Studying Traffic Capacity by New Methods

Photographic Surveys of Automobile Travel on Ohio Roads Are Illuminating

By Bruce D. Greenshields

Associate Member American Society of Civil Engineers

Research Engineer, Traffic Bureau, Ohio State Highway Department, Granville, Ohio

For years the standard method of taking traffic counts has been to employ observers with stop watches and tally sheets. The new method devised by Dr. Greenshields utilizes a motion picture camera designed to take pictures intermittently, at frequent intervals. Superposed on each exposure is a log record showing the exact time, data, and other details. Besides this scale of time, a scale of distance is fixed by markers on the road itself. Such observations on 22,000 vehicles were taken in Ohio during the summer of 1934 and have since been analyzed in detail by groups of 100 cars. As a result, new relations between speed, spacing, and total density have been found. Up to a density of perhaps 600 vehicles an hour, there were no delays due to traffic. In every instance the average unhampered speed was from 42 to 44 miles an hour on pavements. On two-lane roads the maximum capacity was found to be about 2,300 vehicles an hour, at a speed of about 22 miles an hour. This method of making a graphical tally, with its valuable potentialities, should prove a boon to engineers in the making of traffic analyses.

Until recently traffic surveys have been inadequate for determining the capacity of a roadway of a given width and type. The count and stop-watch system cannot be adapted to obtain complete information, especially if numerous automobiles are moving in opposite directions at a variety of speeds. The photographic method of studying and analyzing traffic problems, as here described, is comparatively new. Thus far it has proved highly successful in overcoming the difficulties of the previous systems.

For one thing, the eye of the camera is accurate, and the instantaneous records, or pictures, can be made the basis of a complete study. The pictures taken by a 16-mm motion picture camera not only show the number of cars passing in a given time, but also reveal the type of cars, the paths of their movements, and their rate of travel. A few simple methods of interpretation disclose the desired information.

To take the pictures, the camera should be approximately 300 ft from the roadway and if possible at right angles to it, thus bringing about 125 ft of the highway within range of the lens. By means of a clock arrangement with an electric switch, the pictures are then taken automatically. For convenience, the time interval between pictures is arbitrarily set at 88 per min, so chosen because a vehicle traveling 1 mile per hr would advance 1 ft in $^1/_{88}$ min.

White markers are placed on both sides of the road, usually 50 ft apart longitudinally, to give a scale for the center line of the road. In the case of a two-lane roadway, the scale can be satisfactorily shown when the films are projected by vertical parallel lines equally spaced, which are drawn on the screen. Thus the same scale lines are used for all the films, the throw of the lantern being changed so that the scale lines will fit films taken at different locations. For multiple lanes or where the pictures are not taken at right angles to the road, it may become necessary to construct a scale with converging lines. But this is always possible if enough marked points are in the field of view.

In addition to the markers, each picture shows a bulletin board and clock in the immediate foreground, giving the time, date, location, type and width of pavement, film number, time interval between frames, and weather conditions. Thus the pictures constitute a complete and permanent record which may be analyzed at any time or re-checked for information that may have been overlooked in the first analysis.

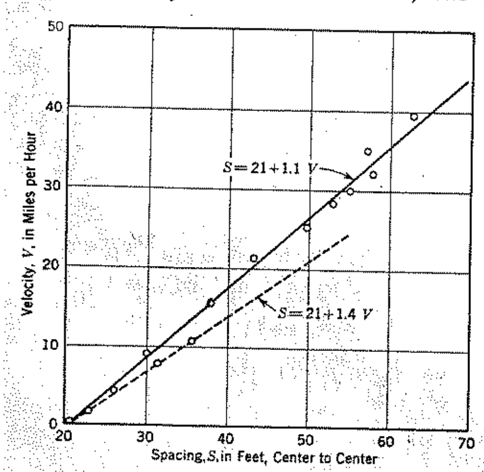


Fig. 1. Speed and Spacing of Vehicles
Point of Zero Velocity Is Average of 143 Observations. Each Other Point Is Weighted Average of 99 Observations. From *Proceedings*, Highway Research Board, 1933, Page 393

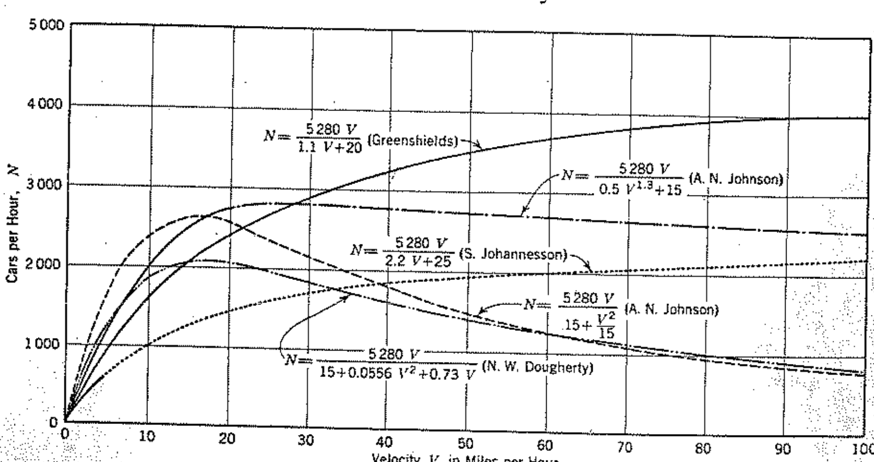
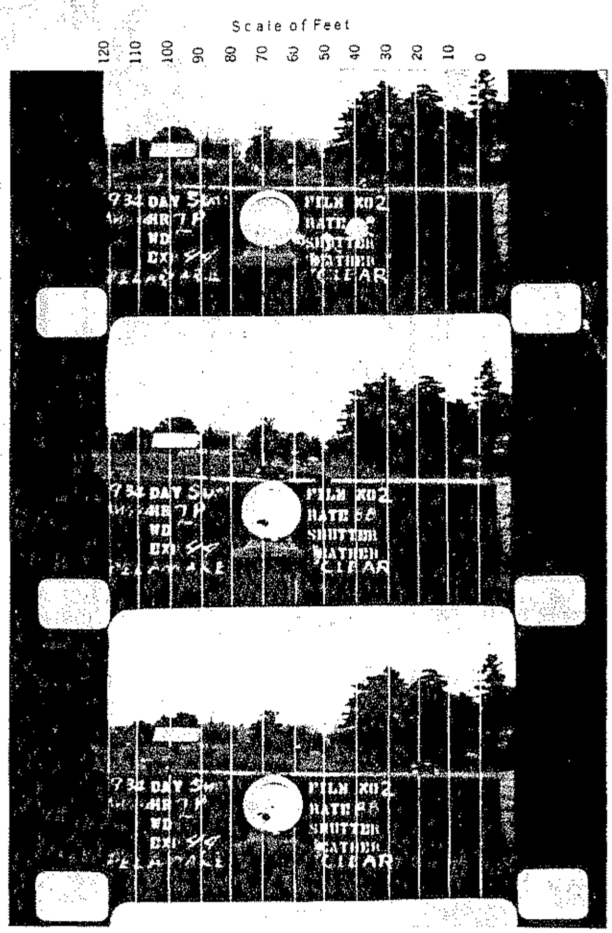


Fig. 2. Graphic Comparison of Formulas for Determining the Relation Between the Number of Vehicles Passing a Given Point and Their Rates of Speed
Reproduced from *Proceedings* of the Highway Research Board, 1933, Page 394

Civil Engineering 1935, Vol 5, No 5

shown. In the first, at the top, the rear car appears at position 38 on the scale. In the second picture it is at position 72 and has advanced 34 ft, which means that it



CONSECUTIVE VIEWS ON U. S. 23, AT A POINT 1.0 MILE NORTH OF DELAWARE, AT A RATE OF 88 PER MIN

Bulletin Board with Clock Appears in Lower Half of Each Photograph. Vertical 10-Ft Lines Show Distance Traveled

is traveling 34 miles an hour. From the first picture it is seen that this car is 82 ft behind the one in front, measured from center to center. From the speed and time at which the cars appear the spacings may be calculated

Obviously the usual speeds and density of traffic are a measure of the comparative ability of various types and widths of highway to facilitate traffic. It is evident that roads permitting the highest available speeds will carry the maximum amount of traffic.

A typical set of data representing free-moving traffic on an uncongested roadway was obtained on State Route 2 (U. S. 6) 4.9 miles east of Vermilion, Ohio. This section of new concrete highway is 30 ft wide. Profilometer readings showed an average of only 12 variations per mile in excess of $^1/_4$ in. in 10 ft. This road is straight, and the view is unobstructed for a long distance, so that it provides an ideal place for high speeds. Its traffic shows the normal tendencies of travel, or what the average driver does on a smooth roadway free from interference from other vehicles. At no time did the road carry sufficient traffic to cause congestion. The data are given in Table I.

TABLE I. SIGNIFICANT TRAFFIC OBSERVATIONS ON U. S. 6, EAST OF VERMILION, OHIO

Density in Vehicles Per Hr	Number of 100-Vehicle Groups	Mean "Smoothed" Speed	Percentage of Trucks	Percentage Traveling in One Direction
270	1	42.5	6.0	48.0
308	2	41.6	7.5	54.5
323	6	42.8	5.7	58.9
330	3	40.7	8.6	56.9
349	14	43.7	6.0	54.1
364	7	43.5	8.9	54.7
389	16	42.5	8.0	53.6
410	6	42.0	8.7	53.0
441	11	40.7	7.6	54.0
464	1	43.2	9.0	55.0
509	1	40.7	8.0	57.0
Av. 379	Sum 68	Av. 42.4	Av. 7.5	Av. 54.4

Averages were computed for the total 68 groups. The term "mean smoothed speed" needs explanation. This speed was taken from a curve so drawn on arithmetic probability paper as to give a "smoothed" value. It will be noted that the vehicles were studied in groups of 100 each. If the number passing in any particular time interval, such as 15 min, is taken as a unit for study, it may be found that there are 50 passing in one case and 200 in another case. Fifty vehicles are not sufficient to give a true average, and their performance should not be compared with that of the 200. By referring to the table it is seen that a group of 100 vehicles gives about the same average speed as a much larger group. Therefore such groups were deemed satisfactory for comparison.

On a roadway the traffic pattern shows vehicles travel-

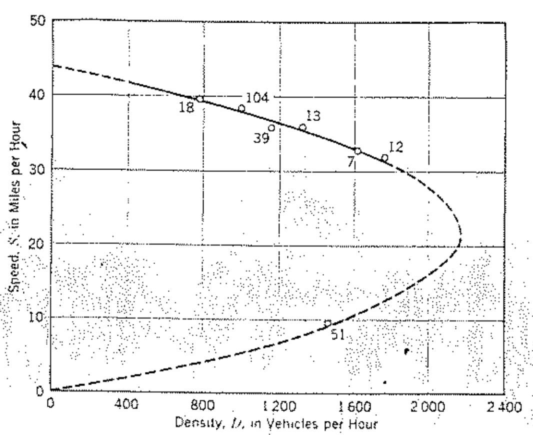


FIG. 3. RELATION BETWEEN SPEED AND DENSITY PER HOUR, ON TWO-LANE HIGHWAYS IN OHIO

Numbers on the Curve Show the 100-Vehicle Groups Observed for Each Point

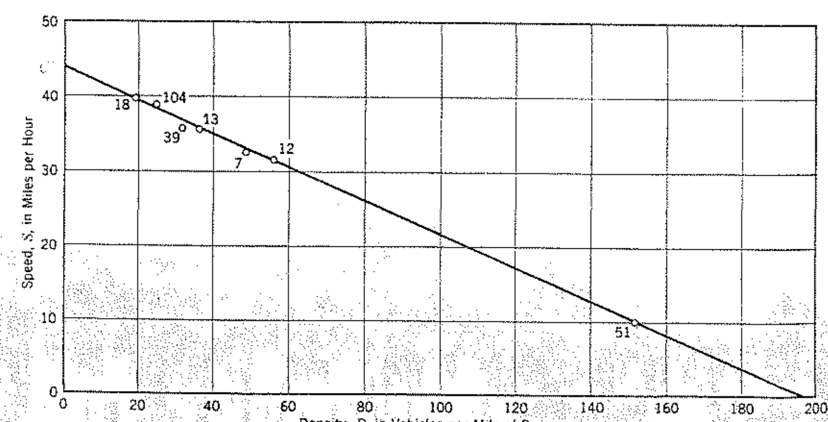
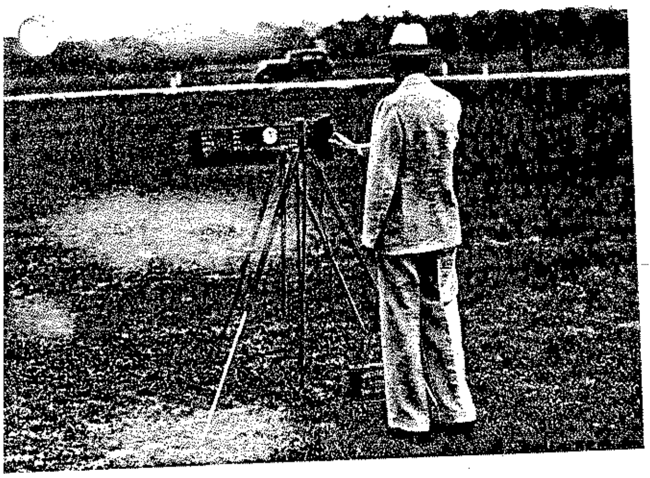


FIG. 4. RELATION BETWEEN SPEED AND DENSITY PER MILE, ON TWO-LANE HIGHWAYS IN OHIO

Numbers on Curve Show the 100-Vehicle Groups Observed for Each Point at diverse speeds and spacings. To take this varia- into account, the 100-vehicle groups were selected is to secure what is known as a "moving" average. the purpose of comparison and analysis, one sample 00 cars is just as good as any other sample. Suppose t one group of 100 vehicles numbered from 1 to 100 just been observed. If the first ten cars of this up, which may have any speeds and any spacings, dropped and ten new ones added, the new group uld not have the same characteristics as the first, even ugh the same 90 cars appear in each group. Plainly cars in this second group are numbered from 11 to), or a third group would be numbered from 21 to 120. Observations were taken at various locations in Ohio brick, concrete, and asphalt pavements, mostly of o-lane width. Profilometer readings showed that



CAMERA IN OPERATION, WITH BATTERY

Bulletin Board in Field of View Indicates Time and Other Data

bumps in excess of $^1/_4$ in. in 10 ft ranged in number from 12 to 492 to the mile. In every case where the surface wa[illegible]rm and dry, however, the average free speed was between 42 and 44 miles per hr. Evidently a certain

TABLE II. DISTRIBUTION OF VEHICLE SPEEDS

Composite Data from Twenty-Four 100-Vehicle Groups, on U. S. 6 East of Vermilion, Ohio. Average Smoothed Speed, 43.0 Miles per Hr; Percentage of Trucks, 6.0

Speed in Miles per Hr	Percentage of Vehicles Traveling at Equal or Lower Speed	Speed in Miles per Hr	Percentage of Vehicles Traveling at Equal or Lower Speed
10	0.01	45	59.0
15	0.1	50	79.0
20	0.6	55	91.0
25	2.5	60	97.0
30	8.0	65	99.2
35	20.0	70	99.8
40	38.0		

amount of roughness has little effect on average speeds. Speeds of over 80 miles per hr for passenger cars, of 60 miles per hr for light trucks (net rate capacity of $2^1/_2$ tons or less), and of 50 miles per hr for heavy trucks were recorded. The average speed of the buses recorded was 41.6 miles per hr. On the other hand, an investigation of the speeds on gravel roads, in connection with a study in Michigan made in the summer of 1933, gave an average speed of 32 miles per hr, showing that a loose or unstable surface causes loss in speed.

The study likewise furnished information on the distribution of vehicle speeds for different densities, as shown in Table II.

HOW SPEED AND SPACING ARE RELATED

In securing the maximum theoretical capacity of a highway, the minimum spacing at which vehicles travel at different speeds is important. It may be reasoned, logically no doubt, that a driver maintains a space between his own car and the car ahead sufficient to permit

HIGHWAY TRAFFIC FILM PROJECTED ON SCREEN

For Study by FERA Students at Denison University. Note Double Exposure of Pictures

a safe stop should the other meet with disaster. Whether or not he does this can be found out only by observation, such as is possible by the photographic method.

In the investigation of speed and spacing of vehicles, an attempt was made to take pictures only of groups of cars that seemed to be moving at controlled speeds and to exclude all observations where the relative velocity of the front vehicle differed by more than 5 ft per sec from that of the one following. It is evident that on a heavily traveled highway the tendency of traffic is to move in crowds, and that the leading vehicle controls the speed of the entire group. At lighter densities, it is harder to determine whether the speeds are affected by congestion.

Observations secured from 6,000 pictures of spacing for each two-mile variation in speed, averaged and plotted on rectangular cross-section paper in Fig. 1, seem to be fairly well represented by the straight-line equation,

$$S = 21 + 1.1\,V \qquad [1]$$

where S equals the spacing of vehicles from center to center, in feet, and V equals the velocity in miles per hour. The lower curve in Fig. 1 represents data taken where speeds were slow and in city traffic. This indicates that different driving conditions may affect spacing.

In an effort to rationalize Equation 1, it may be assumed that the first term, 21, is the spacing in feet at which vehicles come to a stop. It has been observed that vehicles waiting for traffic lights to change are spaced at approximately this distance.

If the speed, V, is expressed in feet per second in place of miles per hour, the coefficient of V in Equation 1 becomes 0.75 instead of 1.1. It is interesting to note that this is about the average time in seconds that it takes a driver to bring his brakes into operation when the occasion arises. In other words, it is the average brake-reaction time. The equation means then that the variation in the average minimum spacing between vehicles depends on reaction time and not on the braking ability of the vehicle. Since deceleration after the brakes have been applied is practically constant, this minimum spacing is sufficient unless the leading car should come to a sudden stop. In such cases there is often a collision.

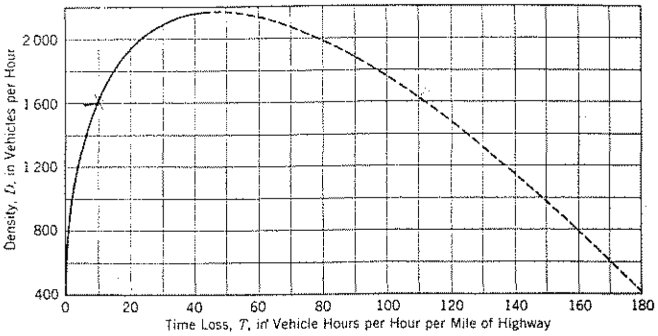


FIG. 5. TIME LOST BY VEHICLES DUE TO REDUCED SPEED ON A CONGESTED TWO-LANE HIGHWAY

Calculation of the maximum number of cars that could go over a highway, all traveling at the same speed and with the average minimum spacing, gives the theoretical maximum capacity shown by the upper curve in Fig. 2. For instance, if all cars were moving at 40 miles per hr, the number that could pass on one lane in one hour would be approximately 3,200. This is never realized except for very short periods of time. The curve does prove, however, that increased average speeds mean increased highway capacity, and that the reason highways do not have a greater capacity is that in any traffic stream of any extent there are always enough slow-moving vehicles to decelerate all the others. Other previously derived curves, also shown in Fig. 2, indicate the considerable variation that may exist between a theoretically derived measurement and one based on actual observations.

What seems to be the proper method of measuring highway congestion or the retardation of vehicles due to heavy traffic is to take actual measurements of the speeds at different densities. A comparatively large amount of such data was collected in Ohio during the summer of 1934 by the Traffic Bureau of the Ohio State Highway Department. This study, based on the observation of over 22,000 vehicles, was analyzed in 1,180 groups of 100 vehicles each. The results show that as the density in vehicles per hour on a two-lane highway increases beyond 400 to 600 vehicles per hour, the average speeds of all vehicles decrease. This density is what may be termed the "free-moving" or "working" capacity of the highway. In other words, 400 to 600 vehicles per hour marks the beginning of congestion.

In Fig. 3, arrived at by plotting the density, D, or the number of vehicles passing in one hour, against recorded speeds, is given the average speed corresponding to any density. For example, at a density of 1,600 vehicles per hour the speed is equal to 33 miles per hr. Then, as the speed continues to decrease due to crowding, the density increases proportionally up to approximately 2,200 vehicles per hour, which represents the maximum carrying capacity of the road. If crowding continues, both speed and density decrease until at a speed of 10.5 miles per hr, the density is again 1,600 vehicles per hour. For a short time a roadway may become so packed with vehicles that all must stop. The density then is zero.

If the speed is plotted against average spacing, the curve in Fig. 4 is obtained. This spacing may be expressed as D', the number of vehicles per mile of pavement. The spacings may be secured from observation, but D' is also the result of dividing the density, D, by the average speed. For example, if the density, D, is 400 vehicles per hour, and the average speed is 40 miles per hr, then the number of vehicles per mile is 10. That is, $D' = 400 \div 40 = 10$. The curve for D' in Fig. 4, drawn from the same data as Fig. 3, is a straight line. Since a straight line is fixed by two points, it is theoretically necessary to have data for only two traffic conditions. Owing to the fluctuations in traffic movements, however, conclusions should be drawn from ample data. Although the curves in Figs. 3 and 4 would not hold for other localities, they may form the basis of estimates.

Economically speaking, congestion is costly. The time loss, in vehicle-hours for each hour on a mile of pavement, resulting from the speed drop shown in Fig. 3, is plotted in Fig. 5. At a density of 400 vehicles per hour, corresponding to the free speed of about 42 miles per hr, there is no time loss. The great waste is shown to occur as congestion takes place, especially in aggravated form.

Since time has an economic value, as proved by the fact that people are willing to pay for the saving of it, it becomes the obligation of highway commissioners to study traffic congestion. By so doing they may determine when a roadway should be widened to meet the needs of the public in reference to economy in time as well as to safety.

FURTHER APPLICATIONS FEASIBLE

Use of the photographic method is reasonable in cost, with the price of 16-mm films on 50-ft rolls about $3 each. A roll with its 2,000 single frames is sufficient to record the movements of about 800 cars. More can be recorded if the traffic is dense enough for more than one car to appear in each frame or picture. An expensive camera is not necessary but it is desirable, for the better the camera, the better the pictures.

Accident prevention has not been mentioned, but all traffic movements have some relation to accidents. The minimum spacing maintained by drivers does not allow time for stopping should the car ahead come to a sudden halt. Slow-moving cars cause not only congestion but also accidents when faster vehicles attempt to pass. Perhaps on busy highways everyone should be required to travel at the same speed.

This brief report has shown that much valuable information about traffic behavior may be gained by the proper approach. Other phases of the subject immediately present themselves for investigation. How do curves, horizontal and vertical, affect speeds? What is the sight distance and the clearance on the opposite lane required for passing a car ahead? Without doubt, further research is not only desirable but necessary if knowledge of traffic is to keep up with the increase in traffic problems. Highways, built to last at least 20 years, are far behind the perfection of the modern motor car, yearly improved and guaranteed to have a speed of from 80 to 100 miles per hr. Safe driving is still subject to the mental perceptions and physical limitations of drivers.

This study has been carried on under the supervision of H. E. Neal, traffic engineer, and J. J. Darnall, superintendent of traffic surveys, both of the Traffic Bureau, Ohio State Highway Department.

Part of the general substance of this article was presented before the Highway Research Board—at the 1933 annual meeting, published under the title, "The Photographic Method of Studying Traffic Behavior," in the *Proceedings* of the organization, Vol. 13 (1934), page 382; and before the December 1934 annual meeting under the title, "Studies of Traffic Capacity," to appear in Vol. 14.