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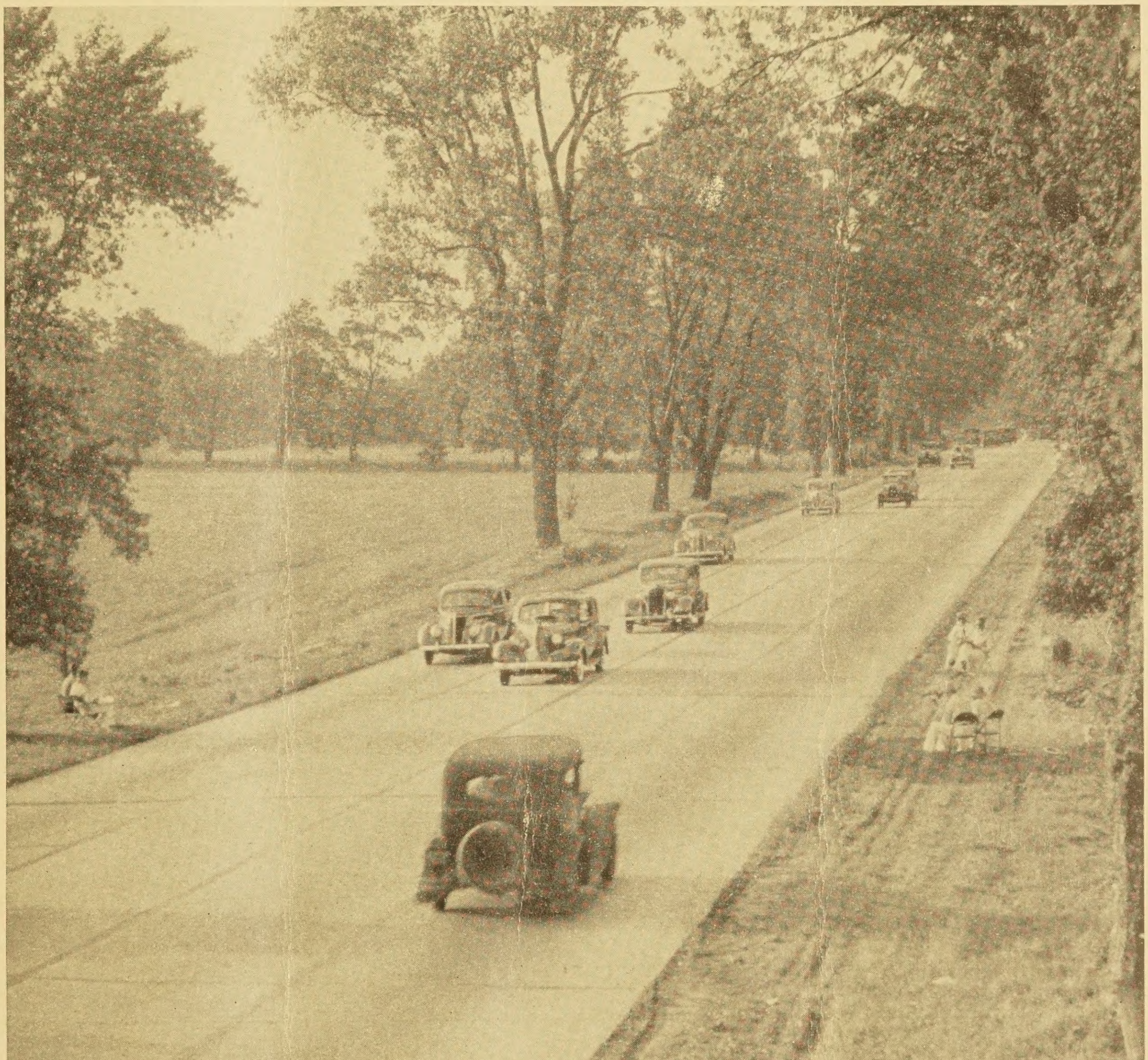

OBSERVERS RECORD HIGHWAY CAPACITY DATA IN ILLINOIS

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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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RESULTS OF HIGHWAY-CAPACITY STUDIES

BY THE DIVISION OF HIGHWAY TRANSPORT, PUBLIC ROADS ADMINISTRATION

Reported by O. K. NORMANN, Highway Engineer-Economist

Preliminary results of highway capacity studies conducted by the Public Roads Administration in cooperation with the highway planning survey organizations in several States were published in 1939 and have been used in the solution of numerous traffic-control and highway-design problems by the various State highway departments and other agencies. Data obtained prior to 1939 have been supplemented by more recent data and the analyses completed to determine theoretical, possible, and practical capacities for 2-, 3-, and 4-lane highways.

Since the results are based on data gathered prior to the present tire and gasoline rationing programs, they will be of maximum value upon a return to normal driving conditions. However, many of the principles developed are applicable to military traffic as well as the efficient movement of civilian traffic in the neighborhood of defense industries.

The maximum theoretical capacity of a single traffic lane is about 2,000 vehicles per hour, occurs at speeds above 30 miles per hour, and can be attained on 4-lane highways or on short sections of 2-lane roads.

The total possible capacity of a long section of 2-lane highway with good alinement, carrying few trucks, is about 2,000 vehicles per hour or one-half its theoretical capacity. A corresponding value for 3-lane, 2-directional highways is 3,600 vehicles per hour. The maximum possible capacity of a 4-lane highway is 8,000 vehicles per hour or 4,000 vehicles per hour for the 2 lanes used by traffic traveling in the one direction. When trucks constitute 17 percent of the traffic the possible capacity of a 2-lane highway is reduced by about 25 percent.

The practical working capacity of a highway is a relative value and depends upon local conditions as well as the width or number of lanes. The maximum practical working capacities for 2-, 3-, and 4-lane rural highways under normal conditions are 800, 1,400, and 2,800 vehicles per hour, respectively. However, the results presented are of sufficient scope to be of value in the determination of the practical capacity for any highway condition and in the solution of numerous traffic control and design problems.

THE highway capacity studies conducted by the Public Roads Administration in cooperation with the highway planning surveys of several State highway departments are closely related to the studies of lateral placement, truck performance, driver behavior, and passing practices. All are part of a program designed to obtain information regarding the operation and performance of motor vehicles under a wide range of traffic and highway conditions. This information will be of practical value in facilitating safe and economical highway transportation. The ultimate objective of the highway capacity studies is to determine practical carrying capacities for all types of highway design, but in particular for modern 2-, 3-, and 4-lane roads, and to determine what effect certain highway design features, motor-vehicle characteristics, highway regulations, and driver characteristics, have on the practical capacities. To reach this objective, use must be made of the facts brought to light by the related studies, especially the passing-practice study, and complete and reliable data on traffic movement during light and heavy densities must be available for each major highway condition that is to be considered.

Some of the preliminary results based on data gathered on about 300,000 vehicles from 1934 through 1937 have been published.[1] Since then, additional studies have been conducted in Massachusetts, Illinois, and California, under traffic conditions that will yield data useful in the determination of highway capacity. Speed-placement studies have also been conducted in Iowa, Minnesota, Ohio, Oregon, South Carolina, Texas, and Washington. However, the data gathered in the latter group of States do not include exceptionally heavy traffic densities, since the studies were made primarily to obtain speed and transverse placement data on various curves, different pavement and shoulder widths, and other highway design features.

Since 1938, greatly improved equipment[2] has been used in obtaining the necessary data but during all studies the speeds and spacings from other vehicles were obtained for practically 100 percent of the vehicles on the highway. This report covers the results of an analysis of all data gathered prior to 1938 and the pertinent 1939 data.

In analyzing the data to determine practical working capacities for 2-, 3-, and 4-lane highways, numerous facts regarding the operation and movement of vehicles on various highways have been brought to light. A few will be presented. A thorough understanding of all of these in addition to the findings of the driver behavior,[3] motor-vehicle performance,[4] and passing practice studies,[5] is necessary in any scientific determination of practical capacities for particular roadway conditions.

[1] Preliminary Results of Highway Capacity Studies, by O. K. Normann. PUBLIC ROADS, February 1939.

[2] New Techniques in Traffic Behavior Studies, by E. H. Holmes and S. E. Reymer. PUBLIC ROADS, April 1940.

[3] A Study of Motor-Vehicle Drivers and Speed in Connecticut, by Harry R. De Silva. PUBLIC ROADS, July 1940.

[4] Hill-Climbing Ability of Motor Trucks, by Carl C. Saal. PUBLIC ROADS, May 1942.

[5] Passing Practice on Rural Highways, by C. W. Prisk. Highway Research Board Proceedings, 1941.

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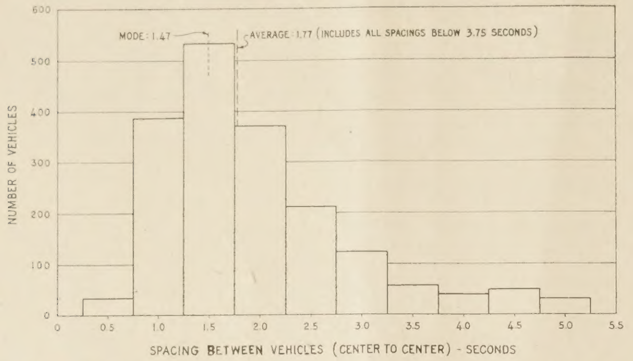

FIGURE 1.—FREQUENCY DISTRIBUTION OF TIME SPACINGS BETWEEN VEHICLES TRAVELING AT THE SAME SPEED. (30–35 MILE-PER-HOUR GROUP ON 2-LANE LEVEL HIGHWAYS).

MINIMUM SPACINGS BETWEEN VEHICLES VARY WITH TYPE OF HIGHWAY AND VEHICLE SPEED

A review of published material on highway capacity [6] shows that practically all attempts to determine the maximum capacity of a highway at various speeds have been based upon safe following distances which in turn have been based upon assumed reaction times, coefficients of friction, etc. The safe following distances as calculated by different authors vary from 40 to 150 feet at 20 miles per hour and from 87 to 1,230 feet at 60 miles per hour. The maximum capacity of a single traffic lane based upon these theoretical derivations varies from 1,500 to 4,800 vehicles per hour. A few authors maintain that there is an increase in capacity with an increase in speed but the majority hold that the maximum capacity is attained at speeds in the neighborhood of 20 miles per hour or less.

The traffic data analyzed by the Public Roads Administration include information for drivers of 11,000 vehicles that were trailing another vehicle in the same traffic lane and traveling at practically the same speed. Figure 1 shows the distribution of time spacing for all vehicles on 2-lane highways that were traveling between 30 and 35 miles per hour and following another vehicle traveling at practically the same speed. Under such a condition it is expected that there will be a range in the time spacings at any particular speed for different drivers as well as for the same driver due to inability to maintain for very long the exact speed of the vehicle being followed. However, in the distribution are also included drivers who chanced to be traveling at the same speed as the preceding vehicle on the highway when their speeds and spacings were recorded but who were not at their minimum spacings. The spacing values for these drivers should not be included and therefore all spaces exceeding 3.75 seconds, which is the highest value that could be considered within the normal distribution, have been excluded in determining the average minimum spacing for the particular condition represented. In a similar manner, exceedingly long time intervals were excluded from the average values for other speeds and highway conditions and the resulting values were used to obtain figures 2 and 3.

Figure 2 shows the average minimum distance spacings allowed by drivers at different speeds. All curves are for daytime operation except the one for 2-lane highways at night. Although insufficient data were obtained to determine accurate spacings at low speeds

[6] Resume of Previously Published Material on Highway Capacity, by O. K. Normann, and Asriel Taragin. Paper presented at meeting of Highway Research Board, 1941.

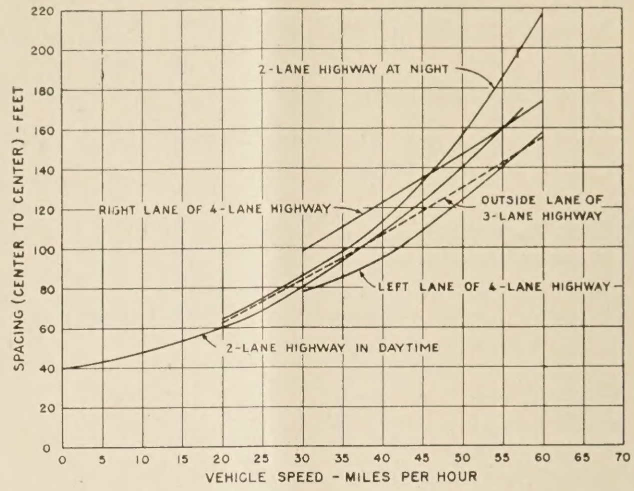

FIGURE 2.—AVERAGE MINIMUM DISTANCE SPACINGS ALLOWED BY DRIVERS WHEN TRAILING ANOTHER VEHICLE.

for any but daylight conditions on 2-lane highways, all curves probably approach the one for the 2-lane highways as the speed decreases.

Although all curves show an increase in the distance spacing with an increase in speed, it is evident that factors other than safe stopping distances are involved in the spacings allowed by drivers when following another vehicle. On 2-lane roads there is a relatively slight decrease in the distance spacing with a decrease in speed below 20 miles per hour. As long as both vehicles are moving at a uniform speed there is an average spacing of at least 40 feet between centers. This is considerably greater than the distance between them when the two vehicles come to a stop on the highway. One reason for this may be that it is hard to maintain a uniform spacing at low speeds. Another reason may be that at low speeds drivers do not desire to drive any closer to the vehicle ahead than the distance required to prevent the vehicle behind from passing and crowding back into line.

At night, drivers allowed a greater clearance than in the daytime for corresponding speeds. On 3-lane roads, a greater distance was allowed at the lower speeds and a shorter distance at the higher speeds than on 2-lane roads. On 4-lane highways the drivers in the left-hand lane allowed shorter spacings than did those in the right-hand lane. It is possible that the right-hand lanes contained a higher percentage of cautious drivers or that while a driver was in the left lane he allowed a shorter distance because he felt that the driver of the preceding vehicle was not likely to slow down suddenly.

A comparison was made of values obtained during 1934 and 1939 and indicated that there was no change during these years in the distance that drivers followed one another when traveling at the same speed.

Figure 3 shows for different conditions the numbers of vehicles traveling in a single traffic lane that could pass a given point if all drivers traveled at the same speed and no space between vehicles exceeded the distance allowed by the average driver while trailing another vehicle. Although the values shown by the curves are based upon observed spacings, they are "theoretical" lane capacities. The maximum theoretical lane capacity on a 2-lane road is 2,000 vehicles per hour in the daytime and about 1,800 at night, both being attained at a vehicle speed of about 33 miles per

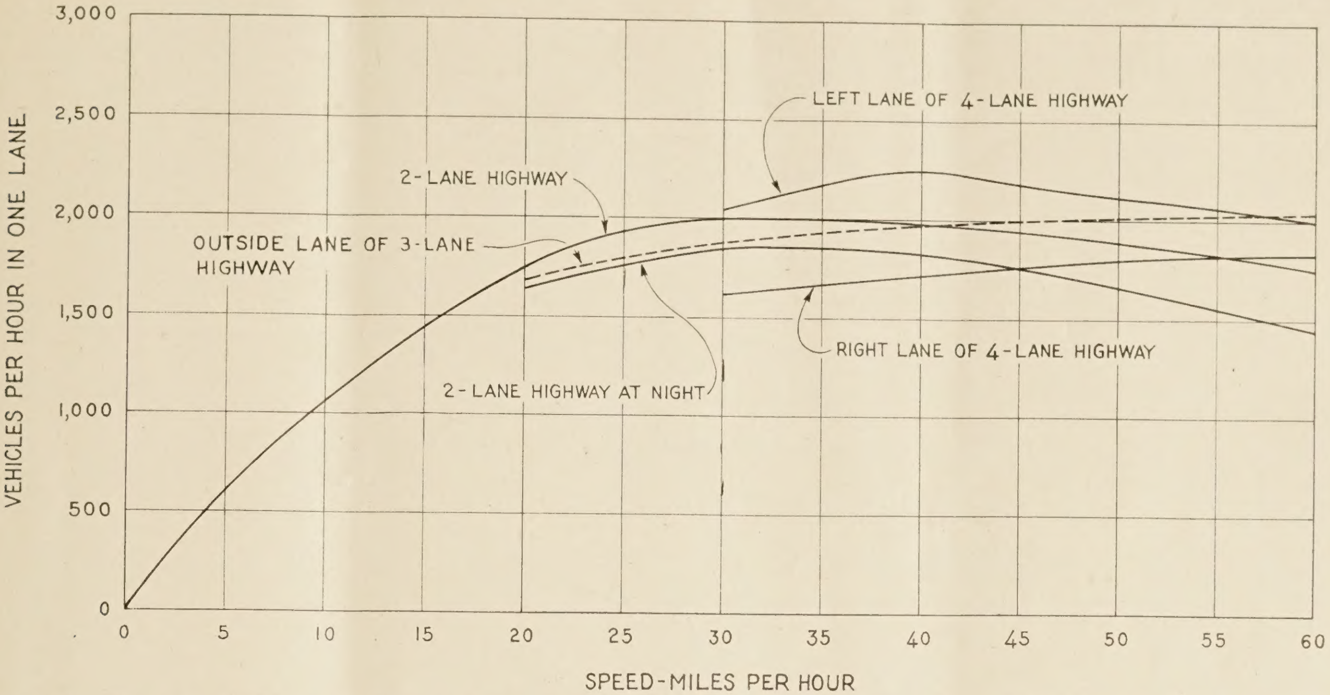

Figure 3.—Theoretical Maximum Traffic Capacity With All Vehicles Traveling at the Same Speed (Based on Average Spacings).

hour. The left lanes of 4-lane highways reach their maximum theoretical capacities of about 2,250 vehicles per hour when the vehicles travel at a speed of 40 miles per hour, while the right-hand lanes and the lanes of 3-lane highways show increased capacities with increased speeds within the range of speeds observed. The values for 3-lane highways refer to the outside lanes. These theoretical lane capacities may be approached over very short sections of highway that act as bottlenecks and where drivers expect to stay in line. However, since all vehicles must stay in line and travel at the same speed, the speed of the slowest moving vehicles in such a case will determine the actual capacity.

MEAN DIFFERENCE IN SPEED BETWEEN SUCCESSIVE VEHICLES BEST INDEX OF POSSIBLE HIGHWAY CAPACITY

Probably the most important conclusion that can be drawn from the results of this analysis based on actual spacings as compared with the results based on assumed or calculated values is that maximum capacities occur at speeds well above 20 miles per hour. If conditions are such that traffic at bottlenecks can be kept moving at speeds of 20 to 25 miles per hour, one lane will handle nearly twice as many vehicles per hour as can be handled if traffic is required to slow down to 10 miles per hour. This is a very important consideration when regulating traffic under emergency conditions such as at construction projects or where an accident has occurred and vehicles that normally use 2 lanes are required to use one lane.

Under actual highway conditions all drivers do not desire to travel at the same speed. To permit drivers to travel at their desired speeds it must be possible for the drivers traveling at the higher speeds to pass those traveling at the slower speeds. Obviously, on a straight, level 2-lane highway this becomes increasingly difficult as the traffic density increases until finally the faster drivers are forced to stay in line and travel at a reduced speed. As the number of opportunities to pass slow-moving vehicles decreases, the highway becomes more and more congested.

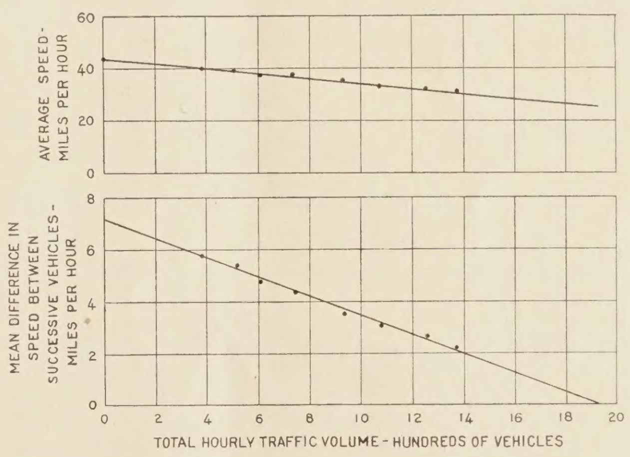

Figure 4.—Speed and Mean Difference in Speed for 2-Lane Level Tangent Highway Section in Illinois.

Efforts to find a measure of the congestion on a highway have revealed that the mean difference in speed between succeeding vehicles is the best index available. Many other indices, including the drop in speed with increased densities, were tried and found lacking.

Figure 4 shows both the average speed and mean difference in speed for various traffic densities on a 2-lane road in Illinois. At the light traffic densities, when all drivers could travel at their desired speed, the average speed on this 2-lane highway was 43 miles per hour and the mean difference in speed between succeeding vehicles was 7.2 miles per hour. As the traffic density increased there was a gradual decrease in the average speed and also in the mean difference in speed, until at a density of 1,380 vehicles per hour the mean difference in speed was only 2.4 miles per hour, although the average speed had only decreased to 31 miles per hour.

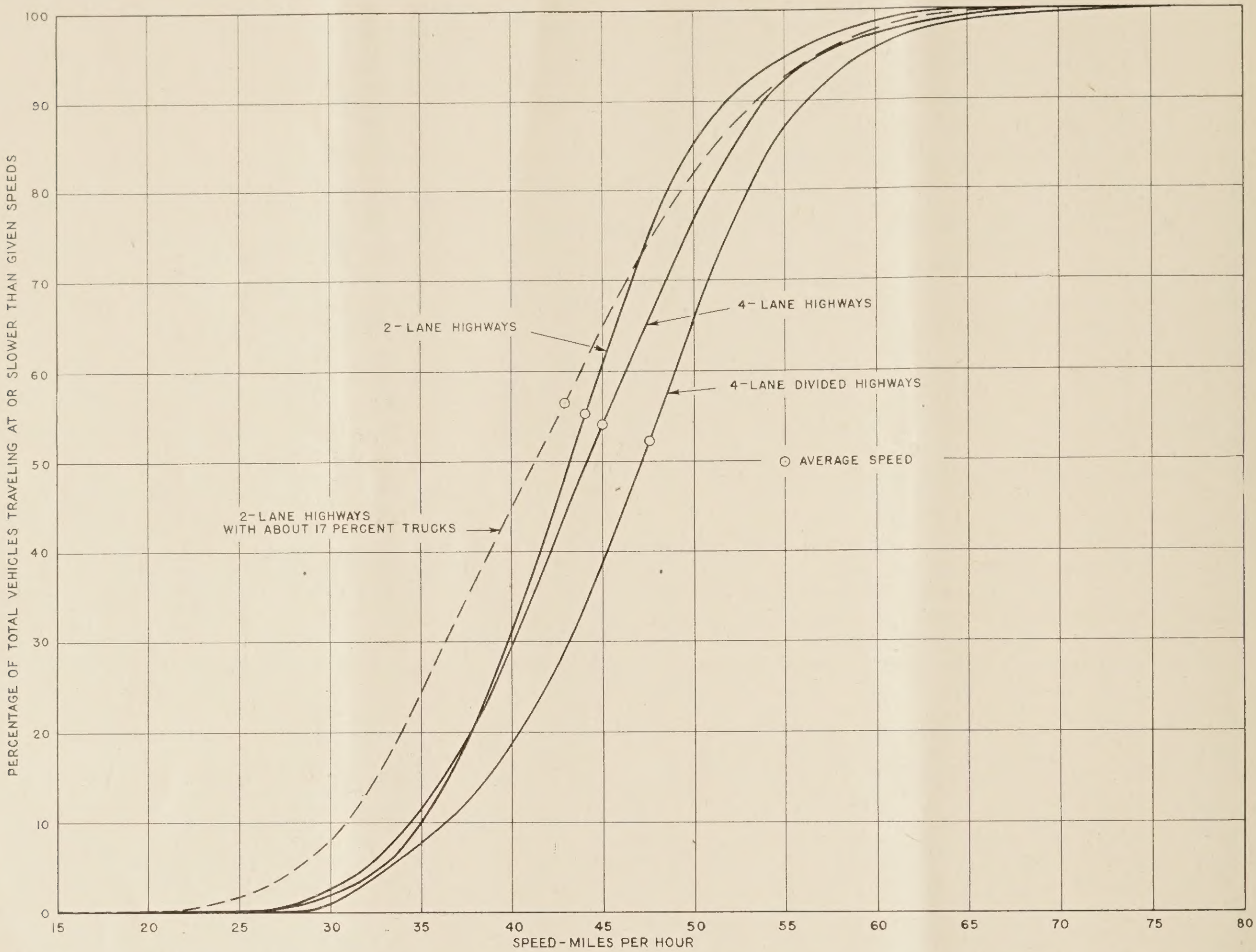

Figure 5.—Cumulative Frequency Distribution of Free Speeds on Level Tangent Sections of Illinois Highways Included in Capacity Studies.

Since it was evident that for all practical purposes the relationship was a straight line, the line for the mean difference in speed was extended until it intersected zero difference in speed at 1,940 vehicles per hour.

It is obvious that when there is a zero difference in speed between succeeding vehicles, no passings can be made and no driver can travel faster than the vehicle immediately ahead. The result is that groups of cars are formed, each following a slow-moving vehicle. If the highway is long enough, one group may catch up to another group, but there is no possibility of filling the spaces between groups by one group passing the other. When this condition occurs, the possible capacity of the highway has been reached, and, although vehicles from side roads may tend to fill the gaps, they cannot travel faster than the group of vehicles ahead. Possible capacities as used in this report, therefore, refer to the number of vehicles per hour that can travel over long stretches of highway that are free from intersections that would further reduce the roadway capacities.

On this particular section of highway, the maximum possible capacity of 1,940 vehicles per hour would be reached when the average speed had decreased to 26 miles per hour. With traffic moving at 26 miles per hour, the highway would not ordinarily be considered completely congested, but the mean difference in speed is a gage that measures the congestion on a highway and shows when the possible capacity is reached. When it has decreased to zero, even a slight additional load or some other factor may cuase a complete tie-up of traffic or an immediate drop in speed to a value below the speed at the possible capacity, which in this case is 26 miles per hour.

The Illinois studies included data for a number of 2-lane, 4-lane undivided, and 4-lane divided highways carrying similar traffic and comparable in all respects except for the number of traffic lanes. At some of the locations studied traffic went directly from one type of highway to another. Figure 5 shows the distribution of speeds and the average speed for vehicles traveling on each type of highway during very low traffic densities when each driver was free from any restriction in speed by other vehicles. The curves look very similar, but if studied closely it may be seen that the data represented by any one are quite different from those for any of the others.

On the 4-lane divided highway the average speed of the free-moving vehicles was 47.5 miles per hour, which is the highest average speed yet recorded in these studies. As far as the highway itself was concerned, there was no reason why all vehicles could not have traveled 70 miles per hour or faster, as the highway was designed for speeds of 100 miles per hour, and has no major intersections at grade. Yet with the study loca-

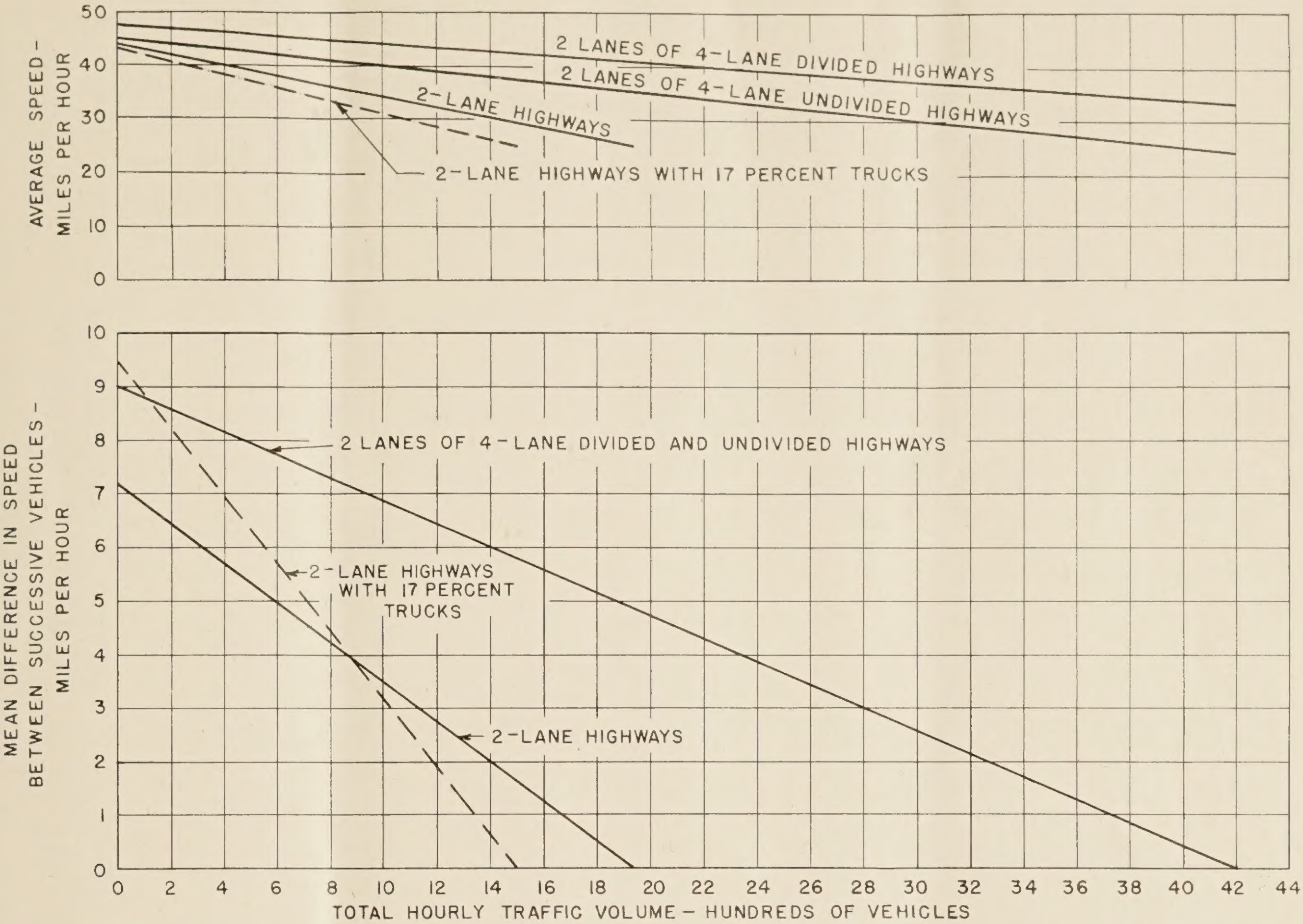

FIGURE 6.—SPEEDS AND SPEED DIFFERENCES ON COMPARABLE LEVEL TANGENT HIGHWAY SECTIONS IN ILLINOIS.

tion on this highway at the center of a 5-mile level tangent, 18 percent of the drivers desired to travel less than 40-miles per hour, 80 percent desired to travel less than 53 miles per hour, and only 5 percent traveled over 60 miles per hour.

The average speed for free-moving vehicles on the 4-lane undivided highway was 45 miles per hour and on the 2-lane highway it was 43 miles per hour. All of these highways carried few trucks during the study periods. The 2-lane highways represented by the dashed curve carried about 17 percent trucks and, as a result, the speed range was greater. Only 20 percent of the vehicles traveled between 40 and 45 miles per hour, compared with nearly 30 percent within the same range on the 2-lane highways carrying a negligible number of trucks.

When the average speed and mean difference in speed between successive vehicles for the various traffic volumes were plotted for each highway condition, figure 6, based upon reliable and detailed data for 81,581 vehicles, was obtained. The 2-lane highways with few trucks had possible capacities of 1,940 vehicles per hour at an average speed of 26 miles per hour. The same type of highway carrying 17 percent trucks had a possible capacity of 1,500 vehicles per hour at a speed of 26 miles per hour.

Two lanes of the 4-lane highways had total possible capacities of 4,200 vehicles per hour, this value occurring at a speed of 24 miles per hour on the undivided sections and at 33 miles per hour on the divided sections.

The points at which the lines for the speed differences intersect the Y-axis show the mean difference in speed when the vehicles could move freely and pass as many other vehicles as was necessary for the drivers to maintain their desired speeds. On the 2-lane highways the average difference in speed was 7.2 miles per hour. When there were 17 percent trucks, the difference was 9.5 miles per hour, due to the wider range in speeds when trucks were intermixed with passenger cars. On the 4-lane highways, during free movement there was a mean difference in speed of 9 miles per hour, which is higher than for the 2-lane highways without trucks. This was caused by the drivers' desire to travel at a wider range of speeds on the 4-lane than on the 2-lane highways.

The capacity studies in New York and Massachusetts were made under a wider range of highway conditions than were those in Illinois. When data from all the locations on level tangent sections of highways were classified by the number of lanes and the speed at which the vehicles were traveling during very light traffic densities, they fell into seven different groups, as shown by figure 7.

AVERAGE VEHICLE SPEEDS VARY WIDELY

The speeds of the free-moving vehicles on 2-lane highways are represented by curves A, B, and C. Curve A shows the frequency distribution of speeds through the residential section of a small town on a highway having no cross traffic and where the two

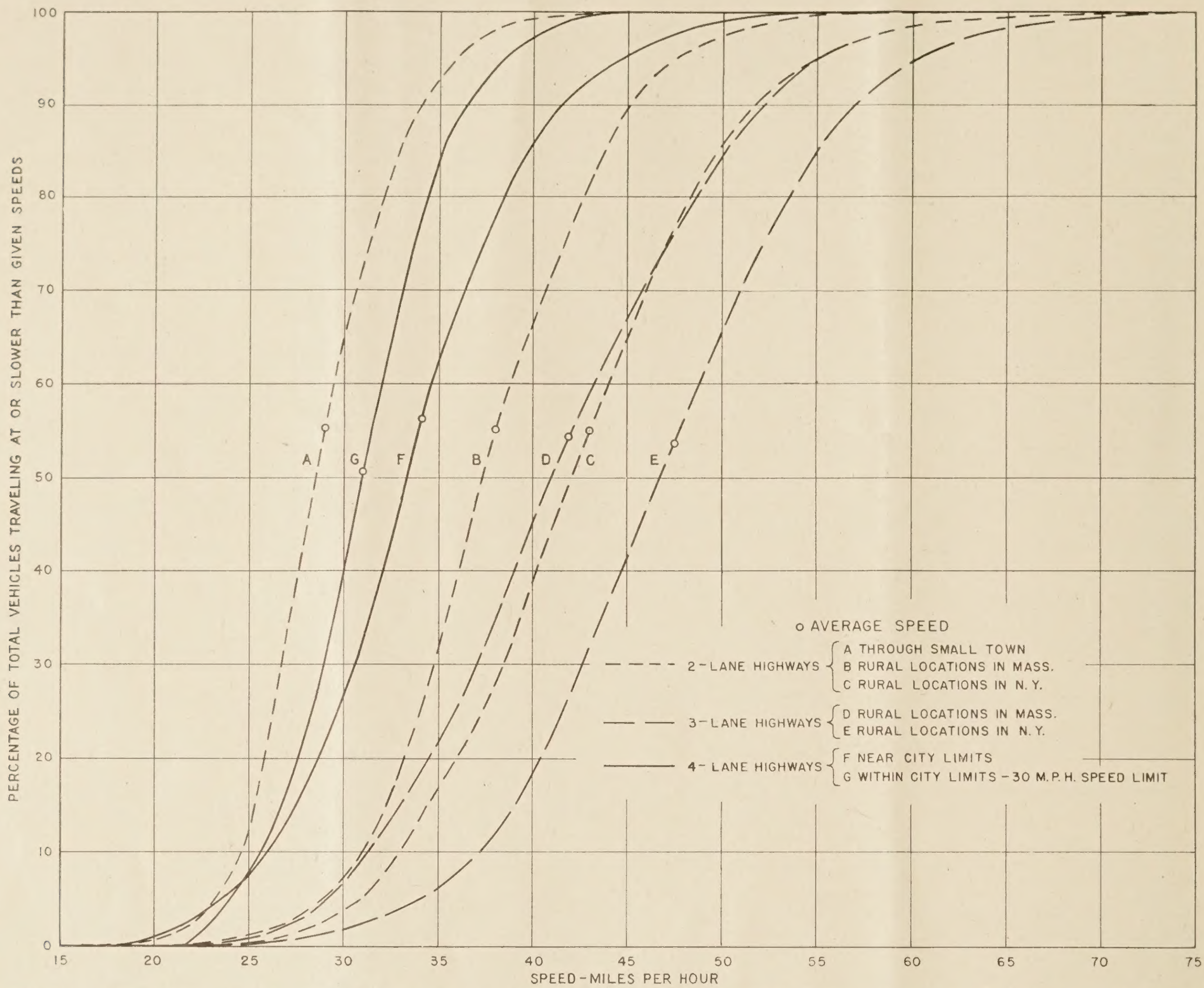

Figure 7.—Cumulative Frequency Distribution of Free Speeds on Level Tangent Highway Sections in New York and Massachusetts.

lanes were free from parked vehicles. At this location, drivers uninfluenced by other traffic traveled from 16 to 45 miles per hour, with 80 percent traveling between 25 and 35 miles per hour. Curve B represents 2-lane highways at three rural locations in Massachusetts, while curve C represents highways in three rural locations in New York.

At each of the Massachusetts locations the average speed for free-moving vehicles was 38 miles per hour, while at the New York locations it was 43 miles per hour. The highways studied do not represent average conditions in each State, since the particular locations were selected to obtain desired data for these capacity studies rather than to make comparisons between highways in different States. Although curves B and C both represent level, tangent, rural locations, the difference of 5 miles per hour in the average free speeds may have been caused by a number of factors, such as the general alinement of the highways, the smoothness of the surface, and the distance between towns.

On each of three 3-lane highways in one group, the average free speed was 42 miles per hour, as represented by curve D, and for another group of two 3-lane highways, as represented by curve E, the average speed was 47.5 miles per hour. Curve F represents the free speeds on a 4-lane highway near the city limits of a town, while curve G represents the free speeds within the city limits where there was a 30-mile-per-hour speed limit. Thus it may be seen that even on level, tangent sections of highway unaffected by intersections or by other traffic, there is a wide range in the average free speeds at different locations.

When the average speeds and mean differences in speed are plotted for different traffic densities for these seven highway conditions, the results illustrated by figure 8 are obtained, based on data for 131,340 vehicles.

The speed and difference in speed values shown for the points where the curves intersect the line representing 0 volume are in effect values for densities approaching 0 vehicles per hour, or for drivers whose speeds are not influenced by other traffic.

Considering first the 2-lane highways (fig. 8), the average speeds on sections A, B, and C at light traffic volumes, or the average free speeds, were 29, 38, and 43 miles per hour, respectively. When all drivers could maintain their desired speeds there was a speed difference of 4.1 miles per hour on section A, 5.7 miles per hour on section B, and 8.7 miles per hour on section

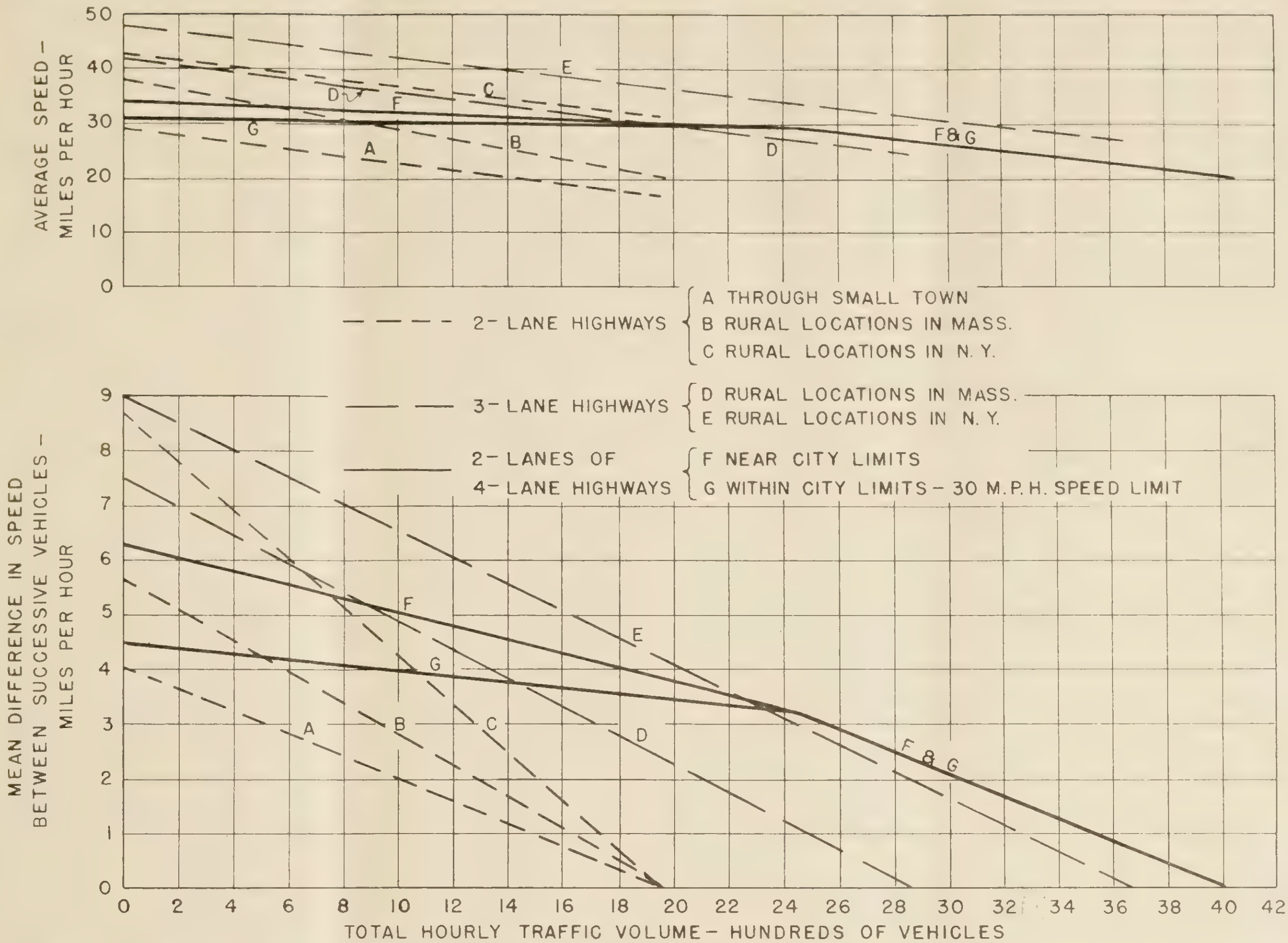

Figure 8.—Speeds and Speed Differences on Level Tangent Highway Sections in New York and Massachusetts.

C. With a given increase in traffic density, there was a greater decrease in the speed difference on section C than on section A or B. The speed difference became zero at about 1,950 vehicles per hour on sections A and C, and at 1,980 vehicles on section B. The possible capacities are practically the same for conditions represented by curves A, B, and C, although they occur at average speeds of 16.5, 20, and 31 miles per hour, respectively. The possible capacity of the Illinois 2-lane section with few trucks was 1,940 vehicles per hour at an average speed of 25 miles per hour.

Each of the 3-lane sections represented by curve D had a possible capacity of 2,860 vehicles per hour at 24 miles per hour, while each of the 3-lane sections represented by curve E had a possible capacity of 3,660 vehicles per hour at 26 miles per hour.

The speed restrictions on the 4-lane sections F and G caused lower speeds and speed differences at low volumes, but the speed restrictions apparently had no effect when the traffic volume in one direction reached 2,450 vehicles per hour. The possible capacity in both cases was about 4,000 vehicles per hour at a speed of 20 miles per hour.

From the studies in Illinois, Massachusetts, and New York, it is evident that:

1. Two-lane, level, tangent sections of highway carrying few trucks have a possible capacity of nearly 2,000 vehicles per hour. With 17 percent trucks their capacity is reduced about 25 percent.

2. Two lanes of level tangent sections of 4-lane highway carrying few trucks have a possible capacity of about 4,000 vehicles per hour. If the possible capacity of a 4-lane highway is considered to be reached when the lanes in one direction are carrying their maximum possible capacity, the possible capacity of the entire roadway depends upon the relative number of vehicles traveling in each direction. With all traffic in one direction during peak periods, the total possible capacity of a 4-lane road (retaining the two-directional character of the road) is 4,000 vehicles per hour; with traffic equally divided by direction, the total possible capacity becomes 8,000 vehicles per hour. However, since about two-thirds of the traffic is usually in one direction on most highways during peak periods, the lanes in one direction will be carrying their maximum possible capacity with a total volume of 6,000 vehicles per hour.

3. Three-lane level tangent sections of highway apparently do not all have the same maximum possible capacities, as is the case for 2- and 4-lane highways. A possible capacity of 2,800 vehicles per hour was obtained for one group of 3-lane highways, and a possible capacity of 3,600 vehicles per hour was obtained for another group. The latter group included highway sections with exceptionally long sight distances, smooth surfaces on all three lanes, and lanes that were well defined by painted lines. These factors all had a tendency to encourage the use of the center lane for passing purposes. The best 3-lane roads can therefore

be expected to have maximum possible capacities of 3,600 vehicles per hour. Since the capacity of each of the other 3-lane roads was only 2,800 vehicles per hour, there apparently is a tendency for the capacity to decrease rapidly with a lowering of the design standards.

4. The speed at which vehicles will travel when the possible capacity of a highway is reached will depend entirely upon the speed at which the slowest vehicles on the highway are traveling. Usually this will be about the same as the speed of the slowest group of vehicles during light traffic densities.

POSSIBLE CAPACITY OF 2-LANE HIGHWAY ABOUT HALF OF THEORETICAL CAPACITY

It is interesting to compare the possible capacities with the theoretical capacities. For a 2-lane highway, the possible capacity is about half of the theoretical capacity. With practically all traffic traveling in one direction on a 2-lane highway the lane normally used by oncoming traffic provides the means for passing the slow-moving vehicles so that the exceedingly long spaces ahead of slow-moving vehicles may be filled. However, one oncoming vehicle will require all other vehicles to crowd into their own lane, making the total possible capacity equal to the theoretical capacity of one lane. With traffic equally divided by direction it will be shown by figures to be presented later that few spaces sufficiently long to permit a passing exist when there are over 1,000 vehicles per hour traveling in each direction, but the drivers do not take advantage of these passing opportunities.

On 3-lane tangent highways carrying practically all traffic in one direction and two lanes filled, the possible capacity of all three lanes cannot exceed the theoretical capacity of two lanes. With traffic evenly divided, the number of passings required to keep both outside lanes full apparently cannot be made in the one center lane.

On 4-lane highways, the possible capacities are very close to the theoretical capacities. Both lanes can be used to carry traffic and at the same time provide a means of passing slow-moving vehicles so that the spaces that occur ahead of the slow vehicles can be filled.

When a highway is carrying its maximum possible capacity, no vehicle can travel at an average speed in excess of the speed of the slowest vehicle on the highway. It has been shown that all drivers do not desire to travel at the same speed even under identical highway conditions and that the speed of the slowest vehicle is generally far below the speed at which a great majority of the drivers desire to travel or should be expected to travel. It is therefore desirable to establish practical capacities for 2-, 3-, and 4-lane highways based upon the maximum interference between vehicles, or the maximum congestion, that the drivers can reasonably be expected to tolerate.

The figures that have been presented show that for any particular highway location there is no sudden drop in speed or sudden increase in interference between vehicles with an increase in the traffic density until the possible capacity of the highway is reached. Rather, the opportunity for each individual driver to travel at his desired speed is gradually reduced as the density increases. The standard of practical capacity adopted for a highway is therefore a relative value that will vary even for highways of the same design and will depend upon:

1. The particular type of traffic the highway serves,
2. The congestion that will be tolerated by drivers in various sections of the country and localities under certain conditions, and
3. Economic considerations such as the funds available for highway construction and congestion reduction.

In addition to figures already presented showing the relative congestion at different traffic volumes on tangent sections of highway, other information regarding driver behavior on 2-, 3-, and 4-lane tangent sections that is useful in arriving at practical highway capacities has been obtained from the study data. Such information includes the number of passings that occur, and the distribution of time spacings between vehicles, the distribution of speeds at various traffic densities, and for 3- and 4-lane highways the number and speed of vehicles traveling in the inside and outside lanes.

Figure 9 shows the percentage of vehicles, moving in one direction on 4-lane level tangent rural highways, that use the right-hand and left-hand (outside and inside) lanes during a wide range of hourly traffic volumes. Data for a total of 102,807 vehicles obtained on six undivided 4-lane highway sections and five divided sections were analyzed to construct this figure. All highways had smooth surfaces with lane widths as shown in table 1. On all roads during the studies there were relatively few trucks, the number usually not exceeding 5 percent of the total traffic.

With the exception of the one undivided highway with 9-foot lanes, there was no marked difference at the same traffic density in the number of vehicles using the respective lanes on highways with different lane widths. Although more vehicles used the outside lanes on the divided than on the undivided highways, the difference was slight and occurred only at the low hourly traffic volumes. Therefore, for all practical purposes the results as shown by figure 9 may be considered as representative of all 4-lane rural highways in connection with any calculations with respect to capacities.

Table 1.—*Width of lanes on 4-lane undivided and divided highways on which distribution of vehicles between traffic lanes was studied*

Number of highway sections included	Lane widths	
	Outside	Inside
	Feet	*Feet*
4-LANE UNDIVIDED HIGHWAYS		
1	9	9
1	9	11
3	10	10
1	12	13
4-LANE DIVIDED HIGHWAYS		
2	10	10
2	10	11
1	11	11

At traffic volumes up to 1,700 vehicles per hour for both lanes more vehicles traveled in the right-hand lane than in the left-hand lane. Above this traffic volume a majority of the drivers chose to travel in the left or inside lane until, at a volume of 3,200 vehicles per hour, 60 percent, or 1,920 vehicles, were in the left lane. Since this value approaches the maximum theoretical capacity of the left lane (fig. 3) the right lane must carry a larger proportion of the total number of vehicles during volumes above 3,200 vehicles per hour. The difference between the relative number in each lane is considerably amplified at the low traffic

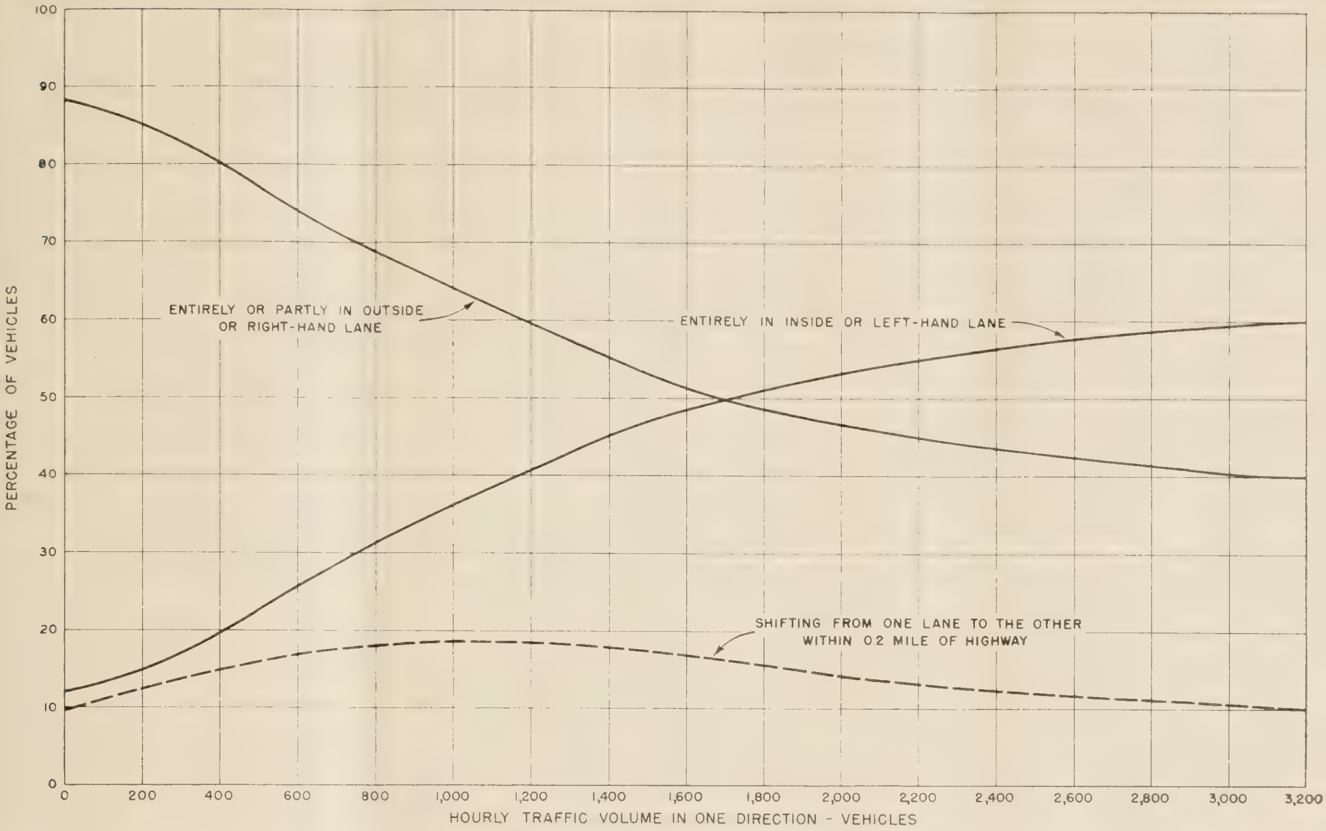

Figure 9.—Distribution of Vehicles Between Traffic Lanes on 4-Lane Highways During Various Hourly Traffic Volumes.

densities by including the vehicles straddling the lane line with those in the right-hand lane. The data for most of the study did not permit vehicles straddling the lane line to be segregated. However, on two of the more recent studies transverse placements to the nearest foot were obtained for all vehicles. At low traffic densities about 17 percent of the vehicles on an undivided highway were straddling as against 12 percent on a divided highway.

The lower curve (fig. 9) shows the percentage of vehicles that shifted from one lane to the other in a section of highway 0.2 mile long. The maximum occurs at a volume of 1,000 vehicles when, on an average, all vehicles went from one lane to the other within 1.1 miles of straight level highway.

It can reasonably be expected that if there were no congestion or interference between vehicles, the percentage of vehicles that would shift from one lane to the other would increase or at least would not decrease with an increase in traffic density. When the traffic volume exceeded 1,100 vehicles per hour in one direction, the vehicles were not moving freely since at this density the percentage of vehicles that shifted from one lane to the other started to decrease. However, the interference between vehicles probably was not great enough at this density to consider the highway congested.

The results shown by this figure illustrate the futility of basing highway design on oil patterns. On practically all highways at least 95 percent of the total travel is performed during periods when traffic is relatively light as compared to the volumes a highway must be designed to handle without being considered congested. Some design features, such as acceleration and deceleration lanes, are designed mainly to be of service during high traffic densities. Oil patterns, which represent primarily low traffic densities, are not a true index of their value.

As expected, the average speed for vehicles traveling in the left-hand lane on 4-lane divided or undivided highways was always higher than for vehicles in the right-hand lane. There was also a tendency for the difference in speed, as well as the percentage difference, to be greater for roads where the average speed was high than for roads where the average speed was low. On highways where the average speed was about 32 miles per hour at low densities, the average speeds in the left-hand lanes were from 11 to 16 percent higher than those for the right-hand lanes, while on sections with an average free speed of about 45 miles per hour the difference varied from 15 to 22 percent.

RELATIVELY LITTLE TRAFFIC CARRIED BY CENTER LANE OF 3-LANE HIGHWAY

There was no apparent tendency for the difference in average speed on the lanes to decrease uniformly as the traffic density increased except at the very high hourly volumes. Figures 10 and 11 show the distribution of vehicle speeds between lanes at five of the study locations during the lowest and highest traffic densities during the study. The distribution at an intermediate traffic volume is also shown for study section 1–E, the only section where there was a speed limit. Although a majority of the low-speed vehicles travel in the right lane and a majority of the high speed vehicles travel in the left lane, speed distributions by lanes show that there is not the segregation of speeds between lanes

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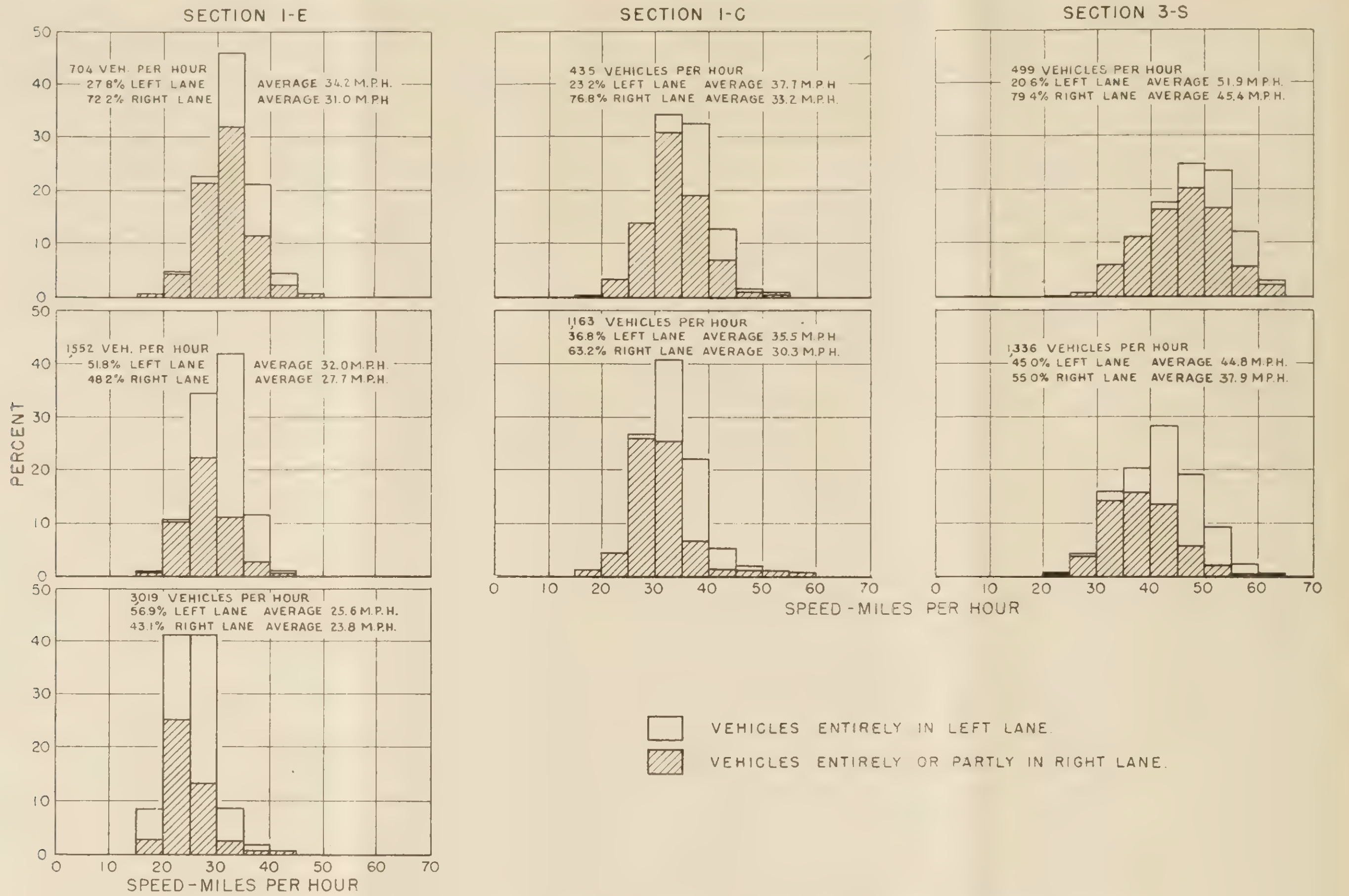

FIGURE 10.—DISTRIBUTION OF VEHICLES BY SPEED GROUPS ON 4-LANE UNDIVIDED HIGHWAYS.

that one would expect. Slow-moving vehicles use the left lane to pass vehicles traveling at even slower speeds and passings are made to the right when more convenient than to the left. It is not uncommon to find from 13 to 19 percent of the passings being made to the right of the passed vehicle.

Three-lane, two-directional highways are constructed to accommodate traffic volumes in excess of those that a 2-lane highway will handle efficiently but that are not great enough to require a 4-lane road. To obtain a better understanding of driver behavior on 3-lane highways under various total traffic densities and directional distributions, data from studies made in 1939 on sections of 3-lane highways having 30-foot surfaces (three 10-foot lanes), level tangent alinements, and other design details which permitted high speed operation, have been analyzed (table 2). Since the sections were located in a State where 3-lane construction is common practice, most of the drivers were familiar with the operation of vehicles on 3-lane roads.

It is commonly assumed that a 3-lane highway is most efficient for locations where at least two-thirds of the traffic travels in one direction during the high-volume periods. However, it is the rule, rather than the exception, that at least twice as many vehicles will be traveling in one direction as in the other on any highway, especially during periods in which the highest densities occur.

Figure 12, based on data for 12,119 vehicles, shows that under these conditions on level tangent sections of highway the percentage of the total vehicles traveling in the center lane at any one point increases as the total volume increases to 1,500 vehicles per hour. At 1,500 vehicles per hour, only 15.9 percent were in the center lane, 13.8 percent traveling in one direction, and 2.1 percent in the other. Indications are that a maximum of about 300 vehicles per hour, or 15 percent, will be traveling in the center lane at any one point on the highway when the total hourly volume reaches 2,000 vehicles. This fact will be a surprise to anyone who has thought that about one-third of the total traffic would use each lane, that the vehicles in the center lane would consist almost entirely of vehicles overtaking the slow-moving vehicles traveling in the direction of the heavy density, and that these circumstances would be the reason for a most efficient operation of a 3-lane road when two-thirds of the traffic is in one direction.

Figure 13 shows the average speeds for the vehicles in the center and outside lanes at different traffic densities. The average speeds for vehicles in the center lane remained practically constant, while for vehicles in the right-hand lanes there was a marked decrease in speed with an increase in the total traffic volume. Even at rather high densities the average speed of vehicles while using the center lane for passing was nearly as high as the average speeds for all vehicles on high-speed, 4-lane highways during low traffic volumes. The high speeds would certainly seem to be far more hazardous on the 3-lane road, where there was always the possibility of oncoming traffic entering the same lane, than on a 4-lane road.

Figure 14 shows the distribution of speeds by lanes and direction at both a low and high total traffic density. At the higher traffic density a much larger propor-

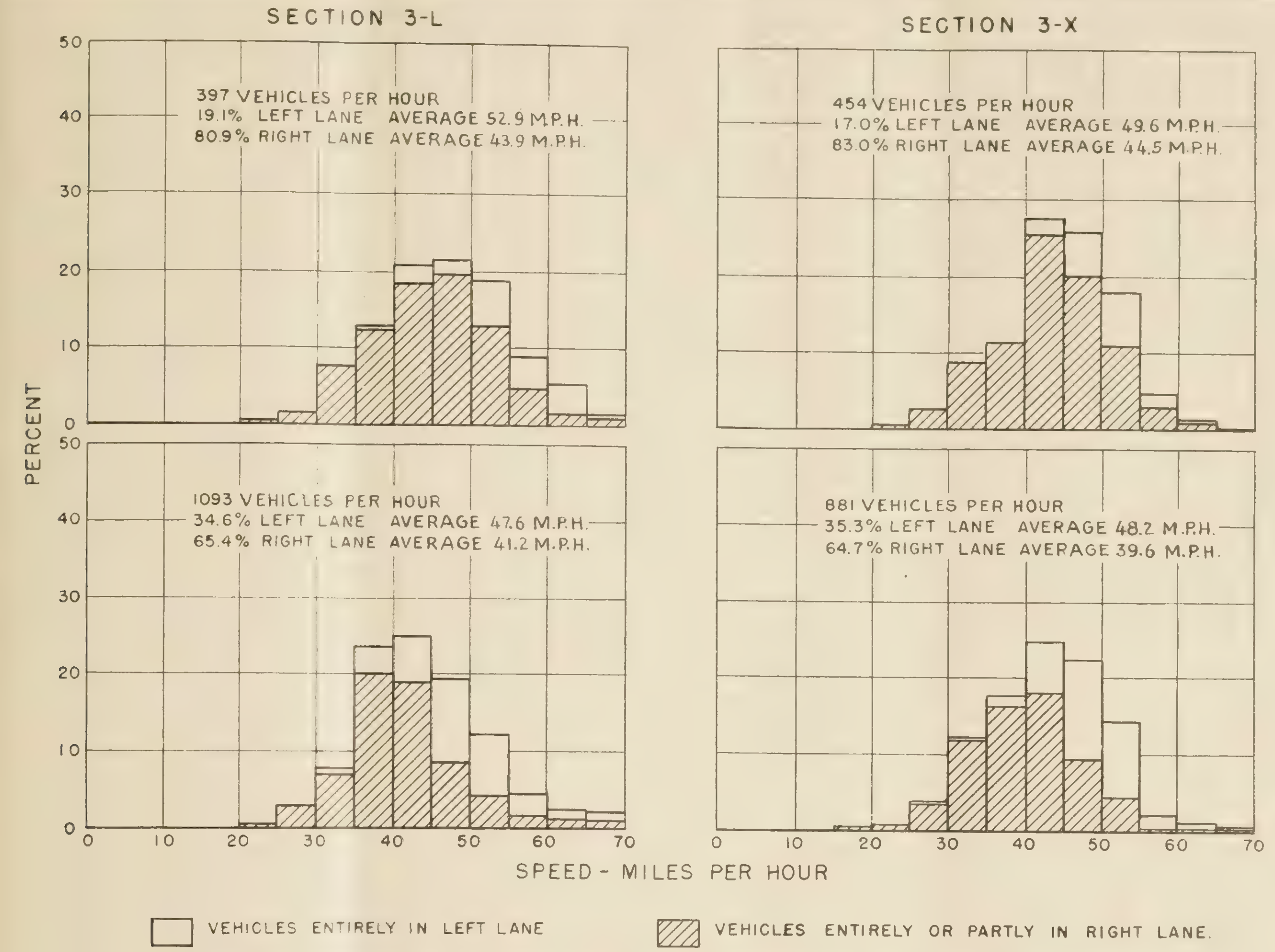

Figure 11.—Distribution of Vehicles by Speed Groups on 4-Lane Divided Highways.

Table 2.—*Distribution of vehicles between lanes and average speeds on 3-lane highway during various traffic densities while about two thirds of all traffic traveled in one direction*

	342 vehicles per hour			470 vehicles per hour			694 vehicles per hour			899 vehicles per hour			1,072 vehicles per hour			1,338 vehicles per hour			1,517 vehicles per hour			1,728 vehicles per hour		
	Vehicles			Vehicles			Vehicles			Vehicles			Vehicles			Vehicles			Vehicles			Vehicles		
	Number per hour	Percent	Average speed	Number per hour	Percent	Average speed	Number per hour	Percent	Average speed	Number per hour	Percent	Average speed	Number per hour	Percent	Average speed	Number per hour	Percent	Average speed	Number per hour	Percent	Average speed	Number per hour	Percent	Average speed
Traffic in direction of lesser density:																								
Right lane	114	33.3	35.0	185	39.4	38.7	254	36.6	38.0	224	24.9	37.5	347	32.4	36.8	398	29.8	38.0	447	29.4	37.8	464	26.9	35.4
Center lane	3	1.0	42.3	4	.8	41.6	14	2.0	45.9	15	1.7	44.3	20	1.8	41.9	31	2.3	44.0	31	2.1	46.2	23	1.3	49.6
Total	117	34.3	35.2	189	40.2	38.8	268	38.6	38.4	239	26.6	38.5	367	34.2	37.1	429	32.1	38.5	478	31.5	38.4	487	28.2	36.1
Traffic in direction of greater density:																								
Right lane	214	62.6	37.8	259	55.1	38.9	380	54.8	39.6	560	62.3	39.0	610	56.9	34.9	750	56.1	34.4	830	54.7	35.0	1,000	57.9	32.7
Center lane	11	3.1	46.0	22	4.7	42.9	46	6.6	43.6	100	11.1	42.5	95	8.9	44.2	159	11.8	44.8	209	13.8	43.0	241	13.9	44.6
Total	225	65.7	38.2	281	59.8	39.4	426	61.4	40.0	660	73.4	39.5	705	65.8	36.2	909	67.9	36.3	1,039	68.5	36.7	1,241	71.8	35.1
All traffic:																								
Center lane	14	4.1	45.2	26	5.5	42.7	60	8.6	44.1	115	12.8	42.7	115	10.7	43.7	190	14.1	44.7	240	15.9	43.4	264	15.2	45.0
Right lanes	328	95.9	37.0	444	94.5	39.2	634	91.4	39.1	784	87.2	38.6	957	89.3	34.5	1,148	85.9	35.6	1,277	84.1	36.0	1,464	84.8	33.6
Total	342	100.0	37.2	470	100.0	39.4	694	100.0	39.4	899	100.0	39.1	1,072	100.0	35.5	1,338	100.0	37.0	1,517	100.0	37.2	1,728	100.0	35.4

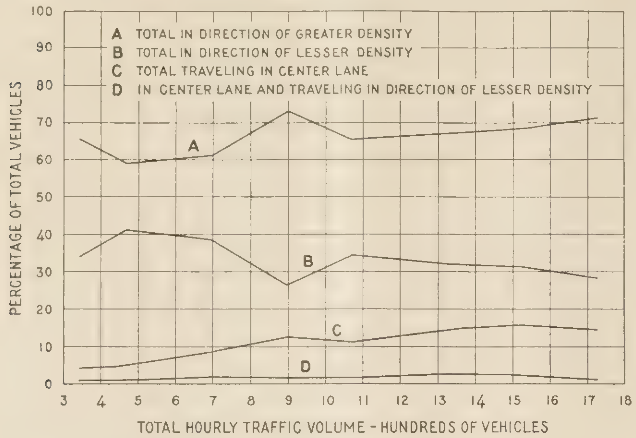

Figure 12.—Distribution of Vehicles Between Lanes on 3-Lane Level Tangent Highway.

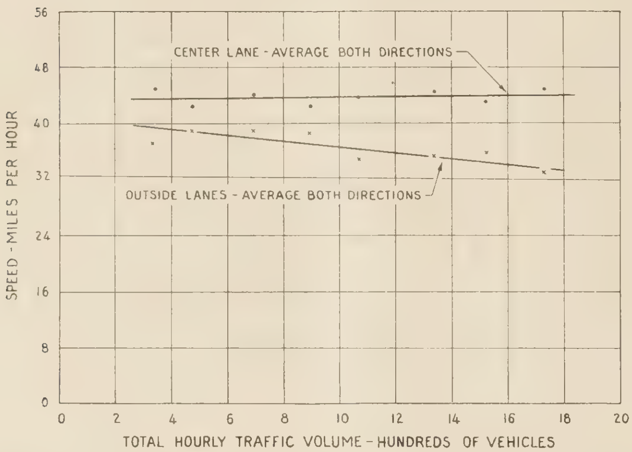

Figure 13.—Vehicle Speeds in Center and Outside Lanes on 3-Lane Highways.

tion of the high-speed vehicles was in the center lane. Although only 15.2 percent of the vehicles were in the center lane, 41.7 percent of those traveling over 40 miles per hour, 58.3 percent of those over 45 miles per hour, and 72.7 percent of those traveling over 50 miles per hour were in the center lane. At the heavy density

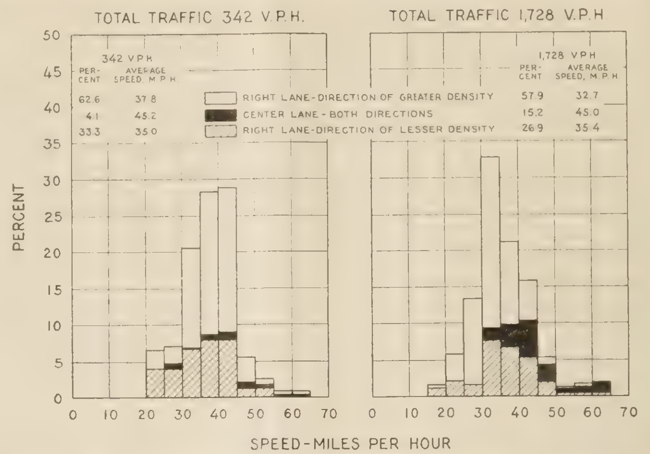

Figure 14.—Frequency Distribution of Vehicle Speeds on 3-Lane Highways.

no vehicle traveling less than 30 miles per hour was in the center lane. Apparently the vehicles had to complete the passing maneuvers and return to the right-hand lane as quickly as possible. The decreased speed of the vehicles traveling in the right-hand lane and in the direction of the heavier traffic movement was the main reason the average speed was lower during the higher total traffic volume.

3-LANE HIGHWAY MOST EFFICIENT WHEN TRAFFIC IS EVENLY DIVIDED BY DIRECTION

A similar analysis was made of traffic on the same 3-lane highways during periods when traffic in the direction of heaviest travel did not exceed 60 percent of the total and averaged between 54 and 57.6 percent at the different traffic densities (table 3). For this condition, speeds for corresponding total traffic volumes were a little higher than when about two-thirds traveled in one direction. The most significant difference occurred at the highest comparable traffic densities of about 1,500 vehicles per hour when there was a difference of 1.9 miles per hour in the average speed and a difference of 2.6 miles per hour in the speed of the slowest-moving lane of traffic. The total number of vehicles making use of the center lane was about the same in both cases.

Table 3.—*Distribution of vehicles between lanes and average speeds on 3-lane highway during various traffic densities while about half of all traffic traveled in each direction*

	310 vehicles per hour			670 vehicles per hour			1,248 vehicles per hour			1,530 vehicles per hour		
	Vehicles		Average speed	Vehicles		Average speed	Vehicles		Average speed	Vehicles		Average speed
	Number per hour	Percent		Number per hour	Percent		Number per hour	Percent		Number per hour	Percent	
Traffic in direction of lesser density:												
Right lane	129	41.6	36.6	290	43.3	38.2	504	40.4	37.3	600	39.2	38.6
Center lane	11	3.6	44.3	18	2.7	45.7	45	3.6	46.1	49	3.2	49.0
Total	140	45.2	37.2	308	46.0	38.6	549	44.0	38.0	649	42.4	39.4
Traffic in direction of greater density:												
Right lane	158	51.0	37.7	346	51.6	39.9	599	48.0	36.1	696	45.5	37.6
Center lane	12	3.8	44.7	16	2.4	45.9	100	8.0	44.5	185	12.1	43.8
Total	170	54.8	38.2	362	54.0	40.2	699	56.0	37.3	881	57.6	38.9
All traffic:												
Center lane	23	7.4	44.5	34	5.1	45.8	145	11.6	45.0	1,296	15.3	44.9
Right lanes	287	92.6	37.2	636	94.9	39.1	1,103	88.4	36.6	234	84.7	38.1
Total	310	100.0	37.8	670	100.0	39.5	1,248	100.0	37.6	1,530	100.0	39.1

The conclusions reached from both analyses for 3-lane level tangent sections of highway carrying few trucks were:

1. At any one point on a 3-lane highway relatively few vehicles are traveling in the center lane. The maximum number that can be in the center lane is about 300 per hour, regardless of the total traffic volume, when up to 70 percent of the total traffic is traveling in one direction.
2. Although there is a very marked drop in the average speed of traffic in the outside lanes with an increase in volume, there is no drop in the speeds of vehicles in the center lane.
3. As long as the hourly traffic volume traveling in one direction does not exceed 70 percent of the total traffic, the center lane will be used by vehicles traveling in both directions.
4. The average speed of all vehicles was slightly higher when the traffic was nearly evenly divided by direction than when two-thirds traveled in one direction.

Other obvious facts are:

1. At places where the sight distance is restricted, the use of the center lane for passing is dangerous, so in effect a 3-lane highway will carry only two lanes of traffic at such points.
2. A 3-lane highway having even one restricted sight distance cannot carry more vehicles per hour in one direction than the number that can crowd into one traffic lane.

It may be concluded, therefore, that a 3-lane highway is more efficient when traffic is evenly divided by directions than when two-thirds of the traffic travels in one direction. There is a possibility that a two-directional, 3-lane highway would be more efficient when practically all traffic moved in one direction than when traffic was evenly divided, but the percentage traveling in one direction in such a case would be closer to 100 than to 67. However, since no data were available for this condition, this possibility could not be explored.

DESIRED NUMBER OF PASSINGS PER MILE OF HIGHWAY CALCULATED

By knowing the frequency distribution of vehicle speeds for a particular hourly traffic volume on a tangent section of highway, it is possible to calculate the approximate number of passings that will take place per hour per mile of highway. As an example, if there were 10 drivers traveling 50 miles per hour and 20 drivers traveling 40 miles per hour, each hour in the same direction on a highway, each driver traveling 50 miles per hour would, on an average, pass a vehicle traveling 40 miles per hour every 12 minutes. The total number of passings per hour on each mile of highway would be:

$$P=\frac{AB\ (F-S)}{FS}$$

where

P=number of passings per hour on each mile of highway,
A=number of the faster moving vehicles per hour,
B=number of the slower moving vehicles per hour,
F=speed of the faster moving vehicles in miles per hour,
S=speed of the slower moving vehicles in miles per hour,

and in the above example

$$P=\frac{10\times 20\ (50-40)}{50\times 40}=1 \text{ passing per mile of highway,}$$

per hour.

In a similar manner the number of passings per hour on each mile of highway for any frequency distribution of speeds can be calculated by obtaining a summation of the number of passings made by vehicles moving at each speed passing vehicles moving at each lower speed.

When the number of passings as calculated in this manner from the frequency distribution of speeds recorded during a large number of studies on tangent sections of highway are compared with the passings that actually took place during the same period, the calculated number is generally somewhat higher than the actual number. The difference is no doubt caused by the fact that the speed frequencies represent speeds at a particular point on the highway rather than the distribution of average speeds for the vehicles over the entire portion of the highway having the same design features as the study location. From a frequency distribution showing 10 percent of the vehicles traveling over 50 miles per hour, it is not correct to assume that 10 percent of the drivers traveled over 50 miles per hour all the time under similar conditions. Neither is it correct to assume that all drivers traveled over 50 miles per hour 10 percent of the time. However, the first assumption is more nearly correct than the second for the short time period required by each vehicle to traverse the 0.2 mile section of highway on which the number of passings was recorded. A passing as recorded for this study consisted of two vehicles changing position with respect to one another between the time they entered and left the study section. Whether or not the entire passing maneuver was completed within the study section was not considered.

If it were not for the interference between vehicles as the traffic volume on a highway increases, all drivers could travel at their desired speeds regardless of the traffic density and the distribution of speeds would be the same as the free-speed distributions. In such a case, the total number of passings per hour made by vehicles traveling in one direction on the highway would increase as the square of the hourly traffic volume in that direction.

Using the free-speed distributions for each 2- and 3-lane highway section, the numbers of passings per mile of highway per hour were calculated for the different hourly traffic volumes at each location and compared with the numbers of passings that occurred. Figure 15 shows the percentages that the actual number of passings performed were of the desired number of passings, or passings that would have been performed providing the drivers could have traveled at their desired speeds. Individual points are shown only for the 2-lane highways, each point representing the result for a particular traffic volume at one of 12 level tangent locations.

Although there is a scattering of points at all hourly traffic volumes, the straight-line relationship calculated by the method of least squares shows a very definite decrease in the percentage with an increase in the total traffic density. The line for 3-lane highways was based on data for the same locations as those for curve E of figure 8. Data for both highway types include a total of 11,005 passings performed during the time that 91,866 vehicles traversed the 16 study sections each 0.2 mile long.

It is significant that the hourly traffic volumes of 1,933 vehicles and 3,490 vehicles when no passings could be made on the 2- and 3-lane highways, respec-

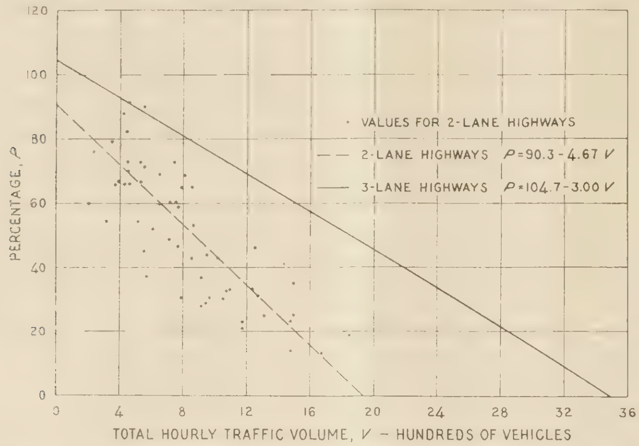

Figure 15.—Percentage of Desired Number of Passings That Are Performed on Level Tangent 2- and 3-Lane Highways.

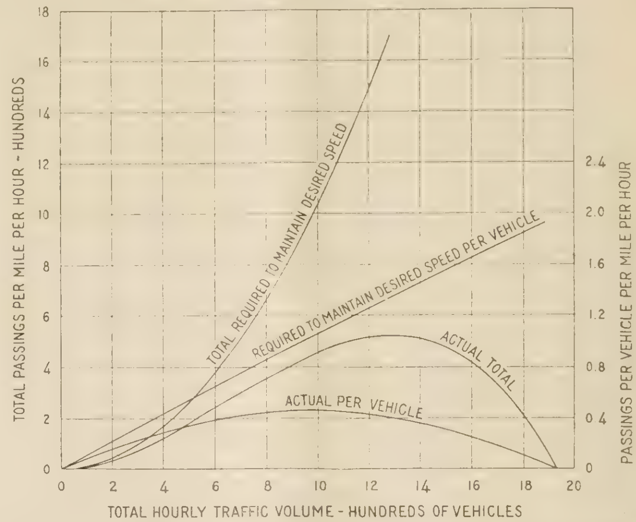

Figure 16.—Comparison of Actual Number of Passings Performed and Number That Would Be Required at Various Traffic Volumes for All Vehicles to Maintain Their Free Speed on 2-Lane Highway With Two-thirds of Total Traffic in One Direction.

tively, are approximately the same as the possible capacities of the corresponding highways determined by using the mean difference in speed between successive vehicles as an index of the passing possibilities.

Figure 16 shows the actual number of passings compared with the required number of passings for drivers to maintain their free speeds on a 2-lane highway with two-thirds of the traffic in one direction where the variation in speed was great enough to cause a total of 18.5 passings per mile per hour at a volume of 100 vehicles per hour in one direction. This figure represents a typical 2-lane level tangent highway carrying few trucks and with a frequency distribution of free speeds as shown by the curve for 2-lane highways in figure 5.

The total number of passings required for all drivers to maintain their desired speed increases as the square of the traffic volume. Actually, however, the total number of passings that occur increases with an increase in the total traffic volume up to 1,300 vehicles per hour and then decreases rapidly. To maintain his free speed each driver should be able to increase the number of passings he makes directly as the traffic volume increases. Actually, however, the number of passings made by the average driver increases as the density increases up to 800 vehicles per hour, remains about the same between 800 and 1,200 vehicles per hour, and then decreases with a further increase in the traffic density. The fact that the average driver on a 2-lane tangent highway should increase the number of passings he makes as the traffic volume goes above 800 vehicles per hour, but can make no material increase due to the traffic density, is a very important consideration in the determination of practical capacities for rural highways.

VEHICLE SPEEDS IN 1934 AND 1939 COMPARED

Another important factor in the determination of practical capacities, especially for design purposes, is the speeds at which drivers travel at the present time and the speeds at which they will desire to travel at some future date. Until recent years little data have been available regarding speeds on rural highways, but it is known that motor-vehicle speeds increased rapidly until about 1930. During recent years the performance of motor vehicles has continued to improve and there has been a marked improvement in rural highways. Both have tended to increase the average travel speed on rural highways. However, estimates of future performance must be based on speed trends during recent years on modern, well-designed highways. The capacity studies in 1939 included one location of this type that had also been included in the 1934 studies, a section of 3-lane highway. From 1934 to 1939, the paved surface width, alinement, and other general features had not been changed. The speeds of over 8,000 vehicles were obtained during the studies in each of the years. Weather conditions, hours of study, etc. were also the same.

Table 4 shows a comparison of the average speeds for the 2 years. It is rather surprising to find that the average speed for the free-moving vehicles, that is, those that were traveling without interference from other vehicles, or at the driver's desired speed, was slightly lower in 1939 than in 1934. However, at the highest traffic density recorded, the speeds during 1939 were higher than in 1934. In other words, an increased traffic volume had a greater effect on the average speed in 1934 than in 1939.

Table 4.—*Comparison of speeds during 1934 and 1939 on the same 3-lane highway during similar traffic densities*

1934 studies		1939 studies	
Traffic density	Average speed	Traffic density	Average speed
Vehicles per hour	*Miles per hour*	*Vehicles per hour*	*Miles per hour*
(1)	40.8	(1)	39.6
1,069	36.8	1,072	35.7
1,391	36.6	1,338	37.0
1,544	34.4	1,517	37.2
		1,684	35.3

1 Free-moving vehicles.

Table 5 shows that in 1939 there was a greater variation in speeds than in 1934. In 1934 only 0.5 percent of the free-moving vehicles traveled less than 25 miles per hour and 0.6 percent traveled over 60 miles per hour, while in 1939 5.2 percent traveled less than 25 miles per hour and 3.4 percent traveled over 60 miles per hour.

There was a corresponding or even greater difference between the two years for the extreme speeds at the heaviest comparable densities studied. Since trucks were a negligible portion of the total vehicles on this road during both years, they do not account for this difference. However, a much longer road section was used to determine the speeds for 1934 than for 1939. With the shorter section there was a greater likelihood of obtaining extreme speeds and therefore little significance can be placed on the fact that the results show a greater variation in speeds for the 1939 than the 1934 values.

The important conclusion that can be drawn from this comparison is that there was a relatively small change in speeds from 1934 to 1939 under similar highway and traffic density conditions. This is very significant since the comparison has been made on a highway where there should be the greatest probability of increased speed due to improved vehicle performance. The drivers utilized the potential speeds of their vehicles to a greater extent in 1934 than in 1939.

TABLE 5.—*Comparison of distribution of speeds during light and heavy traffic volumes on same highway in 1934 and 1939*

Speed group (miles per hour)	Free-moving vehicles		Heavy traffic density (about 1,500 vehicles per hour)	
	1934	1939	1934	1939
	Percent	*Percent*	*Percent*	*Percent*
Below 20	0.1	2.7	0.3	2.2
20–24	.4	2.5	1.5	3.2
25–29	1.9	3.9	10.0	5.9
30–34	12.0	23.4	33.6	33.1
35–39	31.8	17.7	29.8	21.7
40–44	25.4	26.1	16.7	18.7
45–49	17.1	12.9	6.0	8.1
50–54	9.1	3.9	1.7	2.6
55–59	1.6	3.5	.2	2.3
60–up	.6	3.4	.2	2.2
Total	100.0	100.0	100.0	100.0

At present it is not possible to predict with any degree of accuracy what the maximum highway speeds in the future will be. The development of the airplane and its construction by mass production methods will undoubtedly tend to reduce the demand for exceedingly high-speed operation of the motor vehicle. Based on recent trends, there will be an increase in speed chiefly by the modernization of substandard highways and by a reduction in the percentage of drivers who travel at exceedingly low speeds on highways designed for high-speed operation, but there is no basis for the assumption that maximum motor-vehicle speeds will be materially higher than they have been on our modern, well-designed highways. Apparently, maximum speeds of passenger cars have been and will continue to be governed to a larger extent by characteristics of the driver, such as his reaction time and ability to see other vehicles and estimate their speeds, than by the possible speed of the vehicle he is operating.

CHARACTERISTICS OF TRAFFIC FLOW USEFUL IN DETERMINING PRACTICAL CAPACITIES GIVEN

When the preliminary results of these capacity studies were published in 1939, a number of figures were presented showing certain characteristics of traffic flow on tangent highway sections that have since been very useful in the determination of practical capacities for different highway conditions. The results as given by these figures have been verified and their possible application expanded by checking them with the results of additional and more recent data. One of the figures presented [1] showed that on 2-lane tangent highways operators of vehicles at or above a time spacing of 9 seconds from the preceding vehicles are not influenced by the speed of the preceding vehicle, but drivers of vehicles spaced at less than 9 seconds govern their speeds to an increasingly greater extent by the speed of the preceding vehicles as the spacing decreases.

The numbers of vehicles traveling at various time spacings from a preceding vehicle on a typical 2-lane tangent highway are shown by figure 17. Similar data representing other 2- and 3-lane tangent highways show that practically the same distribution of time spaces occurs for the same traffic volume in one direction regardless of the average vehicle speed, distribution of speeds, or whether or not the vehicles appeared to be bunched. Any marked difference between the distribution on the various highways generally occurred in the number of vehicles at the extremely short time spacings.

Likewise, the time spacings between successive vehicles traveling in one direction on 4-lane highways regardless of the traffic lane the vehicles were in are shown by figure 18. There was a more uniform distribution of the shorter time spacings and fewer of the extremely long time spacings on the 4-lane roads than on the 2-lane roads for corresponding hourly traffic volumes.

Were it not for the wide variation in vehicle speeds and resulting variation in the time spacings between vehicles, the determination of practical highway capacities and numerous other traffic problems would be relatively easy. In this connection it is rather surprising, when reviewing published material regarding the movement and delay of vehicles under certain conditions, that many theoretical derivations are based on the assumption that all time spaces are equal. In most cases entirely different results would be obtained if consideration were given to the variation that actually exists. The relation between the average time spacing for a given traffic volume and the spaces that exist on 2- and 4-lane tangent rural highways is given by figures 19 and 20. At a traffic volume of 600 vehicles per hour in one direction on a 2-lane highway, instead of a vehicle passing a given point on the highway every 6 seconds, 58 percent of the vehicles will pass within 3 seconds (half the average interval) of another vehicle and there will be an appreciable number of times during the hour that a time interval exceeding 24 seconds will elapse between two vehicles.

For the solution of certain traffic problems involving time spacings between vehicles, such as calculations regarding the average wait before a space sufficiently long occurs in a stream of traffic to permit crossing it with safety, or determinations of the percentage of time that the lane normally used by oncoming traffic may be used to perform passing maneuvers, it is necessary to know the percentage of the total time that the spaces between vehicles are in excess of certain time values in addition to the number of times per hour a space exceeding a certain value occurs. Figures 21 and 22 have been constructed to show this information for tangent sections on 2- and 4-lane rural highways where drivers are not influenced by traffic lights at intersections. An analysis of data for a number of

[1] Preliminary results of Highway Capacity Studies, by O. K. Normann. PUBLIC ROADS, February 1939, p. 228.

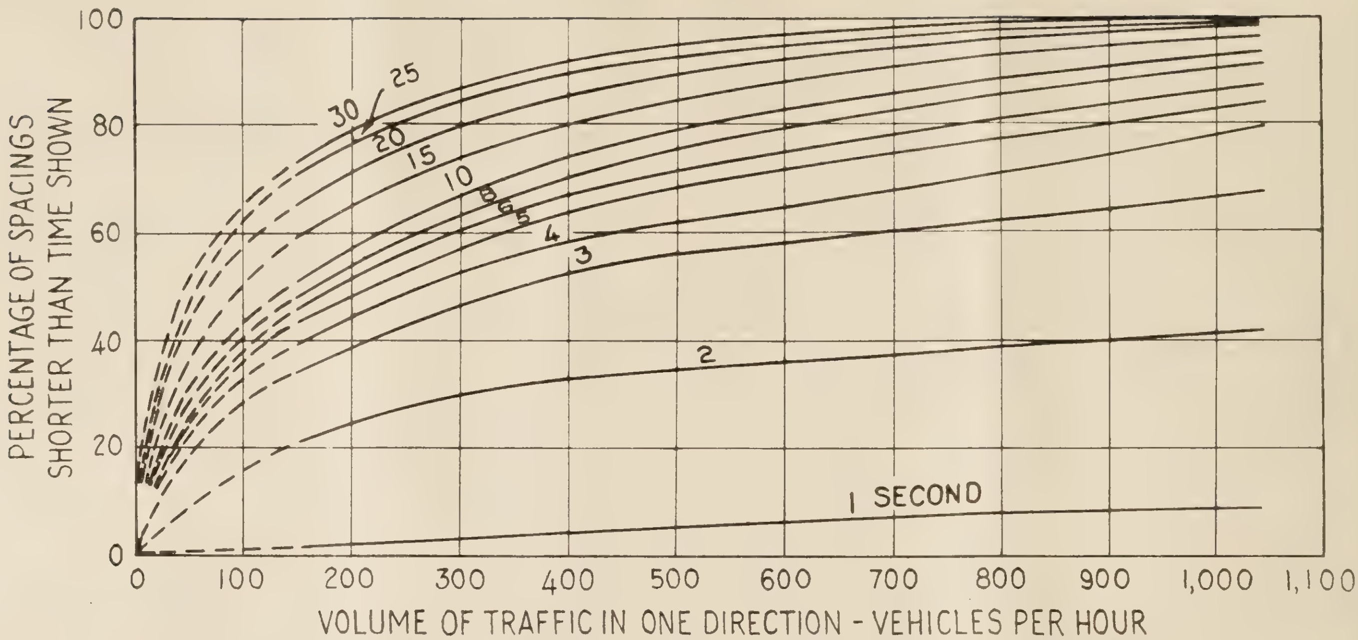

Figure 17.—Frequency Distribution of Time Spacings Between Successive Vehicles Traveling in the Same Direction at Various Traffic Densities on Typical 2-Lane Rural Highway.

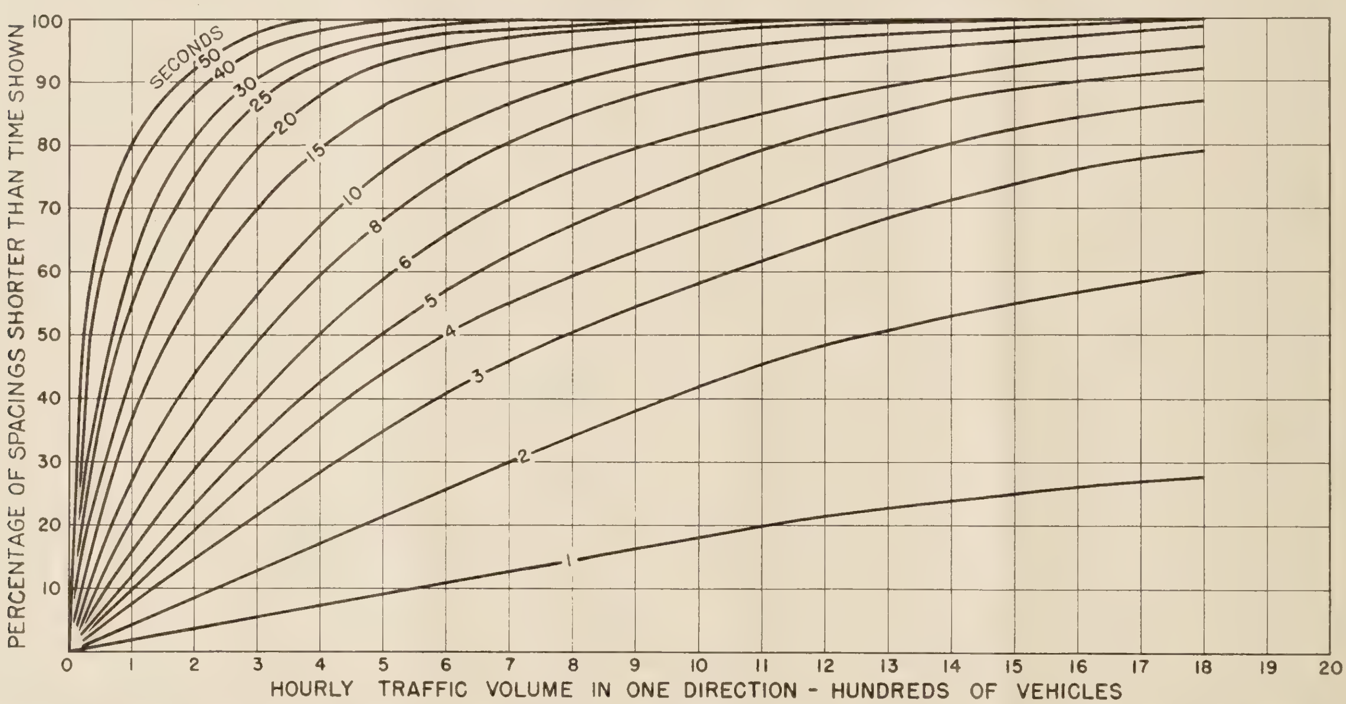

Figure 18.—Frequency Distribution of Time Spacings Between Successive Vehicles Traveling in the Same Direction at Various Traffic Densities on Typical 4-Lane Rural Highway.

locations showed that there was some variation in corresponding values at different locations, but for all practical purposes the values as given by figures 21 and 22 are sufficiently accurate for all 2- and 4-lane highways, respectively. Corresponding values for 3-lane highways were not consistent, generally being in the neighborhood of those for 2-lane highways but oftentimes approaching those for 4-lane highways.

In combination with figures 17 and 18, figures 21 and 22 may be used to solve a number of traffic problems for which it is either impossible or impractical to obtain more accurate results by actual field studies.

PRACTICAL APPLICATION OF RESULTS ILLUSTRATED

To illustrate one of the many uses of figures 21 and 22, assume it is desired to compare the average time lost by a driver in safely crossing 2- and 4-lane highways. Assume that a driver on a minor east and west road approached a 2-lane arterial highway carrying a total of 1,200 vehicles per hour with 400 northbound and 800 southbound and that it will require 5 seconds to cross and be clear of traffic on the through route. Figure 17 shows that 64 percent of the spacings at a volume of 400 vehicles per hour are equal to or less

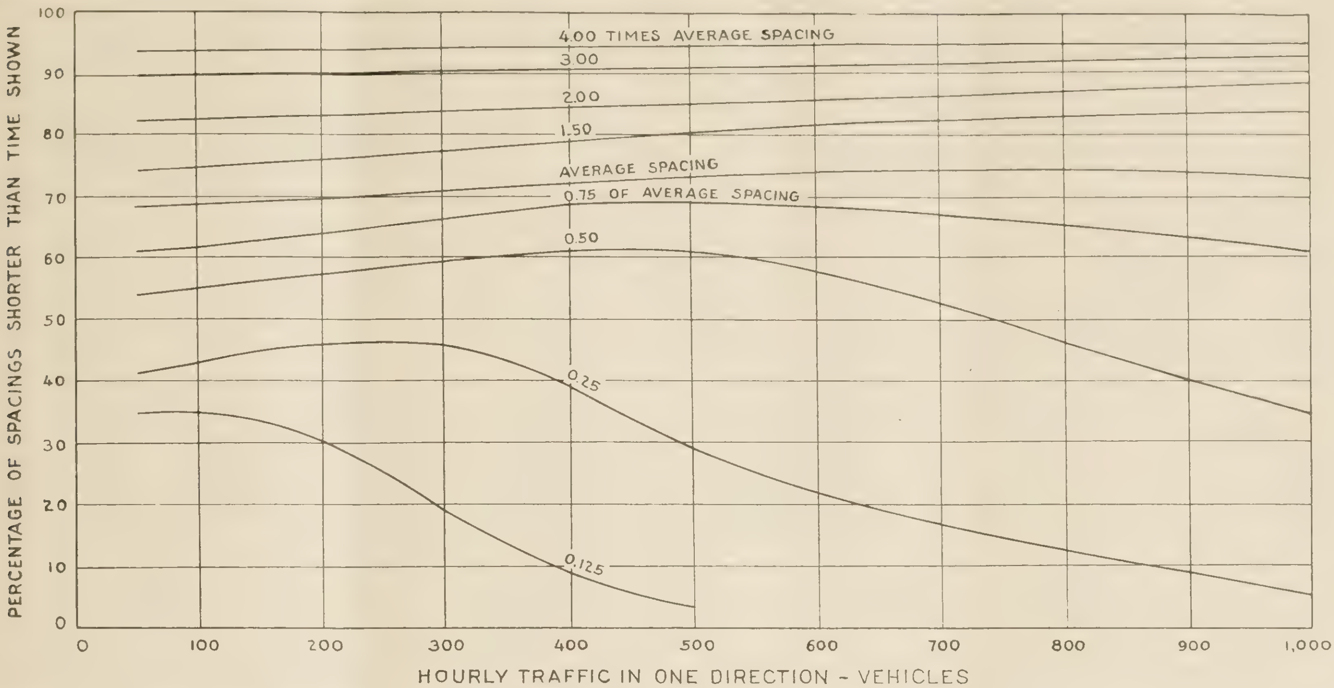

FIGURE 19.—CUMULATIVE PERCENTAGE OF VEHICLES TRAVELING AT TIME SPACING SHORTER THAN MULTIPLES OF AVERAGE SPACING FOR VARIOUS HOURLY TRAFFIC VOLUMES ON TYPICAL 2-LANE RURAL HIGHWAY.

than 5 seconds, therefore spaces greater than 5 seconds occur 144 times per hour in the northbound traffic. Likewise, spaces greater than 5 seconds occur 180 times per hour in the southbound traffic. The spaces in the northbound traffic are in excess of 5 seconds 66.5 percent of the time and those in the southbound traffic are in excess of 5 seconds 40 percent of the time (fig. 21). So, out of 100 drivers on the minor road, 27 drivers ($0.40\times0.665\times100$) will be able to cross without any delay after coming to a stop. The other 73 will be delayed, 20 by traffic in both lanes [$100\ (1.00-0.40)\ (1.00-0.665)$], 19 by traffic in the northbound lane $\left(53\times\frac{0.335}{0.335+0.600}\right)$, and 34 by traffic in the southbound lane $\left(53\times\frac{0.600}{0.335+0.600}\right)$. After the 34 delayed by traffic in the southbound lane have waited an average of 6 seconds $\left[\frac{1}{2}\left(\frac{0.60\times3{,}600}{180}\right)\right]$, 23 will be able to cross with no further delay (34×0.665) and the other 11 will not be able to cross because of traffic in the northbound lane. By continuing the calculations it can be shown that the average delay for the 73 delayed vehicles will be 9.5 seconds and the average delay for all 100 drivers will be about 7 seconds. Some drivers will be delayed up to 50 seconds. In a similar manner the average delay to cross 2- or 3-lane highways, or 4-lane divided or undivided highways with any traffic volume on the arterial highway, may be calculated provided the crossing time is known.

Based on a reasonable acceleration value it has been estimated that 5 seconds are required to cross a 2-lane highway, 6 seconds to cross a 4-lane undivided highway, 7 seconds to cross the first 2 lanes of a 4-lane divided highway and come to a stop within a 30-foot median strip, and 5 seconds to cross the second 2 lanes. Using these time periods, the data shown by figures 17, 18, 21, and 22, and assuming that a safe crossing will not be made when it is necessary for vehicles on the arterial highway to slow down to avoid an accident, figure 23 has been constructed. The values shown are applicable only to vehicles on a cross road carrying very little traffic and do not include the delay in stopping for the "stop" sign.

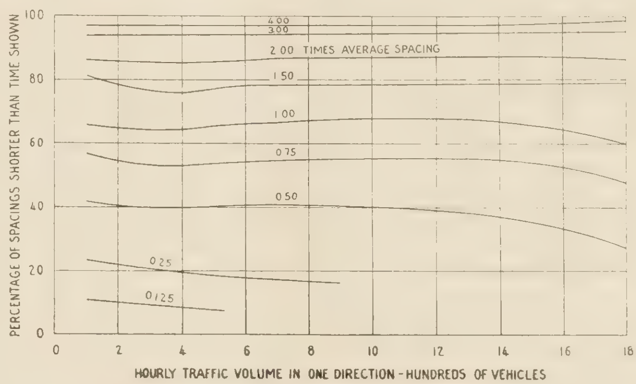

FIGURE 20.—CUMULATIVE PERCENTAGE OF VEHICLES TRAVELING AT TIME SPACINGS SHORTER THAN MULTIPLES OF AVERAGE SPACING FOR VARIOUS HOURLY TRAFFIC VOLUMES ON TYPICAL 4-LANE RURAL HIGHWAY.

The average delay is lower at the 2-lane highway than at the 4-lane undivided highway for the same hourly volume not only because a slightly shorter time is required to cross the 2-lane highway, but also because traffic cannot travel as freely on the 2-lane highway and becomes more bunched, resulting in longer open spaces that permit crossings to be performed. Up to a total of 1,400 vehicles per hour, the delay is about the same when crossing 2-lane and 4-lane divided highways. Above 1,400 vehicles per hour it is easier to cross the divided highway and considerably less delay will be experienced by drivers that start the maneuver by

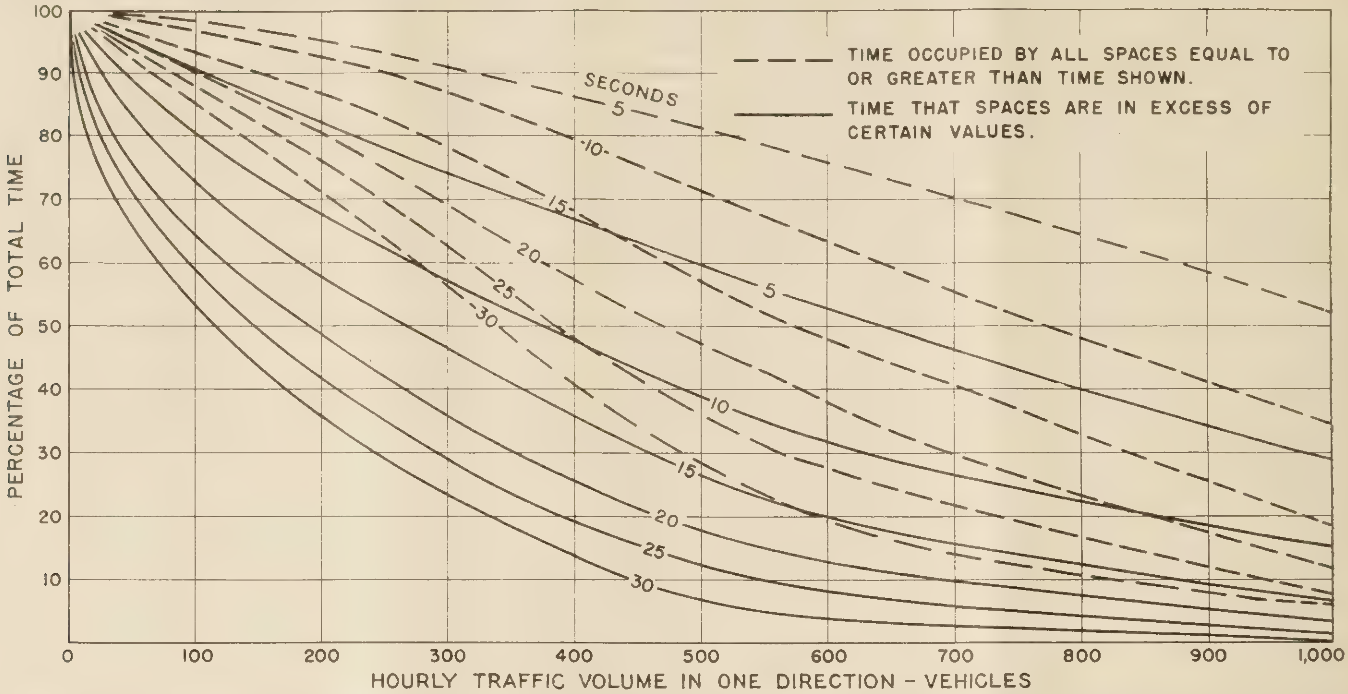

Figure 21.—Percentage of Total Time Occupied by Various Time Spacings Between Vehicles Traveling in the Same Direction and Percentage of Total Time That Spacings Are in Excess of Certain Values on Typical 2-Lane Rural Highway.

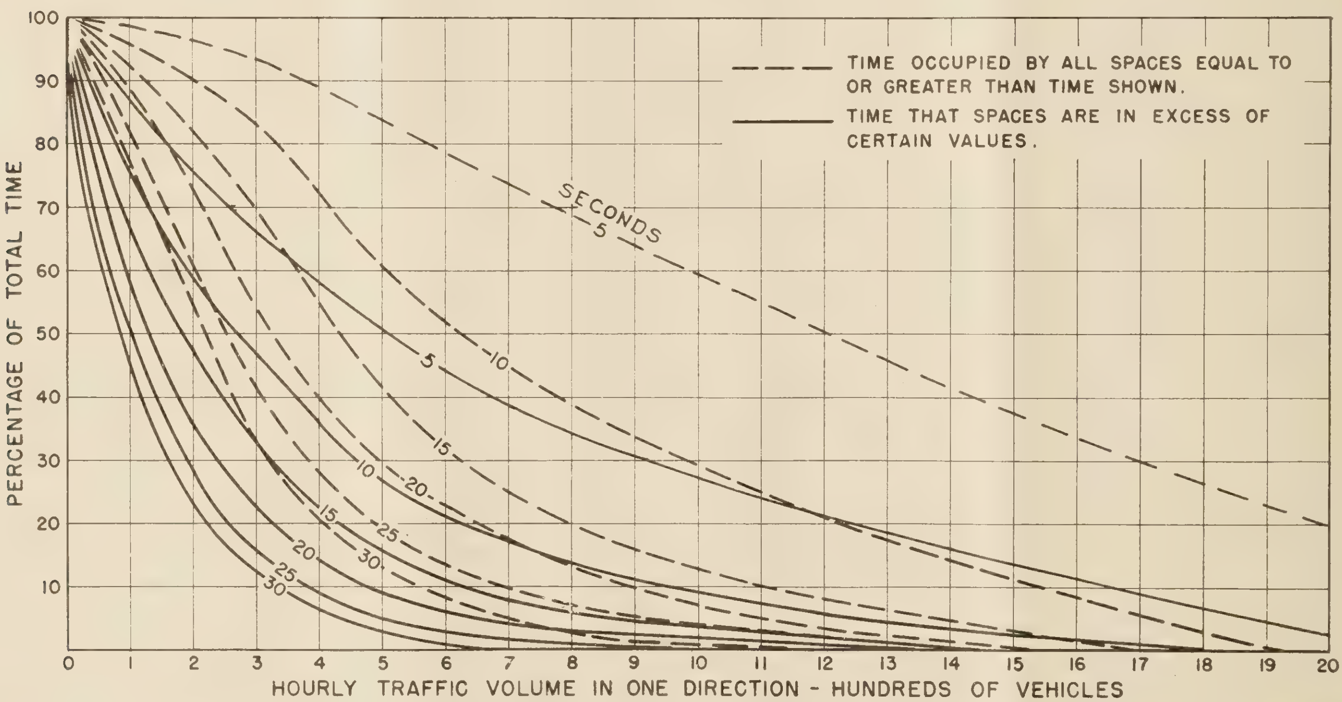

Figure 22.—Percentage of Total Time Occupied by Various Time Spacings Between Vehicles Traveling in the Same Direction and Percentage of Total Time That Spacings Are in Excess of Certain Values on Typical 4-Lane Rural Highway.

crossing the two lanes carrying the lighter traffic volumes than by drivers that first cross the lanes carrying the heavier traffic volumes.

Using the same basic data, calculations may be made to determine need for the installation of traffic signals at rural intersections with greater accuracy than would otherwise be possible. However, the information shown in figures 17 and 21 is most useful in a study of practical capacities for 2-lane roads by supplying data of value for an analysis of the extent to which oncoming traffic restricts the use of the left lane for passing purposes. To illustrate, assume that a driver is trailing a slow-moving vehicle and that to pass this vehicle he must encroach on or be in the left lane for a period of 10 seconds, traveling at an average speed of 30 miles per hour. The "hole" or time space between successive

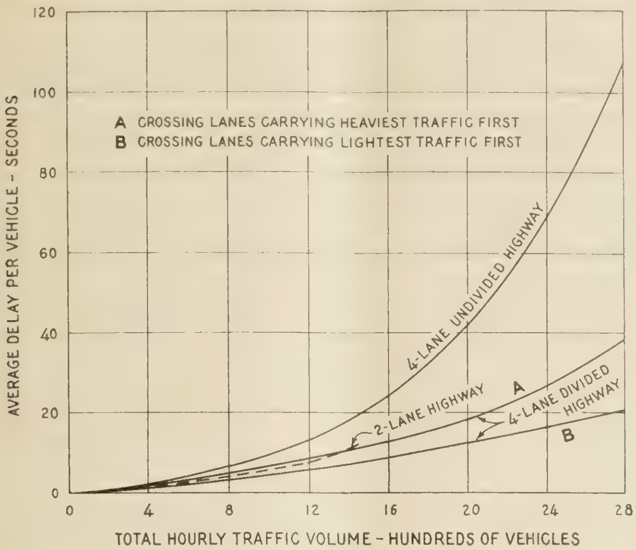

FIGURE 23.—DELAY FOR INDIVIDUAL VEHICLES TO CROSS 2- AND 4-LANE HIGHWAYS CARRYING TWO-THIRDS OF TOTAL TRAFFIC IN ONE DIRECTION.

vehicles in the opposing traffic lane could not be less than 20 seconds $\left(10\times\frac{30+30}{30}\right)$ if the oncoming vehicle met immediately after completing the maneuver is traveling at 30 miles per hour, not less than 25 seconds $\left(10\times\frac{20+30}{20}\right)$ with the oncoming vehicle traveling at 20 miles per hour, and not less than 16 seconds $\left(10\times\frac{50+30}{50}\right)$ with the oncoming vehicle traveling at 50 miles per hour.

PASSING POSSIBILITIES A FUNCTION OF TRAFFIC DENSITY

Likewise, to perform a passing maneuver requiring 10 seconds in the left lane at a speed of 50 miles per hour with the oncoming vehicle traveling 20, 30, or 50 miles per hour would require time spacings between vehicles in the opposing traffic lane of not less than 35, 27, or 20 seconds, respectively. How often the required time spaces will occur with a corresponding speed for the approaching vehicle is not shown by figure 21. However, analysis of the detailed data shows that the sum of the opportunities to pass at the different time spacings with oncoming vehicles traveling at different speeds may be determined from figure 21 by use of the following equation:

$$T=\frac{T_p(S_0+S)}{S_0}$$

where

T =equivalent spacing in seconds to be used in determining opportunities to pass from figure 21,
T_p=time required in left lane to complete passing maneuver,
S_0=average speed of opposing traffic in left lane, and
S =average speed of passing vehicle while in the left lane.

For example, assume that it is desired to find the average time a driver wanting to pass a vehicle traveling 20 miles per hour on a 2-lane tangent section of highway carrying 400 vehicles per hour in the opposing direction will be required to follow the slow vehicle before an opportunity to pass occurs. Assume also that 10 seconds will be required to complete the maneuver at an average speed of 30 miles per hour, and that the average speed of oncoming traffic is 40 miles per hour; then $T=\frac{10\ (40+30)}{40}=17.5$ seconds.

A spacing of 17.5 seconds or greater will occur 18 times (fig. 17) for every 100 cars in the opposing lane and 32 percent of the time (at volume of 400 in fig. 21) it will be possible to start the passing. So, for every 100 times a driver overtakes a vehicle traveling 20 miles per hour, it will be possible for him to start the passing maneuver with no delay 32 times and the other 68 times he will be required to follow the slow vehicle for some distance before he has an opportunity to pass. The average time in seconds that the slow vehicles must be trailed whenever the passing cannot be started immediately will be

$$F=\tfrac{1}{2}\left[\frac{3600(1.00-P_E)}{P_NV_0\left(\frac{S_0+S_p}{S_0}\right)}\right]$$

where

F=average time in seconds slow vehicle must be followed before opportunity to pass occurs,
P_E=ratio of time that spacings in opposing lane are in excess of T seconds for the particular traffic volume in the opposing lane to total time,
P_N=ratio of number of spaces in the opposing lane that are in excess of T seconds to total number of spaces,
V_0 =hourly traffic volume in opposing lane,
S_0 =average speed in miles per hour of traffic in opposing lane, and
S_p =speed in miles per hour of vehicle to be passed.

Then

$$F=\tfrac{1}{2}\left[\frac{3600(1.00-0.32)}{0.18\times400\left(\frac{40+20}{40}\right)}\right]=11.3 \text{ seconds.}$$

The average distance that it will be necessary to trail the slow vehicle moving 20 miles per hour before an opportunity to pass occurs will be 332 feet.

Figure 24 shows similar delay values for a number of different conditions using the average speeds of oncoming traffic as shown for 2-lane highways by figure 6. The two assumed values, 40 and 25 miles per hour, for the speed of the vehicle to be passed are the maximum and minimum speeds of vehicles that other vehicles should be able to pass, without an exceedingly long delay, if a 2-lane level highway is not to be considered congested. The speed of the passing vehicle while in the left lane is based on the preliminary results of the passing studies [5] which show that, on an average and in the majority of cases when a passing maneuver is delayed, the passing vehicle travels about 10 miles per hour faster than the passed vehicle during the maneuver. The two time values given for each condition as the period that the passing vehicle is in the left lane cover the range as shown by the passing studies for the majority of maneuvers performed under the two conditions.

[5] Passing practice on rural highways, by C. W. Prisk. Highway Research Board Proceedings, 1941.

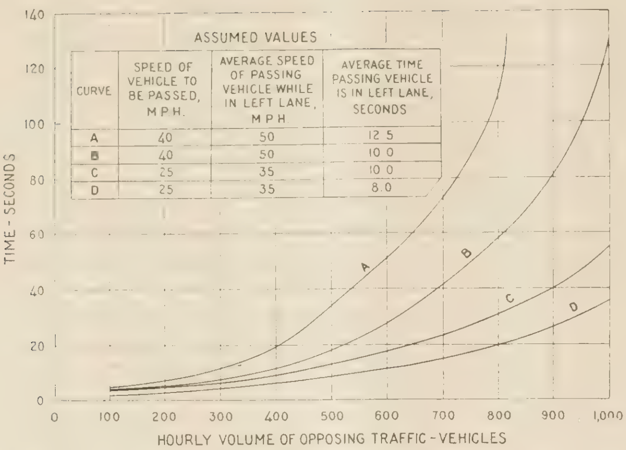

Figure 24.—Average Time in Seconds That Driver Desiring to Pass Will Be Required to Trail a Slow-moving Vehicle Before an Opportunity to Pass Will Occur in the Opposing Traffic Lane Under Certain Conditions on a 2-Lane Highway.

Curve A (fig. 24) shows that opportunities to pass a vehicle traveling 40 miles per hour and requiring 12.5 seconds in the left lane will occur until the density in the opposing traffic lane reaches about 800 vehicles per hour. Likewise, for the condition shown by curve B (fig. 24) an opportunity to pass will occur until the traffic volume in the opposing lane reaches 1,000 vehicles per hour. Curves C and D show that opportunities to pass vehicles traveling 25 miles per hour occur when the opposing traffic volume exceeds 1,000 vehicles per hour. However, since the openings in the opposing traffic that were used to calculate the passing possibilities are minimum requirements, the drivers performing the passing maneuvers must be able to judge the speeds of the oncoming vehicles to take full advantage of their passing opportunities and the return to the right-hand lane must be made before meeting the oncoming vehicle.

The passing studies show that drivers do not take full advantage of their passing opportunities even under congested conditions, but often allow a considerable portion of the time space in the opposing traffic to pass before starting the maneuver. Also the majority of drivers will not start the maneuver unless the space between vehicles in the oncoming lane is considerably greater than the minimum requirement. This results in few passings being performed when the volume of opposing traffic exceeds 1,000 vehicles per hour and, therefore, curve B probably represents fairly accurately the actual trailing times before the slowest vehicles are passed.

HIGHEST PRACTICAL CAPACITY OF A RURAL 2-LANE HIGHWAY IS 800 VEHICLES PER HOUR

Based on the time that the slow-moving cars must be trailed before a passing maneuver can be made, a traffic volume of 400 vehicles per hour in each direction is the highest density that may be considered as the practical capacity for a 2-lane level tangent section of highway. Regardless of whether the actual average trailing time is as shown by curve B or a longer period as shown by curve A (fig. 24), 400 vehicles per hour is the highest volume in the opposing lane that will not cause a relatively large increase in the trailing time as compared to the amount that the traffic volume is increased. From curve B, increasing the opposing traffic volume from 300 to 400 vehicles per hour results in an increase of 33 percent in the number of vehicles and 40 percent in the trailing time, while increasing the volume from 400 to 500 vehicles per hour results in a 25 percent increase in the number of vehicles and a 61 percent increase in the trailing time. Using curve A there is an increase of 64 percent in the trailing time when the opposing traffic volume increases from 300 to 400 vehicles per hour and an increase of 85 percent when the hourly volume increases from 400 to 500 vehicles. The ratio between the increase in volume and the increase in delay decreases very rapidly as the opposing traffic volume goes above 400 vehicles per hour.

Other traffic characteristics that indicate a total traffic volume of 800 vehicles per hour to be the highest practical capacity for a 2-lane level tangent rural highway carrying few trucks are:

1. Seventy-two percent of the drivers will be at spacings of less than 9 seconds (fig. 17) from the preceding vehicle and they will be governing the speeds of their vehicles to some extent by the speeds of the preceding vehicles.
2. The average driver will only perform 54 percent of the passing maneuvers that would be required for him to maintain his desired speed (fig. 15).
3. As the total traffic volume increases to 800 vehicles per hour, the average driver increases the number of passings he makes. Above 800 he does not increase the number he makes although to maintain his desired speed there should be a continued increase in the number of passings made (fig. 16).
4. With a total traffic volume of 800 vehicles per hour on a rural highway the average driver is restricted to approximately the same extent as when traveling during low traffic densities within a city on an arterial street without traffic lights but where there is a 30-mile-per-hour speed limit (fig. 8).

Eight hundred vehicles per hour is about 40 percent of the possible capacity of a 2-lane rural highway carrying few trucks. The same percentage of the possible capacities of the 3-lane highways is 1,120 vehicles per hour for the study sections in Massachusetts, and 1,460 vehicles per hour for the study sections in New York. Forty percent of the possible capacity for two lanes of the 4-lane sections in Illinois was 1,680 vehicles per hour or a total of 2,520 vehicles for all four lanes assuming that two-thirds of the traffic will be traveling in the one direction. At these densities, the speed differences as shown by figures 6 and 8 are higher on the 3- and 4-lane highways than on the 2-lane highways.

For speed differences corresponding to the speed difference on the 2-lane roads carrying 800 vehicles per hour the 4-lane Illinois highways could carry 3,150 vehicles per hour and the 3-lane highways in Massachusetts or New York could carry 1,600 vehicles per hour. However, since the speed differences were higher on the 3- and 4-lane roads during low traffic densities than on the 2-lane roads, it seems reasonable to believe that the drivers will expect a greater freedom of movement on 3- and 4-lane roads than on 2-lane roads. Practical capacities for 2-, 3-, and 4-lane roads with good alinements and carrying few trucks are therefore in the neighborhood of 800, 1,400, and 2,800 vehicles per hour respectively. This is a ratio of 1:1.75:3.5.

In case local conditions demand that 400 vehicles per hour be the standard adopted for the practical or working capacity for a 2-lane highway with few limiting sight distances, as may well be the case for express or toll highways, corresponding capacities for 3- and 4-lane roads would be 800 and 1,800 vehicles, respectively. This is a ratio of 1:2:4.5. Likewise, for conditions where the working capacity of a 2-lane highway may be considered to be above 800 vehicles per hour, the ratio for 2-, 3-, and 4-lane highways approaches the same ratio as the possible capacities are to one another.

For certain conditions, such as those illustrated by curves F and G in figure 8 where a speed limit is enforced, the practical capacity of two lanes of a 4-lane highway is 2,450 vehicles per hour. Any lower value would result in only a slight increase in the average speed or freedom of movement for the individual drivers, while a volume above 2,450 per hour would result in a marked reduction in both speed and freedom of movement.

EFFECT OF CURVES AND GRADES ON HIGHWAY CAPACITY STUDIED

There are so many types of curves and grades, and they may be combined with level tangent sections to form so many different highway alinements, that a comprehensive study of their effect on highway capacity involves an unlimited number of conditions. Although additional studies have been made, data for only 5 curves and 10 grades involving a total of 62,289 vehicles have been analyzed.

Curves affect the movement of vehicles on 2- and 3-lane highways mainly by restricting passing maneuvers. Theoretical capacities of all highways are probably affected to some extent by the speed at which the various curves can be negotiated safely and the distance spacing between vehicles allowed by the drivers while on a curve as compared to the spacings allowed on tangent sections. However, since the maximum theoretical capacities occur at relatively low speeds, the difference between the maximum theoretical capacities of a curved section of highway and a tangent section is probably not large.

The possible capacity of a 2-lane road is reached on tangent sections of highway when vehicles cannot pass one another. Therefore, an individual curve will cause no reduction in the possible capacity of a highway since it will impose no further restriction to passing than already exists. However, at lower traffic densities, a curve with a restricted sight distance prevents passing maneuvers that could otherwise be performed safely.

Of the few curves for which the data have been analyzed, the one with the greatest degree of curvature and the shortest sight distance that had no apparent effect on traffic was a 4° curve with a minimum sight distance at one point of about 900 feet. The pavement was 20 feet wide and had a superelevation of 0.06 foot per foot. There were only slightly fewer passings performed on the curve than on an equal length of tangent section under similar traffic densities. As a comparison, during low traffic densities, an 11° curve, with a minimum sight distance of 400 feet and superelevated 0.085 foot per foot, caused passenger cars to reduce their average speeds from 43 to 35 miles per hour, busses from 48 to 35 miles per hour, trucks from 37 to 32 miles per hour, and tractor-truck semitrailers from 33 to 30 miles per hour.

In addition to limiting the sight distance along the highway, steep grades also limit the speed at which vehicles, especially heavily loaded trucks, can travel. Table 6 shows the average speed of free-moving trucks, busses, and passenger cars while traveling on 3-, 5-, and 7-percent grades that were approximately ¼ mile long and had level tangent approaches. Excluding the vehicles on the level sections, speed data for 1,611 trucks, 133 busses, and 21,036 passenger cars were used to obtain these averages.

Figure 25 shows the distribution of truck and passenger-car speeds on the various grades. When comparing these distributions, one must remember that (1) the speed distributions include all trucks on the highway, both loaded and empty, (2) no vehicle was restricted by any other vehicle, (3) the grades were only ¼ mile long, and (4) the speeds at the bottom of the grades were not necessarily the same as on the level sections since the drivers could see the grades for some distance and may have speeded up before reaching the grade.

Since some of the data included in these results were obtained during 1934 and 1935 when the engine power of both trucks and passenger cars was considerably less than at present, a comparison was made of the speeds on the different grades in 1934 and 1940. The resulting average speeds were practically identical. Evidently, the increased loads hauled by the trucks have compensated for the increase in horsepower, while the drivers of passenger cars utilized a larger percentage of the vehicles' potential power in 1934 than in 1940.

TABLE 6.—*Free vehicle speeds on grades* [1]

Grade	Trucks	Busses	Passenger cars
	M. p. h.	*M. p. h.*	*M. p. h.*
Level	36.9	45.9	45.8
Downgrade:			
3 percent	37.6	46.4	46.5
5 percent	38.9	41.4	42.1
7 percent	34.1	37.4	40.2
Upgrade:			
3 percent	34.3	37.0	43.5
5 percent	26.6	29.3	39.5
7 percent	24.6	26.6	34.4

[1] All grades had level tangent approaches and were about ¼ mile long.

Figure 25 shows that a 3-percent grade ¼ mile long had only a slight effect on the free speeds of passenger cars and that the decrease in speed was about the same in going from a 3- to a 5-percent grade as from a 5- to a 7-percent grade. Most passenger cars are capable of maintaining high speeds on 7-percent grades. The decrease is therefore caused primarily by the operation rather than the possible performance of the vehicle.

Trucks traveled nearly as fast up the 3-percent grades as on the level but there was a large reduction in going from a 3- to a 5-percent grade.

From the speed distributions as shown by figure 25 and using methods previously explained, table 7 has been prepared to show the number of passings that would take place on grades ¼ mile long if all drivers could maintain their free speeds and the traffic volume was 100 vehicles per hour. The increase in the number of passings with an increase in the grade is relatively slight until the grade goes above 5 percent regardless of the percentage of trucks. The increase in the variation in passenger car speeds as the grade increases from 5 to 7 percent causes a larger increase in the desired number of passings than does increasing the number of trucks to 20 percent of all traffic. However, when a desired passing cannot be made, the trucks cause a greater delay since they travel at lower speeds.

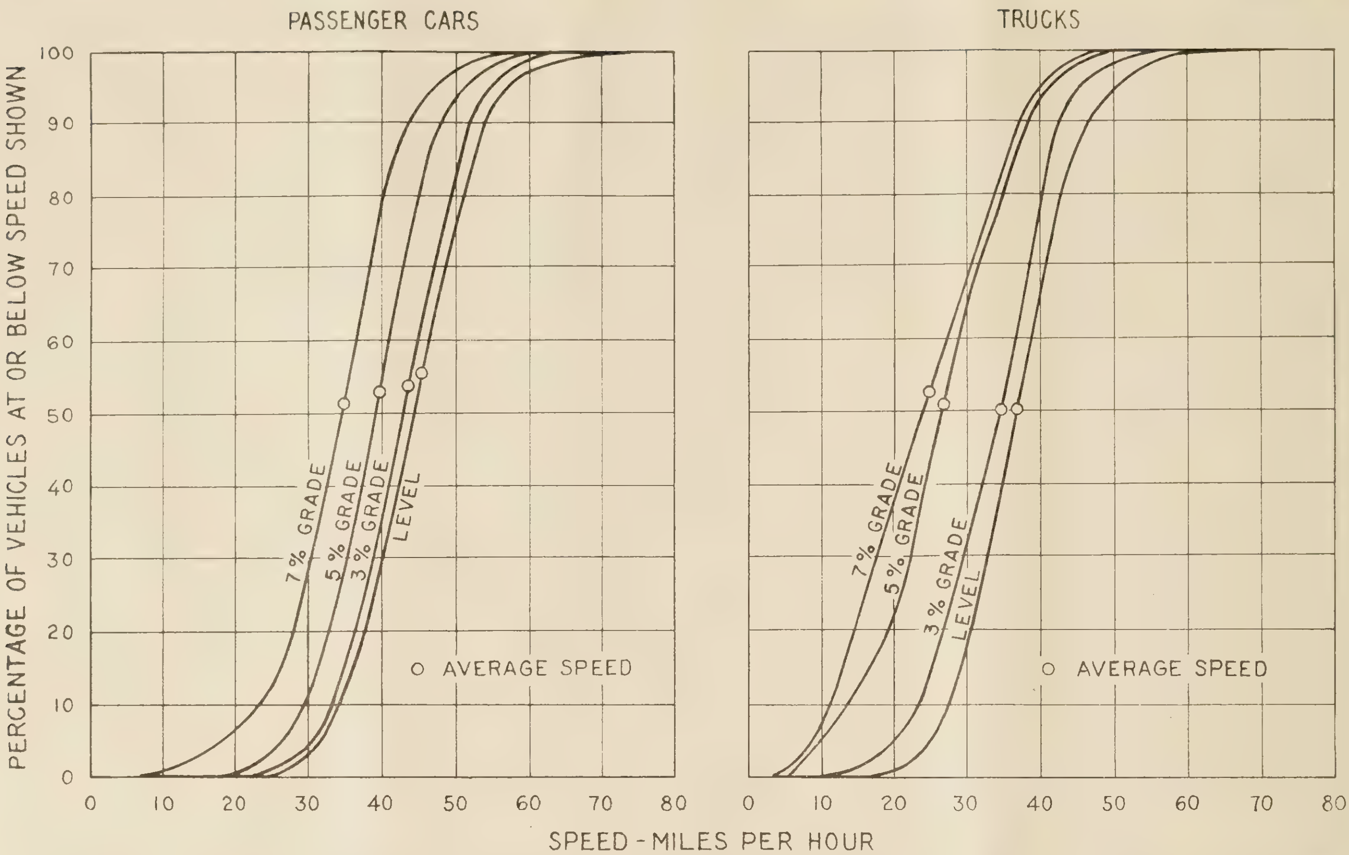

FIGURE 25.—CUMULATIVE FREQUENCY DISTRIBUTION OF FREE SPEEDS UP GRADES ¼ MILE LONG WITH LEVEL TANGENT APPROACHES.

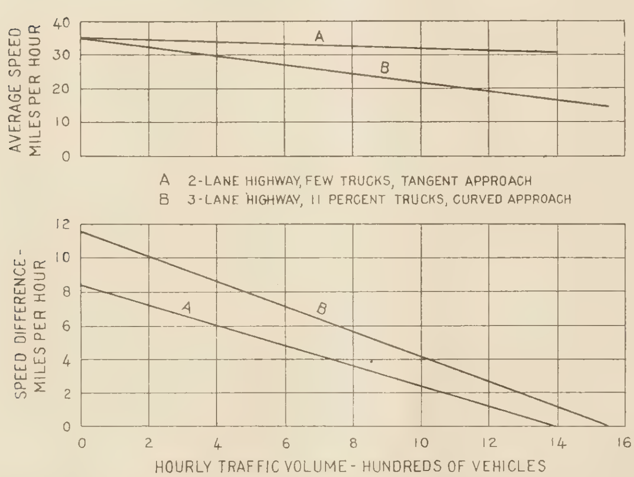

FIGURE 26.—AVERAGE SPEEDS AND SPEED DIFFERENCES ON TANGENT 7 PERCENT GRADES ¼ MILE LONG.

TABLE 7.—*Desired number of passings per hour to maintain free speeds with 100 vehicles per hour in one direction on ¼-mile section of highway*

Grade, percent	No trucks	Trucks 10 percent of all traffic	Trucks 20 percent of all traffic
	Passings per hour	*Passings per hour*	*Passings per hour*
0	5.6	6.2	7.1
3	5.7	6.4	7.3
5	6.7	7.1	8.1
7	12.8	15.5	17.9

From the available data on grades, it has been possible to determine capacity figures for only two highway conditions. One condition represents 7-percent grades ¼-mile long on 2-lane highways that carry few trucks and have level tangent approaches to the grades. The other condition represents 7-percent grades ¼-mile long on 3-lane highways that carry 11 percent trucks and have curved approaches to the grades.

Figure 26 shows that although the average free speed was 35 miles per hour for both conditions, the drop in speed was much greater as the density increased on the 3-lane roads than on the 2-lane roads. Passing was not possible on the grades when the density reached 1,400 and 1,560 vehicles per hour on the 2- and 3-lane highways, respectively. However, in the one case the vehicles averaged 30 miles per hour and in the other they averaged 14.5 miles per hour. The trucks and the curved approaches reduced the possible capacity of the 3-lane highways to a value nearly as low as the value for the 2-lane highways and caused a much larger reduction in speed. Vehicles ceased to pass on the 2-lane highway grades at only seven-tenths of the density at which they stopped passing on level sections.

EFFECT OF SHORT SIGHT DISTANCES ON HIGHWAY CAPACITY EVALUATED

To evaluate the effect that short sight distances at both horizontal and vertical curves have on the practical working capacity of a 2-lane highway, it is necessary to know the number and type of passing maneuvers that the short sight distances prevent from being performed safely. This requires a knowledge of the frequency of the different types of passings under various traffic conditions, the time and space requirements for the different types of maneuvers, and the sight distance or clear space in the opposing traffic lane that must be available before safe drivers will attempt to pass.

While the passing studies on 2-lane highways were designed to provide the main source of information for determining economical sight distance requirements, some very useful information has also been obtained from an analysis of the speed-capacity study data. Figure 27 shows the distribution of speeds for all vehicles and the vehicles that were passed on a 4-lane divided highway during low traffic densities when none of the drivers were prevented from passing other drivers traveling at slower speeds. To illustrate the accuracy of the method previously explained and used to calculate the desired passings from the free-speed distributions, a curve is also shown for the speed distribution of passed vehicles as calculated.

Even though 8 percent of the drivers traveled over 60 miles an hour and a few went over 75 miles an hour, no driver traveling over 60 miles an hour was passed and 95 percent of the passed drivers were traveling less than 50 miles per hour. Since the speeds at this particular location were higher than at any other of the many locations where high speeds were recorded in these studies, the expenditure of additional funds to obtain sight distances greater than those required for a driver to pass a vehicle going 50 miles per hour cannot be justified on any highway, at least not until more concrete evidence is available to show that future speeds will be considerably higher than present speeds. Fifty miles per hour is the 66 percentile value of the free speeds. A more conservative design that would provide for 80 percent of the passings would require a sight distance sufficient to pass a vehicle going 45 miles per hour which is only the 38 percentile value of the free speeds.

Figure 28 shows cumulative speed distribution curves for all vehicles and the vehicles that were passed on a 2-lane tangent section of level rural highway during total hourly traffic volumes up to 1,179 vehicles. At this particular location where drivers were not restricted in any way by sight distances, no vehicle going over 50, 47.5, and 45 miles per hour was passed when the total hourly traffic volumes were 496, 823, and 1,179 vehicles, respectively.

If a portion of this same highway had numerous curves with restrictive sight distances, increasing the sight distances to a value longer than required to pass a vehicle going 45 miles an hour would be of no benefit to the traffic using the highway when the total hourly volume was above 1,179 vehicles per hour, and since the slopes of the curves showing the speed distributions for the passed vehicles change very rapidly between the 90 and 95 percentile values, very little would be gained in increasing the sight distance at any point above the value required to pass a vehicle going 36 miles an hour. Likewise, sight distances longer than those needed to pass vehicles going 39 and 42 miles an hour are of little benefit when the hourly traffic volumes are above 823 and 496 vehicles, respectively. Speeds of 36, 39, and 42 miles per hour are the 14, 30, and 55 percentile speeds, respectively, of the free speed distribution.

The analysis of the passing practice studies has not progressed far enough to show definitely what sight distances drivers require before undertaking to pass vehicles traveling at these speeds, but the average

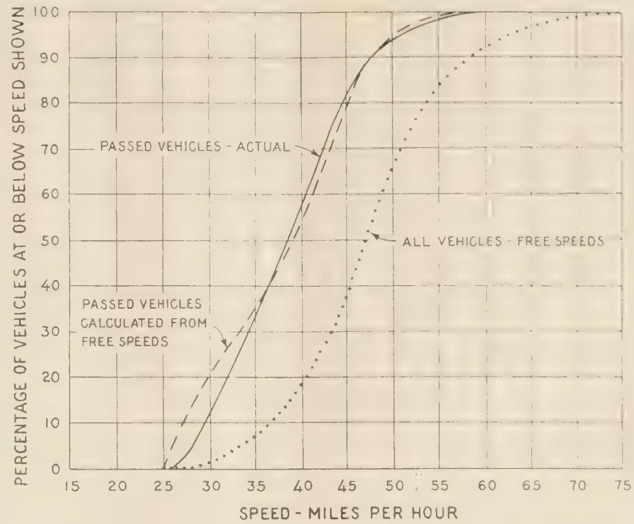

Figure 27.—Cumulative Frequency Distribution of Speeds of All Vehicles and Passed Vehicles on 4-Lane Divided Highway During Low Traffic Densities.

travel distances in the left lane are 576, 621, and 665 feet, respectively.

In case satisfactory conditions exist on long tangent sections of this highway when the traffic volume is 800 vehicles per hour, conditions will also be satisfactory on all sections of the highway where there are no sight distances shorter than the one required to pass a vehicle going 40 miles per hour.

The sight distance required to pass a vehicle going at a certain speed will depend on the speed of oncoming traffic, which on a 2-lane highway decreases as the total traffic volume increases. Figure 28 shows that the slope of the cumulative curves for the speed distribution of all vehicles changes very rapidly above the 90 percentile value. The 90 percentile speed value for oncoming traffic when providing adequate passing sight distances seems, therefore, to be the highest that can be justified in obtaining an economical design. As an example, if traffic conditions were satisfactory on the tangent section of highway where data were obtained for figure 28 when there was a total traffic volume of 800 vehicles per hour, any sight distance, on any section of the highway, long enough to permit a driver to pass a vehicle going 40 miles an hour with an oncoming vehicle approaching at a speed of 45 miles an hour cannot be considered a restrictive sight distance. A longer sight distance would increase the freedom of movement at lower volumes but not at the critical volume.

MORE COMPLETE ANALYSIS OF PASSING PRACTICES NEEDED

The relation between the percentage of all vehicles and the percentage of passed vehicles that exceed various speeds at different total hourly traffic volumes, as shown by figure 28, may also be shown as percentile values of the cumulative free-speed distribution. For example, with traffic volumes of 496, 823, and 1,179 vehicles per hour, the fastest vehicles traveled 57½, 54, and 50½ miles per hour, respectively. These speeds are the 99, 97, and 93 percentile values of the free-speed distribution (fig. 28). The 100-percent curve for all vehicles (fig. 29) shows these same percentile values. The other curves on figure 29 show the relation between the cumulative percentile speed values at different traffic volumes and the cumulative percentile speed

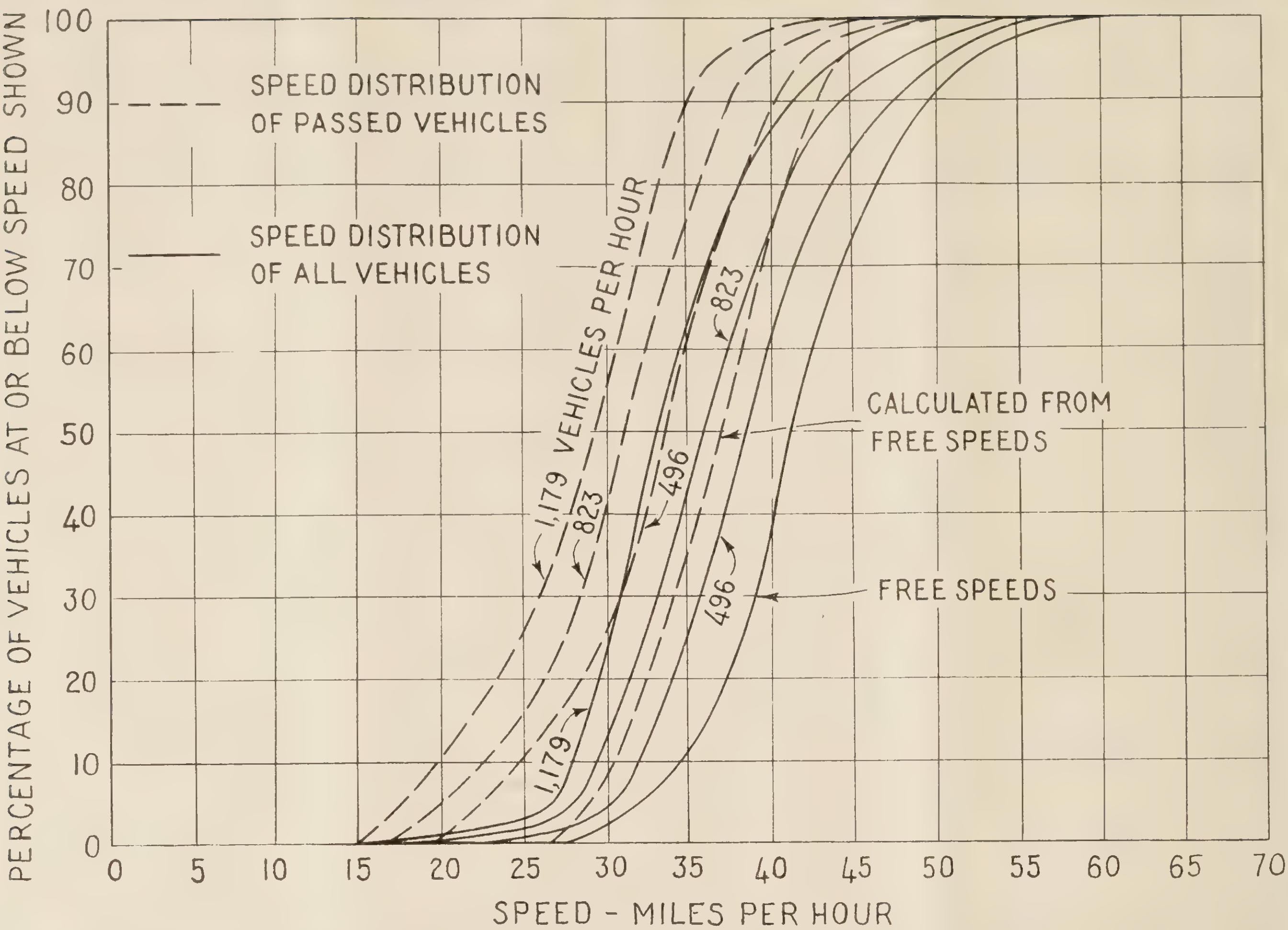

Figure 28.—Cumulative Frequency Distribution of Speeds of All Vehicles and Passed Vehicles on 2-Lane Tangent Highway During Various Total Hourly Traffic Volumes.

values of the free-moving vehicles. When the total traffic volume was 400 vehicles per hour, the 80 percentile speed for all vehicles was the same as the 70 percentile speed of the free-moving vehicles, the 85 percentile speed for all vehicles was the same as the 77 percentile speed of the free-moving vehicles, etc. Also with 400 vehicles per hour the 80 percentile speed for the vehicles that were passed was the same as the 29 percentile speed of the free-moving vehicles, the 95 percentile speed of the passed vehicles was the same as the 60 percentile speed of the free-moving vehicles, etc.

Similar data for other 2-lane tangent highway sections indicate that the values shown by figure 29 hold true within practical limits for any long 2-lane tangent location. If this is verified by the passing study data, the analysis of which is nearing completion, it will be possible to determine whether or not a certain sight distance acts as a restriction to the free movement of traffic and the degree of restriction imposed at various hourly traffic volumes for highways with different free-speed distributions. This, in turn, will make possible the establishment of definite working capacities for any alinement based on the traffic density that is satisfactory for a tangent alinement.

Until the sight distances that must be available for safe drivers to pass vehicles going at a given speed in face of approaching vehicles traveling at various speeds are obtained from the analysis of the passing study data no definite values can be given for the practical traffic capacities of highways having numerous short sight distances at which none or only the slowest of the slow-moving vehicles can be passed. Each place on a highway where all passings are restricted for a certain distance places a restriction on the higher-speed passings for a greater distance.

It may be possible for a highway with alinement that restricts drivers from passing vehicles traveling 40 miles per hour 50 percent of its entire length to have a higher practical capacity than a highway with alinement that restricts all types of passings only 10 percent of its entire length. With 800 vehicles per hour as the practical capacity of a tangent highway, sight distances that prevent vehicles going 40 miles per hour from being passed would not reduce the capacity of a highway with free speeds as shown by figure 28, while the practical capacity of a highway with an alinement that prevented all passings over 10 percent of its length could not exceed 750 vehicles per hour to allow the same freedom from congestion as on a tangent section. The traffic density of 750 vehicles per hour was calculated by using the following formula:

$$V_R=\frac{2{,}000\ V_T\ (1-R)}{2{,}000-V_TR}$$

where

V_R = practical capacity in vehicles per hour on alinement where all passings are restricted for some distance,

V_T = practical capacity in vehicles per hour on tangent alinement, and

R = ratio of the distance that all passings are restricted to the entire length of the highway.

$$V_R = \frac{2{,}000 \times 800 \times 0.9}{2{,}000 - 80} \text{ or 750 vehicles per hour.}$$

This formula was derived from previously presented facts; namely,

1. That the maximum possible capacity of a 2-lane tangent highway is 2,000 vehicles per hour and occurs when no passings can be made (figs. 6, 8, and 15).
2. That a straight-line relationship exists between the hourly traffic volume and the ratio of the desired to the actual number of passings that are made (fig. 15).
3. That the ratio between the desired and actual number of passings that can be made is an index of the freedom from congested conditions.

FLUCTUATIONS IN TRAFFIC FLOW IMPORTANT CONSIDERATION

The formula is correct only when all types of passings that are made on a tangent section can also be made on all portions of the highway except where no passings can be made. Actually, the alinement would restrict the higher-speed passings over sections exceeding the length of the sections where all passings are restricted so the practical capacity of a highway that restricts all passings for 10 percent of its length would generally be somewhat less than 750 vehicles per hour. However, the formula may also be used when such a condition exists by substituting the summation of the product of the restricted portions of the highway by the percentage of passings restricted, as determined by figure 29, for the values substituted for R in the equation.

For example, when all passings are restricted on 10 percent of the highway, passing a vehicle going between 30 and 35 miles per hour is restricted on an additional 5 percent, and passing a vehicle going over 35 miles an hour is restricted on an additional 10 percent, R would be $0.10+(0.35\times0.05)+(0.25\times0.10)$ or 0.143 for the free speed distribution shown by figure 28 and the practical capacity becomes 728 vehicles per hour. (At a volume of 800 vehicles per hour on the tangent section 35 percent of the vehicles passed are going between 30 and 35 miles per hour and 25 percent are going over 35 miles per hour.) However, the results of the special passing studies are needed before the portion of any alinement that partially restricts passing maneuvers can be determined accurately.

The capacity figures thus far presented refer to hourly volumes for rural highways. Since there is a large variation in seasonal, daily, and hourly traffic volumes on any highway, it is not economical to design for the highest hourly density during the year. From an analysis [7] of data from several hundred automatic traffic recorders on rural highways throughout the country it has been found that relatively few drivers will be inconvenienced if a design is used that will provide for the traffic volume during the fiftieth highest hourly density during the year. Very little will be saved in the construction cost and a large number of drivers will be inconvenienced if a design value appreciably lower than the fiftieth highest hourly volume is used.

On an average, the fiftieth highest hourly density during the year on roads in northern States is about 15 percent of the annual average daily traffic. However, for certain roads this figure may be as high as 22 percent or as low as 12 percent. Two-lane roads with good alinements can therefore be expected to carry annual average 24-hour traffic volumes in excess of 3,500 vehicles, while congested conditions may occur on other 2-lane roads with poor alinement when the average annual volume exceeds 2,000 vehicles per day. Average traffic volumes are not a true index of the number of lanes necessary to handle traffic efficiently at a particular location. The type of traffic and the variation in traffic flow must be considered.

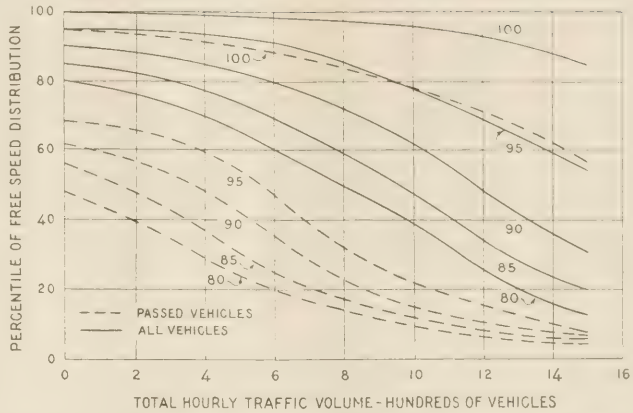

Figure 29.—Relation Between High Percentile Speeds of Passed Vehicles and All Vehicles at Various Traffic Volumes and Free Speeds.

CONCLUSIONS

The following statements give what are believed to be the most important conclusions to be drawn from the analysis of traffic data obtained at a large number of highway locations in several States.

1. While the theoretical and possible capacities of a highway are absolute values, the practical working capacity of a highway is a relative value that will vary for different local conditions.
2. The maximum traffic volumes that can be considered practical working capacities for 2-, 3-, and 4-lane rural highways are 800, 1,400, and 2,800 vehicles per hour, respectively.
3. The lower the hourly volume that is used as the practical capacity of a 2-lane road, the greater will be the difference between the practical capacities of 2-, 3-, and 4-lane roads with the same general alinement.
4. The design of a highway to handle traffic efficiently must be based on actual practices of all drivers in relation to the traffic on the highway rather than on the movement of individual vehicles over the highway.
5. Sight distances that restrict passing maneuvers on 2-lane highways vary with the traffic volume on the highway. Economical sight distances are a function of the traffic density.
6. The most important information needed to complete the study of practical working capacities for 2-lane highways with numerous nonpassing sight distances is the clear road space that drivers require before they will attempt to pass vehicles traveling at various speeds. Compared to this information, the time and distance requirements arrived at by assuming possible performance of vehicles and drivers are of little value.

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[7] Applications of Automatic Traffic Recorder Data in Highway Planning, by L. E. Peabody and O. K. Normann. PUBLIC ROADS, January 1941.

"PUBLIC ROADS" TO APPEAR QUARTERLY IN FUTURE

Beginning with the next issue, PUBLIC ROADS will be issued as a quarterly rather than a monthly magazine. This course has been decided on as an economy in publication for the duration of the war and also because personnel formerly engaged in making highway research investigations have been assigned work directly connected with the war effort. The next issue (No. 5 of volume 23) will be for the July, August, and September, 1942, quarter and will be published in August.

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Subscriptions already placed with the Superintendent of Documents will be extended to include the number of issues originally subscribed for.

STATUS OF FEDERAL-AID HIGHWAY PROJECTS

AS OF MAY 31, 1942

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	$6,535,684	$3,293,985	228.2	$4,198,949	$2,284,183	115.2	$198,900	$99,450	0.2	$2,503,898
Arizona	1,874,458	1,412,624	73.8	1,093,598	884,779	41.6	238,615	188,508	1.7	1,814,393
Arkansas	3,666,578	1,675,354	57.9	1,146,936	572,392	59.5	206,581	124,149	1.7	1,700,402
California	9,269,588	5,242,912	153.6	5,011,061	3,448,485	58.5	1,518,357	1,072,374	39.8	3,153,054
Colorado	2,382,364	1,353,127	155.2	3,838,626	2,461,491	160.8	829,453	468,309	28.7	2,095,089
Connecticut	1,419,554	696,181	17.1	1,988,467	957,191	23.1	550,734	357,260	5.9	975,677
Delaware	595,356	345,071	17.1	428,811	210,460	9.0	268,040	134,020	8.4	1,491,402
Florida	1,342,189	698,897	66.7	3,492,278	2,027,851	52.9	150,000	112,500	.8	2,915,875
Georgia	3,085,217	1,526,545	111.7	7,875,091	4,102,996	290.8	2,765,380	1,382,690	117.6	6,704,986
Idaho	1,915,201	1,262,028	95.4	1,154,204	817,839	61.4	376,987	294,038	19.4	1,747,003
Illinois	4,124,984	2,003,325	89.5	7,388,745	4,292,602	125.3	2,762,528	1,680,096	22.1	5,390,859
Indiana	4,632,031	2,134,213	75.1	7,369,543	3,604,506	107.1				2,895,401
Iowa	4,220,074	2,043,789	184.5	4,398,037	1,884,495	123.0	133,767	32,100	5.6	2,310,531
Kansas	4,862,010	2,519,870	272.6	6,308,370	3,418,914	259.2	637,126	322,725	33.0	4,584,419
Kentucky	4,466,081	2,208,661	154.9	5,737,785	2,725,922	110.8	2,897,458	1,605,022	30.3	1,353,420
Louisiana	1,709,397	890,773	39.6	1,175,515	810,697	22.4	3,077,111	1,609,627	60.7	3,921,449
Maine	954,941	475,405	26.8	2,053,632	1,050,642	27.8	125,910	74,780	.5	1,095,000
Maryland	3,625,267	1,811,529	30.2	2,636,909	1,053,654	14.3	900,000	528,750	4.3	1,058,457
Massachusetts	2,770,017	1,387,639	19.2	1,915,968	1,021,145	13.7	1,170,360	581,593	8.4	3,824,051
Michigan	8,637,309	4,207,058	174.3	3,382,148	2,260,949	55.5	1,597,300	1,020,875	9.5	2,475,111
Minnesota	4,686,910	2,385,416	384.8	9,589,412	5,285,671	391.5	113,720	56,860	10.0	2,870,276
Mississippi	5,933,098	2,906,318	315.4	3,155,024	1,585,062	186.8	346,700	256,175	5.3	2,028,403
Missouri	5,589,688	2,877,438	173.1	10,256,772	6,005,148	184.6	2,145,532	1,131,492	25.2	3,365,594
Montana	2,471,129	1,482,070	138.1	3,887,470	2,399,603	181.5	210,734	119,823	26.6	4,276,700
Nebraska	3,560,106	1,748,959	346.2	4,603,229	2,330,504	408.3	629,763	454,687	36.1	4,065,412
Nevada	2,211,680	1,886,038	110.6	911,064	796,018	26.0	962,769	870,805	24.6	660,807
New Hampshire	337,058	213,772	5.9	1,700,559	1,148,668	20.2				691,062
New Jersey	3,613,528	1,767,619	29.6	2,374,192	1,254,616	13.2				2,984,381
New Mexico	1,870,408	1,236,746	125.0	920,899	701,088	51.1	29,346	24,078	5.0	2,651,571
New York	9,503,520	4,722,722	126.7	8,683,631	5,558,186	86.7	429,000	193,500	6.4	5,215,966
North Carolina	4,737,420	2,556,296	188.3	2,167,664	1,144,767	98.0	561,756	283,902	8.8	3,674,957
North Dakota	3,224,478	1,874,388	287.6	2,810,655	1,635,782	223.2	2,173,990	1,090,365	186.2	4,020,406
Ohio	9,976,118	5,459,242	97.9	14,665,022	7,632,574	84.1	1,924,480	847,988	19.2	2,935,007
Oklahoma	2,651,649	1,383,859	122.3	2,692,322	1,500,534	64.9	1,613,930	928,149	39.7	5,960,800
Oregon	2,826,493	1,801,454	73.0	3,285,375	1,716,916	76.5	1,271,346	988,690	36.7	718,935
Pennsylvania	10,852,021	5,354,296	107.0	10,083,473	5,321,771	74.4	1,229,936	780,404	9.6	4,208,632
Rhode Island	1,194,495	678,166	10.0	1,046,898	669,630	5.0	479,631	239,757	2.6	601,761
South Carolina	2,987,866	1,606,085	109.5	3,402,258	2,130,846	83.5	1,138,590	747,575	20.0	971,996
South Dakota	2,373,781	1,399,681	287.9	4,709,133	3,116,405	533.3	545,110	325,580	59.3	2,882,579
Tennessee	4,616,521	2,592,911	110.5	4,744,348	2,743,791	102.6				3,454,968
Texas	14,171,091	7,026,419	676.5	10,265,021	4,894,258	305.9	1,215,090	609,635	35.6	8,787,008
Utah	1,251,036	939,893	53.8	1,838,587	1,393,120	46.7	33,518	26,800	6.8	1,229,710
Vermont	802,020	449,293	28.8	1,193,326	715,241	20.7	36,906	18,453	.3	395,551
Virginia	4,280,307	1,981,873	81.1	3,271,128	1,780,479	51.0	35,490	17,745	.4	2,745,066
Washington	1,808,560	987,042	26.6	2,514,659	1,362,842	30.5	204,707	109,600	3.4	2,077,996
West Virginia	3,318,393	1,674,884	57.2	2,259,388	1,206,153	25.3	1,261,269	773,589	6.5	1,322,960
Wisconsin	2,178,714	1,133,634	92.7	6,445,284	4,177,243	175.6				3,656,668
Wyoming	1,439,453	1,021,694	148.4	1,773,023	1,317,527	123.5				1,278,336
District of Columbia	1,055,468	541,238	3.5	214,289	127,960	.9	1,147,456	665,688	1.5	44,668
Hawaii	141,835	75,057	2.8	1,115,128	759,983	10.9	499,587	480,115	5.2	1,477,578
Puerto Rico	499,945	238,835	3.9	2,504,688	1,237,102	21.3	37,725	27,994	.2	652,951
TOTALS	188,253,089	99,192,324	6,368.1	201,678,594	113,540,681	5,439.6	40,682,688	23,758,315	979.8	135,919,132

STATUS OF FEDERAL-AID SECONDARY OR FEEDER ROAD PROJECTS

AS OF MAY 31, 1942

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	$1,392,054	$691,362	62.5	$685,882	$362,410	31.1	$40,801	$19,550	0.1	$586,086
Arizona	255,110	184,247	14.1	138,065	101,042	6.8				513,118
Arkansas	629,977	237,235	33.1	483,854	241,861	26.5	171,789	84,297	6.0	251,526
California	1,062,396	656,498	18.3	723,924	554,248	7.6	66,000	47,400	1.8	982,940
Colorado	209,672	112,570	20.9	131,800	73,914	3.2	152,386	35,323	5.0	502,702
Connecticut	298,035	136,331	6.1	266,247	115,937	4.8				199,604
Delaware	164,535	79,371	.4	141,464	70,732	11.9	102,873	37,618	3.9	246,037
Florida	1,042,471	519,285	11.6	292,018	153,304	6.2				398,953
Georgia	557,275	263,474	43.4	1,193,931	689,315	74.9	400,257	200,129	43.7	1,126,812
Idaho	299,357	172,516	26.1	225,220	157,021	7.7	38,149	23,587	2.8	285,992
Illinois	1,087,608	515,800	59.4	1,264,884	632,442	65.1				896,158
Indiana	586,368	285,054	39.8	1,283,255	608,471	51.0	88,800	44,400	3.1	920,323
Iowa	658,901	309,137	165.1	558,583	251,770	79.5	126,376	57,350	29.1	584,790
Kansas	865,347	436,593	112.1	1,790,788	900,372	92.1	238,353	119,177	29.7	1,031,750
Kentucky	1,154,545	321,329	83.2	1,249,010	417,668	37.2	74,213	24,400	5.6	324,331
Louisiana	539,462	265,678	20.6	7,700	3,850		289,362	138,761	21.5	666,650
Maine	89,922	44,961	4.6	223,818	111,909	9.6	16,850	2,714	.5	160,925
Maryland	579,966	289,808	20.7	226,410	113,205	1.8				345,564
Massachusetts	187,789	101,569	4.1	700,733	390,183	10.1				526,805
Michigan	1,299,446	633,000	81.4	760,498	380,249	29.5	245,970	122,985	1.3	654,241
Minnesota	1,613,984	792,692	217.1	1,021,469	516,473	91.8	279,496	139,348	26.8	592,011
Mississippi	851,015	424,488	47.7	1,494,546	709,614	59.0				376,864
Missouri	481,174	237,794	55.8	886,338	425,581	91.1	186,244	63,193	32.4	1,045,734
Montana	374,571	210,387	58.6	292,724	170,722	31.0	13,569	7,715	4.5	904,396
Nebraska	457,436	225,708	57.3	404,827	207,640	58.7				694,594
Nevada	331,931	266,129	28.6	92,429	60,188	4.6				234,872
New Hampshire	156,054	95,143	4.7	239,437	163,488	3.6				88,975
New Jersey	518,759	254,877	9.6	437,305	245,055	13.8				571,260
New Mexico	566,935	357,245	47.7	262,325	169,211	19.5				250,178
New York	956,940	468,240	28.8	1,160,340	620,808	14.9	245,600	122,800	.9	1,088,867
North Carolina	331,976	170,672	34.8	522,407	278,748	36.3	150,810	60,330	6.8	654,350
North Dakota	29,802	15,664	2.4	7,382	7,382		808,050	793,860	42.7	755,172
Ohio	1,780,920	886,359	57.6	901,610	498,775	14.5	157,640	78,820	2.9	1,336,590
Oklahoma	400,166	210,874	27.6	27,872	14,715	4.0	1,240,706	655,126	75.9	905,068
Oregon	547,387	298,453	50.0	395,568	230,087	20.3	30,482	18,000	1.3	322,972
Pennsylvania	2,004,228	986,137	37.6	513,989	256,587	10.4	73,588	36,794	1.8	786,814
Rhode Island	231,189	119,932	2.6	11,884	9,692		104,895	52,447	1.0	78,463
South Carolina	773,386	307,260	54.6	221,700	79,945	.5				398,326
South Dakota	37,125	22,152	15.2	9,056	9,056		1,143,430	1,047,600	114.5	757,118
Tennessee	689,893	343,243	16.8	1,141,522	580,761	43.2	158,042	79,021	4.5	747,642
Texas	1,577,788	769,471	165.0	512,790	250,470	34.9				2,237,214
Utah	204,014	136,160	20.3	136,491	88,790	3.5	38,932	28,724	.8	308,319
Vermont	40,708	18,109	1.2	222,515	117,328	8.9				53,580
Virginia	403,187	189,037	16.2	348,516	156,180	4.6	23,400	11,700	3.8	679,170
Washington	391,635	228,446	23.7	349,818	147,362	7.8				410,431
West Virginia	428,549	215,282	19.9	285,664	142,219	6.3				510,286
Wisconsin	947,262	475,932	42.7	1,460,828	668,455	46.4	35,787	17,000	.8	580,134
Wyoming	365,617	160,649	18.8	508,423	218,112	34.3				218,048
District of Columbia	79,178	39,035	.9							163,600
Hawaii	1,158	1,096		1,279	1,279					334,875
Puerto Rico	170,027	77,541	7.5	73,642	38,810	3.1				217,968
TOTALS	30,704,230	15,260,025	1,998.8	26,292,780	13,413,436	1,223.6	6,742,850	4,170,169	475.5	29,509,198

U. S. GOVERNMENT PRINTING OFFICE: 1942

PUBLICATIONS of the PUBLIC ROADS ADMINISTRATION

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 Agency and as the Agency does not sell publications, please send no remittance to the Federal Works Agency.

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, 1932. 5 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.

Report of the Chief of the Bureau of Public Roads, 1939. 10 cents.

Work of the Public Roads Administration, 1940, 10 cents.

Work of the Public Roads Administration, 1941, 15 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.

An Economic and Statistical Analysis of Highway-Construction Expenditures. 15 cents.

Highway Bond Calculations. 10 cents.

Transition Curves for Highways. 60 cents.

Highways of History. 25 cents.

Specifications for Construction of Roads and Bridges in National Forests and National Parks. 1 dollar.

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 Public Roads Administration upon request. They cannot be purchased from the Superintendent of Documents.

MISCELLANEOUS PUBLICATIONS

No. 296MP. . Bibliography on Highway Safety.

House Document No. 272 . . . Toll Roads and Free Roads.

Indexes to PUBLIC ROADS, volumes 6–8 and 10–21, inclusive.

SEPARATE REPRINT FROM THE YEARBOOK

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

REPORTS IN COOPERATION WITH UNIVERSITY OF ILLINOIS

No. 303. . . Solutions for Certain Rectangular Slabs Continuous Over Flexible Support.

No. 304. . . A Distribution Procedure for the Analysis of Slabs Continuous Over Flexible Beams.

No. 313. . . Tests of Plaster-Model Slabs Subjected to Concentrated Loads.

No. 314. . . Tests of Reinforced Concrete Slabs Subjected to Concentrated Loads.

No. 315. . . Moments in Simple Span Bridge Slabs With Stiffened Edges.

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 Public Roads Administration, classified according to subject and including the more important articles in PUBLIC ROADS, may be obtained upon request addressed to Public Roads Administration, Willard Bldg., Washington, D. C.

STATUS OF FEDERAL-AID GRADE CROSSING PROJECTS

AS OF MAY 31, 1942

STATE	COMPLETED DURING CURRENT FISCAL YEAR					UNDER CONSTRUCTION					APPROVED FOR CONSTRUCTION					BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
			NUMBER					NUMBER					NUMBER			
	Estimated Total Cost	Federal Aid	Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise	Estimated Total Cost	Federal Aid	Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise	Estimated Total Cost	Federal Aid	Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise	
Alabama	$154,270	$153,734	2	4	2	$416,125	$412,903	6	2	2	$230,835	$230,835	4		5	$918,999
Arizona	184,378	184,361	1	1		138,529	129,839		1	2	4,095	4,095			1	230,684
Arkansas	474,307	471,932	5		9	169,829	168,116	1		2	18,911	18,515			6	676,286
California	1,036,632	844,943	7	1	7	676,477	676,477	3			3,775	3,775			1	2,319,499
Colorado	52,743	52,704	1		1	623,402	623,402	6		2	14,914	14,914			7	745,764
Connecticut	166,222	165,415	2			61,712	60,676		1		231,374	222,740		1		540,683
Delaware	89,725	89,725	1		1	191,599	189,867	1	1		508,406	321,785	2			179,564
Florida	120,961	120,961			20	843,067	840,887	8		6	82,492	82,432			14	871,382
Georgia	681,733	681,525	7	2	7	994,222	994,222	6	6	13	785,985	785,985	2	4	9	1,505,777
Idaho	113,531	109,262	1		3	236,450	227,778	3	1		4,190	4,190			2	427,835
Illinois	851,316	601,160	2		97	1,649,097	1,565,901	8	1	2	387,209	387,009	1	1	30	2,54[illegible],298
Indiana	624,117	618,249	6		31	461,883	461,883	2	1	14	95,230	95,230			28	1,14[illegible],196
Iowa	378,416	372,400	3	1	36	1,519,599	1,262,426	11	2	23	114,376	112,120			29	62[illegible],079
Kansas	93,276	83,870	2		8	742,064	742,064	9		3	141,011	141,011	3		6	1,30[illegible],512
Kentucky	1,148,734	1,146,371	9	1	1	402,849	402,849	4								41[illegible],382
Louisiana	14,170	14,170			2	586,220	586,220	8			474,630	473,463	4		2	924,798
Maine	10,383	10,383			3	364,948	364,948	2		1						286,599
Maryland	500,850	469,057	2	2	12	874,458	730,660	4		4	30,175	30,175			6	405,[illegible]24
Massachusetts	346,270	335,829	1		1	791,642	790,770	5	2		763,830	763,830	2	1		1,250,554
Michigan	1,416,063	1,397,726	3	4	25	562,166	562,166	2		2	866,629	836,468	2		7	395,559
Minnesota	641,332	640,745	5	4	2	977,175	977,175	5	4	6	4,985	4,985			1	1,238,518
Mississippi	253,874	253,874	2	1	10	862,718	862,718	10			6,200	6,200			2	646,344
Missouri	593,138	414,702	2	2		1,719,957	1,442,973	6	2		203,565	203,565		2		1,480,365
Montana	141,549	141,549	2		2	99,778	99,778	1								733,051
Nebraska	484,061	482,941	7		22	837,830	837,830	16			13,020	13,020			3	473,749
Nevada	126,306	121,955	2		3	57,946	57,946	2			22,635	22,635			7	196,853
New Hampshire	287,335	287,036	4	2	5	74,598	74,273	2								313,961
New Jersey	852,812	834,882	4	1	2	622,904	497,354	3	1		354,985	295,560	1	2		956,807
New Mexico						71,000	71,000	1			259,103	252,068	3		1	519,348
New York	2,422,733	2,364,650	2	13		1,982,146	1,941,007	3	8		502,645	464,285		1		3,729,719
North Carolina	626,618	623,740	2	6	34	187,142	187,142	1	1	4	33,695	33,695			8	1,407,650
North Dakota	289,022	287,819	5			470,895	470,895	5								872,117
Ohio	1,557,247	1,542,030	8	1	12	2,752,053	2,428,331	10		1	684,590	480,460	2		2	1,423,700
Oklahoma	256,234	250,950	2		35	880,359	878,439	6		3	392,744	354,707	3		3	1,432,840
Oregon	423,249	358,685	4		3	281,499	228,712	2			13,433	13,433			4	399,969
Pennsylvania	1,907,614	1,876,905	14	1		3,140,659	3,126,130	15			235,355	235,355	1			2,526,669
Rhode Island	205,241	205,241		1		3,655	3,655									273,921
South Carolina	529,339	510,274	7	2	25	84,269	69,128	2	1		211,228	96,095		2	6	992,889
South Dakota	511,729	511,618	13		9	515,821	499,871	9			41,200	41,200	2			829,404
Tennessee	371,045	359,151	4	3		1,256,182	1,256,182	6	1		427,478	427,478	1	1	4	680,015
Texas	1,674,280	1,654,917	21			1,025,741	1,006,216	8		4	4,350	4,350			1	2,376,450
Utah	86,598	85,856	2		28	43,874	43,874	1		1	57,831	57,831			22	359,638
Vermont	17,426	16,698			4	322,869	293,090	2								114,657
Virginia	566,180	566,180	4	4	4	347,127	327,167	3	1	1						965,269
Washington	395,005	394,758	3	2	4	1,041,232	344,558	5			2,478	2,478			1	441,484
West Virginia	253,143	247,512	3		6	658,477	658,477	6	1	2	447,830	447,830	1		1	328,286
Wisconsin	477,790	460,449	2		41	560,581	559,593	3	2	5	12,687	12,687			2	1,675,841
Wyoming	481,187	466,531	6		1	1,974	1,974				8,417	8,416			6	430,012
District of Columbia	3,655	3,655				298,213	273,744		1							103,351
Hawaii	189,832	189,811	2			211,977	211,462	2								282,756
Puerto Rico	103,629	102,980	1			780,618	772,706	11								363,914
TOTALS	25,187,300	24,181,871	188	59	518	34,477,607	32,297,454	235	41	103	8,698,521	8,006,905	34	15	227	46,280,921