PUBLIC ROADS • Vol. 39, No. 3 • December 1975

# Highway Design for Motor Vehicles: A Historical Review

Cornell Local Roads Program
Tech Tips

## PART 4: THE VEHICLE-CARRYING CAPACITY OF THE HIGHWAY

Traffic congestion is not new; the streets of Imperial Rome were indescribably congested, day and night. But until the advent of the automobile, seldom did enough vehicles assemble on a single stretch of road-except in the largest cities-to cause serious congestion; or seldom did the congestion continue long enough to raise doubts as to the capacity of the road to handle the traffic using it.

### Early Capacity Research

In the United States serious congestion began to be felt on certain inter-city rural roads by 1920. In that year 9,200,000 motor vehicles - not including 239,000 motorcycles - were registered, and the number was increasing at an annual rate of 22 percent[(1)]. Most of the rural roads of this period were two-lane roads, 14-18 feet wide, and a number of engineers were beginning to question the roads' adequacy to handle the rapidly increasing volumes of motor traffic. One of these engineers was A. N. Johnson, dean of the University of Maryland Engineering College, who, perhaps more than anyone else, deserves to be called the father of the science of traffic analysis.

Johnson was one of the first engineers to advocate the widespread and systematic use of traffic research to collect factual data on which to base highway decisions: "Even a brief study of the problems of highway research shows many of them of the most fundamental character require for their solution a comprehensive knowledge as to the traffic which moves over the highways"[(2)]. In 1921 from a study of the meager data then available, he concluded that except for a very small fraction of the State highway systems, two-lane roads would suffice for years to come and that "highway plans contemplating an extended system of highways of greater width than is required for two lanes of traffic are extravagant and have no economic basis"[(3)].

**CORNELL LOCAL ROADS PROGRAM**
416 RILEY-ROBB HALL, ITHACA, NY 14853
PHONE: (607) 255-8033
FAX: (607) 255-4080
E-MAIL: *clrp@cornell.edu*
INTERNET: *www.clrp.cornell.edu*

*Tech Tips* are published by the Cornell Local Roads Program with support from the Federal Highway Administration, the New York State Department of Transportation, and Cornell University. The content is the responsibility of the Local Roads Program.

To arrive at this conclusion Johnson first calculated the theoretical capacity of vehicle discharge of a single lane of traffic, based on the following:

$$N = \frac{5{,}280V}{D}$$

Where,
N=Total vehicles passing in 1 hour
V=Vehicle speed in miles per hour.
D=Average spacing center to center of Vehicles in feet.

Thus, if all of the vehicles were 15 feet long and there was 15 feet between them, D would be 30 and for a speed of 15 mph the discharge of a single lane would be 2,640 vehicles per hour. From observation of actual traffic on the Baltimore-Washington Road, Johnson noted that the clearance between vehicles traveling 10 to 15 mph was only about 15 feet, whereas at 25 to 30 mph the average clearance was 50 to 60 feet. He therefore concluded that the average minimum spacing of vehicles in a traffic stream varies as the square of the speed; and that if all the vehicles are 15 feet long, the formula for maximum discharge of a single lane at uniform flow would be:

$$N = \frac{5{,}280V}{15 + \frac{V^2}{15}}$$

Paradoxically, according to this formula a larger number of vehicles will pass a given point at a speed of 15 mph than at 30 mph (fig. 1, curve B).

For a speed of 30 mph with an average center-to-center vehicle spacing of 75 feet, the theoretical discharge would be 2,100 vehicles per hour per lane. This, Johnson realized, did not allow for passing and normal interruptions under real driving conditions, so he arbitrarily set the comfortable discharge at 500 to 750 vehicles per hour per lane or 1,000 to 1,500 vehicles per hour in both directions for a two-lane highway. Such a road, he explained, could if necessary handle double this traffic during special rush hours.

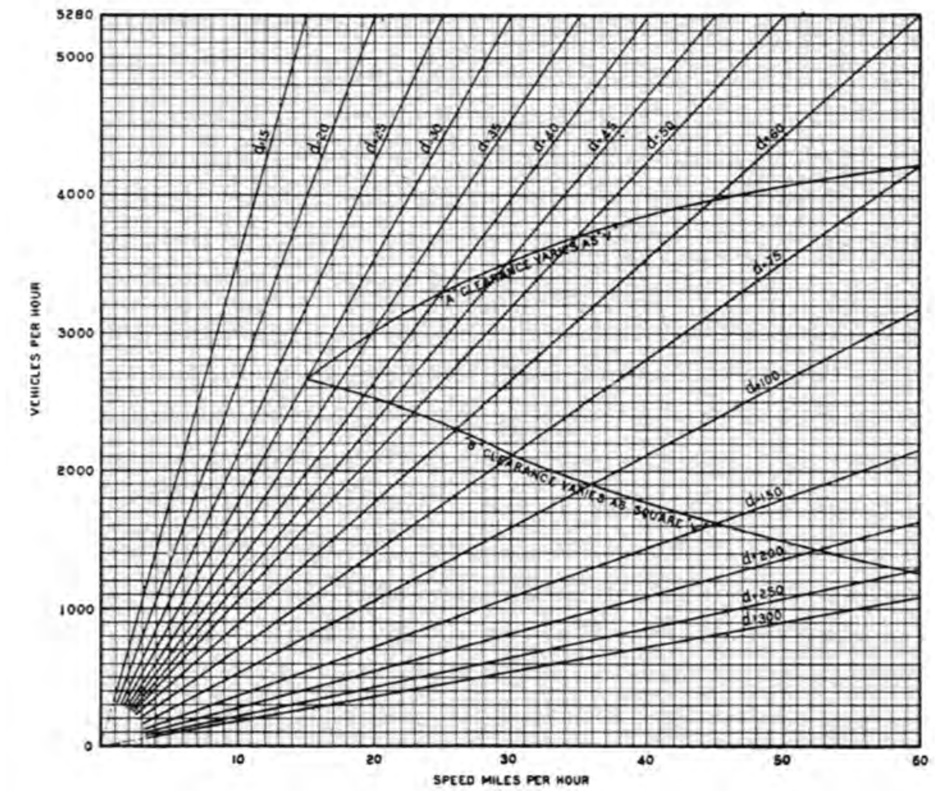



*Figure 1: Traffic discharge diagram.*
*d = distance center to center of vehicles. d - 15 = clearance between vehicles (3)*

**Estimated Traffic for a Connected National Network**

From the known or surmised information about traffic, Johnson then built up an estimate of what average traffic might be for a connected national network of main highways. His procedure was as follows:

- Total U.S. registration of motor vehicles, including motorcycles, in 1920 was 9,471,000 units.
- According to the American Automobile Association (AAA) average usage per vehicle was 6,000 miles per year. (No one knew exactly, and the Bureau of Public Roads' guess was only 4,500 miles per year.)
- At 6,000 miles per vehicle, annual usage in the United States in 1920 was 57 billion vehicle miles.
- The total mileage of rural roads in the United States, according to the BPR inventory of 1914 was 2,478,552 miles.

- According to prevailing opinion, 10 percent of the roads in any State carry 75 percent of the total traffic. Therefore 250,000 miles of roads will carry 43 billion vehicle miles of traffic, or an average of 172,000 vehicles per mile per year. This is a little under 500 vehicles per day.
- From the Maryland traffic censuses of 1917, 1918, 1919, and 1920, Johnson knew that the seasonal daily peak traffic on heavily traveled highways, such as the Baltimore-Washington Road, was about 135 percent of the average annual daily traffic. From the BPR-California Traffic Study of 1922-23, he learned that the maximum hourly traffic was about 130 percent of the average hourly traffic for the day. “It is this high hourly traffic occurring during the months of high average daily traffic for which provision should be made,” he said. Applying these factors to the average traffic of 500 vehicles per day, and assuming a 12-hour day, he came up with an average peak discharge of 73 vehicles per hour for the main rural highways in the United States, which was only a small fraction of his estimated capacity for a two-lane road [3].

Johnson conceded that traffic would not be distributed evenly over the 250,000 miles of main highways and that there would be tremendous variations in volume near large cities that would produce peaks many times higher than 73 vehicles per hour. (In fact, traffic between Washington and Baltimore was already more than 400 vehicles per hour at times.) But his principal assumptions were conservative: He used AAA’s estimate of annual usage per vehicle instead of the lower BPR estimate; and although most vehicles, then as now, were owned and used in the cities, he distributed their entire annual usage to the *rural* road system. Later events showed that his other principal assumption - that 10 percent of all roads carry 75 percent of all traffic - was also on the high side. The Ohio Transportation Survey of 1925, for example, showed that the State system, with 13 percent of the total mileage, carried 58 percent of the total traffic while in Vermont the same year, 13.5 percent of the roads carried 66 percent of the total traffic.

It is interesting to note that by 1971 vehicle registration had increased 12 times over 1920, and rural highway travel 22 times, yet only 1.4 percent of all rural roads had three or more lanes.

### First Aerial Traffic Survey

In 1927 at Johnson’s instigation the Maryland State Roads Commission made an aerial photographic survey of the Baltimore-Washington Road, the main purpose of which was to determine the actual spacing of vehicles on a road during periods of heavy traffic flow. The time selected for the flight was the afternoon rush on the Fourth of July.

While the photo flight was in progress, ground crews counted traffic at four places along the route at 5-minute intervals. In addition, six “spot cars” were phased into the traffic stream at various points, their drivers instructed to drive with the traffic. The tops of these cars were covered by white cloth so that they could be easily identified on the photos and each carried an observer who noted the vehicle speed at intervals. These speeds were from 20 to 30 mph - the highest being 33 mph.

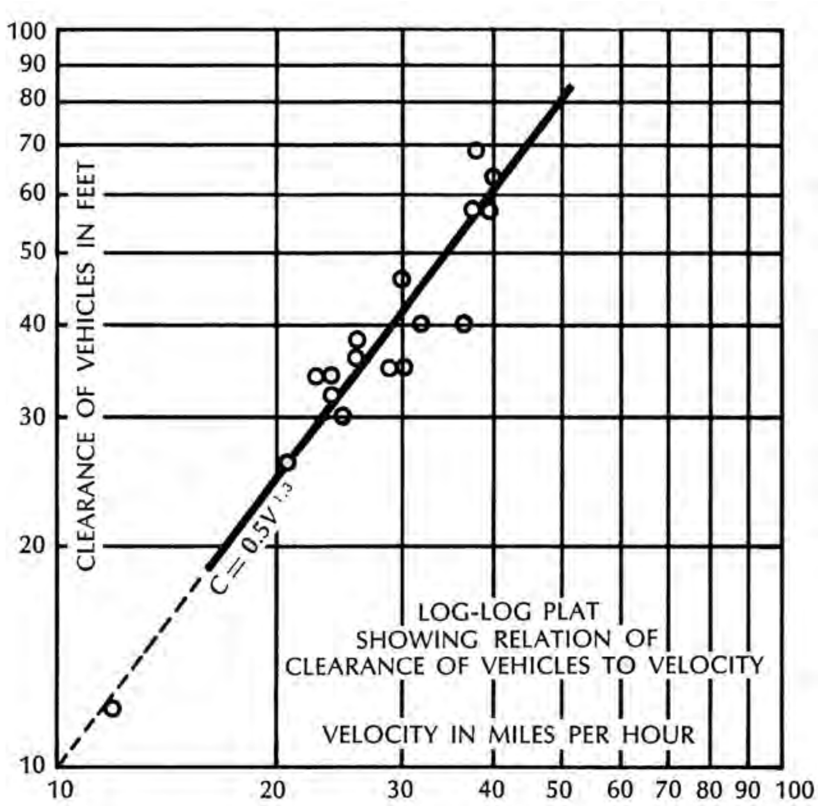



*Figure 2: Spacing of vehicles on Washington-Baltimore Road, July 4, 1927* [4]

Traffic as shown by the hourly counts was remarkably uniform during the photo flight, ranging between 769 and 860 vehicles per hour for the rural sections of the road. But when analyzed by 5-minute intervals, the distribution was quite different. The hourly rate varied from a low of 504 vehicles per hour up to a maximum of 1,284 vehicles per hour. The photos showed that traffic was bunched in queues, some of which were composed of 23 or more cars. When the photos were analyzed by ¼-mile sections, the researchers found that some sections had as many as 20 cars while in others nearby there was only one vehicle or even none at all.

The scale of the photos and the time interval between exposures were known, therefore the investigators could determine the speed and spacing of the vehicles by measuring their positions in the overlap between successive photographs. This kind of analysis showed that the spacing between vehicles varied approximately as the ⁴⁄₃ power of the velocity, rather than as the square, as Johnson had assumed from his previous studies (fig. 2), and that maximum discharge occurred when traffic was moving at an average speed of 34.5 mph rather than 15 mph (fig. 3)[4].

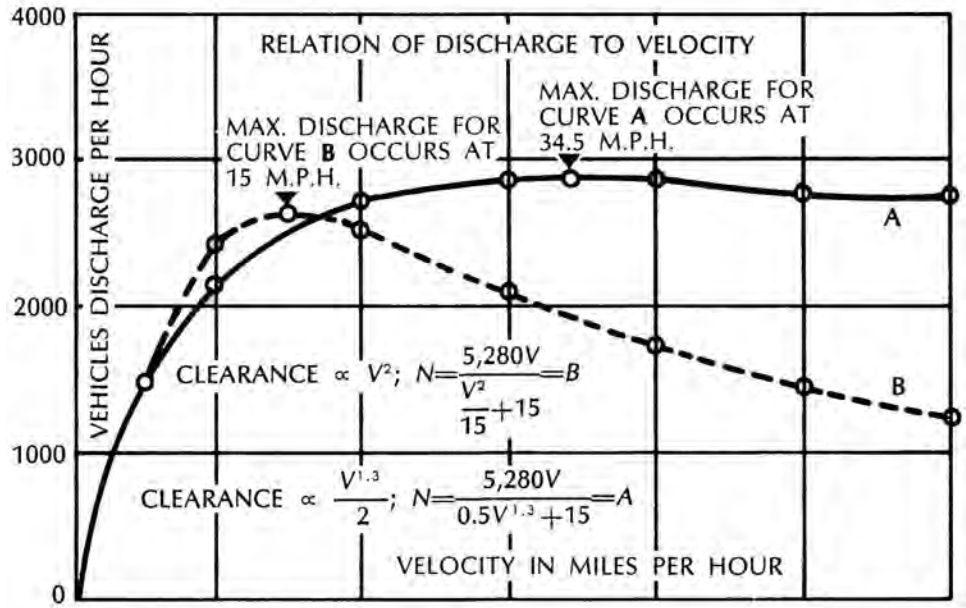



*Figure 3: Hourly vehicle discharge according to two formulas derived by A. N. Johnson* [(4)]

### The Cleveland Capacity Studies

While A. N. Johnson and the Maryland Roads Commission were engaged in this novel research, the BPR, with State and local cooperation, was making a comprehensive study of traffic in the Cleveland regional area of Ohio. An important part of this project was a traffic capacity analysis of roads of various surface widths from 18 to 40 feet. For this study the researchers devised a *traffic flow recorder* - essentially a box containing a speedometer, an odometer, a clock, and a motion picture camera. The odometer and speedometer were geared to the test vehicle which was operated to float with the traffic while the camera photographed the data on speed, distance, and elapsed time. The test crew consisted of a driver, an observer, and a recorder. The observer could see the instruments through a glass window and whenever the vehicle had to stop or reduce speed, he called out the mileage and time and the apparent cause of the delay and the recorder wrote this information on a form [(5)].

For the traffic analysis, representative sections of highway were selected ranging in width from 18 to 50 feet and in peak traffic from 2,000 to more than 30,000 vehicles per day. At these places traffic counts were made every 15 minutes throughout the day. Once in every 15-minute period the test car with the traffic flow recorder made a run through each section to measure the average speed of the traffic stream. Since traffic varies widely throughout the day on any road, the researchers were able to gather a wide range of 15-minute traffic volumes and their corresponding average speeds. Assuming that "congestion" was invariably reflected by abnormal retardation of the average speed of the traffic stream, they were able to determine for each width of road the traffic volume at which congestion first became apparent. They concluded that under open road conditions at a traffic speed of 25 mph a two-lane, 20- foot-wide highway would carry 10,000 vehicles per day. Under suburban conditions - with a larger volume of local traffic, some marginal parking, and more cross roads - capacity would drop to about 8,000 vehicles per day [(6)].

## Other Theoretical Studies

While Johnson was working out his discharge formula, others were attacking the capacity problem from slightly different angles. The Pennsylvania Department of Highways determined the spacing between vehicles traveling in a lane at uniform speed according to the time it would take for a following driver to perceive that the car ahead was stopping, then react, apply the brakes, and bring his own vehicle to a stop. This time of course would vary widely according to the driver, the vehicle, and the road, especially the road gradient. At this time, 1927, four-wheel brakes were being introduced and not all cars were equipped with them, so the Pennsylvania researchers assumed that only half of the vehicles in the traffic stream would have four-wheel brakes. They assumed a perception-reaction-braking time for the following driver varying from ½ second if his speed were 10 mph to 1 ½ seconds for 30 mph. Under these conditions, they calculated the *maximum carrying capacity* of one lane of a two-lane road on level grade to be 2,264 vehicles per hour at an average speed of 15 mph, decreasing to 1,970 vehicles at 25 mph and 1,456 vehicles at 40 mph [(7)].

However, such theoretical capacities are never encountered in practice because of the presence of slow-moving vehicles in the traffic stream and an insufficient number of gaps of suitable length in the opposing lane to permit free passing. The Pennsylvania investigators therefore concluded that the capacity of a two-lane road was “very approximately equivalent to the capacity of a single lane with traffic moving uniformly at the rate of speed of the majority of traffic units of the two-lane road being measured” [(7)]. This rule indicated a capacity of 1,970 vehicles per hour in both directions for a two-lane highway at 25 mph average speed, which was almost double the BPR’s figure based on the Cleveland research.

N. W. Dougherty of the University of Tennessee used practically the same approach as the Pennsylvania researchers. He assumed a perception reaction time of ½ second for all speeds and a braking distance to bring the following vehicle to a stop of $5=0.0556V^2$, where V is the velocity in feet per second [(8)].

Sigvald Johannessen’s studies in New Jersey showed that following drivers tend to preserve a certain time interval between themselves and the vehicle ahead which he found to be 1 ½ seconds. The distance between vehicles on the road would approach a fixed distance of 5 feet plus the distance the vehicles would travel in 1 ½ seconds at the prevailing road speed [(8)].

## Moving Picture Camera Analysis

In 1930 Bruce Greenshields of the University of Michigan studied vehicle spacing by photographing the traffic stream from the side with a motion picture camera. The camera was placed at right angles to the road and 300 feet away, which gave a field wide enough that the photographed vehicles would appear in two successive frames. Knowing the time interval between exposures and the scale of the image, Greenshields could calculate the speed and acceleration of the vehicles and the interval between them. He found that on heavily traveled roads where traffic tends to bunch up, the speed of the vehicles in the queue is controlled by the leading vehicle, a fairly obvious conclusion. When creeping along at crawl speed, the spacing center to center of vehicles was 15 to 30 feet. At higher speeds the spacing followed the straight-line equation:

$$S=21+1.1V$$

where S was the spacing center to to center in feet, and V the average speed in miles per hour [8].

Table 1 shows the theoretical capacity of a single lane of traffic of a two-lane road as calculated from these various formulas. These formulas had the common fault of assuming uniform flow of traffic - something that does not occur in real life. Also, they did not take into account the constantly varying speeds of vehicles and the passing opportunities or lack of opportunities afforded by opposing traffic. In the end, the authors were thrown back on unverifiable assumptions to arrive at reasonable figures for the total discharge *in both directions* of a two-lane highway (such as the Pennsylvania assumption that total two-way traffic would be about the same as that of one lane flowing freely).

**Table 1: Theoretical carrying capacity of a single lane of a two-way, two-lane road (vehicles per hour)**

| | Average speed of the traffic stream | | |
|---|---|---|---|
| According to: | *15 mph* | *25 mph* | *40 mph* |
| Johnson (1921) [3] | 2,640 | 2,330 | 1,740 |
| Johnson (1927) (From aerial photo studies) [4] | 2,490 | 2,780 | 2,800 |
| Pennsylvania Division of Highways (1927) [7] | 2,264 | 1,970 | 1,456 |
| Dougherty (about 1929) [8] | 2,040 | 1,950 | 1,585 |
| Johannessen (about 1930) [8] | 1,365 | 1,650 | 1,875 |
| Greenshields (1932) [8] | 2,110 | 2,720 | 3,250 |
| Bureau of Public Roads (1934-37) [12] | 1,500 | 2,000 | 1,990 |

## Cooperative Study of 1930-31

In 1930 the BPR, the Maryland State Roads Commission, and the University of Maryland launched a cooperative study of the capacity of two-, three-, and four-lane highways, with A. N. Johnson in charge. At the very outset of the study the researchers realized that they would have to define traffic capacity before they could measure it. They finally agreed that the *working capacity* or *free-moving capacity* would mean the point at which congestion first becomes apparent:

> When a road carries only a few vehicles all will move freely and there can be no question of congestion. As the number of vehicles increases there will be reached a point at which some will be delayed because they can not immediately pass slower vehicles ahead of them. This delay indicates congestion.
>
> Beyond the free-moving capacity of a highway the number of vehicles passing in a given time may still increase, but traffic will move with more and more restrictions. The individual driver will have less and less freedom of action, being compelled to follow the vehicles directly ahead of him. The number of vehicles may increase until the rate of flow is at a maximum, when the ultimate capacity of the highway may be said to have been reached. Any attempt to put still more vehicles through will result in serious interference with the movement of traffic, and the number of vehicles passing a given point in a given time will actually decrease because of overcrowding [9].

The field work for the study was done by two teams of two observers each who roamed the highways from Washington to Boston looking for spots where traffic was heavy during rush hours. During the summers of 1930 and 1931 the observers counted traffic at 71 such spots in 7 eastern seaboard States. They were instructed to record the number of vehicles in each 5-minute interval in each direction for each lane. Automobiles, trucks, and buses were recorded separately. Congestion was considered to occur when the number of vehicles became great enough to fill the road and make turning out of line to pass impracticable: “When congestion occurs, reduction of speed will be noticed, along with the tendency for drivers to crowd one another” [9]. Congestion was to be recorded only if it prevailed at least 1 minute in each 5-minute interval.

The observers had some difficulty finding two-lane highways that were congested by this definition, but no difficulty finding congested two-lane and three-lane roads. At all stations the heaviest traffic came between 3 p.m. and 7 p.m.

For purpose of analysis, the observations were first grouped according to whether they were on two-, three-, or four-lane highways. Within each of these groups the 5-minute counts were placed in four subgroups according to the directional distribution of traffic, ranging from 50 percent-50 percent (equal split) to 20 percent-50 percent. This gave 12 subgroups into which all the 5-minute counts for all the observation stations were divided. Within each of these four subgroups the individual 5-minute counts were plotted as vertical bars according to the number of vehicles counted, producing an array such as that shown in figure 4. The minutes of congestion observed in each 5-minute interval were then plotted cumulatively as in the lower graph of figure 4. The first sharp break in this cumulative congestion curve was interpreted to be the point at which working capacity was reached, and the corresponding 5-minute discharge rate was then taken as the working capacity of the road for that particular directional split. Since the maximum 5-minute discharge for any highway is seldom sustained for an entire hour, they reduced the former somewhat to arrive at the *practical hourly capacities* shown in table 2.

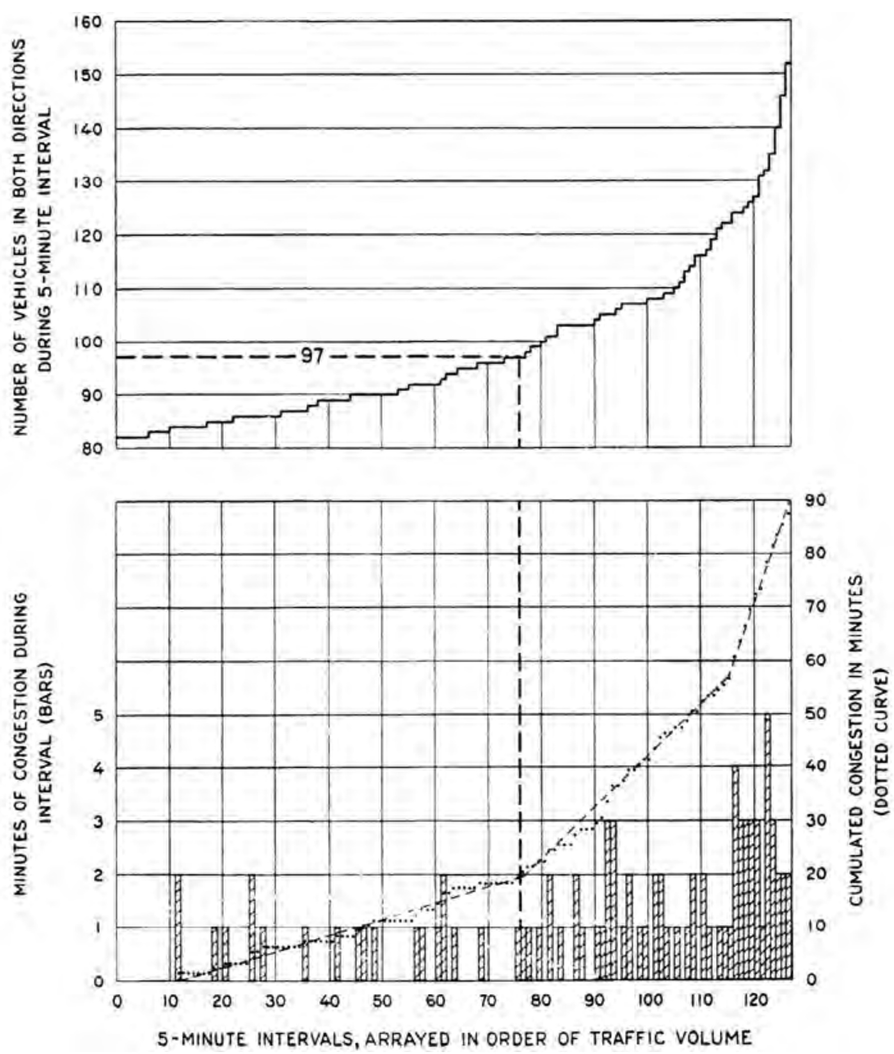



*Figure 4: Determination of traffic capacity of two-lane roads, 60 percent of traffic in one direction* (9)

*Table 2: Working capacity of two-, three-, and four-lane highways*

| No. of lanes | Vehicles per 5-minute interval | | | | | Practical capacity in both directions |
|---|---|---|---|---|---|---|
| | Percentage of Traffic in one direction | | | | | |
| | *50* | *60* | *70* | *80* | *Average* | *Vehicles per hour* |
| Two | 90 | 97 | 90 | 105 | 97 | 1,000 |
| Three | 185 | 165 | 195 | 175<br>180 | 2,000 | |
| Four | [1]300 | [1]300 | 290 | 270 | 290 | 3,000 |

[1] Estimated, because actual congested four-lane highways could not be found for these conditions.

Thus, without considering the relative safety of the three types of road the investigators concluded that the addition of one lane to a two-lane road doubles its capacity, while addition of two lanes triples the capacity.

### The Ohio Study of 1934

In 1934 the Ohio State Highway Department undertook to measure the working capacity of a two-Lane highway, using Greenshields' photographic method. In all, the investigators studied 1,180 groups of 100 vehicles each, on both "congested" and "uncongested" highways. "Congestion" was assumed to exist when the average speed of all vehicles was observed to decrease below the "free running speed," this latter being the speed of the traffic stream when conditions are such that drivers can overtake and pass slower drivers at will.

When they tabulated the results, the researchers found that the average free running speed of 434 groups on uncongested two-lane highways was 43.6 mph, and that the corresponding average hourly volume[1] of the traffic was 469 vehicles per hour, of which 5.3 percent were trucks.

For congested roads, the average speed declined as the density in vehicles per mile increased (fig. 5). The investigators found that the slope, m, of the speed/ density curve was related to the number of slow-moving vehicles in the traffic stream, ranging from 0.232 for 1 to 5 percent trucks, to 0.272 for 2 to 12 percent trucks. When they expressed the traffic in vehicles per hour rather than vehicles per mile of pavement, the speed/volume curve

1. In the early days of traffic studies the terms density and volume were used interchangeably. Volume is now defined as the number of vehicles passing a given point on the highway in a given period of time; while density is the number of vehicles occupying the moving lanes of a highway at a given instant, usually expressed in vehicles per mile. In the discussions herein, appropriate changes have been made to convert to the modern usage.

assumed the shape of figure 6 which shows that for a given traffic volume there can be two speeds up to the point where maximum volume is reached (10).

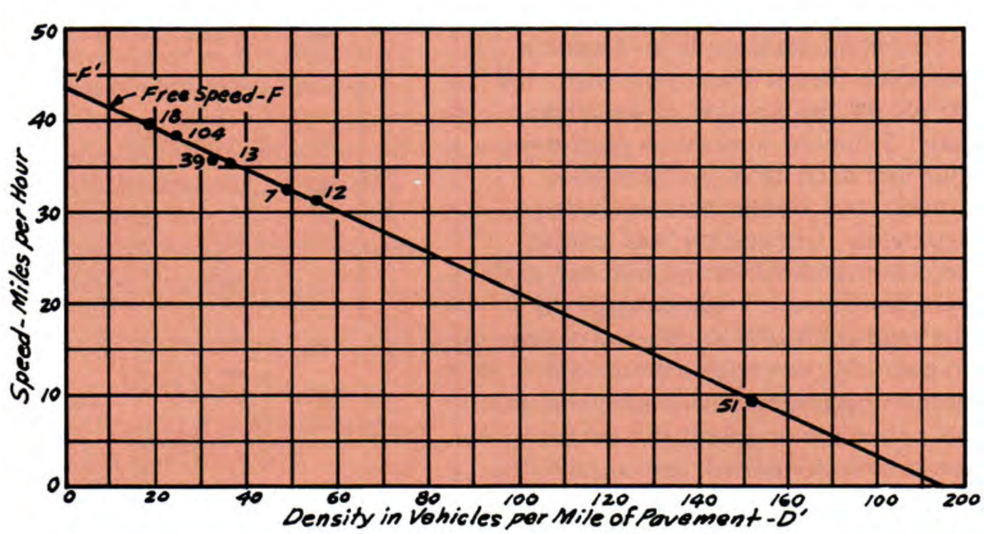



*Figure 5: Speed in miles per hour corresponding to a given average density in vehicles per mile of pavement (10)*

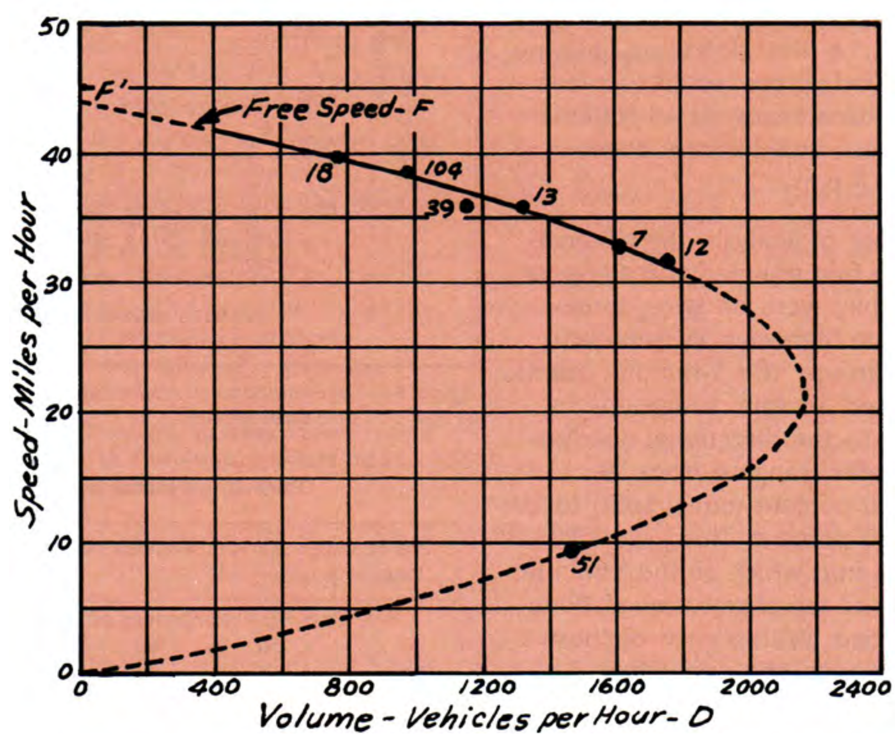



*Figure 6: Speed in miles per hour corresponding to a given volume in vehicles per hour on a two-lane highway (10)*

By 1934, after wrestling with it for over a decade, highway engineers had lost all illusions that a simple solution could be found for the capacity problem. Enough information had been gathered by then to convince even the most skeptical that capacity was the result of a mix of climatological, dynamic, mechanical, and psychological factors so complex as to defy exact measurement.

Nevertheless, the constantly increasing number of motor vehicles made it imperative that some practical solution be found. What was needed, according to E. H. Holmes of the BPR, was a "concerted, intelligently directed effort to determine the effectiveness of the highway in performing one of its most important functions, that of permitting the safe and expeditious movement of traffic" (11). This, he stated, was "a problem of dynamics in which it is necessary not only to study the movement of the individual units of the traffic stream, but also to determine how the movement of these units is affected by the external forces within and without the stream itself." Furthermore, according to Holmes, there was an urgent need to coordinate geometric design with traffic requirements. "There is no justification for building, for example, a three-lane road, perfectly designed as to economy of construction, if its alignment is such that traffic must be restricted to two lanes on frequently recurring hillcrests or curves. In providing opportunity for passing only where the topography is especially suitable, the road does not fulfill the demands of the traffic which justified it" (11).

## Coordinated Effort to Solve the Capacity Problem

The necessary coordinated effort got underway in 1934 under the leadership of the Bureau of Public Roads. This effort was pushed in several directions simultaneously:

- Development of improved methods for counting and forecasting traffic.
- Lateral placement studies to determine how traffic actually utilizes the roadbed and how it is affected by shoulders and nearby obstacles.
- Passing studies to determine the distances required for overtaking and passing.
- Speed studies of individual vehicles and groups of vehicles.
- Studies of the spacing of vehicles in a traffic stream and how they interact with each other.
- Studies of the hill-climbing abilities of motor vehicles, particularly trucks.
- Development of improved instruments for counting vehicles and measuring their speed and position on the highway.
- Development of methods for analyzing and interpreting huge volumes of factual data gathered in the field.

The first four of these fields of research have been reviewed in Parts 1, 2, and 3, and the preliminary work done by various investigators on the spacing of vehicles in traffic has been covered briefly in the preceding paragraphs. Now let us examine the studies of the spacing and interaction of vehicles in a traffic stream in greater detail.

In 1934 the BPR, after reviewing the various studies of volume versus speed and spacing, concluded that theoretical studies would never yield reliable results, and that the field studies previously made were "too limited or lacking in essential data, such as the speeds at which the individual vehicles were traveling, to yield accurate and conclusive results" (12). The Bureau engineers decided that a large quantity of detailed data on many roads in different parts of the country would have to be gathered before reliable indexes of capacity could be formulated. One of those assigned to this massive data collection program was a young highway economist, Olav K. Normann, who in the next 15 years was to play a major part in the solution of the capacity problem.

Data collection began the summer of 1934 with capacity studies on the most heavily traveled highways in New York and New England. The study stations were situated at substantially level tangent locations where there was adequate sight distance for passing. At each station the investigators laid out a course ⅕-mile long. Observers at each end of the section noted the license number of each vehicle as it entered and left the test section and recorded the time by closing a circuit with a telegraph key. This in turn caused a pen to mark a strip chart driven by clockwork at a fixed speed in an automatic graphic recorder. Two observers were required at each end of the test section for each direction of traffic, or a total of eight. One observer in each pair read the license number aloud and simultaneously recorded the time of passage with the telegraph key, while the other wrote the last three digits of the license number on a data sheet. To correlate the time recording on the strip chart with the license record on the data sheet every 10th, 50th, and 100th vehicle was checked on the data sheet and also distinguished by a special telegraph manipulation on the strip chart. With a little practice two observers could record as many as 800 vehicles per hour "with little difficulty" (13).

The studies were conducted for 8 daylight hours per day starting while traffic was light and continuing through the heaviest volumes, giving a range of volumes for each station. The BPR observations were carried through the summers of 1934 and 1935 in New York and New England, and in Illinois in cooperation with the Illinois Division of Highways during the summer of 1937. In all, data were assembled on over 300,000 vehicles traveling on two-, three-, and four-lane highways (12).

From the basic data recorded during these studies it was possible to obtain the speed of each vehicle, its time or distance spacing with respect to other vehicles in the traffic stream, and the exact volume of traffic in each direction during any desired time period. However, the reduction of this mass of data was a tedious process, even with the aid of card tabulating machines, so it was not until 1939 that preliminary conclusions became available. One of the first discoveries was that, contrary to some published discussions, the average vehicle speed of the traffic stream is not by itself a reliable measure of working capacity. Much more meaningful as an index of relative interference between vehicles was the average difference in speed between successive vehicles (12).

## Measure of Capacity

On a rural highway, when traffic is light and the speed of each individual vehicle is not governed by the speed of the vehicle immediately ahead, fast drivers can pass slow ones almost at will, and there are large differences in speed between successive vehicles. As the volume increases, passing opportunities become scarcer and the speed of individual vehicles is governed more and more by the speed of preceding vehicles. Thus, their time spacing tends to become more and more uniform. This is shown graphically in figure 7. Curve B indicates that when the average time spacing between successive vehicles is 9 seconds or more, there is little interference between vehicles and the faster drivers tend to travel 6 to 7 mph faster than those they are overtaking. This is true at all speeds from 10 to 40 mph. At spacings below 9 seconds the faster drivers are more and more influenced by preceding vehicles until at a time difference of 1 ½ seconds there is an average speed difference of only 2 mph.

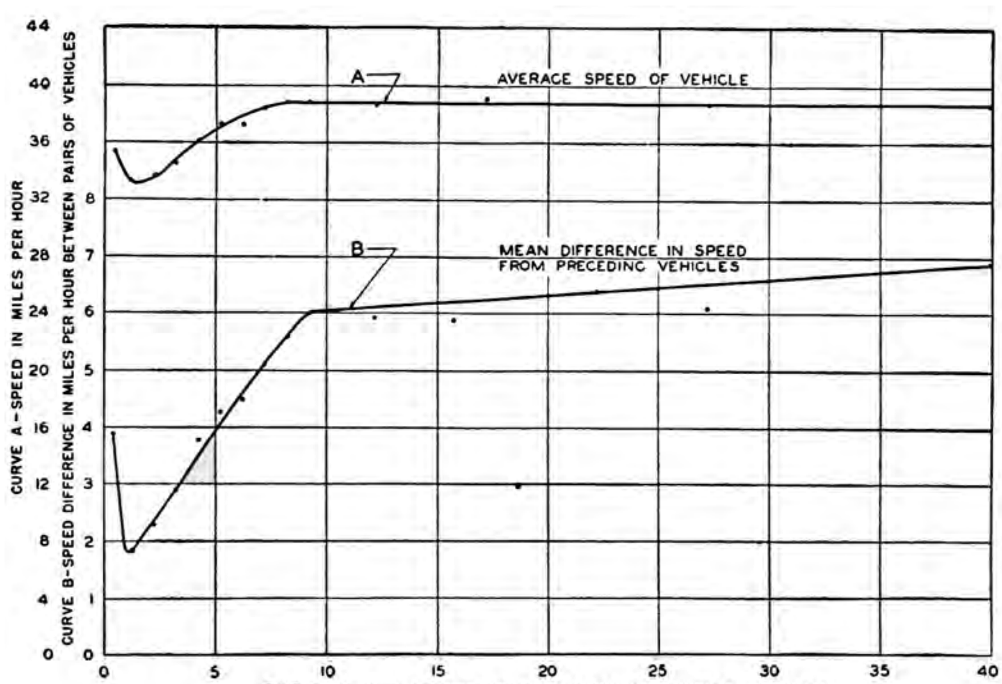



*Figure 7: Speed characteristics of vehicles traveling at given time spacings behind preceding vehicles (16)*

The researchers then analyzed the spacings between vehicles that were traveling at the same speed as preceding vehicles and not being passed by others behind them - in other words, vehicles whose drivers were content with their relative positions in the traffic stream. This analysis is shown graphically in figure 8. In all cases, the *modal spacing* preferred by the largest group was very close to 1 ½ seconds, and also less than the average spacing of all vehicles. Furthermore, the modal spacing of 1 ½ seconds was remarkably uniform at all speeds from 20 to 50 mph (fig. 9).

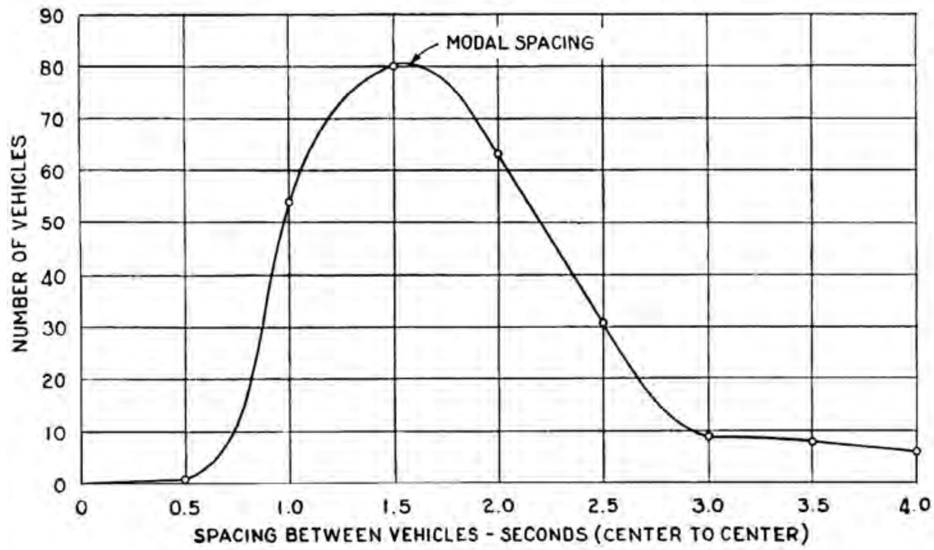
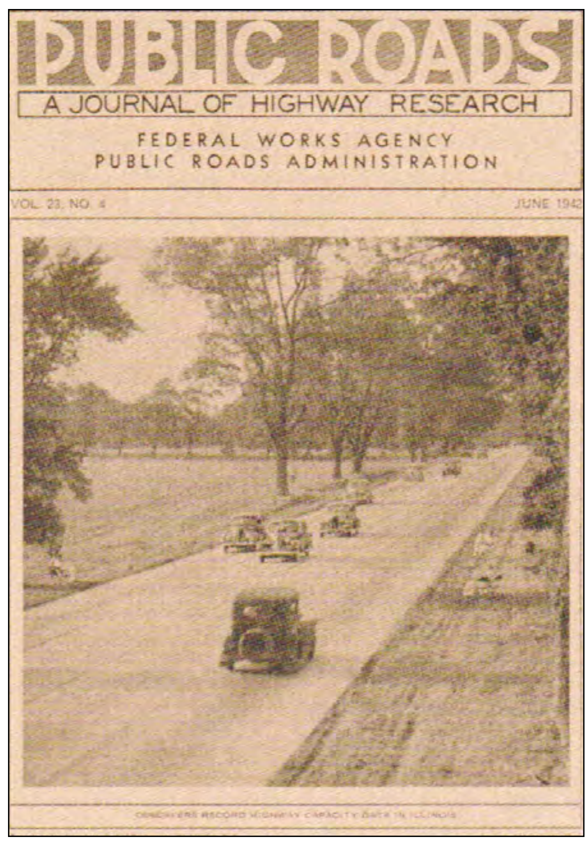



*Figure 8: Frequency distribution of spacings between vehicles traveling 31 mph preceded by vehicles traveling at the same speed on a two-lane tangent* (12)

It is interesting to note that this interval of 1112 seconds between succeeding vehicles traveling at the same speed is exactly the interval proposed by Johannesson in the late 1920's.



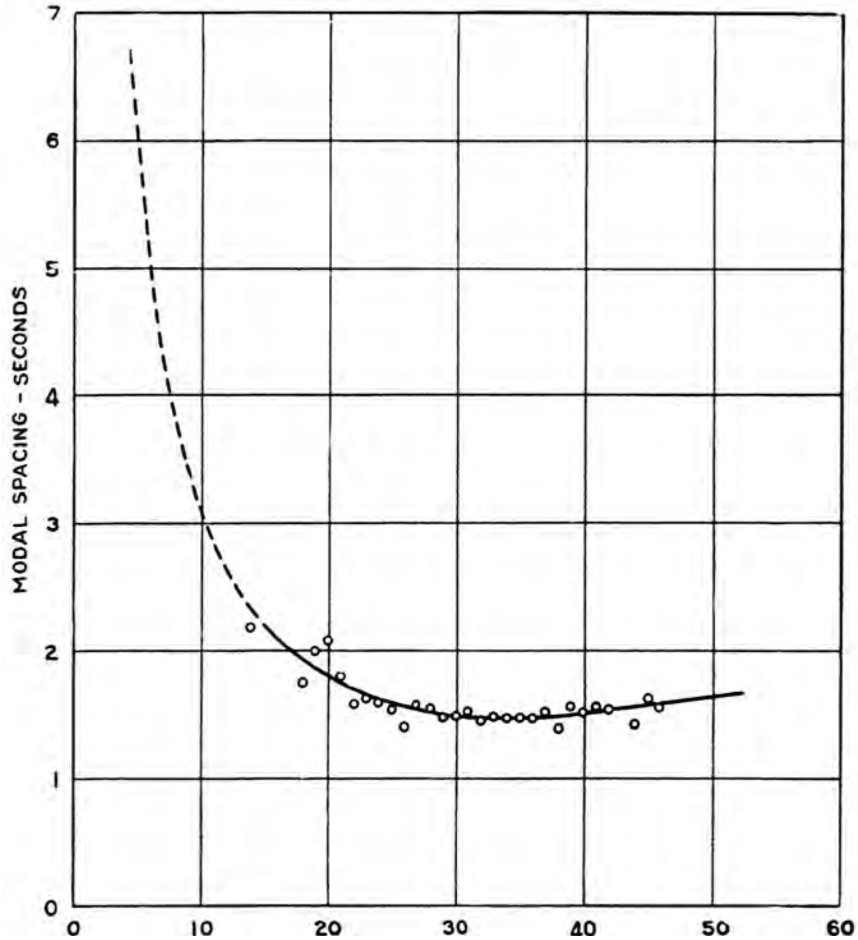



*Figure 9: Modal spacing in seconds between vehicles traveling at the same speed on a two-lane tangent* (12)

Using their field-derived modal spacings in the classic capacity formula, the BPR engineers found the theoretical capacity of one lane of a two-lane highway to be about 2,400 vehicles per hour at 33 mph. However, they also realized that this figure had little practical value because it could be a true value only for the ideal condition where all vehicles were traveling freely at the same speed in one direction and there was no opposing traffic. Actually, of course, there would surely be opposing traffic in real life and its amount would have a direct effect on the capacity of the other lane by limiting passing opportunities.

## Analysis of Data

The researchers then plotted mean differences in the speed of groups of vehicles against observed hourly volumes in one direction. This resulted in a seemingly hopeless scatter (fig. 10) but by applying multiple correlation to the data - using the mean difference in speed as the dependent variable and the volume of traffic in one direction together with the volume in the other direction as the two independent variables - they were able to resolve the scatter into a series of straight-line curves such as figure 11.

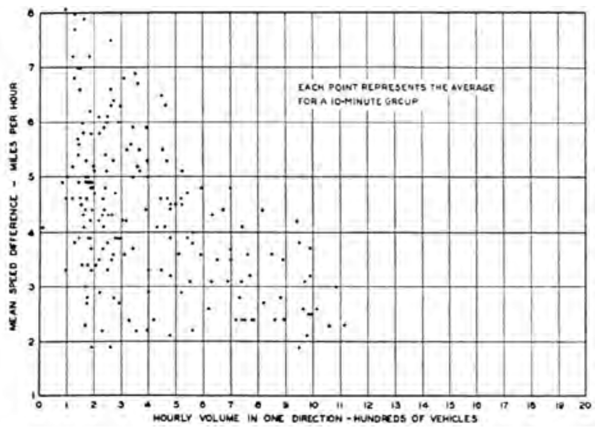



*Figure 10: Mean difference in speed on a two-lane tangent between successive vehicles for various volumes of traffic* (12)

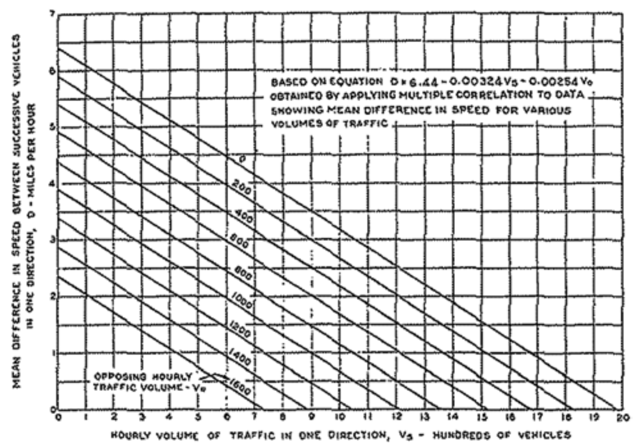



*Figure 11: Mean difference in speed on a two-lane tangent between successive vehicles with various volumes of traffic* (12)

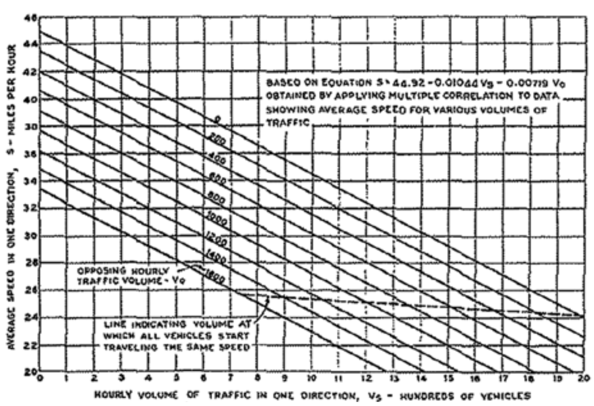



*Figure 12: Average speed with various volumes of traffic on a two-lane tangent* (12)

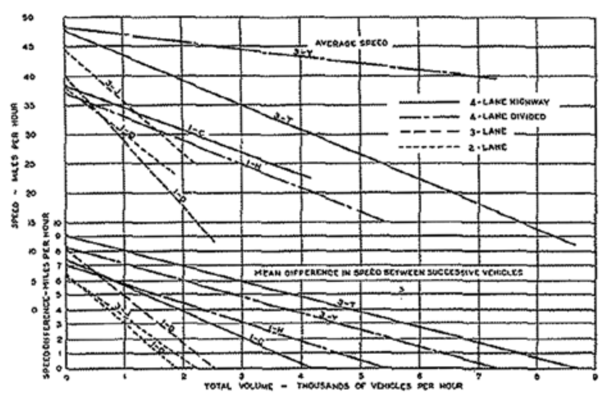



*Figure 13: Speed and mean difference In speed for level tangents with various total volumes equally distributed between the two directions* (12)

Figure 11 shows that when there is no opposing traffic and all vehicles are traveling at the same speed, a single Lane of a two-lane road will carry 1,980 vehicles per hour. As opposing traffic builds up, this figure diminishes until with evenly balanced traffic it becomes 1,100 vehicles per hour in each Lane.

By substituting speed in one direction for mean difference in speed, the analysts were able to construct figure 12. In this figure the dashed line indicates the volumes at which all vehicles will have to travel at the same speed; for values below this line one slow-moving vehicle can hold up all following vehicles, so working capacity values must always be above this line.

Curves such as those in figures 11 and 12 were constructed for three-lane and four-lane divided and undivided highways. The maximum hourly observed volumes *in both directions* when traffic was equally balanced are shown in figure 13 for seven typical locations. These curves show rather wide differences in capacity for apparently similar roads. For example one of the four-lane, undivided highways had a maximum capacity of 4,150 vehicles per hour at a speed of 22 mph, while the other peaked at 8,600 vehicles per hour at a speed of 11 mph.

The studies described above were intentionally limited to level tangent sections. In their conclusions the BPR engineers stressed the need for additional observations at other locations where the alignment was curved or on grades, and especially the need for greatly expanded knowledge of passing practices. As a final conclusion they stated:

> Although there is a wide variation in the driving characteristics of individual vehicle operators, certain fundamental principles of traffic behavior can be developed that will be generally applicable. The results may be entirely different from those derived by assuming average conditions [(12)].

**Capacity Defined**

One of the problems faced by the early traffic researchers was to define the term *capacity*. The earliest estimates of capacity, for example A. N. Johnson's, were theoretical capacities based on assumed vehicle spacings and uniform flow. Later *theoretical capacities*, such as those derived by O. K. Normann from the early BPR capacity studies of 1934-37, assumed uniform flow but used empirical *modal spacings* derived from a large number of field observations.

Normann coined the term *maximum hourly capacity* for the hourly discharge that occurs just before all vehicles lose their freedom to pass and have to start traveling at the same speed as the preceding vehicle. This later became known as the *possible capacity*.

*Practical working capacity* was defined by Normann in 1942 as the hourly discharge when the density of traffic is not so great as to unreasonably restrict passing opportunities. This, he added, was a relative rather than an absolute value, and might vary depending on the local conditions [(14)].

The development of the speedmeter and the pneumatic tube traffic counter by the BPR, as described in Parts 2 and 3, gave a tremendous boost to the investigations of highway capacity. The original studies of 1934-37 were extended to Massachusetts, Illinois, and California in 1938, and studies of capacity on grades and curves were included in the program. The data gathered in these studies of 1938-39 substantially confirmed the earlier preliminary findings. Among these were the following (14):

- The maximum theoretical capacity of a single traffic lane is about 2,000 vehicles per hour and occurs at speeds slightly above 30 mph. It can be attained only on four-lane roads, or for short periods, on short sections of two-lane roads.
- The possible capacity of a long section of two-lane highway with good alignment and carrying few trucks is about 2,000 vehicles total in both directions. Three-lane, two-directional highways under similar conditions will carry 2,600 vehicles per hour in both directions; and four-lane highways, 8,000 vehicles per hour in both directions.
- Under normal conditions, the maximum practical working capacities (totals in both directions) are 800 vehicles per hour for two-lane highways; 1,400 vehicles per hour for three-lane highways; and 2,800 vehicles per hour for four-lane highways.

*Wilshire Boulevard and Homby Avenue, Los Angeles, CA*

## HRB Organizes Committee on Highway Capacity

During World War II traffic research was largely suspended while the highway organizations and their engineers devoted themselves to other activities. However, the work already done on capacity studies was of such magnitude that, in 1944, the Highway Research Board (HRB) organized a Committee on Highway Capacity to coordinate the work in this field. For chairman of this committee the obvious choice was O. K. Normann of the BPR who, since 1934, had been in the forefront of the nationwide studies. "Over the years he organized and participated in a wide range of research studies of what he recognized as a dynamic system involving vehicle, road, and driver. Using the traffic stream as a laboratory, he imaginatively created apparatus and analytical methods to collect and reduce vast quantities of data to findings that greatly increased our scientific knowledge and understanding of traffic movement" [15].

With the conclusion of the war, traffic research was resumed, particularly research on the influence of lane width, grades, and curvature on rural highway capacities and on the capacities of freeways, ramps, weaving facilities, and urban streets and intersections. By 1949, an enormous volume of factual material had accumulated. The Committee on Highway Capacity and the Bureau of Public Roads undertook to reduce this mass of material to a form that would be usable by highway designers and traffic engineers. The result of this monumental labor originally appeared in *Public Roads* magazine, and was later reprinted by the BPR as the justly famous Highway Capacity Manual of 1950 [16]. For 15 years, this manual was the faithful friend of highway engineers in the United States - a practical guide which had impressive influence on the planning of all subsequent highways, including the far-flung Interstate System.

Highway traffic research did not stop with the publication of the 1950 Highway Capacity Manual. Indeed, the pace quickened, and the need for updated information was soon evident. However, most of the underlying principles of traffic and driver behavior had been worked out by 1950, completing one of the longest-sustained research endeavors of history.

## REFERENCES

(1) Andrew P. Anderson, "9,231,941 Motor Cars and Trucks Registered by the States in 1920," *Public Roads*, vol. 3, No. 36, April 1921, p. 21.

(2) A. N. Johnson, "The Traffic Census," *Public Roads*, vol. 3, No. 32, December 1920, p. 16.

(3) A. N. Johnson, "The Traffic Census and Its Use in Deciding Road Width," *Public Roads*, vol. 4, No. 3, July 1921, pp. 7, 23.

(4) A. N. Johnson, "Maryland Aerial Survey of Highway Traffic Between Baltimore and Washington," *Proceedings of the 1928 Meeting, Highway Research Board*, Washington, D.C., 1929, pp. 113, 114, 115.

(5) J. G. McKay, "New Traffic Flow Recorder in Use on Cleveland Traffic Survey," *Proceedings of the Seventh Annual Meeting, Highway Research Board*, Washington, D.C., 1928, p. 247.

(6) “A Study of Highway Traffic in the Cleveland Regional Area,” *Public Roads*, vol. 9, No. 7, September 1928, p. 134.

(7) G. E. Hamlin, “Report of Committee on Highway Traffic Analysis,” *Proceedings of the Seventh Annual Meeting, Highway Research Board*, Washington, D.C., 1928, pp. 233, 234.

(8) Bruce D. Greenshields, “The Photographic Method of Studying Traffic Behavior,” *Proceedings of the 13th Annual Meeting, Highway Research Board*, Washington, D.C., 1934, pp. 388-390.

(9) A. N. Johnson, “Highway Traffic Capacity,” *Public Roads*, vol. 13, No. 3, May 1932, pp. 41, 43.

(10) Bruce D. Greenshields, “A Study of Traffic Capacity,” *Proceedings of the 14th Annual Meeting, Highway Research Board*, Washington, D.C., 1934, pp. 468, 470.

(11) E. H. Holmes, “Procedure Employed in Analyzing Passing Practices of Motor Vehicles,” *Public Roads*, vol. 19, No. 11, January 1939, p. 209.

(12) O. K. Normann, “Preliminary Results of Highway Capacity Studies,” *Public Roads*, vol. 19, No. 12, February 1939, pp. 225-240.

(13) E. H. Holmes and Lawrence S. Tuttle, “An Improved Method of Measuring Speed of Traffic,” *Public Roads*, vol. 14, No. 12, February 1934, p. 243.

(14) O. K. Normann, “Results of Highway Capacity Studies,” *Public Roads*, vol. 23, No. 4, June 1942, pp. 57-81.

(15) “O. K. Normann-A Tribute,” Highway Capacity Manual-Special Report No. 87, *Highway Research Board*, Washington, D.C., 1965, p. vii.

(16) O. K. Normann and W. P. Walker, “Highway Capacity: Practical Applications of Research,” *Public Roads*, vol. 25, No. 10, October 1949, and No. 11, December 1949. This report of the Highway Research Board Committee on Highway Capacity was later republished by the U.S. Department of Commerce under the title, “Highway Capacity Manual-Practical Applications of Research,” *U.S. Government Printing Office*, Washington, D.C., 1950.