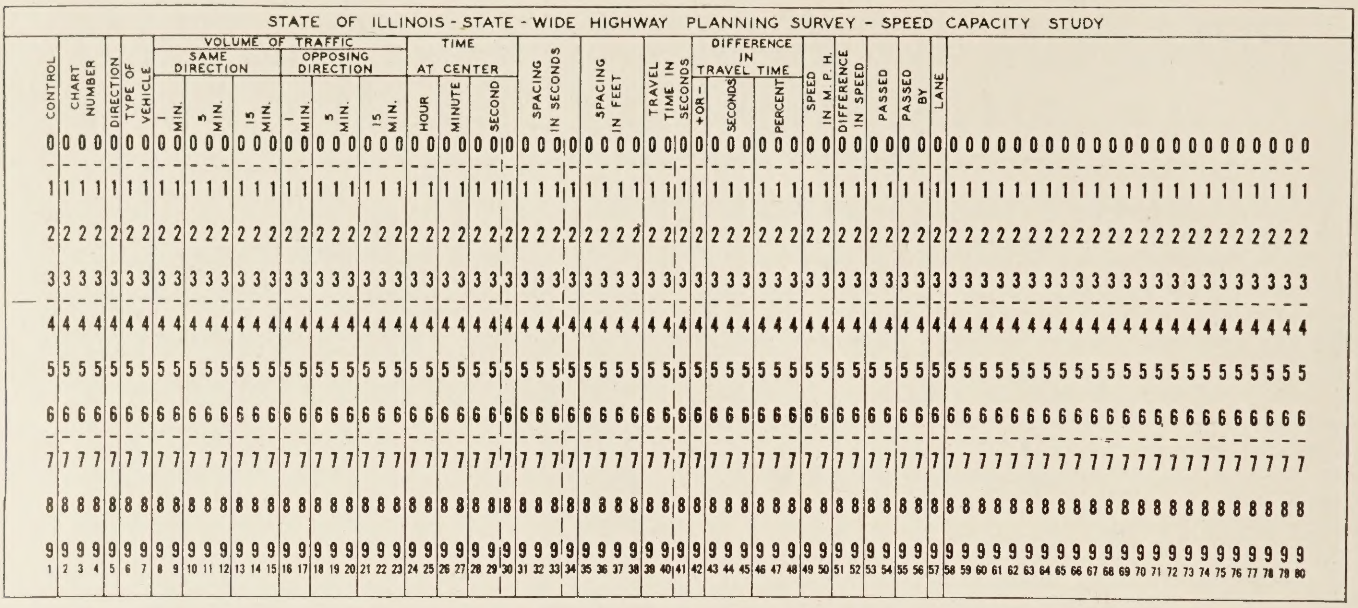
FIGURE 1.—GRAPHIC RECORDER USED IN HIGHWAY CAPACITY STUDY.

MAXIMUM TRAFFIC VOLUME WHEN ALL VEHICLES TRAVEL 33 MILES PER HOUR

The theoretical maximum capacity of a traffic lane for various vehicle speeds was first determined for one location by a method similar to that used in many of the theoretical derivations, but instead of using a calculated uniform spacing between vehicles, the actual spacings obtained by the study were used. Of the 8,500 vehicles recorded at this location, 2,055 were traveling at the same speed as the preceding vehicle and were not passed or did not pass another vehicle while in the section. By classifying these vehicles into speed groups, the modal spacing for each group was determined mathematically and checked by constructing a curve showing the frequency distribution of spacings for each speed. Figure 3 shows the frequency distribution of spacings for the 31-mile-per-hour group.

The modal spacings for all speed groups are shown in figure 4. At speeds greater than 20 miles per hour there was very little difference in the time spacing allowed by the driver in the majority of cases between his vehicle and the vehicle ahead when both were traveling at the same speed.

The distance spacings as shown in the lower curve of figure 5 are readily computed from the time spacings. The upper curve was constructed by using the average spacings for all vehicles spaced at less than 4 seconds.



STATE OF ILLINOIS - STATE - WIDE HIGHWAY PLANNING SURVEY - SPEED CAPACITY STUDY

CONTROL | CHART NUMBER | DIRECTION | TYPE OF VEHICLE | VOLUME OF TRAFFIC: SAME DIRECTION (1 MIN., 5 MIN., 15 MIN.), OPPOSING DIRECTION (1 MIN., 5 MIN., 15 MIN.) | TIME AT CENTER (HOUR, MINUTE, SECOND) | SPACING IN SECONDS | SPACING IN FEET | TRAVEL TIME IN SECONDS | DIFFERENCE IN TRAVEL TIME (+ OR -, SECONDS, PERCENT) | SPEED IN M. P. H. | DIFFERENCE IN SPEED | PASSED | PASSED BY | LANE

Figure 2.—Tabulating Machine Card Used in Analyzing Data Collected in Highway Capacity Studies.

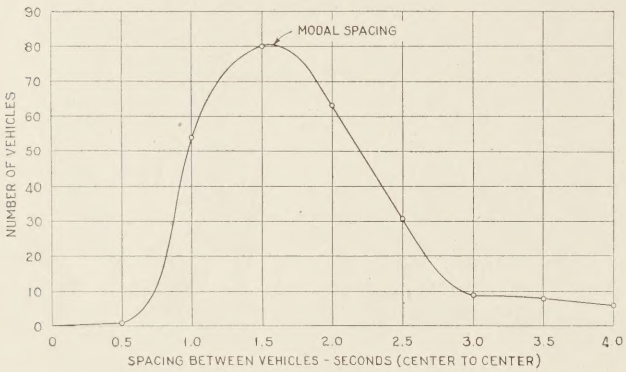


Figure 3.—Frequency Distribution of Spacings Between Vehicles Traveling 31 Miles Per Hour Preceded by Vehicles Traveling at the Same Speed. Section 3-J, 2-Lane Tangent.

It was assumed that a car traveling at a spacing greater than 4 seconds was not traveling at the minimum spacing but just happened to be going at the same speed as the preceding vehicle. These two curves, therefore, represent the distance spacings that the average driver allows between his vehicle and the vehicle just ahead when following at the same speed, and the distance allowed by the largest group of drivers under the same conditions.

It is of interest to know what percentage of these vehicles could have stopped without hitting the preceding vehicle had it suddenly stopped. If it is assumed that the brakes on the following vehicles were as good as those on the leading vehicles and that a ½-second reaction time would be required, 4.4 percent of the vehicles could not have avoided rear-end collisions. This figure increases to 28 percent for a 1-second reaction time, and to 50.5 percent when 1.5 seconds is allowed for a combined perception and reaction time.

Although the possibility of the leading vehicle stopping almost instantaneously, as in the event of a head-on collision, is rather remote, the drivers of 77.3 percent of the vehicles could not have stopped in time to avoid a rear-end collision or the necessity of swerving to the shoulder or ditch had they suddenly been confronted with such a condition. This assumes a ½-second reaction time, four-wheel brakes in perfect order, and the most nonskid type of road surface. These figures illustrate one reason why more than two vehicles are so often involved in one accident.

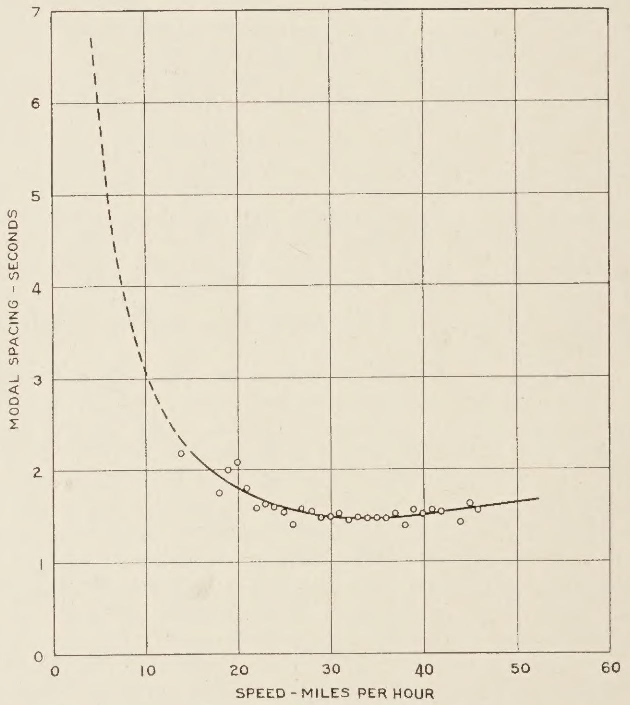


Figure 4.—Modal Spacing in Seconds Between Vehicles Traveling at the Same Speed. Section 3-J, 2-Lane Tangent.

Using the values shown in figure 5, figure 6 was constructed to show the theoretical maximum number of vehicles per hour that one traffic lane will accommodate at various speeds if all vehicles travel the same speed. The maximum volume occurs at a vehicle speed of 33 miles per hour and does not vary more than 20 percent from this volume for any speed between 20 and 50 miles per hour.

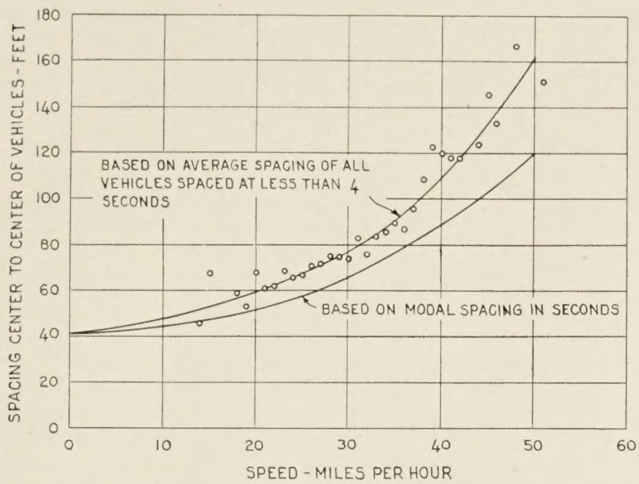


Figure 5.—Minimum Average Spacing in Feet Between Vehicles Traveling at the Same Speed. Section 3–J, 2-Lane Tangent.

Similar curves could be constructed for other sections of highway having various designs, but would be of doubtful value. They would hold true only in instances where all vehicles were required to move at the same speed—none could go faster or slower than the vehicle ahead and there could be no passing or interruptions of any kind. Such uniformity would be practically impossible to attain except in rare instances such as through tunnels or over long bridges where strict control would be possible, but certainly not on rural highways. A practical working capacity that will permit a reasonable range of speeds and a reasonable amount of freedom from interference between vehicles must, therefore, be determined. It would not even be justifiable to assume that volumes for practical working capacities at various average speeds will be proportional to the volumes shown on the curves developed by the method illustrated.

Many of the available articles on highway capacity indicate that as the volume of traffic increases, a point will be reached beyond which the average speed of the vehicles will decrease. Some indicate that there will be a sudden and appreciable drop in the speed. The majority of present definitions for maximum capacity, working capacity, practical working capacity, and the beginning of congestion, are based on the assumption that such a point does exist. To determine if there is such a point, separate curves were made using data collected at each of the 35 locations by plotting the average speed for various volumes of traffic. Data for about 180,000 vehicles were grouped in 100-vehicle groups, 15-minute groups, and 1-hour groups, and these were used together with both the total and one directional volumes. In most instances there was a gradual decrease in average speed with an increase in volume. A number of locations showed a relatively high rate of decrease in speed at the high volumes, but several showed a relatively low rate of decrease at the high volumes. The traffic volumes and densities at these locations varied from values below to values well above those that are definitely known to be in excess of reasonable working capacities for rural highways, yet none of the curves showed a sudden or marked decrease in speed at any particular traffic volume or density. The individual points for groups of vehicles in similar volumes were scattered over a relatively wide range of speeds, although the averages for groups within a limited volume range formed fairly uniform curves.

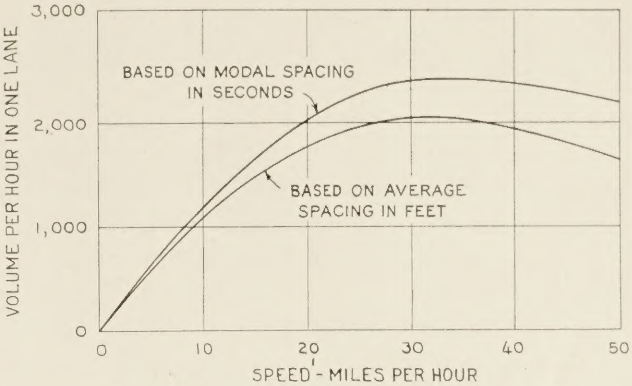


Figure 6.—Theoretical Maximum Traffic Volume With all Vehicles Traveling at the Same Speed. Section 3–J, 2-Lane Tangent.

AVERAGE SPEED DIFFERENCE USED AS AN INDEX OF TRAFFIC CONGESTION

Speed-volume or speed-density curves for traffic at various locations do not give a basis for determining either absolute or relative values for the capacities of highways or amount of interference between vehicles. It cannot be assumed that the interference between vehicles increased only 30 percent merely because the average speed dropped 30 percent with an increase in volume from 400 to 1,400 vehicles per hour at one location.

It is apparent that a measure other than average vehicle speed alone must be used to determine the working capacities of highways. Were it possible and practical to measure the physical, mental, and nervous energy used by the average driver per mile, when traveling in various volumes of traffic, this would be an ideal index for determining working capacities. As this method has not been found practical, a search for another index obtainable from available data was made.

Curves were drawn showing the standard deviation from the average speed, the standard deviation of the differences in speed from the preceding vehicle, and the actual number of passings made within a given length of highway. The most significant index found to measure the relative interference between vehicles on rural highways was the mean or average difference in speed between successive vehicles.

With light traffic on a rural highway, the speed of each individual vehicle is not governed by the speed of the vehicle immediately ahead, and there is a relatively high mean difference in speed between successive vehicles. As the volume increases, there is an increasing tendency for the speed of the individual vehicles to be governed by the speed of the preceding vehicles. This causes a marked decrease in the mean difference in speed between successive vehicles, although the decrease in average speed may be slight.

To illustrate how the index may be used as a measure of the relative interference between vehicles, figure 7 was constructed from the data for one section of a two-lane highway. The individual vehicles were classified into groups as determined by the spacing in seconds from the preceding vehicle. The average speed and the mean difference in speed between successive vehicles were then obtained for each group. This figure indicates: (1) That operators of vehicles at or above a time spacing of 9 seconds from the preceding vehicles were not influenced by the speed of the preceding vehicle; (2) at spacings below 9 seconds some of the operators

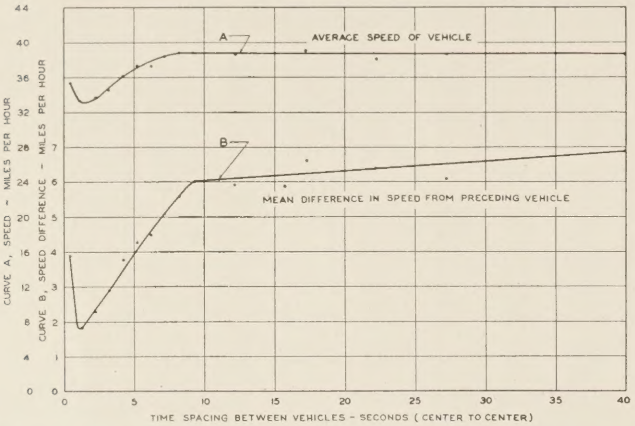


Figure 7.—Speed Characteristics of Vehicles Traveling at Given Time Spacings Behind Preceding Vehicles. Section 3–J, 2-Lane Tangent.

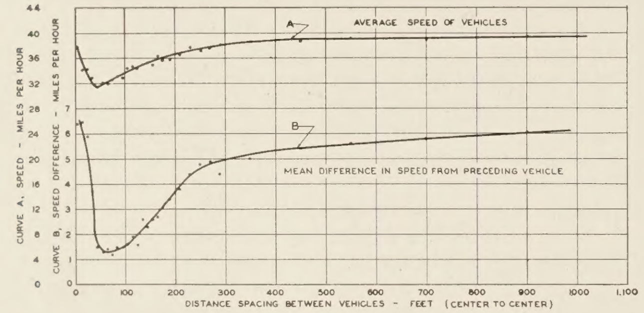


Figure 8.—Speed Characteristics of Vehicles Traveling at Given Distance Spacings Behind Preceding Vehicles. Section 3–J, 2-Lane Tangent.

were influenced by the speed of the preceding vehicles; and (3) at a spacing of 1½ seconds, a large majority of the drivers were influenced by the speed of the preceding vehicle. The increase in the average speed and difference in speed for spacings below 1½ seconds was undoubtedly caused by vehicles passing one another.

Similar curves were constructed using only the vehicles traveling as fast or faster than the preceding vehicle. Except that the speed curve was about 2 miles per hour higher for values above 9 seconds, the curves were identical with those of figure 7.

Figure 8 was constructed in the same manner as figure 7, except that distance spacing groups were used instead of time spacing groups. The same general characteristics are evident. Although the traffic speed curves are considerably higher for some locations than for others, the break in the curves occurs consistently at about 9 seconds when time spacings are used but varies widely for the distance spacing curves. This indicates that the average driver starts to be influenced by the speed of the preceding vehicle at a fairly constant time spacing or at a distance spacing that varies with his speed.

On a two-lane highway, the average vehicle spacing is 9 seconds with 400 vehicles per hour in each direction. There would be no interference between vehicles at this volume if all vehicles were uniformly spaced and traveled at the same speed. Because of the large variation in individual vehicle speeds, the time spacings between vehicles are continually changing so that even with traffic volumes considerably lower than 400 vehicles per hour, a large percentage of the vehicles travel at spacings much shorter than 9 seconds. The percentage of vehicles traveling at the shorter time spacings will obviously increase with an increase in volume.

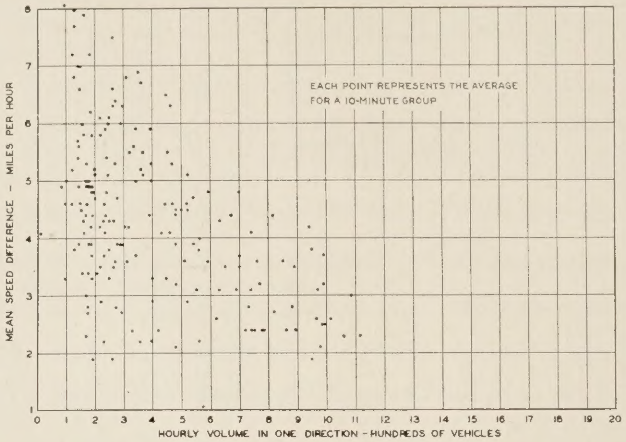


Figure 9.—Mean Difference in Speed Between Successive Vehicles for Various Volumes of Traffic. Section 3–J, 2-Lane Tangent.

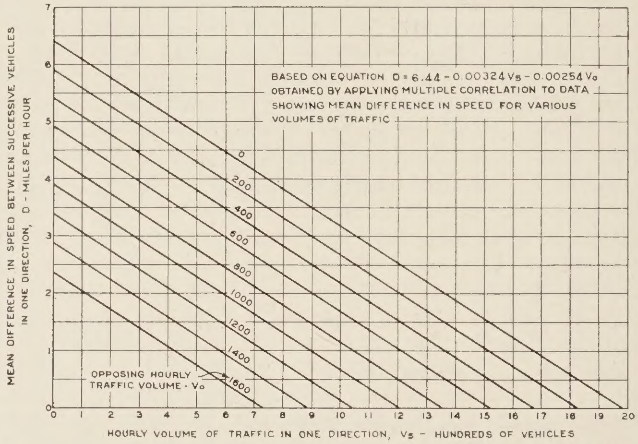


Figure 10.—Mean Difference in Speed Between Successive Vehicles With Various Volumes of Traffic. Section 3–J, 2-Lane Tangent.

By plotting the mean difference in speed for individual time period groups against the volume of traffic, a large scattering of points for each location was obtained as illustrated by figure 9. Some factor other than the volume of traffic in one direction evidently causes the large scattering of points.

A similar scattering occurs when total traffic volumes are used, but by applying multiple correlation to the data, using the mean difference in speed as the dependent variable and the volume of traffic in one direction together with the volume of traffic in the other direction as the two independent variables, the equation shown in figure 10 was developed. The series of lines obtained by solving the equation accounts for the wide scattering of points in figure 9. It is possible that a slightly curved series of lines would fit the points better and result in a slightly higher coefficient of correlation, but the coefficient of −0.812 indicates that the straight-line equation is highly significant within the range of values covered by the data.

To illustrate how figure 10 may be used in determining the relative interference between vehicles at various traffic volumes, assume that the volume of traffic traveling in one direction on this two-lane tangent is

200 vehicles per hour. If the opposing traffic is 700 vehicles per hour, the 200 vehicles will have the same freedom as a traffic volume of 500 per hour with an opposing traffic volume of 300 per hour.

MAXIMUM HOURLY CAPACITIES COMPUTED FOR VARIOUS HIGHWAYS

The maximum number of vehicles per hour that can travel over this two-lane tangent before all vehicles must start traveling at the same speed as the preceding vehicle and the drivers have no individual freedom, is 1,980 per hour with all traffic in one direction, and 1,100 in each direction with balanced traffic (see fig. 10). Should it be desired to limit the working capacity to the volume at which the freedom of the average vehicle would not be restricted more than 30 percent of the difference between the restriction with practically no other traffic on the road, and the restriction when all vehicles are required to travel at the same speed, the hourly traffic volume could not exceed 600 vehicles with substantially all traffic in one direction, or 330 vehicles in each direction.

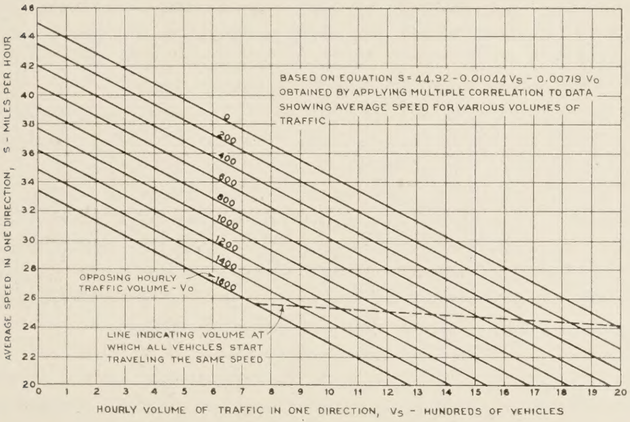


FIGURE 11.—AVERAGE SPEED WITH VARIOUS VOLUMES OF TRAFFIC. SECTION 3–J, 2-LANE TANGENT.

By correlating the speed of the vehicles with the volumes of traffic in the same and opposing directions, a coefficient of correlation of −0.877 was obtained for the equation shown in figure 11 and represented by the series of lines. It is obvious that the relationship will not hold true for values below the dashed line indicating the traffic volumes at which all vehicles must travel at the same speed according to figure 10. For values below this dashed line, one slow-moving vehicle could prevent all following vehicles from traveling faster than its speed. In determining practical working capacities, only traffic volumes lower than the values at which such a condition exists need be considered.

The same type of curves as those presented for this two-lane highway were constructed for a number of other sections of highway. To illustrate and compare a few of the results, figure 12 has been constructed using only the values representing an even distribution of traffic between the two directions. Results are shown for seven study sections, all tangents, including 2 two-lane, 1 three-lane, 2 four-lane undivided, and 2 four-lane divided highways.

The total maximum hourly capacity of one of the two-lane highways was 1,880 vehicles at a speed of 23 miles per hour. For the other, it was 2,200 vehicles at a speed of 25 miles per hour.

The maximum hourly capacity of the three-lane highway was 2,540 vehicles at a speed of 12 miles per hour. One of the four-lane highways had a total maximum capacity of 4,150 vehicles per hour at a speed of 22 miles per hour, and the other a total maximum capacity of 8,600 at a speed of 11 miles per hour. One of the four-lane divided highways could accommodate a total maximum of 5,400 vehicles at a speed of 15 miles per hour, and the other 7,300 vehicles at a speed of 40 miles per hour. It should be remembered that these total maximum hourly capacities and corresponding speeds are for tangent sections, and that at the maximum volumes each driver must govern the speed of his vehicle entirely by the speed of the preceding vehicle, a condition that the average driver considers very unfavorable, especially for rural highways.

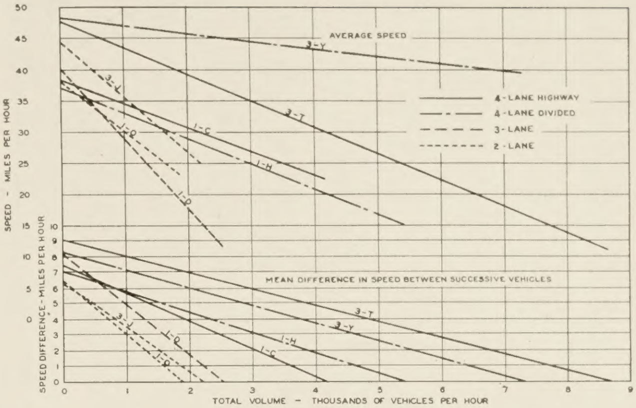


FIGURE 12.—SPEED AND MEAN DIFFERENCE IN SPEED FOR LEVEL TANGENTS WITH VARIOUS TOTAL VOLUMES EQUALLY DISTRIBUTED BETWEEN THE TWO DIRECTIONS.

It must also be remembered that the values for these sections do not represent values for all highways having a corresponding number of lanes. These particular sections cannot be considered typical two-lane, three-lane, and four-lane highways, but were selected to illustrate that in determining the practical working capacity of a highway, consideration must be given to the speed at which the vehicles will be able to travel and the relative interference between vehicles that will be present. Thus, if it were desired to maintain an average speed of 35 miles per hour, the working capacity for the two-lane section 3–J would be 1,100 vehicles per hour, and for the four-lane section 3–T it would be 3,000 vehicles per hour. If it were also desired to limit the interference between vehicles to that present when there is a mean difference in speed of 4 miles per hour, the working capacity of section 3–J would be limited to 850 vehicles per hour. Only after analyzing data collected at many locations can generalizations be drawn for highways of various widths.

It is evident that practical working capacities are relative rather than absolute values, just as the safety factors used in structural design are relative rather than absolute values. The speed and interference factor selected for a highway in determining its practical working capacity must be governed by local conditions and the interference that the particular type of traffic carried by the highway will tolerate.

In designing highways for present or future traffic volumes, consideration must also be given to the individual traffic flow diagrams indicating the number of times certain hourly volumes will be exceeded and the percentage of the total vehicles traveling in each direction during such periods.

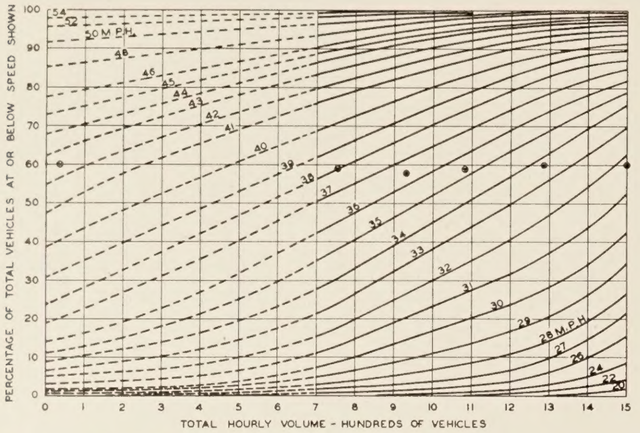


FIGURE 13.—CUMULATIVE PERCENTAGE DISTRIBUTION OF SPEEDS IN RELATION TO VOLUME OF TRAFFIC. SECTION 3-J, 2-LANE TANGENT.

So far, this analysis has been limited to level tangent sections with long sight distances. The effect that grades, intersections, and various degrees of curvature have on the capacity must be determined before it will be possible to arrive at practical working capacities for highways of various designs.

Highway transportation plays such an important part in the life of everyone that it is surprising how little is known about the fundamentals of traffic behavior. Great care is taken in the construction of highways, yet comparatively little is known regarding the effectiveness with which the facilities provided fulfill traffic requirements. A number of figures illustrating a few of the fundamentals of traffic behavior have been constructed from the capacity study data. These should be useful to traffic and highway engineers.

REGARDLESS OF VOLUME, THE SAME PERCENTAGE OF VEHICLES WENT SLOWER THAN THE AVERAGE SPEED

Figure 13 was constructed by plotting the percentage of vehicles traveling at or below given speeds for various total volumes of traffic on a certain two-lane rural highway. The solid lines cover the range of hourly volumes observed during the study. In order to extend these lines to cover lower volumes, a frequency distribution of speeds for all individual vehicles spaced at least 2,000 feet behind the preceding vehicle and without interference from oncoming traffic was used to represent the distribution of speeds as the volume approached zero. As far as the design of the highway was concerned, all of these vehicles could have traveled 50 miles per hour. However, observations of these vehicles which represent low traffic volumes showed that 10 percent of the vehicles traveled less than 35 miles per hour and only 8 percent traveled faster than 50 miles per hour. With a traffic volume of 1,000 vehicles per hour, 53 percent of the vehicles traveled at or less than 35 miles per hour, and only 4 percent went faster than 50 miles per hour.

The circles in figure 13 represent the average speeds for various total hourly traffic volumes. Regardless of the total traffic volume on this highway, the percentage of the vehicles traveling slower than the average speed remained practically constant. Were the curves extended, at a total traffic volume of 2,200 vehicles per hour, the average vehicle speed would be approximately 25 miles per hour, which checks with the average speed previously determined for the total maximum capacity of 2,200 vehicles per hour at this same location.

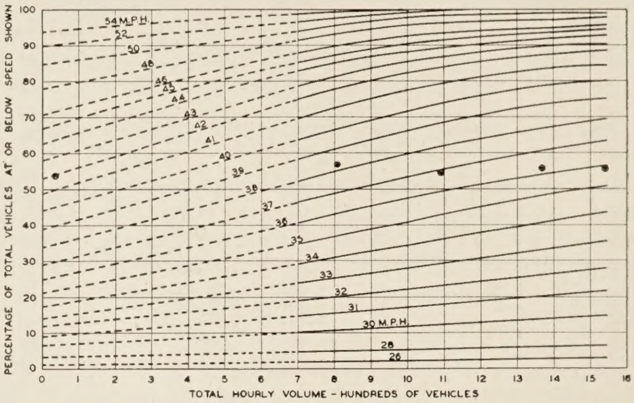


FIGURE 14.—CUMULATIVE PERCENTAGE DISTRIBUTION OF SPEEDS IN RELATION TO VOLUME OF TRAFFIC. SECTION 1-M, 3-LANE TANGENT.

Figure 14 shows the same data for a three-lane tangent. The speeds at the low traffic volumes are slightly higher than for the two-lane tangent and change less with an increase in volume. On this highway the percentage of vehicles going slower than the average speed of all traffic also remains practically constant as the total traffic volume changes, but is approximately 55 percent rather than 60 percent.

The curves for a four-lane divided tangent shown in figure 15 and those for a two-lane tangent shown in figure 16 also reveal that a fairly constant percentage of the vehicles travel slower than the average speed, the percentage being 55 for the four-lane divided highway and about 70 for the two-lane highway.

Figure 17 shows the distribution of speeds on a four-lane undivided tangent on which the speed limit was 30 miles per hour. At the low traffic volumes about 60 percent of the vehicles exceeded the speed limit. The range of speeds at the low volumes was much less than for highways on which speed was not restricted. The frequency distribution curves for the speeds did not change to any marked extent until a traffic volume of 1,600 to 2,000 vehicles per hour in one direction was reached. Here again, it is seen that the percentage of vehicles traveling slower than the average speed did not vary to any marked degree as the volume changed. These figures and similar data for other locations indicate that although the percentage of vehicles traveling below the average speed varies for different highways, the percentage traveling below the average speed on any particular highway does not change an appreciable amount with a change in traffic volume.

The data recorded also made it possible to determine the frequency distribution of time spacings between successive vehicles traveling in the same direction for various volumes of traffic, as illustrated by figure 18. On this particular two-lane tangent when the volume in one direction was 300 vehicles per hour, 25 percent of the vehicles or 75 of the 300 vehicles passing each hour reached a given location on the highway less than 2 seconds after the preceding vehicle. Likewise, 37 percent, or 111 of the 300 vehicles, were less than 3 seconds behind the preceding vehicles. Twelve per cent, or 36 of the 300 vehicles, were, therefore, spaced between 2 and 3 seconds from the preceding vehicle.

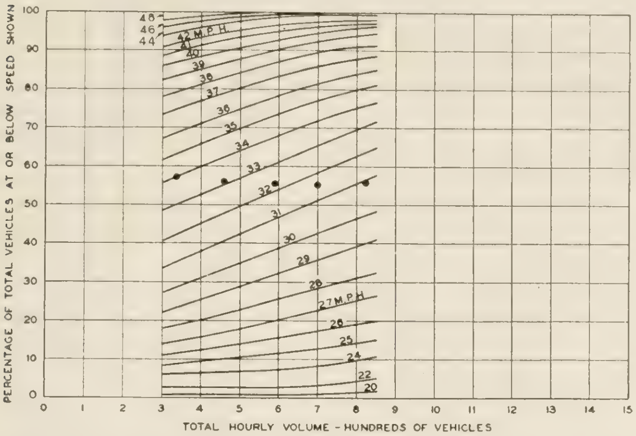


FIGURE 15.—CUMULATIVE PERCENTAGE DISTRIBUTION OF SPEEDS IN RELATION TO VOLUME OF TRAFFIC. SECTION 1-H, 4-LANE DIVIDED TANGENT.

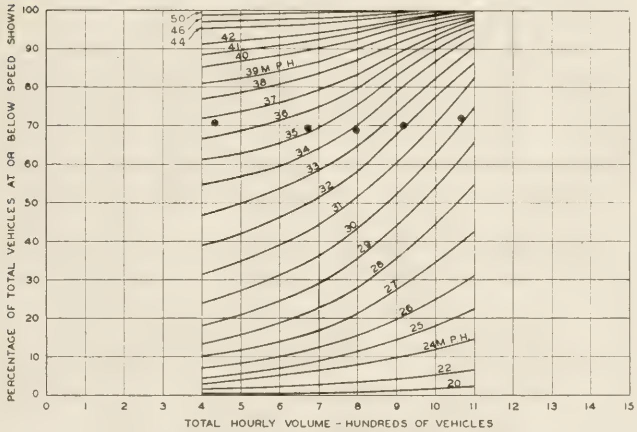


FIGURE 16.—CUMULATIVE PERCENTAGE DISTRIBUTION OF SPEEDS IN RELATION TO VOLUME OF TRAFFIC. SECTION 1-O, 2-LANE TANGENT.

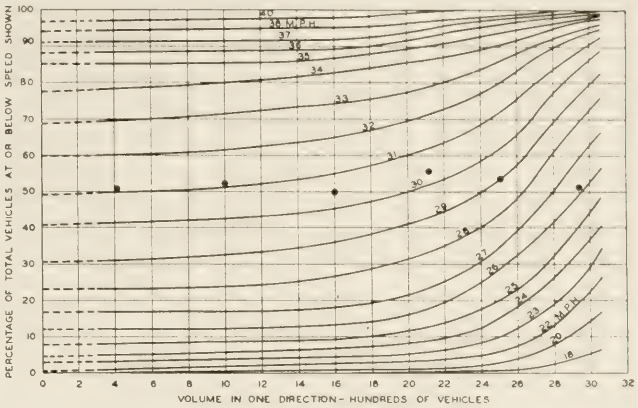


FIGURE 17.—CUMULATIVE PERCENTAGE DISTRIBUTION OF SPEEDS IN RELATION TO VOLUME OF TRAFFIC. SECTION 1-E, 4-LANE UNDIVIDED TANGENT.

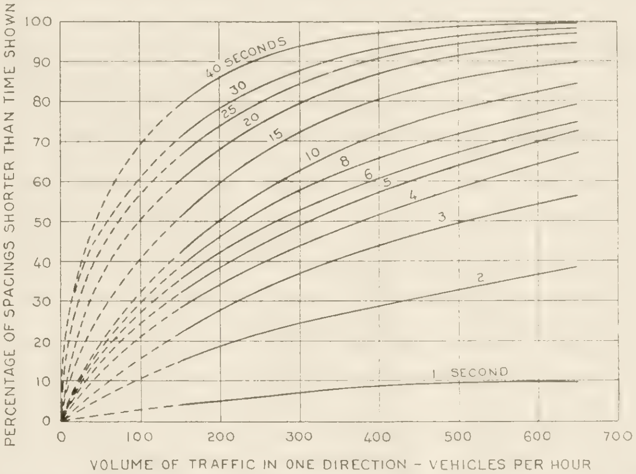


FIGURE 18.—FREQUENCY DISTRIBUTION OF TIME SPACINGS BETWEEN SUCCESSIVE VEHICLES AT VARIOUS VOLUMES OF TRAFFIC. SECTION 2-H, 2-LANE TANGENT.

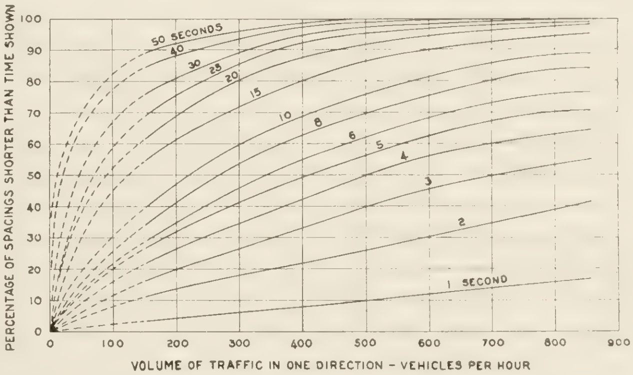


FIGURE 19.—FREQUENCY DISTRIBUTION OF TIME SPACINGS BETWEEN SUCCESSIVE VEHICLES AT VARIOUS VOLUMES OF TRAFFIC. SECTION 2-J, 3-LANE TANGENT.

All time spacings between vehicles in one direction passing in 1 hour obviously total 3,600 seconds, and the average time spacing in seconds may be determined by dividing 3,600 by the hourly traffic volume in that direction. One would normally expect to find 50 percent of the time spacings shorter than the average spacing and 50 percent longer than the average spacing. At this location, when the volume was 200 vehicles per hour and the average spacing 18 seconds, 66 percent of the spacings were less than 18 seconds. At 300 vehicles per hour, 66 percent of the spacings were less than the average spacing of 12 seconds, and at 600 vehicles per hour, 72 percent of the spacings were less than the average spacing of 6 seconds. Regardless of the traffic volume, from 66 to 72 percent of the vehicles were at spacings shorter than the average spacing, and from 45 to 55 percent of the spacings were shorter than one-half of the average spacing.

The distribution of time spacings for corresponding volumes of traffic on the three-lane section illustrated by figure 19 was almost the same as for the two-lane section, although the average speeds were not the same. At a volume of 200 vehicles per hour, 66 percent of the spacings were shorter than the average spacing of 18 seconds, and at 600 vehicles per hour about 68 percent of the spacings were shorter than the average spacing of 6 seconds. Forty-five percent of the spacings were shorter than one-half of the average spacing, regardless of the traffic volume.

The curves shown in figure 20, representing the time spacings for another two-lane section, are nearly the same as those for the other two-lane section, and all except those for the very short time intervals are nearly the same as those for the three-lane highway. From 68 to 75 percent of the spacings were shorter than the average spacing and (for volumes up to 800 vehicles per hour in one direction) from 45 to 62 percent

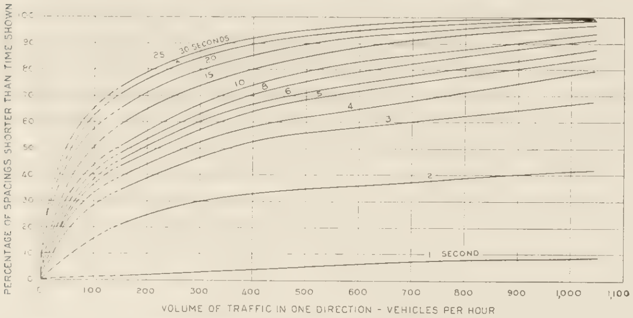


Figure 20.—Frequency Distribution of Time Spacings Between Successive Vehicles at Various Volumes of Traffic. Section 3–J, 2-Lane Tangent.

of the time intervals were shorter than one-half of the average time interval.

The most significant facts revealed by the study of the frequency distribution of the time spacings for a number of highway locations are:

1. As the volume of traffic increased on any particular highway there was a fairly uniform change in the frequency distribution of the time spacings rather than a sudden change at any particular volume of traffic.

2. Except for the very short time spacings, the frequency distribution of the spacings for any particular volume of traffic in one direction was practically the same on one highway as another regardless of the speed that the vehicles were traveling.

3. There was a very skewed distribution of the time spacings regardless of the volume or speed of traffic or type of highway. At any traffic volume, from two-thirds to three-fourths of the vehicles were at less than the average time spacing from the preceding vehicle.

TIME SPACING DATA USED TO DETERMINE OPPORTUNITIES TO PASS

A study of the distribution of distance spacings between successive vehicles showed the same relative distribution as the time spacing, but they varied with the average vehicle speed as well as with the volume of traffic. That is, a highway accommodating 300 vehicles per hour at a speed of 30 miles per hour would have the same percentage of the spacings exceeding 500 feet as the percentage that exceeded 750 feet on a highway accommodating 300 vehicles per hour at a speed of 45 miles per hour.

Traffic cannot move freely on a highway unless it is possible for faster moving vehicles to overtake and pass slow moving vehicles. On two-lane highways passing is not possible even on tangent sections except during periods when the left lane is not occupied by oncoming traffic. With the oncoming traffic moving at the same speed as the passing vehicle, the time spacing between succeeding vehicles in the opposing lane of traffic must be at least twice as great as the time required by the passing vehicles to perform the passing maneuver.

Characteristic patterns of time spacing distributions as illustrated in figure 20 can be used to determine the number of times per hour that any given time spacing between succeeding vehicles in the opposing lane will be exceeded. The percentage of the total time that a vehicle is opposite a time spacing in the opposing traffic which exceeds a certain magnitude may also be determined from the data. As an example, assume that a car is traveling on a two-lane highway with 400 vehicles per hour in the opposing lane of traffic. Out of every 400 vehicles that the car meets, 80 vehicles or 20 percent of the total vehicles will be 15 seconds or more behind the vehicle they are following. The 80 spaces total 2,448 seconds, so for 68 percent of each hour the car is opposite spaces equal to or exceeding 15 seconds. The dashed lines on figure 21 show the percentage of the total time that the car will be opposite spaces equal to or in excess of 15, 20, 25, and 30 seconds for volumes as high as 900 vehicles per hour in the opposing lane. These values will be the same regardless of the speed the car travels and will not vary appreciably for different average speeds of traffic in the opposing lane.

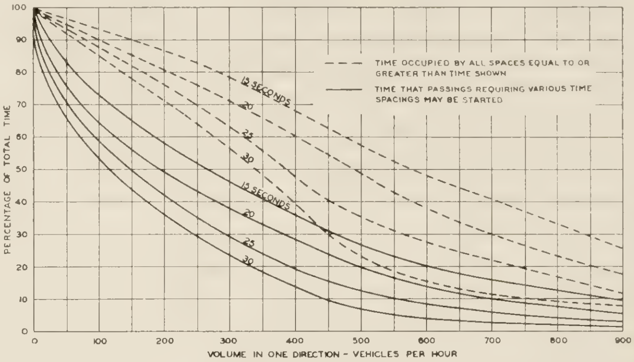


Figure 21.—Percentage of Total Time Occupied by Various Time Spacings Between Vehicles and Percentage of Total Time That Passings Requiring Various Time Spacings May Be Started. Section 3–J, 2-Lane Tangent.

A passing requiring a time interval of 15 seconds in the opposing traffic cannot be started after a portion of the 15-second interval has elapsed. It is only while the time interval is in excess of 15 seconds that such a passing may be started. To find the percentage of the total time that a passing may be started, it is necessary to subtract the required passing time interval from each of the intervals in excess of the minimum spacing. Thus from the total of 2,448 seconds occupied by the 80 spaces equal to or in excess of 15 seconds, 80 × 15 or 1,200 seconds must be subtracted leaving 1,248 seconds, or about 35 percent of the time, that such a passing may be started.

The solid lines of figure 21 indicate the percentage of the total time that passings requiring time intervals of 15, 20, 25, and 30 seconds in the opposing traffic may be started. Until the results of the passing studies recently conducted are analyzed, the exact time intervals required for various passing operations will not be known, but from available data it is believed that the intervals shown will include a large majority of the passings that occur on two-lane highways.

There are a number of ways in which this information may be used: First, assume that a fast-moving vehicle, traveling on a long tangent, is overtaking a slow-moving vehicle traveling in the same direction, and that a minimum interval of 15 seconds between vehicles in the opposing lane will be required to allow the fast-moving vehicle to pass. When the opposing traffic is 150 vehicles per hour, the chances are that 65 percent of the time, or two out of every three times, the passing maneuver can be made without first slowing down and waiting for an opportunity to pass. With an opposing volume of 600 vehicles per hour the chances are reduced to 20 percent or 1 out of every 5 times.

For the second illustration, assume that the fast-moving vehicle has been required to slow down to the

(Continued on page 240)

COMPARISON OF METHODS FOR DETERMINING THE HILL CLIMBING ABILITY OF TRUCKS

Reported by CARL C. SAAL, Assistant Highway Engineer, Bureau of Public Roads

ONE of the most serious problems confronting highway engineers today is that of increasing the traffic capacity of the more congested two-lane highways. The simple solution to this problem—the construction of additional traffic lanes—is prohibitive in cost for application to any but a limited mileage of the most heavily traveled roads. Alternative methods include the increasing of sight distances to provide more frequent opportunity for faster moving vehicles to pass slow vehicles, and the speeding up of slow-moving vehicles.

Particularly on hills do slow moving vehicles restrict traffic flow, with consequent delay, inconvenience, and hazard.

Commercial vehicles especially are frequently loaded so heavily that with the power available their speeds are so reduced on the steeper grades that long lines of vehicles accummulate behind them. Under such conditions, drivers become impatient and attempt passing maneuvers their better judgment would warn them against.

Such remedies as increasing sight distances or, as has been suggested, building additional lanes on hills, are localized in their character. A more comprehensive solution of the broad problem lies in measures to speed up the slower vehicles, either by reducing the steeper grades or by increasing the engine power of the slower vehicles. The State-wide highway planning surveys will reveal the number and lengths of excessive grades. From these figures, estimates may be made of the cost of reducing the steepest of the grades on the more heavily traveled roads to some more reasonable slope.

If the steepest gradients were, for example, 9 percent, it is possible that at no great expense all such grades could be reduced to 8 percent. At a greater cost, the more numerous 8-percent grades could be reduced to 7 percent, and so on, each successive step involving mileage increasing in a geometric ratio until some point would be reached beyond which it would be hopeless with available funds to attempt further reductions. The grade represented by this point would then be one over which speeds within the desired range must be maintained. The lower limit of this speed range is one at which all vehicles may travel without undue restriction of power or load, yet not so low that the drivers of following vehicles will by their impatience become reckless in their actions.

That the problem is becoming critical is evidenced by the numerous proposals advanced regarding the regulation of the performance of motor trucks. To forestall the imposition of hasty or ill-advised regulation, and to facilitate an intelligent evaluation of the relative economies of reducing gradients and of increasing the power of trucks, are the purposes of an exhaustive study of motor trucks now in progress. In cooperation with a number of truck manufacturers, the Quartermaster Corps of the United States Army, and the National Bureau of Standards, the Bureau of Public Roads is now determining the hill-climbing ability of some 30 new trucks, covering the range of sizes and makes most generally encountered in the eastern portion of the country.[1]

These studies will determine the maximum performances of new vehicles in the best of condition, operating under the heaviest loads they may be expected to carry. That throughout the life of these vehicles their performance will remain at the original level is unreasonable to expect; accordingly similar studies must be conducted on used vehicles in various stages of wear. Finally, any vehicle, new or used, may perform much less satisfactorily under ordinary driving in actual use than when under test. The complete analysis of performance will then require a determination of the best performance, the loss of ability through wear and age, and the factor to apply to compute the normally anticipated performance from the maximum performance for the vehicle condition.

ACTUAL GRADE TESTS MOST ACCURATE AND COMPLETELY ADEQUATE METHOD

Data collected in the State-wide highway planning surveys will show the types of vehicles and loads they carry on any given highway. Use of these data in conjunction with information on the road profile and the results of the ability tests will reveal within very close limits the effect of any performance regulation that might be enacted. By judicious correlation between grade reduction and regulation of the loads and power of vehicles, reasonable freedom of movement may be effected with the greatest economy.

A number of methods are being used to determine the hill-climbing abilities of new motortrucks. They are: (1) Actual grade tests made by applying various loads to vehicles and observing the speeds that they can maintain on a series of known grades, (2) theoretical hill-climbing ability computed from engine-torque and power curves, (3) acceleration tests by which the drawbar effort available at various road speeds over the entire useful speed range of each gear is determined, and (4) drawbar dynamometer tests which measure the drawbar pull available over the entire useful speed range of each transmission gear.

The actual grade tests are the most satisfactory in that no question can be raised as to their adequacy. These tests are laborious and expensive, and thus would not be practical where it is necessary to test a large number of trucks in a short period of time. One of the purposes of the study now being conducted is to develop a method by which accurate results can be obtained more quickly and economically. The results of the grade tests will be used to evaluate the results obtained by various other methods.

This report discusses the results obtained from tests made by the various methods on one truck designated as truck A operating in third gear on five grades. The grade ability, as determined by the grade tests, is ex-

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[1] Facilities used in analyzing the data are provided by the Johns Hopkins University.

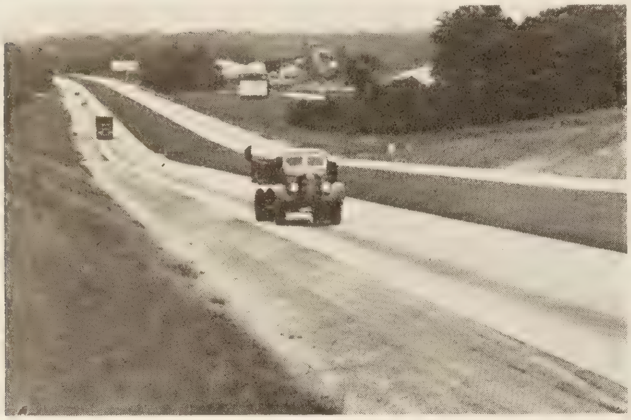

Figure 1.—Truck Climbing Grade in Grade Ability Tests.

Figure 3.—Chronograph Tape Record Being Analyzed in the Office

pressed in terms of the gross vehicle weight that the truck can pull up the particular grade at a given speed. The results obtained by the other methods are converted to the same units. A comparison is then made between the results of the grade tests and those of each of the other methods.

Figure 2.—Truck Equipped with Chronograph and Bicycle Wheel as Used in Grade Ability Determinations.

Grade tests.—In the grade tests known loads are applied to the truck and the maximum speed that it can maintain on known grades with each load is determined. The maximum gross vehicle weight that the truck can pull up the grade at a constant speed in a given gear is determined by trial, using the performance indicated by an ability formula as a guide. Starting with the maximum weight that can be hauled in a given gear, the load is decreased by 1,000-pound decrements and the maximum sustained speed for each load determined. The gross vehicle weight is decreased until the road speed observed corresponds to an engine speed that approximates the maximum recommended by the manufacturer for safe operation of the engine. As soon as the tests in one gear are completed, they are repeated in the gear with the next higher gear ratio. Figure 1 shows a truck climbing one of the test grades.

Several test runs on the grade are required to determine the maximum sustained speed for each load. The test truck approaches the grade at a speed estimated to be the speed that can be sustained over the entire length of the grade. All test runs are made with full throttle. An observer in the cab of the truck records the speed indicated by the truck speedometer at the start and finish of the run, and determines whether a sustained speed is reached. If the vehicle accelerates or decelerates on the first test run, the grade is entered on the next run at the speed that was recorded when the truck left the test course on the preceding run. After a constant climbing speed is observed on one run, it is verified by a check run. Generally the grade is reentered at speeds first above and then below that finally determined as the sustained speed to insure that it has been correctly determined.

The speedometer is used only as a guide in the field work. The actual speed maintained on the grade is measured by means of a time-distance recorder. The recording unit is a chronograph with three magnetic recording styles. Two brushes riding on a two-point cam, mounted on the axle of a bicycle wheel attached to the truck bumper, are wired in series with one of the styles, and cause each half revolution of the wheel to be recorded. A clock with six contacts on the second hand shaft wired in series with another of the styles furnishes a time record at 10-second intervals. A telegraph key, wired in series with a third style, is used to

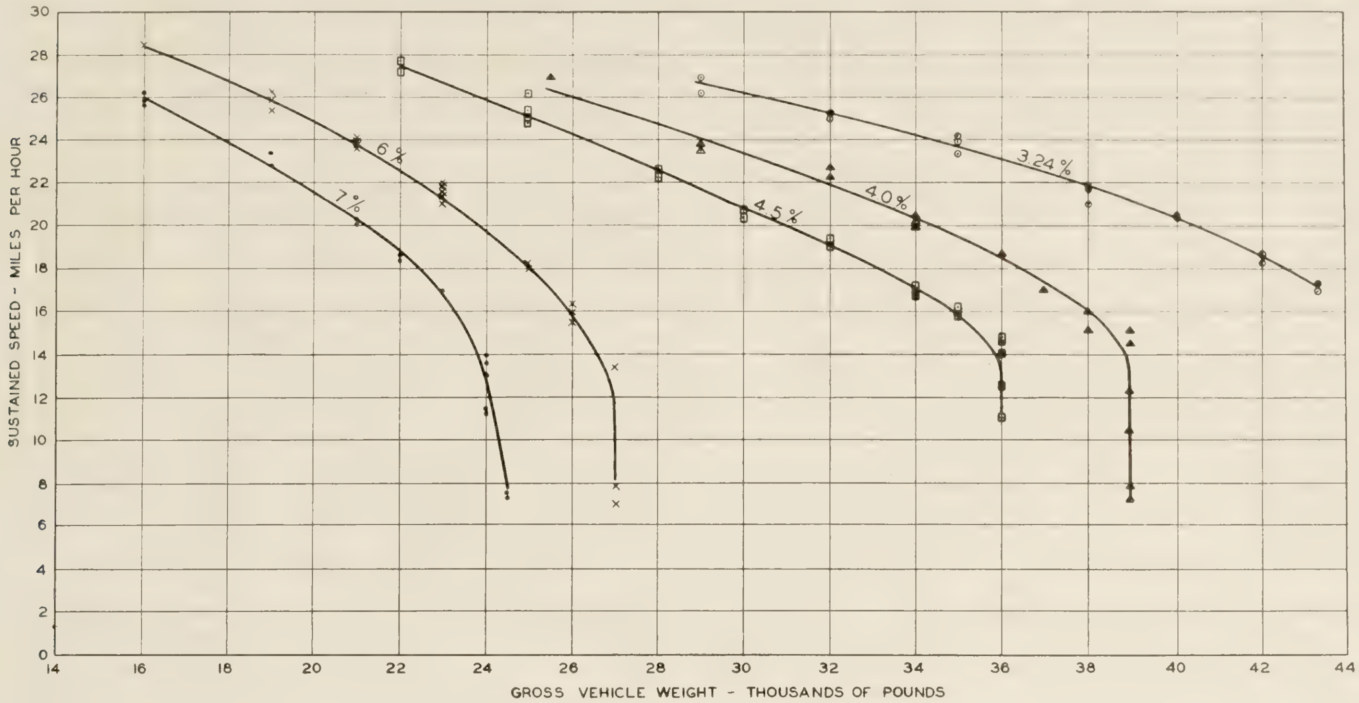

Figure 4.—Hill Climbing Ability of Truck A Operating in Third Transmission Gear, by Actual Grade Tests.

mark the beginning and the end of the test course. Figure 2 shows a truck with the bicycle wheel attached to the front bumper.

Approximately instantaneous speeds are computed at short intervals by scaling the time required for a given number of revolutions of the bicycle wheel. The revolutions per second are computed and multiplied by the circumference of the bicycle wheel in feet to give the speed in feet per second, which in turn is converted to speed in miles per hour. Figure 3 shows a chronograph tape record being analyzed. From the record of instantaneous speeds it is possible to determine whether the vehicle is accelerating, decelerating, or maintaining a uniform speed at any desired time. Having thus determined the distance over which a uniform speed was maintained, the average speed for that entire distance is computed to give results with an error of less than 1 percent.

THEORETICAL PERFORMANCE CLOSELY CHECKED ACTUAL PERFORMANCE

The results obtained from grade tests on truck A operating in third gear on grades 3.24, 4, 4.5, 6, and 7 percent are shown in figure 4. The gross vehicle weights in thousands of pounds are plotted as abscissae and the speed in miles per hour as ordinates. The results shown here are the base data to which the results obtained from the other methods are compared.

Theoretical performance.—The theoretical performance of a vehicle is computed by reducing the engine torque through the transmission gears, axle gears, and driving wheels to rim pull or tractive effort. The tractive effort is the force produced, at the tire surface of the driving wheels, that is available to act against the resistances that oppose the motion of the vehicle.

The performance formula is derived by equating the tractive effort to the rolling resistance plus grade resistance. The tractive effort is obtained by dividing the torque at the driving axle by the rolling radius The torque produced at the driving axle for a given engine speed is the product of the engine torque, the total gear reduction, and the over-all efficiency. The grade resistance is the component of the gross vehicle weight along the grade and is the product of the tangent of the grade and the gross weight for all small grades, since the sine and the tangent of such angles can be considered equal without introducing substantial error. The rolling resistance is the product of the coefficient of rolling resistance, and the gross vehicle weight. The following formula then results: Tractive effort is equal to grade resistance plus rolling resistance.

$$\frac{T\times E\times R}{r}=(W\times f)+(W\times G)$$

or

$$W=\frac{T\times E\times R}{r\ (f+G)}$$

where T=Torque at a given engine speed, in pound-inches.
E=Over-all efficiency of vehicle.
R=Total gear reduction.
r=Rolling radius, in inches.
W=Gross vehicle weight, in pounds.
f=Coefficient of rolling resistance, in pounds per pound of weight.
G=Grade, in feet of rise per foot.

The torque as determined from engine performance curves for any given engine speed can be substituted in the above formula. The engine speed can be converted to road speed by reducing it by the total gear reduction and multiplying by the circumference of the driving wheels. In this manner the gross vehicle weight that can be pulled up a given grade at a given road speed can be determined.

The comparison between the hill-climbing ability indicated by the performance formula and that determined by actual grade tests is shown in figure 5. Again gross vehicle weight in thousands of pounds is plotted

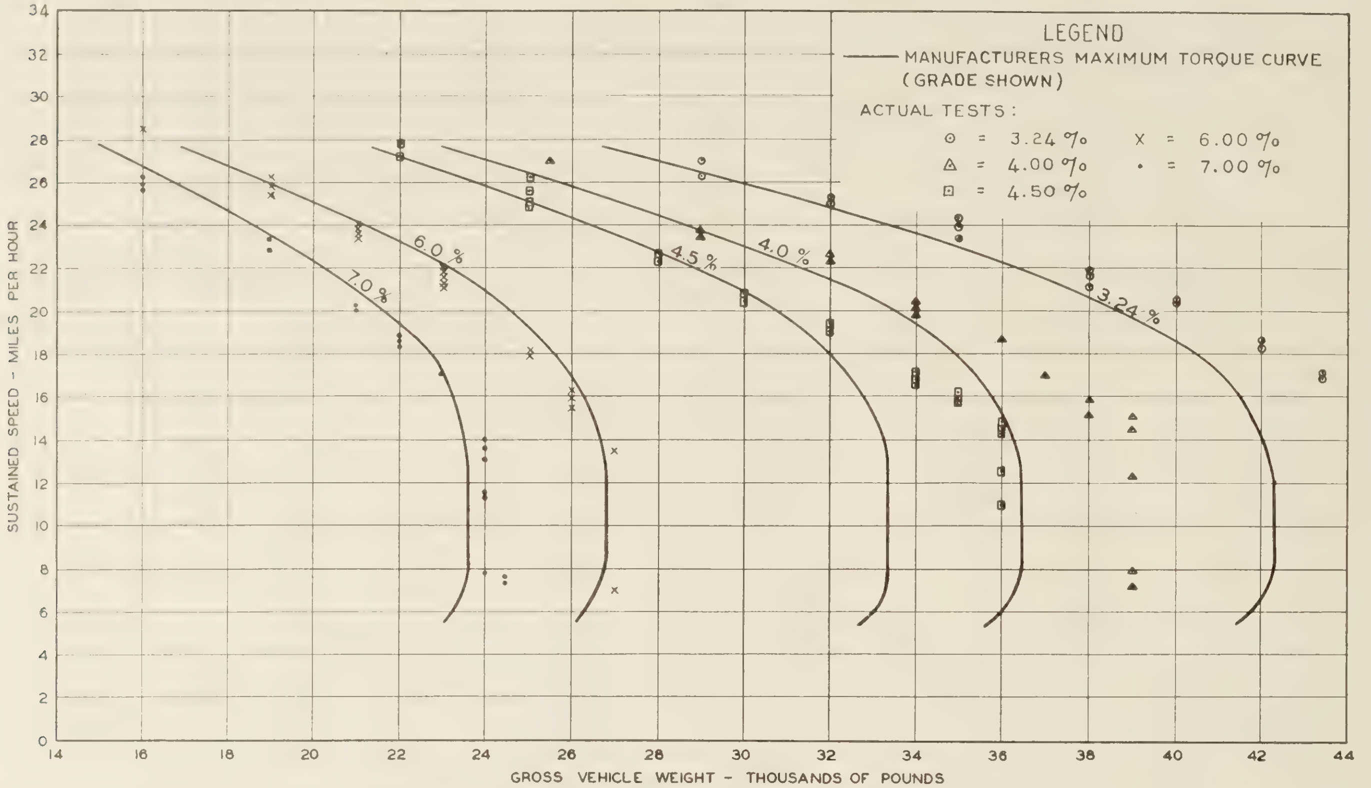

FIGURE 5.—COMPARISON OF HILL CLIMBING ABILITY AS DETERMINED BY ACTUAL GRADE TESTS AND BY PERFORMANCE FORMULA, FOR TRUCK A OPERATING IN THIRD GEAR.

against speed in miles per hour for each of the five grades. The plotted points indicate the actual performance, and the solid curves the theoretical performance.

An efficiency factor of 85 percent, and a coefficient of rolling resistance of 15 pounds per thousand, are assumed for computing theoretical performance. These values are the ones most commonly used. The engine torque is taken from curves furnished by the manufacturer. The rolling or loaded radius given by tire manuals for the size of tires on truck A is used.

The accuracy of the engine torque curves and of the assumptions made concerning efficiency and rolling resistence is indicated by the variation of the results obtained by the two methods. The results check remarkably closely except over the peak torque range. The rolling resistance as determined by deceleration tests on the level indicate that the coefficient of rolling resistance for truck A, operating at the road speeds at which peak torque is developed, is approximately 10 pounds per thousand. The difference between 15 pounds per thousand used here and 10 pounds per thousand is equivalent to ½ percent of grade. It will be noticed in figure 5 that results for the 4 and 4.5 percent grades verify this.

Dynamometer tests are being made on the engine of each truck after the grade tests have been completed. The results of these tests, together with the actual performance and the coefficient of rolling resistance measured by deceleration tests, will be used later to determine the true efficiency factor, and with these more accurate factors, it is believed that the performance can be computed with a fairly high degree of accuracy.

Acceleration and deceleration tests.—These tests are made on a level section of road. The truck is accelerated in each transmission gear at full throttle, starting at the slowest speed at which the engine will operate smoothly and continuing to the maximum recommended engine speeds. The drawbar pull or force produced at the drive wheels of the truck for any given road speed throughout the useful speed range of any gear is a function of the acceleration at that road speed and the mass of the truck.

SAMPLE COMPUTATIONS GIVEN FOR DRAWBAR PULL AND COEFFICIENT OF ROLLING RESISTANCE

Deceleration tests are made on the level by first attaining a desired speed and then permitting the truck to coast with transmission in neutral. The deceleration measured at a given road speed is proportional to the force that opposes the motion of the vehicle. This force or tractive resistance is composed principally of the friction between the tires and the road surface, and air resistance.

A time-distance record of each acceleration and deceleration run is obtained with the same time-distance recorder that was used in the grade tests. The time-distance record obtained is divided into two-second intervals, and instantaneous speeds are computed at each time interval. Time-speed curves are plotted whose abscissae are time in seconds and ordinates are speed in miles per hour. Thus the slope of the time-speed curve at any point is the acceleration or deceleration of the test truck. The acceleration or deceleration in miles per hour per second is determined at various road speeds and plotted against speed in miles per hour. The values of acceleration and deceleration as shown by these curves are used to compute the drawbar pull and the tractive resistance in the following manner:

Since the tractive resistance is a function of the deceleration and the mass of the vehicle, the following relation is true:

$$R = -a\ (M + K_0) \quad \text{(1)}$$

where R = tractive resistance in pounds.
$-a$ = deceleration, in feet per second per second.
K_0 = mass equivalent constant for vehicle coasting in neutral.
M = mass of vehicle $\left(\frac{w}{g}\right)$.

The drawbar pull is proportional to the acceleration and the mass of the vehicle and the following relation is derived:

$$P = a\ (M + K_x) \quad \text{(2)}$$

where P = drawbar pull, in pounds.
a = acceleration of vehicle, in feet per second per second.
M = mass of vehicle $\left(\frac{w}{g}\right)$.
K_x = mass equivalent constant for vehicle operating in a given transmission gear.

Rotating parts of a vehicle store up energy when the vehicle is accelerating. Since in every ordinary motor vehicle the speed ratio of these parts to road speed is fixed, the magnitude of this stored energy is in constant relation to the mass of the vehicle. This mass equivalent constant is determined with the engine operating in each transmission gear and for the vehicle coasting in neutral.

The tractive resistance is computed at 2-mile-per-hour intervals. This force is divided by the weight of the test truck in thousands of pounds to obtain the coefficient of tractive resistance or rolling resistance. Figure 6 shows the coefficient of rolling resistance plotted against speed in miles per hour. A typical point is determined as follows: At 20 miles per hour the deceleration is −0.258 feet per second per second. The weight of the vehicle (23,000 pounds) divided by the acceleration of gravity (32.2 feet per second per second) equals the mass of the vehicle (714). The mass equivalent constant for the vehicle coasting in neutral is 82. The tractive resistance, computed by equation (1), is found to be 205.4 pounds. This force of 205.4 pounds is divided by the weight of the vehicle in thousands of pounds (23) to give the coefficient of rolling resistance. The coefficient is 8.9 pounds per thousand and is plotted opposite 20 miles per hour on figure 6.

The drawbar pull is also computed at 2-mile-per-hour intervals over the useful speed range of each transmission gear. For truck A operating in third gear the results are shown in figure 7, in which drawbar pull in pounds is plotted against speed in miles per hour. A typical point is determined as follows: The acceleration measured at 20 miles per hour is 1.788 feet per second per second. The mass of the vehicle (714) is the weight (23,000 pounds) divided by the acceleration of gravity (32.2 feet per second per second). The mass equivalent constant for truck A operating in third gear is 132. The drawbar pull is therefore 1,513 pounds as computed by equation (2). This force is plotted opposite 20 miles per hour in figure 7.

The total force produced at the tire surface of an accelerating vehicle at any given speed is equal to the drawbar pull plus the tractive resistance of the test vehicle. This force can be utilized to pull a certain gross vehicle weight up a given grade at the road speed for which the force is measured. The force is equated to the component of the gross vehicle weight along the grade and the tractive resistance of the vehicle on the grade. The gross vehicle weight is computed, using the following formula:

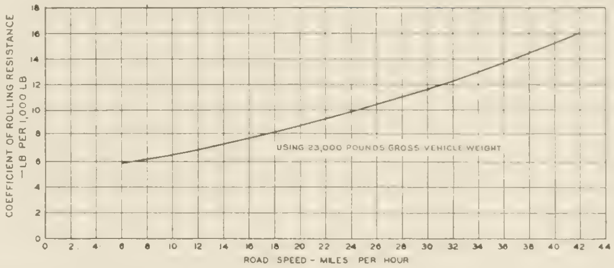

FIGURE 6.—RELATION BETWEEN COEFFICIENT OF ROLLING RESISTANCE AND SPEED, FOR TRUCK A.

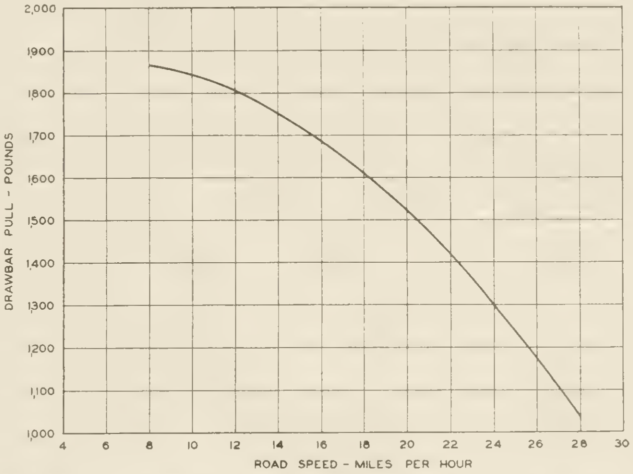

FIGURE 7.—DRAWBAR PULL AVAILABLE AT VARIOUS ROAD SPEEDS, FOR TRUCK A.

$$P + (w \times f) = (W \times G) + (W \times f) \quad \text{(3)}$$

where

P = the force proportional to the acceleration of the vehicle.

$(w \times f)$ (weight of vehicle × coeficient of rolling resistance) = tractive resistance of accelerating vehicle at speed for which drawbar pull was measured.

$(W \times G)$ (gross vehicle weight × tangent of gradient) = grade resistance.

$(W \times f)$ (gross vehicle weight × coefficient of rolling resistance) = tractive resistance of vehicle on grade.

DYNAMOMETER TESTS QUICKLY PERFORMED AND RESULTS EASILY COMPUTED

The drawbar pull measured at various road speeds for truck A operating in third gear is converted to grade ability for the five grades. The results are shown in figure 8, in which gross vehicle weights are plotted against speeds in miles per hour. The solid lines indicate the results obtained by acceleration tests and the plotted points again show the results obtained by the actual grade tests. Typical points are determined as follows: The drawbar pull at 20 miles per hour is 1,513 pounds, as indicated in figure 7. The coefficient of rolling resistance at 20 miles per hour is 8.9 pounds per thousand, from figure 6. The tests were made with a gross vehicle weight of 23,000 pounds. For the test grades of 3.24, 4, 4.5, 6, and 7 percent the gross vehicle weights that can be carried on each grade at 20 miles per hour are 41,500, 35,100, 31,800, 24,900, and 21,800

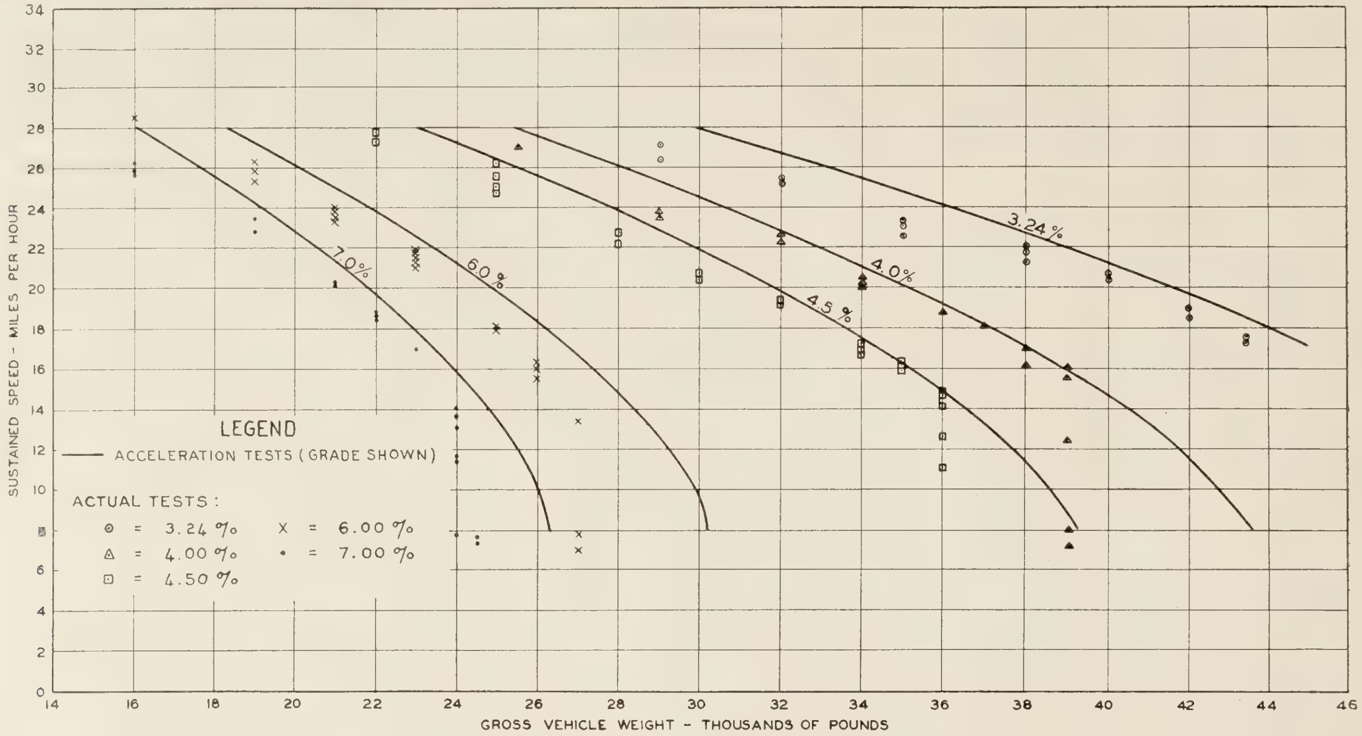

FIGURE 8.—COMPARISON OF HILL CLIMBING ABILITY AS DETERMINED BY ACTUAL GRADE TESTS AND ACCELERATION TESTS, FOR TRUCK A OPERATING IN THIRD GEAR.

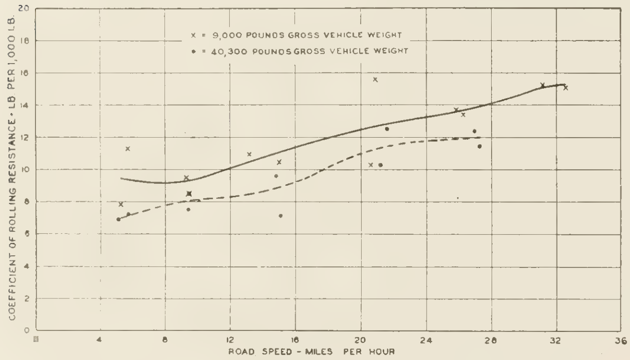

FIGURE 9.—RELATION BETWEEN COEFFICIENT OF ROLLING RESISTANCE AND ROAD SPEED AS MEASURED BY FIELD DYNAMOMETER, FOR TRUCK A.

pounds respectively. These weights are plotted opposite 20 miles per hour in figure 8.

Drawbar dynamometer.—A special dynamometer, called a "field" dynamometer, developed by the Ordnance Department of the United States Army, was made available for these studies. This dynamometer consists of a 10-ton truck on which two fire pumps are mounted. The pumps are connected to the main propeller shaft back of the transmission by means of a two-speed auxiliary transmission. When the dynamometer vehicle is towed by the test vehicle, the rear wheels of the truck actuate the pumps, forcing water from a tank through a pipe with an adjustable orifice and then back to the tank. By regulating the size of orifice the discharge pressure of the pumps can be increased or decreased, which in turn increases or decreases the torque required to turn the rear wheels. In this manner various loads can be applied to the vehicle pulling the dynamometer.

Drawbars are mounted on the front and rear of the dynamometer truck. Each drawbar is composed of a cylinder and piston, the former being held stationary relative to the dynamometer truck, while the latter is connected to the drawbar eye. Thus when the test vehicle tows the artificially loaded dynamometer truck, the pressure in the cylinder is recorded through an oil line and spring gage on a metallic chronograph tape. At the same time, marks from which road speed can be computed are recorded on the same chronograph tape to permit, by relatively easy means, the computation of the available drawbar pull at various road speeds. Resistance to traction is determined by towing the test vehicle behind the dynamometer truck. All drawbar-pull tests are conducted on a level course at full throttle, the artificial load and, correspondingly, the speed of the vehicles being regulated by an operator who varies the size of the orifice as indicated by an electric tachometer.

Figure 9 shows the coefficient of rolling resistance in pounds per thousand pounds plotted against speed in miles per hour. The drawbar pull obtained by means of the dynamometer is converted to hill-climbing ability in terms of gross vehicle weight and speed in the same manner as for the drawbar pull measured by the acceleration tests. The results for truck A operating in third gear are shown in figure 10. The solid curve indicates the results of the dynamometer tests, and the plotted points those of the actual grade tests.

The grade ability measured by the two methods varies by an amount that is approximately equivalent to a grade of one-half of 1 percent, the curve for calculated ability on a 4-percent grade coinciding very closely with the points showing the actual ability on a 4.5-percent grade. Although the results of the tests by this method do not compare too favorably with the actual grade results, it should not be concluded that the method is unsound. The field dynamometer was designed for use in testing heavy, slow-speed equipment such as tractors and tanks. The results obtained by

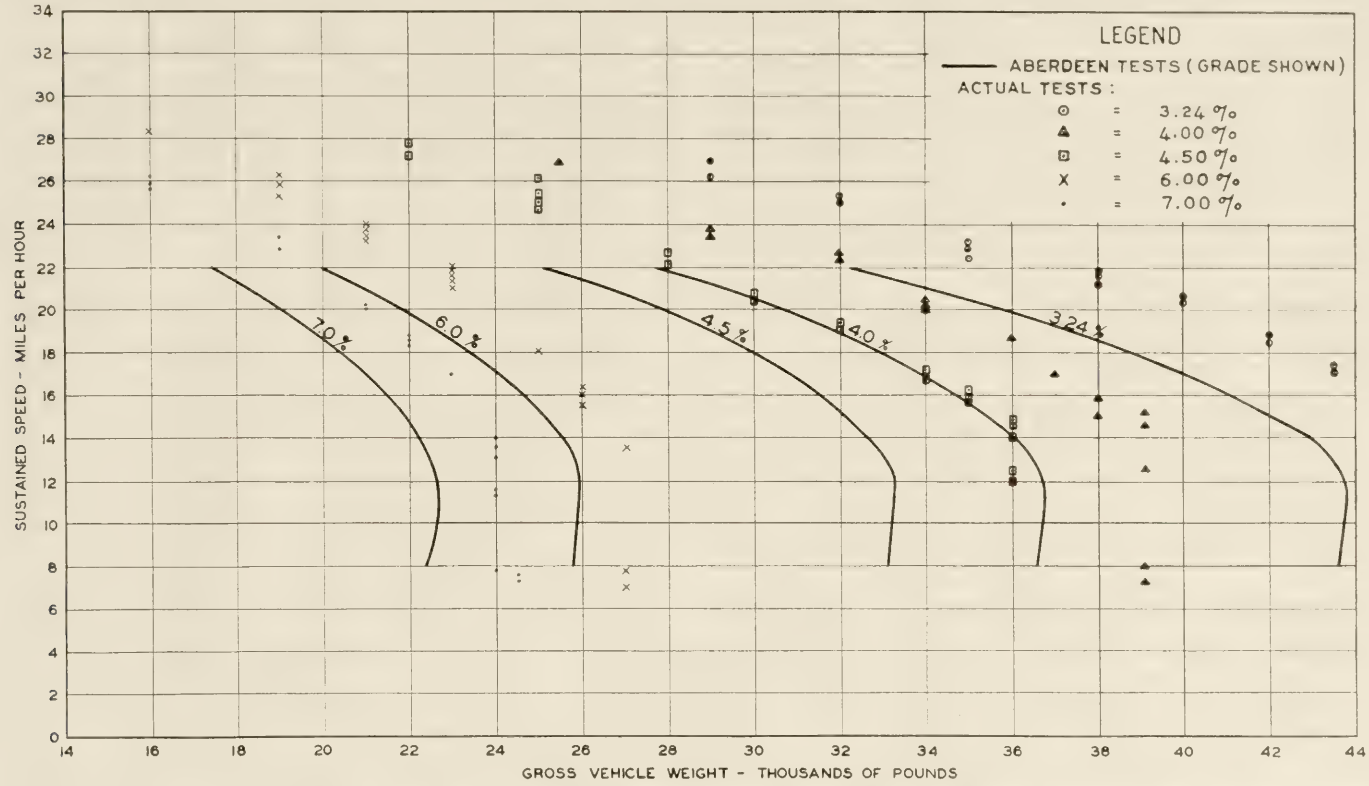

FIGURE 10.—COMPARISON OF HILL CLIMBING ABILITY AS DETERMINED BY ACTUAL GRADE TESTS, AND ABERDEEN PROVING GROUND DRAWBAR PULL TESTS, FOR TRUCK A OPERATING IN THIRD GEAR.

the two methods compared much more favorably when the vehicle was tested in the lower gears, although the speeds in those gears were well below normal road speeds. The differences were even more pronounced in towing the test vehicle to determine its tractive resistance, for the truck offered very little resistance and accordingly it was difficult to maintain a constant speed with the heavy dynamometer truck.

The method offers a distinct advantage in that relatively little computation is required to interpret the results, whereas involved calculations are required in analyzing the acceleration test data. Should a lighter dynamometer be available, it is likely that very accurate results could be easily and economically obtained.

The results discussed above have been confined to tests of one truck in one transmission gear. Similar comparisons have been made for each gear for each of the 18 units tested during the fall months of 1938. Additional new units will be tested in the spring months of 1939, after which attention will be directed to the testing of used vehicles.

It is anticipated that actual grade tests will be continued on all of the new vehicles, since they have been made available for exhaustive tests by various manufacturers who are cooperating in the study. Coincident with the determination of actual performance, other means of determining the performance such as those already described will be continued in anticipation of finally adopting the one that will provide data of sufficient accuracy most feasibly for the testing of large numbers of used vehicles.

CONCLUSIONS

Results thus far obtained, of which those presented here are reasonably typical, lead to the following conclusions:

1. Testing under actual load conditions over several grades will, of course, provide results of the greatest accuracy; however, this method is so laborious and expensive as to preclude its general usefulness.

2. The computation of grade ability from manufacturer's torque curves, provided reliable factors for overall efficiency and rolling resistance at various speeds are available, may be expected to yield reasonably accurate results.

3. The computation of grade ability from acceleration and deceleration tests will yield accurate results, especially in the more generally used range of engine speeds, and requires no data from the manufacturer. Complete tests require but a few hours in the field, but office computations are laborious. The method is, however, far cheaper than the actual grade tests, and the Bureau is now considering the development of instruments for a more precise determination of acceleration rates, in view of the probability of adopting this method for future work.

4. The towing dynamometer, or some similar device such as a chassis dynamometer, can undoubtedly produce accurate results quickly and in a usable form. Their high initial cost limits their use to operations requiring the testing of a large number of vehicles quickly.

(Continued from page 232)

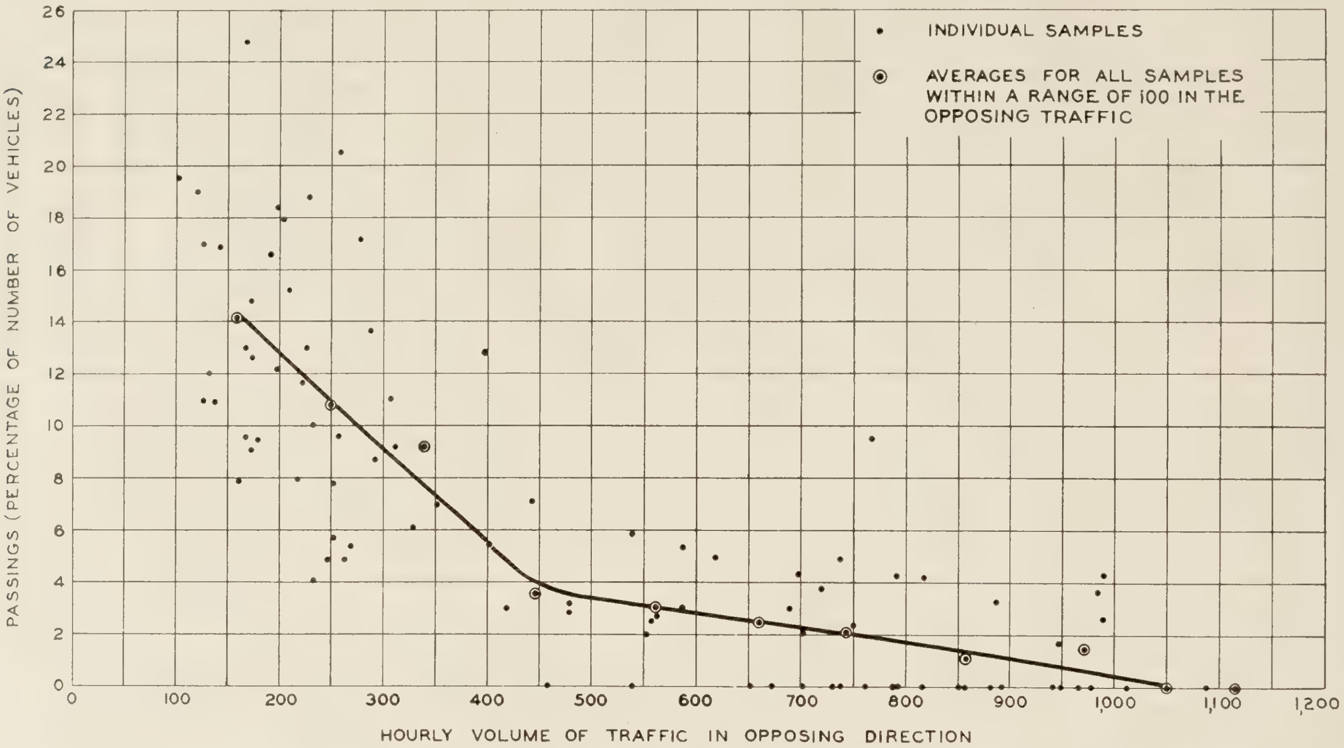

Figure 22.—Percentage of Vehicles Passing in One Direction with Various Volumes of Traffic in the Opposing Direction. Section 3-J, 2-Lane Tangent.

same pace as the slow-moving vehicle and that a 25-second interval in the opposing traffic will therefore be required for the passing maneuver. With an opposing volume of 600 vehicles per hour, the vehicle desiring to pass will have to wait 6¼ times as long (on the average) as if the opposing volume had been 150 vehicles per hour.

For the third condition, assume that the alinement of the highway is such that passing cannot be accomplished with safety except on tangent sections just long enough to see that an interval of sufficient length exists in the oncoming traffic. When the required interval is 25 seconds and the opposing traffic is 150 vehicles per hour, the chances are that there will be no oncoming traffic on the passing section 50 percent of the time, but with an oncoming volume of 600 vehicles per hour, the chances are that the vehicle desiring to pass will have to stay behind the slow-moving vehicle for an average of 12 such passing sections before one opportunity to pass will present itself.

At a volume of 1,100 vehicles per hour in each direction, there is practically no opportunity to pass, even on a highway with unlimited sight distances. This was the maximum possible volume arrived at by using mean differences in speed as the congestion index.

It may also be seen from figure 22 that no passings were made on section 3-J when the traffic volume in the opposing lane exceeded 1,100 vehicles per hour.

CONCLUSIONS

The results that have thus far been obtained by analyzing a comparatively small portion of the data furnish sufficient proof to conclude that:

1. Neither maximum nor practical working capacities can be determined solely from the relation between average speed and volume.
2. Consideration must be given to both speed and the relative interference between vehicles in determining practical working capacities.
3. All highways of the same width or number of lanes will not have the same maximum possible capacities or the same practical working capacities.
4. Although there is a wide variation in the driving characteristics of individual vehicle operators, certain fundamental principles of traffic behavior can be developed that will be generally applicable. The results may be entirely different from those derived by assuming average conditions.
5. The various study sections for which data have been obtained do not cover a sufficient range of highway designs and alinement to obtain the effect of all the variable factors on practical working capacities. Further data are necessary, especially as to the time required for vehicles to pass one another under various conditions.

A NEW HANDBOOK ON TRANSITION CURVES FOR HIGHWAYS

A handbook entitled "Transition Curves for Highways," by Joseph Barnett, Senior Highway Design Engineer, has recently been issued by the Bureau of Public Roads. The Bureau recommends the general use of transitions to increase safety and ease of travel and to improve the appearance of highways. The book includes a set of tables with which the design and location of curves with transitions involve only simple calculations and it is practicable to project an initial alinement that includes transitions for horizontal curves without material delay or expense because of the transitions. This procedure has decided advantage over projecting the alinement as tangents with simple curves and later revising it to include transitions. Such revision frequently involves repeated trials with consequent expense and delay.

Sections of the handbook discuss speed in relation to highway design, design of curves with equal transitions by use of tables, design of curves with transitions as a general case, parallel transitions, transitions for compound curves, adjusting alinement of simple curves for transitions, widening pavements on curves, and right-of-way lines in relation to transitions. All tables needed in applying the methods described are included.

The handbook, in a durable binding, is available only by purchase from the Superintendent of Documents, Government Printing Office, Washington, D. C., at 60 cents a copy.

STATUS OF FEDERAL-AID HIGHWAY PROJECTS

AS OF JANUARY 31, 1939

STATE	COMPLETED DURING CURRENT FISCAL YEAR			UNDER CONSTRUCTION			APPROVED FOR CONSTRUCTION			* BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	
Alabama	$ 5,498,126	$ 2,467,965	154.1	$ 8,404,552	$ 4,189,675	342.8	$ 1,261,780	$ 630,185	42.3	$ 3,532,108
Arizona	1,945,123	1,477,635	107.4	1,268,127	878,692	55.4	406,447	189,998	4.1	2,181,941
Arkansas	1,049,928	1,039,554	77.7	3,340,692	3,336,763	203.2	645,361	641,914	38.4	1,911,802
California	9,164,615	4,993,691	204.8	5,441,669	2,927,221	81.9	1,525,129	814,379	39.4	4,924,892
Colorado	2,489,482	1,347,520	90.5	2,804,813	1,478,357	93.8	1,531,850	851,780	31.5	2,861,883
Connecticut	934,030	455,835	8.9	684,518	337,455	7.9				2,149,026
Delaware	485,437	241,521	14.1	708,131	349,289	9.9	259,490	125,600	6.6	1,625,207
Florida	1,978,800	989,400	46.3	3,066,438	1,533,219	54.5	827,200	413,600	17.2	3,778,595
Georgia	4,512,812	2,205,528	225.4	4,817,250	2,408,625	227.9	1,127,860	563,930	83.4	7,717,488
Idaho	2,097,341	1,219,823	200.7	1,189,537	710,407	38.9	271,587	161,923	10.9	2,168,394
Illinois	10,983,560	5,457,228	299.7	7,228,026	3,610,414	151.8	3,318,011	1,658,960	76.8	5,016,862
Indiana	5,583,501	2,746,342	146.5	2,712,920	1,356,460	51.6	2,606,435	1,250,832	63.6	4,152,766
Iowa	7,372,868	3,437,619	238.9	4,901,212	2,072,883	156.9	526,096	119,000	34.8	2,605,932
Kansas	4,253,136	2,114,573	673.6	4,553,611	2,276,780	215.4	3,229,010	1,607,505	170.6	4,880,290
Kentucky	5,600,469	2,783,663	199.3	2,744,126	1,372,063	59.0	855,312	427,854	29.6	4,005,944
Louisiana	1,294,187	646,891	38.2	10,863,226	2,516,164	30.1	1,761,038	775,592	28.6	3,224,540
Maine	2,797,885	1,394,536	65.5	1,570,121	785,059	32.8	174,108	87,054	1.4	1,015,391
Maryland	1,085,456	542,728	17.1	2,516,978	1,233,351	40.7	726,570	363,000	10.2	2,362,285
Massachusetts	1,870,824	935,409	9.0	2,977,050	1,488,066	19.4	908,647	452,155	11.1	3,444,511
Michigan	7,698,130	3,716,055	163.7	4,024,208	2,011,452	117.7	1,348,325	672,430	32.3	3,829,757
Minnesota	4,760,858	2,296,147	289.3	6,086,869	3,020,665	279.3	1,153,760	575,975	61.2	4,629,540
Mississippi	2,049,958	940,417	82.8	10,043,462	3,857,052	435.4	1,723,590	666,270	73.3	3,525,814
Missouri	4,906,136	2,318,207	135.5	3,065,088	1,503,566	62.5	5,262,588	2,506,550	236.0	4,867,930
Montana	1,666,619	936,796	83.6	826,978	464,810	17.6	1,005,542	565,602	69.9	5,884,329
Nebraska	3,408,086	1,666,819	335.7	5,251,762	2,648,794	394.3	5,256,130	1,996,013	389.7	2,920,328
Nevada	1,443,091	1,236,906	168.8	1,301,341	1,122,550	51.0				2,015,222
New Hampshire	988,462	489,559	22.4	382,110	190,095	3.3	93,802	46,900	1.4	1,633,423
New Jersey	1,897,135	939,155	16.7	2,386,206	1,191,378	15.9	734,880	366,610	6.9	3,304,813
New Mexico	2,036,551	1,241,587	237.1	2,206,606	1,445,972	99.3	129,658	45,742	9.0	1,950,911
New York	14,153,092	6,947,158	253.2	9,751,777	4,830,992	158.6	3,347,230	1,527,398	60.2	5,033,757
North Carolina	6,425,599	3,088,829	254.8	5,110,619	2,554,152	342.3	838,540	395,000	41.0	3,727,947
North Dakota	3,372,957	3,241,828	261.5	500,901	290,805	57.5	69,522	37,236	6.8	5,091,159
Ohio	7,851,663	3,864,788	94.4	7,667,382	3,824,092	76.9	2,287,220	1,141,060	21.9	8,811,332
Oklahoma	5,118,083	2,691,081	226.1	3,493,243	1,802,200	79.6	1,692,800	892,645	51.6	4,491,195
Oregon	3,131,556	1,849,620	110.7	1,534,640	936,957	83.6	811,005	494,640	39.0	2,778,954
Pennsylvania	8,425,702	4,179,539	140.6	7,227,459	3,611,151	74.7	4,401,989	2,024,555	35.1	5,537,528
Rhode Island	1,179,290	589,645	16.4	372,212	186,106	3.5	307,320	153,660	3.2	1,394,638
South Carolina	4,543,984	1,999,748	247.1	3,362,381	1,508,776	94.4	287,891	137,700	11.1	2,493,886
South Dakota	1,974,839	1,106,433	245.7	4,674,676	2,585,190	441.5	339,070	187,490	27.8	4,157,378
Tennessee	5,183,970	2,576,497	168.0	2,973,769	1,487,606	49.6	1,503,040	751,520	44.7	5,413,859
Texas	11,548,473	5,711,218	757.0	12,852,190	6,347,476	554.4	4,063,009	1,946,379	284.6	9,017,839
Utah	1,055,963	740,744	112.0	2,139,223	1,517,650	73.4	109,720	78,320	4.2	1,605,990
Vermont	1,281,653	577,197	33.9	722,784	343,793	17.7	196,970	98,295	4.3	661,932
Virginia	5,918,394	2,957,016	204.9	2,956,476	1,476,203	89.1	876,084	435,937	11.0	2,160,077
Washington	3,977,752	2,080,870	99.5	2,751,911	1,441,059	28.3	369,697	193,800	7.9	2,082,024
West Virginia	1,784,387	1,287,765	65.4	1,296,682	649,266	26.5	916,770	454,535	26.7	2,977,222
Wisconsin	4,806,849	2,370,817	165.9	6,564,866	3,096,880	177.5	507,035	251,000	5.9	3,435,768
Wyoming	2,577,039	1,566,911	281.4	471,542	285,851	59.5	654,750	404,590	43.7	1,470,425
District of Columbia										487,500
Hawaii	834,497	414,174	18.0	822,330	403,270	9.3	22,380	8,600		1,692,677
Puerto Rico	53,980	26,990	2.1	1,428,309	710,910	29.0	292,606	144,945	5.8	839,030
TOTALS	197,052,328	102,147,977	8,111.9	186,042,999	92,207,662	5,877.1	62,564,854	30,336,658	2,316.7	173,484,041

* INCLUDES APPORTIONMENT FOR FISCAL YEAR 1940.

STATUS OF FEDERAL-AID SECONDARY OR FEEDER ROAD PROJECTS

AS OF JANUARY 31, 1939

STATE	COMPLETED DURING CURRENT FISCAL YEAR			UNDER CONSTRUCTION			APPROVED FOR CONSTRUCTION			* BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	
Alabama	$197,900	$ 98,950	11.9	$ 699,535	$ 347,300	37.7	$ 145,300	$ 72,650	7.4	$ 844,346
Arizona	306,947	204,457	20.6	140,213	98,773	15.5	7,440	5,357		561,405
Arkansas				214,013	206,520	19.6	177,852	176,436	19.8	736,539
California	1,192,055	677,708	84.8	862,219	480,053	53.8	474,629	249,730	9.1	1,009,418
Colorado	812,169	443,250	51.1	393,760	218,125	19.3	163,150	75,059	3.9	456,322
Connecticut	69,450	34,705	1.3	41,584	20,632	.2	73,750	17,780	1.1	338,764
Delaware	18,950	9,475	4.0	53,394	26,697	8.8	47,240	23,135	9.9	260,693
Florida				294,238	146,661	1.6	225,517	112,400	11.2	616,044
Georgia	227,175	107,451	29.4	638,206	319,103	81.0	152,620	76,310	21.6	1,132,139
Idaho	451,521	204,347	46.9	166,441	87,870	11.9	25,544	15,263	1.1	350,359
Illinois	1,622,533	809,530	139.9	1,360,732	626,366	71.5	410,500	196,750	28.1	1,002,676
Indiana	599,857	255,400	64.8	679,900	322,150	62.0	694,048	337,152	62.8	691,623
Iowa										1,679,807
Kansas	53,582	26,791	8.6	209,772	104,885	16.3	175,226	87,613	32.3	1,487,558
Kentucky	779,275	240,584	100.9	712,452	186,076	28.3	779,443	229,948	88.6	435,839
Louisiana	64,069	31,900	6.9	548,671	245,325	43.1	525,449	231,310	43.7	431,113
Maine	362,500	181,250	23.3	262,662	126,214	12.5	18,700	9,350	1.2	142,777
Maryland				145,174	67,987	11.2	220,800	82,855	14.2	384,839
Massachusetts				139,441	69,604	2.4	222,970	110,905	4.9	672,214
Michigan	409,561	203,281	37.0	648,404	324,202	42.2	433,200	215,850	23.6	1,244,155
Minnesota	280,091	131,160	42.2	520,760	258,336	39.1	293,532	146,766	23.4	1,248,943
Mississippi				299,000	149,500	23.8	44,700	22,350	17.0	979,016
Missouri	320,539	152,877	43.1	326,360	145,320	28.3	763,280	335,900	103.8	879,539
Montana				27,601	15,525					1,324,368
Nebraska	464,760	230,241	81.4	409,692	198,615	66.1	537,358	265,209	102.0	610,393
Nevada	424,798	354,271	68.8	116,832	98,265	15.5	26,563	23,035	1.6	211,675
New Hampshire	245,058	121,630	6.0	60,759	29,708	2.3				168,662
New Jersey	123,040	61,520	2.4	199,860	91,195	2.6				718,263
New Mexico	563,070	343,413	36.9	642,199	391,668	41.0				310,985
New York	2,309,847	1,145,068	166.3	1,751,000	875,500	88.2	148,000	74,000	11.4	994,816
North Carolina	605,156	302,064	72.3	948,444	474,200	76.8	73,270	32,400	9.4	621,719
North Dakota	52,020	27,860	9.0	169,910	90,999	26.1	42,770	22,907	8.2	875,311
Ohio	156,560	78,280	3.8	100,970	57,260	1.8	473,200	236,600	25.2	1,996,979
Oklahoma	166,690	88,690	16.2	280,142	147,943	22.1	617,940	305,608	37.0	990,263
Oregon	421,378	247,170	56.3	59,454	36,322	5.0	32,248	18,940	2.2	698,524
Pennsylvania	1,699,993	823,463	120.7	1,751,101	857,769	95.8	635,950	317,975	33.1	750,639
Rhode Island	66,840	33,420	3.5	162,675	81,314	4.8	74,070	37,035	.9	109,247
South Carolina	404,550	174,382	43.5	806,307	336,469	88.1	228,170	93,300	16.7	273,761
South Dakota				11,300	6,250					1,058,050
Tennessee	221,720	110,860	11.0	555,244	204,722	28.8	199,040	93,050	4.7	962,828
Texas	2,441,362	1,143,243	349.0	1,804,074	779,023	175.1	896,775	416,884	111.0	1,719,683
Utah	446,508	233,685	41.1	236,967	127,060	18.5	166,230	79,254	16.1	279,081
Vermont	240,777	109,790	13.8	90,306	45,153	4.0	43,300	20,500	.5	107,278
Virginia	508,847	237,293	61.2	741,920	335,935	44.9	180,212	90,106	26.4	501,361
Washington	552,121	287,690	63.7	381,920	200,878	20.1	349,621	184,100	20.1	292,460
West Virginia	211,600	105,800	16.5	149,546	74,773	11.1	45,300	22,650	2.1	508,756
Wisconsin	490,676	230,918	23.0	695,644	341,190	31.7	83,660	41,190	1.4	961,346
Wyoming	416,146	254,582	59.0	285,102	176,169	11.9	121,478	75,041	10.4	266,758
District of Columbia										73,125
Hawaii				56,250	28,125	2.4				291,875
Puerto Rico	74,740	37,370	3.9	274,584	136,020	16.2				146,610
TOTALS	21,076,431	10,595,819	2,046.0	22,126,734	10,815,749	1,531.0	11,050,045	5,280,653	969.1	35,410,943

* INCLUDES APPORTIONMENT FOR FISCAL YEAR 1940.

PUBLICATIONS of the BUREAU OF PUBLIC ROADS

Any of the following publications may be purchased from the Superintendent of Documents, Government Printing Office, Washington, D. C. As his office is not connected with the Department and as the Department does not sell publications, please send no remittance to the United States Department of Agriculture.

ANNUAL REPORTS

Report of the Chief of the Bureau of Public Roads, 1931. 10 cents.
Report of the Chief of the Bureau of Public Roads, 1933. 5 cents.
Report of the Chief of the Bureau of Public Roads, 1934. 10 cents.
Report of the Chief of the Bureau of Public Roads, 1935. 5 cents.
Report of the Chief of the Bureau of Public Roads, 1936. 10 cents.
Report of the Chief of the Bureau of Public Roads, 1937. 10 cents.
Report of the Chief of the Bureau of Public Roads, 1938. 10 cents.

HOUSE DOCUMENT NO. 462

Part 1 . . . Nonuniformity of State Motor-Vehicle Traffic Laws. 15 cents.
Part 2 . . . Skilled Investigation at the Scene of the Accident Needed to Develop Causes. 10 cents.
Part 3 . . . Inadequacy of State Motor-Vehicle Accident Reporting. 10 cents.
Part 4 . . . Official Inspection of Vehicles. 10 cents.
Part 5 . . . Case Histories of Fatal Highway Accidents. 10 cents.
Part 6 . . . The Accident-Prone Driver. 10 cents.

MISCELLANEOUS PUBLICATIONS

No. 76MP . . The Results of Physical Tests of Road-Building Rock. 25 cents.
No. 191MP . . Roadside Improvement. 10 cents.
No. 272MP . . Construction of Private Driveways. 10 cents.
No. 279MP . . Bibliography on Highway Lighting. 5 cents.
Highway Accidents. 10 cents.
The Taxation of Motor Vehicles in 1932. 35 cents.
Guides to Traffic Safety. 10 cents.
Federal Legislation and Rules and Regulations Relating to Highway Construction. 15 cents.
An Economic and Statistical Analysis of Highway-Construction Expenditures. 15 cents.
Highway Bond Calculations. 10 cents.
Transition Curves for Highways. 60 cents.

DEPARTMENT BULLETINS

No. 1279D . . Rural Highway Mileage, Income, and Expenditures, 1921 and 1922. 15 cents.
No. 1486D . . Highway Bridge Location. 15 cents.

TECHNICAL BULLETINS

No. 55T . . . Highway Bridge Surveys. 20 cents.
No. 265T. . . Electrical Equipment on Movable Bridges. 35 cents.

Single copies of the following publications may be obtained from the Bureau of Public Roads upon request. They cannot be purchased from the Superintendent of Documents.

MISCELLANEOUS PUBLICATIONS

No. 296MP. . Bibliography on Highway Safety.

SEPARATE REPRINT FROM THE YEARBOOK

No. 1036Y . . Road Work on Farm Outlets Needs Skill and Right Equipment.

TRANSPORTATION SURVEY REPORTS

Report of a Survey of Transportation on the State Highway System of Ohio (1927).
Report of a Survey of Transportation on the State Highways of Vermont (1927).
Report of a Survey of Transportation on the State Highways of New Hampshire (1927).
Report of a Plan of Highway Improvement in the Regional Area of Cleveland, Ohio (1928).
Report of a Survey of Transportation on the State Highways of Pennsylvania (1928).
Report of a Survey of Traffic on the Federal-Aid Highway Systems of Eleven Western States (1930).

UNIFORM VEHICLE CODE

Act I.—Uniform Motor Vehicle Administration, Registration, Certificate of Title, and Antitheft Act.
Act II.—Uniform Motor Vehicle Operators' and Chauffeurs' License Act.
Act III.—Uniform Motor Vehicle Civil Liability Act.
Act IV.—Uniform Motor Vehicle Safety Responsibility Act.
Act V.—Uniform Act Regulating Traffic on Highways.
Model Traffic Ordinances.

A complete list of the publications of the Bureau of Public Roads, classified according to subject and including the more important articles in PUBLIC ROADS, may be obtained upon request addressed to the U. S. Bureau of Public Roads, Willard Building, Washington, D. C.

STATUS OF FEDERAL-AID GRADE CROSSING PROJECTS

AS OF JANUARY 31, 1939

STATE	COMPLETED DURING CURRENT FISCAL YEAR					UNDER CONSTRUCTION					APPROVED FOR CONSTRUCTION					* BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
	Estimated Total Cost	Federal Aid	NUMBER			Estimated Total Cost	Federal Aid	NUMBER			Estimated Total Cost	Federal Aid	NUMBER			
			Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise			Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise			Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise	
Alabama	$ 243,609	$ 243,410	6		4	$ 947,379	$ 945,524	9	1		$ 292,600	$ 292,600	6		3	$ 897,537
Arizona						9,452	9,452				236,674	225,087	3			521,135
Arkansas	253,258	252,101	7			468,537	468,257	8			101,133	101,133	2			1,281,009
California	669,417	669,417	2	2		1,338,720	1,338,095	8	1		562,382	561,890	2			1,859,663
Colorado	32,559	29,328	1		2	295,248	295,248	4			355,770	347,638	2		19	867,313
Connecticut						18,930	12,665									998,900
Delaware	39,000	39,000			13						47,420	47,420	2		10	504,830
Florida						445,510	445,510	3			75,900	75,900	1			1,161,858
Georgia						382,930	382,930	6			66,020	66,020	1		1	2,445,720
Idaho	174,973	174,800	4			280,682	249,386	4			131,898	120,500	1			439,963
Illinois	369,500	369,500	2		1	2,160,905	2,160,905	14	2	60	910,740	910,740	7		16	2,794,281
Indiana	688,715	599,689	3	5		875,513	848,613	3	1	90	152,200	152,200		1		1,328,146
Iowa	1,026,186	972,425	10	1	19	203,820	191,700	2	1	1	182,684	168,308	8		1	1,780,596
Kansas	453,985	453,880	7		4	671,850	671,850	10			511,160	511,160	5		9	1,442,577
Kentucky	145,000	145,000	1			344,297	344,297	4	1	31	471,324	471,324	6	3		1,210,270
Louisiana						233,220	226,478	3			657,724	623,090	11			1,038,359
Maine	48,590	48,590	2			332,396	332,396	3	2		69,630	69,630	1		1	375,778
Maryland						72,188	72,188	1								1,155,308
Massachusetts	54,710	54,710		1		220,486	220,290	1	1		386,385	385,425	1	3		1,661,149
Michigan	930,783	924,372	8	1	35	653,796	653,796	6	2	10	114,000	114,000				2,242,164
Minnesota	39,556	39,556		1	1	760,185	759,864	3	5		18,297	18,297			3	2,152,975
Mississippi	70,800	70,800	1			394,200	394,200	5			323,900	323,900	2			1,105,901
Missouri	296,674	295,552	4	1		111,370	111,370	1			1,027,890	1,027,890	4	3		2,186,625
Montana	355,586	350,704	4			634,520	634,520	6			235,773	235,773	3			364,726
Nebraska	150,374	150,374	4			729,314	729,314	15			757,668	757,668	18		33	474,743
Nevada	149,761	149,761		3	2	203,311	203,311	2			11,280	11,280			4	192,221
New Hampshire	70,205	69,765		1	2	87,856	87,797	5		1						433,688
New Jersey	116,891	111,665	1	1		229,856	229,856	1	1	2						2,018,350
New Mexico	168,984	168,984	4	1		118,994	118,994	3								730,470
New York	992,501	991,800	4	3	2	1,720,351	1,712,101	5	7		413,050	239,610		3	1	5,162,367
North Carolina	121,550	121,550	1	1	1	877,900	845,200	6	5		348,760	348,760	1	2	19	1,629,861
North Dakota	184,700	184,700		1		663,380	614,978	4	1							1,088,707
Ohio						515,870	515,870	6			403,610	377,610	3	1		4,169,541
Oklahoma						143,223	109,223	1			250,305	250,305	1		55	2,377,022
Oregon	308,391	307,742	1	2		384,601	250,243	1			129,997	129,997	2			521,579
Pennsylvania	213,129	197,923	2			1,039,656	827,757	2			931,522	926,878	3			4,908,593
Rhode Island						335,019	335,019	1	2		103,772	103,772		1		152,459
South Carolina	33,376	33,376		1		220,803	165,837	4	1		260,645	260,645	11		40	1,322,994
South Dakota	118,146	118,146	2		8	286,368	286,368	3	2	1	16,910	16,910	2		2	1,167,491
Tennessee						121,490	121,490		2		235,390	235,390	1		7	1,908,340
Texas	34,033	33,377	2			1,651,504	1,621,002	16	6		581,912	569,405	10			4,208,194
Utah	101,648	101,648	2		4	47,359	47,359	2			87,300	87,300			32	465,992
Vermont	215,052	209,695	6	1	5	29,964	29,964		1	1	23,000	23,000			7	315,293
Virginia	330,059	330,059	13	1		332,070	332,070	6	1		451,011	346,361	4	1	24	1,164,173
Washington	247,816	244,475	2	3	2	735,775	734,364	9	1		153,102	153,102	1		13	553,732
West Virginia	221,805	220,785	1		2	311,726	295,966	3		1	31,400	31,400	2		3	1,036,663
Wisconsin	221,661	221,493	3			1,186,812	1,145,988	11			4,917	4,917			1	1,587,185
Wyoming	164,200	164,200		2	4	10,150	10,150				201,010	121,590		1	7	512,924
District of Columbia						30,215	30,215		1							392,716
Hawaii						193,200	193,200	3	1							398,050
Puerto Rico						214,569	213,370	4								667,006
TOTALS	10,057,183	9,864,352	110	33	111	24,277,470	23,576,540	217	49	198	12,328,065	11,845,825	127	19	311	71,377,137

* INCLUDES APPORTIONMENT FOR FISCAL YEAR 1940.

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