Quality of Traffic Transmission

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● THOSE concerned with street and highway traffic have long recognized that there is a need for evaluating the quality of traffic motion. The way in which vehicles move over the road is a fundamental factor in transportation. Large amounts of data on volume, and the distance and direction of traffic flow have been collected and analyzed. But there is very little exact information on those aspects of traffic motion that not only disturb and annoy the driver but add to the cost of driving.

These factors are also of primary importance to the traffic engineer who is forced by the ever increasing traffic load on our streets and highways to make plans for improvements and set up priorities for construction.

In view of the obvious need it was felt by the writer and his associates, that a new measure of traffic motion should be derived. Such a measure would be particularly useful in urban areas where congestion reaches a maximum. It would provide a basis of comparison for any two sections of streets or for one group of streets with another group. It also would enable streets to be classified according to their quality of traffic transmission.

Such a measure would not only show the need for improvements but furnish a means of making before and after checks. Just how much is accomplished by changing to one-way streets or installing a progressive signal system? It would also enable trends in congestion to be determined and thus make possible better future planning. It would provide a more accurate method of estimating the traffic that is attracted to a new or improved route, for traffic naturally flows to the route with the better quality until conditions become equalized.

It was recognized that this new measure must have certain definite attributes. It must be dimensionless, free from arbitrary decision, easily understood and simple of application. It should be objective in yielding accurate and unbiased measurements, and at the same time it should reflect the driver's feelings. Above all it should be free from confusion with the diverse causes which affect motion.

The idea of quality of traffic flow brings to mind the question of efficiency of flow for we are accustomed to associating these two ideas. In fact the development of a quality index number has led directly to the development of an efficiency index but this study of efficiency has not been completed. It will be mentioned only briefly at this time and will be covered more fully in a future report.

A review of previous work will indicate the current thinking on the problem and perhaps give some hint as to the nature of the index measurement to be derived. The next step will be to discuss the nature of the problem. This will be followed by a description of the equipment for gathering field data, and an outline of the method of analysis. The derivation of the quality index number will then be explained.

PREVIOUS WORK

While we have chosen to focus our attention on the development of a quality index, current thinking seems conversely to be toward the development of a "congestion" index.

Highway Research Board Bulletin No. 86, January, 1954, entitled *Urban Traffic Congestion,* serves to summarize the present and previous thinking on the subject. The first of the two papers in the bulletin by John W. Gibbons and Albert Proctor treats of the "Economic Costs of Traffic Congestion." [1]

This paper gives the costs of traffic delays due to increased operation expense and loss of time. Accident losses as well as urban blight and related losses are discussed. The paper brings to mind the possibility of using costs as the basis of an efficiency rating number. The less the cost of traffic transmission the higher the number.

The second paper, "Urban Congestion Index

[1] "Economic Costs of Traffic Congestion," by John W. Gibbons, Director of Publications, and Albert Proctor, Staff Specialist, Publications Division, Automotive Safety Foundation.

Principles" [2] discusses the need for a congestion index. The paper lists three conceptions as an approach to the development of an index; operational characteristics, freedom of movement, and volume-to-capacity ratio. It is pointed out that the operational characteristics concept is at fault in that in running a time-delay over a length of course considered as a unit some sections actually free from impediments are charged with the congestion caused by impediments at other sections. To avoid this it is suggested that any course should be divided into short sections. This would serve to localize adverse conditions.

The freedom-of-movement concept would require measurements of traffic densities to determine whether the movements of vehicles are restricted. It is stated that no studies of this type have been made but that the concept warrants further attention.

The third concept involves taking the ratio of volume to capacity. From this relationship some index may be found that will reveal the demand for additional capacity that causes the congestion.

In summarizing his conclusions, Mr. Rothrock states that in the problem of determining an index some common basis of measurement should be found that would be acceptable to all researchers, and that an attempt should be made to make the modulus as simple as possible.

PRELIMINARY DISCUSSION OF TRAFFIC INDEX NUMBERS

Obviously, in developing a traffic index the first step is to attempt to make as logical a conjecture as possible about the nature of the index, and what attributes of traffic should be measured to establish it. The review of previous work emphasizes the fact that one of the difficulties in establishing a scale for measuring the quality of flow is that there is no generally accepted idea as to what it is that we are to measure.

The flow of a traffic stream is a very complex phenomenon, with the movement of each unit varying with the desire of the driver and limited only by the power of the vehicle, the physical features of the street and the presence of other interfering traffic units. This complexity of flow may be encompassed and characterized in the general terms of quantity and quality.

The quantity of flow is usually expressed as the number of vehicles passing a given point on the highway in one hour and is called the volume. Quality is a function of the smoothness or lack of smoothness of flow. From the driver's standpoint it is a function of the lack of freedom of movement and is measured by his annoyance. Since the concept of quality of flow is the more difficult to comprehend, let us, for the sake of clarity, first turn our attention to the measurement of the quantity of flow.

Quantity of Flow

Actually, we are not interested in the quantity or number of vehicles that pass a point, but in vehicle miles, a vehicle mile being defined as a vehicle traveling one mile. This distinction should be kept in mind. It is convenient to select a one mile lane or roadway as the unit area of measurement, for then the volume count at a point for one hour is numerically equal to the vehicle miles per hour per mile of roadway. This is assuming that all vehicles travel the entire mile. If a significant number are leaving and entering at intermediate points, then the volume should be counted at several points.

For a given length and width of street, the more vehicle miles produced in a given time with a given number of vehicles the more efficient is the operation. If we refer to the street only, the efficiency is proportional to volume alone. Thus a street one mile long may have 300 vehicles per hour pass over it at a speed of either 10 or 20 miles per hour and the vehicle miles of service per hour for the street is 300 vehicle miles in either case. Each driver who passes over the one mile section receives one mile of service from the roadway and vehicle combined. This again is true whether he travels at the rate of five or thirty miles per hour. But obviously he would rather travel at the higher speed.

Quality of Flow

The quality of service is much higher at thirty than at five miles per hour. As congestion increases the speed of the stream not only slows down but becomes uneven with individual vehicles constantly forced to change

[2] "Urban Congestion Index Principles," by C. A. Rothrock, State Planning Engineer, State Road Commission of West Virginia.

speed. It is not only slow speed but the range and the frequency of speed changes that annoy the driver and often cause him to seek a longer route that may take more time to travel. Little is known about the severity of this annoyance or frustration factor. Some people have a lot of patience, others very little. One driver is quickly annoyed to the point of profanity, another more phlegmatic remains calm for a longer time until he too reaches the breaking point. It is reasonable to assume that the annoyance factor increases as the frequency and magnitude of speed changes increase. Very small changes such as 2 m.p.h. are probably not noticed. Absolutely uniform speed is practically impossible of attainment.

The factors upon which the quality of flow depends are readily apparent. They all have to do with speed, for the flow characteristic of a traffic stream is the summation of the speeds of individual vehicles. The pertinent factors of speed are average speed, change of speed and frequency of change. We know from experience that these factors are neither entirely dependent or independent. Since they are partly independent of each other, none can be omitted. The next question to be answered is whether there is some other factor that should be included such as total stopped time per hour. Stopped time, however, is indirectly measured by the average speed, for a stopped vehicle is merely one travelling at zero speed. The more frequent the stops the more frequent the changes of speed. Clearly, stopped time is not an independent variable. It is believed that the three variables mentioned give a complete measure of the quality of flow.

It is also clear that quality of flow cannot be measured at a point but must be measured over a sufficient distance for fluctuations in flow to occur. All measurements should be prorated to a unit distance. The logical distance to choose, as already mentioned, is one mile, for speeds are given in miles per hour and we ordinarily think of highway transportation in terms of vehicle miles. The factors to be considered would then be average speed in miles per hour, change of speed per mile and number of changes of speed per mile.

The next step is to combine the factors in such a way that they (1) give a result in agreement with what we know from judgment and experience to be true and (2) give an expression that is dimensionless. Obviously a number used to measure quality cannot have a dimension such as feet or bushels. It may be argued from analogy that a dimensionless index number should be a very useful tool for dimensionless numbers such as Reynolds number have done much to advance the science of fluid mechanics.

We know from experience that the higher the average speed within practical limits, the more satisfactory the flow, and also that the more turbulent or uneven the flow as measured by the change of speed per mile and the number of changes, the less satisfactory is the flow. This expression may be stated in the form of an equation. Let Q equal the quality of flow, S the average speed, Δ_s the speed changes per mile and f the frequency of speed changes per mile. With these symbols:

$$Q = \frac{S}{\Delta_s f}$$

The next prerequisite is that Q must be dimensionless. In order to determine whether or not Q is dimensionless, let L equal distance and T equal time. Speed, then, equals L/T and change of speed equals $(L/T) - (L/T)$. In this case, $(L/T) - (L/T)$ does not equal zero unless the numerical values are equal. They cannot be equal for then there would be no change in speed. For example, a speed of 10 m.p.h. minus a speed of 5 m.p.h. equals 5 m.p.h. Dimensionally:

$$Q = \frac{\dfrac{L_1}{T_1}}{\sum \left(\dfrac{L_2}{T_2} - \dfrac{L_3}{T_3}\right) f}$$

$\sum$ equals summation, and f is a pure number, therefore

$$Q = \frac{\dfrac{L_1}{T_1}}{\dfrac{L_2}{T_2} - \dfrac{L_3}{T_3}} = \frac{\dfrac{L_1}{T_1}}{\dfrac{L_4}{T_4}} = \text{a pure number}$$

The subscripts are used to indicate that each L and each T has a different numerical value.

There are other features of Q that need to be discussed. Is one of the three factors of more or less importance than the others, and should it be weighted accordingly? Should Q be multiplied by a constant to change its numerical value? It is believed that these and other questions can be more easily answered as they appear during the analysis of the data. The formula as finally derived is:

$$\frac{KS}{\Delta s \sqrt{f}}$$

wherein K is a constant of 1000 and f the frequency has been weighted to power of ½.

COLLECTING FIELD DATA

The preliminary discussion has indicated that ideally the field data should include a count of all vehicles together with a continuous record of the speed of each vehicle. Since such a complete record is almost impossible to obtain, it was logical to try to secure a random sample sufficiently large to be reliable. Two methods seemed feasible. One was to use a test car equipped with a recording speedometer; the other was to use time-motion pictures. We shall first discuss the test car method.

The performance of the test car was assumed to be equal to that of an average car. Fortunately, we had not only proof of this but also had knowledge of the number of tests car runs required to secure an average speed within predetermined limits and assurance. This information was obtained by Donald S. Berry and Forest H. Green and reported in the 1949 *Proceedings of the Highway Research Board*, pp. 311–318. They concluded that the minimum numbers of test runs needed to determine the average travel time within a 10 per cent range of error (90% accuracy) are as follows:

(a) for progressive signal timing (volume below capacity) 8 runs
(b) for signals not coordinated (volume at or near capacity) 12 runs
(c) for signals not coordinated (volume below capacity) 8 runs

The test cars were driven at speeds which in the opinion of the drivers were representative of the average speed of traffic.

In a continuation of this investigation, *Proceedings of the Highway Research Board*, December, 1951, it was found that both the "test car" method and the "floating" car gave reliable overall travel times, the accuracy depending on the size of the sample. The "floating" car driver attempts to pass as many vehicles as pass him.

In two-lane congested traffic, the size of the sample needed to give an accuracy within 5 percent is given as 40 and for 10 percent it is 10. For uncongested traffic the corresponding numbers are 30 and 8. This is what one would suspect, for doubling the accuracy requires a sample of data approximately four times as large. In brief, Berry and Green have demonstrated that the speed of a test car accurately represents the over-all running speed of the traffic stream. If the overall speed is correct then it is logical to assume that the continuous speed record as given by the test car is representative of the traffic stream. The summation of the varying speed throughout a given distance must equal the overall speed.

A search revealed that there was no satisfactory recording speedometer on the market, and of the two or three known to exist, none seemed to be satisfactory for our use. The late Mr. Theodore M. Matson, then Director of the Bureau of Highway Traffic, contacted Mr. John Barker of the Automatic Signal Corporation in Norwalk, Connecticut, and asked him to attempt to design and construct a recording speedometer to meet certain requirements.

The Recording Speedometer

This recording speedometer consists essentially of an Esterline-Angus recorder so ar-

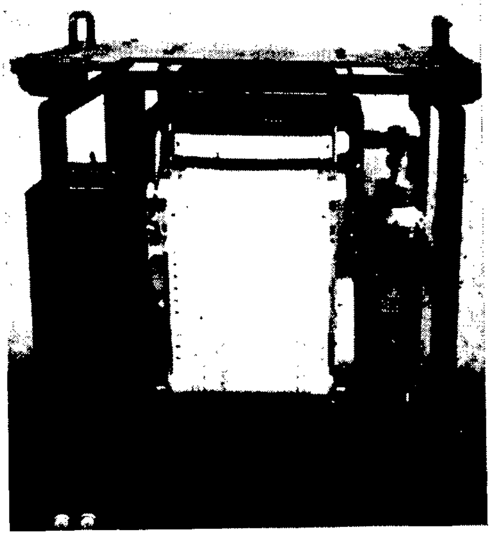


Figure 1

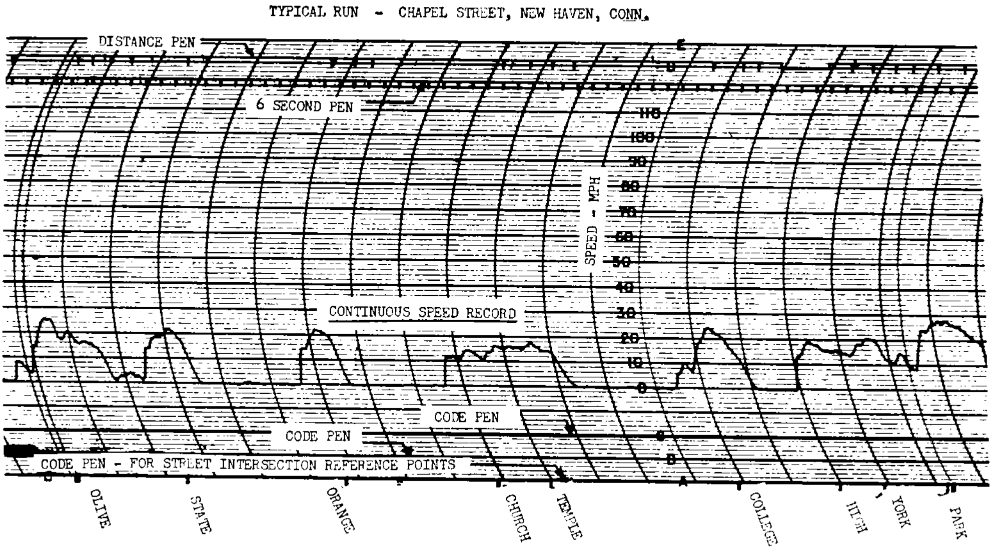


Figure 2. Typical run—Chapel Street, New Haven, Conn.

ranged that the recording paper is advanced as desired by the speedometer drive chain or by the usual clock arrangement. This instrument is shown in Figure 1. One pen is connected to an electric clock so that it makes a blip every 6 seconds. Another pen is actuated by the speedometer chain through a gear system to give a blip every 100 or 200 feet depending on which gear setting is used. Thus there are complete time and distance records. See Figure 2 for typical recording. The recording at the top of the sheet, is that of distance, line D. Each mark indicates 200 feet of travel. The line immediately below shows a blip every 6 seconds. The irregular line in the middle part of the chart is the continuous speed record. Note that the possible speed range is indicated by the scale numbers, 0, 10, 20, 30, 40, etc. The three lines A, B, C may be used for recording any desired data. Line A at the bottom has been used to record the positions of the cross streets.

Aerial Time-Motion Pictures

The other method was that of taking aerial time-motion pictures, or time lapse pictures to secure what might be called a "moving average" sample. This method had been developed as part of a National Science Foundation project at the George Washington University. This project was originally intended to include only rural traffic, but it was found to be possible to take some urban pictures primarily to test the method as a means of gathering traffic data in cities. These films containing rather complete data on two streets in Alexandria, Virginia, have supplied data for the present problem. Kenneth Smith, Traffic Engineer of Alexandria assisted by helping select the streets to be observed in the work, by marking the pavements at intervals of 200 feet and by furnishing other pertinent information. The film was processed by the United States Signal Corps which assisted throughout the whole project. A car of Markel Service, Inc. was driven over the streets at the same time the aerial pictures were being taken. Markel Service, Inc., uses a 35 mm. camera mounted so as to take pictures through the windshield. Included in each picture is a watch and a speedometer. These pictures are ordinarily used to check on the operation of commercial vehicles, but in this case they were used to furnish a ground check against the aerial pictures and to show traffic conditions. The Markel Pictures were taken at intervals of about five seconds. See Figure 3 for typical pictures taken in June 1954.

METHOD OF TRANSCRIBING AND ANALYZING DATA

The method of transcribing data from speedometer recordings may be illustrated by means of the performance record shown in Figure 2. This run was made on Chapel Street, New Haven, Conn.

Starting at the left at Olive Street, the first speed change is from 10 to 25 = 15 m.p.h.; next is from 25 to 17 = 8 m.p.h.; the next is from 17 to 20 = 3 m.p.h., etc. If we proceed to the end of the run at Park Street and add up the changes without regard to whether they are plus or minus changes, we find that the total speed change for the distance of 4240 ft. is 285 m.p.h. Note that a change of 2 m.p.h. or less is ignored. It is believed that the driver cannot detect changes of this small magnitude. The total number of changes = 24. The average speed, since the distance was 4240 ft. and the time to make the runs was 352 seconds = $\frac{4240}{352} \times \frac{1}{1.467} = 8.21$ m.p.h. wherein the factor $\frac{1}{1.467}$ changes ft. per second to miles per hour. If the speed change is pro-rated to one mile, it equals $\frac{5280}{4240} \times 285 = 355$ m.p.h. to nearest whole number. The frequency $= \frac{5280}{4240} \times 24 = 28$.

These three factors, the average speed S, the speed change Δ_s and the frequency f are all that are needed to determine the quality index Q. But there remains the question as to whether the factors should be weighted equally. Of the three factors the frequency of change is the least definite and the hardest to justify. We have arbitrarily chosen to designate a speed change as one involving a reversal of speed and amounting to at least 3 m.p.h. In any one run the frequency is always one more than the number or reversals. Also, we know that since acceleration and deceleration have a small range of variation, it takes more distance for a speed change of say from 1 to 15 miles per hour to take place than it does for a change from 1 to 5 miles per hour. This means that as the range of speed changes increases the number of changes per mile must decrease.

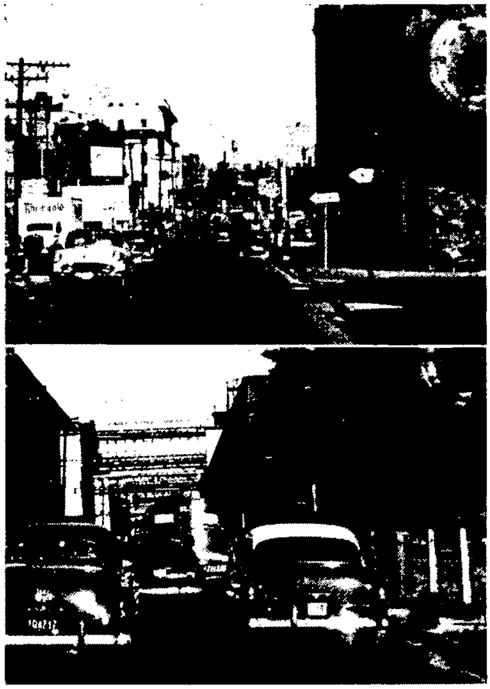


Figure 3

Since small speed changes are not as annoying as large changes and since size of the changes decrease as the frequency increases, it is reasonable to decrease the weight given to larger frequencies. Such a weighting can be accomplished by taking the square root of f, the frequency. Thus the ratio of ten changes to 1 changes would be $\sqrt{10}/\sqrt{1}$ or 3.16. Again the ratio of 10 changes to 5 changes would be $\sqrt{10}/\sqrt{5} = 3.16/2.25 = 1.41$.

It is true that some other weighting system such as using logarithms could be employed. Using logarithms, of course, would give less weight to higher frequencies. Thus the log of 5 = 0.69897, and the log of 30 = 1.47712 giving a ratio of 1.47712/.69896 = 2.12, while the direct ratio of 30/5 = 6, and the ratio of $\sqrt{30}/\sqrt{5} = 5.47/2.24 = 2.44$. The selection of the system to be used is largely a matter of judgment. We have chosen to use the square root of f. If we use $\sqrt{f}$ the Q for the values given is equal to:

$$Q = \frac{8.2}{355 \times \sqrt{28}} = \frac{8.2}{355 \times 5.29} = .00437$$

This number is too small for convenience and in order to avoid this, the constant $k = 1000$ is inserted to give:

$$Q = \frac{KS}{\Delta_s \sqrt{f}} = \frac{1000 \times 8.2}{355 \times 5.29} = 4.37$$

There is another feature of the quality number that must be considered. The three factors of Q, average speed, change of speed, and frequency of change of speed are rates per mile. Since each of the three variables comprising Q varies over a wide range the variable Q may vary over a much wider range. From a practical standpoint this wide variability is undesirable, for it means that a true value of Q can be obtained only from a comparatively large amount of data. We would like to know if it is possible to avoid this. It is, if we are willing to accept a less sensitive measure. But if this is done we are voiding the very thing we are attempting to do, namely, secure an accurate measure of the quality of traffic flow. Rather than to attempt to find a less sensitive index it seems more logical to accept the fact that the flow of traffic is highly variable and that any index number to be of value must reflect this variability.

Transcribing Data from Aerial Pictures

Before continuing the discussion of the Q values, let us explain the method of transcribing the data from the aerial time-motion pictures. The information on a typical data sheet includes in addition to the date, the name and location of the street, and direction of flight of the plane, the scale position of each vehicle in each successive picture. The positions are obtained by noting the location of the vehicle in each picture, as it is projected onto a scale drawing of the street on which distance markers are shown every ten feet. Positions are estimated to one foot. The information shown is taken from a run over Duke Street, Alexandria, Virginia, June 25, 1954. The first line gives the frame number of the picture, the 2nd line gives the position of the vehicle, the third line gives the differences between successive positions which equals the speed, and the fourth line gives the "smoothed" speed. The smoothed speeds are obtained by averaging each three speeds successively. The fifth line gives the speed changes, and the last line gives the number of speed changes.

Frame no.	4884	4885	4886	4887	4888	4889	4890	4891	4892	4893
Position	2842	2816	2799	2775	2750	2724	2701	2678	2656	2631
Speed		26	17	24	25	26	23	23	26	21
Smoothed speed			22	22	25	25	24	24	23	
Speed change			−4	−0	+3	0	−1	0	−1	−2
Frequency					1					1

Note that the frequency of 2 is equal to the number of reversals of speed. Smoothed speeds were used in order to give an approach to a continuous record. Remember that the pictures are taken at the rate of one every 1/88 minute which is too long an interval to give a smooth curve. Such a smooth curve was needed if the data secured from the pictures were to approach those given by the recording speedometer.

In the time-motion picture method all of the data for each vehicle observed in one flight over the street were combined to give one Q value. The data shown gives a traveled distance of 211 feet, a speed change of 12 m.p.h., and a frequency of 2. Note that the sum of the speeds also equal 211. These data were added to those for the next vehicle and so on

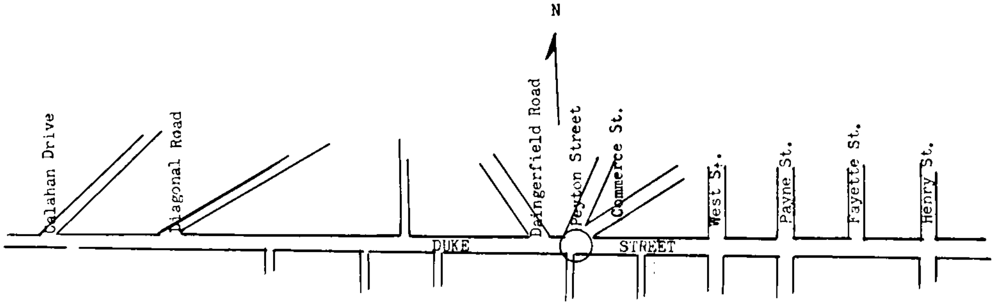


Figure 4. Duke Street, Alexandria, Virginia. Length of street from Calahan Drive to Henry Street, 3,897 feet. One traffic signal in the section studied.

to give the data for one run or for one Q value.

For the particular run from which this data was taken, the length of Duke Street from Henry Street to Callahan Drive is 3,987 feet. See Figure 4. The number of vehicles observed was 29, the total distance traveled by the 29 vehicles during the 43 seconds of the run was 5,438 feet and the speed change equalled 20. Prorating these figures to one mile gives a Q value equal to:

$$Q = \frac{KS}{\Delta_s \sqrt{f}} = \frac{1000 \times 19.85}{287.42 \times 4.30} = 16.04$$

THE ANALYSIS AND INTERPRETATION OF Q VALUES

Once the field data for each run have been recorded and tabulated, the next step is to determine the mean value together with its variation and reliability. For the purpose of illustration, let us analyze the Q values obtained for Chapel Street. A diagrammatic sketch of the street is shown (Figure 5).

This street might be called a typical central business district street. The range of the Q values for the thirty runs was from 1.74 to 11.79, and the arithmetic average was 4.96. The arithmetic average of Q, however, is not altogether satisfactory because of a peculiarity of the Q values which should be explained.

The Non-Additive Property of Q Values

The average value of two or more Q values should not be obtained by taking an arithmetic average except for statistical purposes. That this should not be done is easily demonstrated. Let the Q factors for one mile be $S = 10$ m.p.h., $\Delta_s = 200$ and $f = 25$, and for the succeeding mile let $S = 12$ m.p.h., $\Delta_s = 180$ and $f = 16$. With these values, Q for the first mile $= \dfrac{1000 \times 10}{200\sqrt{25}} = 10$ and for the second mile

$$Q_2 = \frac{1000 \times 12}{180 \times \sqrt{16}} = 16.67$$

The arithmetic average =

$$\frac{Q_1 + Q_2}{2} = \frac{10 + 16.67}{2} = 13.34$$

Now let us consider the two miles as one run and get what we shall call the Q' value. Remember that all Q factors must be prorated to a one mile base. For the two miles $S = \dfrac{10 + 12}{2} = 11$ m.p.h., $\Delta_s = 180 + 200 = 380$, and $f = 16 + 25 = 41$. Prorated to one mile $S = 11$, $\Delta_s = 190$, and $f = 20.5$; therefore for the 2 mile run,

$$Q' = \frac{1000 \times 11}{190 \sqrt{20.5}} = 12.78$$

The nonadditive property of Q values presents a difficult problem but fortunately one that can be avoided. As just indicated, this is accomplished by first averaging the speeds, the speed changes, and the frequencies of the speed changes separately before combining them to get Q'. This procedure also escapes the difficulty of getting a stable Q value for short runs. Since the factors for all the runs are added, giving one long run, the wide fluctuation in any one run does not unduly affect the result.

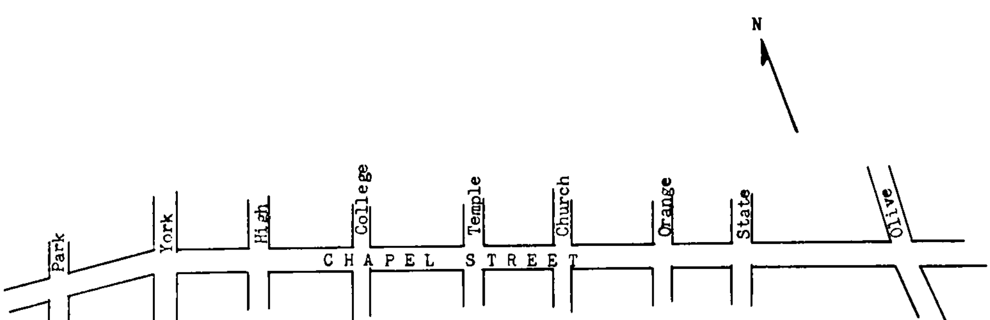


Figure 5. Chapel Street, New Haven, Conn. Length of Chapel Street from Park to Olive Street: 4,135 feet; av. width 40 feet. No parking from Olive to College. No parking on north side from Church to College. Signals at State, Orange, Temple and College Streets are 3 phase, others are 2 phase. Signals not progressive.

While this method is reliable for obtaining a mean value it gives no information as to the statistical stability of Q. We are as much interested in the Q's for individual runs as in the mean of all runs. Any Q may have a wide variation from the mean. The variance of Q is first obtained from the arithmetic mean in the usual manner, and then the variance from Q' is calculated. As can be seen from the examples, the difference between the arithmetic mean of the Q's and the mean obtained by first averaging the factors is slight. But the fact remains that the average Q for a number of sections of street must be obtained by first averaging the factors.

Thus, while the arithmetic average for the thirty Q values obtained for Chapel Street was 4.96, what we shall call "Q^1" obtained by "average factors" equalled 4.43.

The procedure for getting the deviation of Q^1 is quite simple. First the standard deviation from the arithmetic mean is calculated in the usual manner and then referred to Q^1 by a transfer formula. In the present example, the standard deviation σ from the arithmetic mean was found to be 2.18. The difference between Q and Q^1

$$d = 4.96 - 4.43 = .53$$

The deviation S referred to Q^1 (by average factors) is found from the relationship:

$$S^2 = \sigma^2 + d^2$$

$$S^2 = (2118)^2 + (.53)^2 = 4.752 + 0.281 = 5.033$$

$$S^2 = \sqrt{5.033} = \pm 2.24$$

$$\text{Error of } Q^1 = \frac{2.24}{\sqrt{30 - 1}} = \frac{2.24}{\sqrt{5.38}} = \pm 0.42$$

This means that there is about a 68.27 percent assurance that the Q' value lies within the range 4.43 ± 0.42.

While the present project does not include a study of causes, it is desirable that we have some idea of the range of Q^1 values for different types of streets. For this reason Q' values were obtained for several streets in addition to Chapel Street with different volumes and types of signal control. One of these was Whitney Avenue, New Haven, Connecticut.

Q Values for Whitney Avenue

Whitney Avenue is a typical suburban street. See Figure 6. For the section observed the street is 50 feet wide, except for one block which is 42 feet. The length of the section studied, extending from Bradley street to Cliff Street, is 6,950 feet. In this distance there are 3 traffic signals with 30 seconds of green and 30 seconds of red. The volume of traffic in one direction varied from 350 to 968 v.p.h. The range of Q values was from 22.7 to 288.0.

Arithmetic mean	=	79.5
Standard Deviation	=	28.2
Q^1 (by average factors)	=	62.6
Deviation from Q^1	=	32.8
Error of Q^1	=	$\frac{32.8}{\sqrt{95-1}} = \frac{32.8}{\sqrt{9.095}} = \pm 2.99$

This means that there is approximately a 68.27 percent assurance that the true mean lies in the range 79.5 ± 2.99.

Note that the large number of runs, 95, gives a much smaller standard error of the mean than fewer runs would have.

Q Values for Route One

The section of Route One studied extends from East Street along Water Street to Colum-

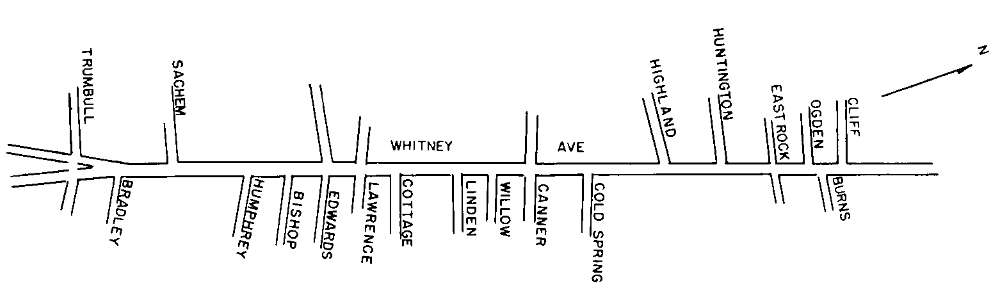


Figure 6. Whitney Avenue, New Haven, Conn. Traffic signals at Sachem, Edwards, Canner and East Rock. Width 50 feet.

bus Avenue and then along Columbus Avenue to Howard Avenue, a distance of 1.47 miles. See Figure 7. The east-bound traffic follows Union Avenue from Columbus Avenue to Water Street. Columbus Avenue is approximately 34 feet wide and Water Street 40 feet.

The total distance from East Street to Howard Avenue is 1.322 miles. The values for the total distance in a westerly direction ranged from 3.8 to 24.9. For the east-bound traffic the Q value ranged from 4.9 to 24.3. There were 17 west-bound and 17 east-bound test runs. The mean value for both east and west was 7.04.

Arithmetic mean	= 11.02
Standard Deviation	= 23.4
Q^1 (by average factors)	= 7.04
Deviation from Q^1	= 24.7
Error of Q^1	= 4.2

The Q value for west-bound traffic on Section II, Water Street, length 1.47, feet ranged from 4.2 to 3.14.

Arithmetic mean	= 13.39
Q^1 (by average factors)	= 10.60
Deviation from Q^1	= 9.38
Error of Q^1	= 2.34

The Q values for Section III, distance 3,694 feet both east and west, ranged from 2.1 to 20.6. Thirty-five test runs were included. The other values were:

Arithmetic mean	= 9.00
Standard Deviation	= 6.31
Q^1 (by average factors)	= 6.87
Deviation from Q^1	= 6.66
Error of Q^1	= 1.14

Q Values for 35th and 36th Streets in New York City

The traffic flow on 35th and 36th Streets in New York is of very low quality. This is to be expected, for the streets are very narrow. For much of the distance they are only 30 feet in width with parking permitted on both sides. Practically all of the parked vehicles are trucks, for this is in the garment district. This permits but one lane of traffic. Thirty-sixth Street is one way east and 35th Street is one way west.

Taking these two streets from 2nd Avenue to 10th Avenue a distance of 7,440 feet, as a unit, the Q values ranged from 0.44 to 6.24 for the 29 test runs.

Arithmetic mean	= 1.96
Standard Deviation	= 1.56
Q'	= 1.55
Deviation from Q'	= 1.60
Error of Q'	= .30

As a further analysis, it was decided to compare the west end of the street from 7th to 10th Avenues with the east portion extending from 2nd to 7th Avenues. For the west end, 7th to 10th Avenues, distance of 2,700 feet, the Q values ranged from 0.21 to 6.93.

Arithmetic mean	= 1.610
Standard Deviation	= 1.52
Q'	= 1.151
Deviation from Q'	= 1.584
Error of Q'	= .299

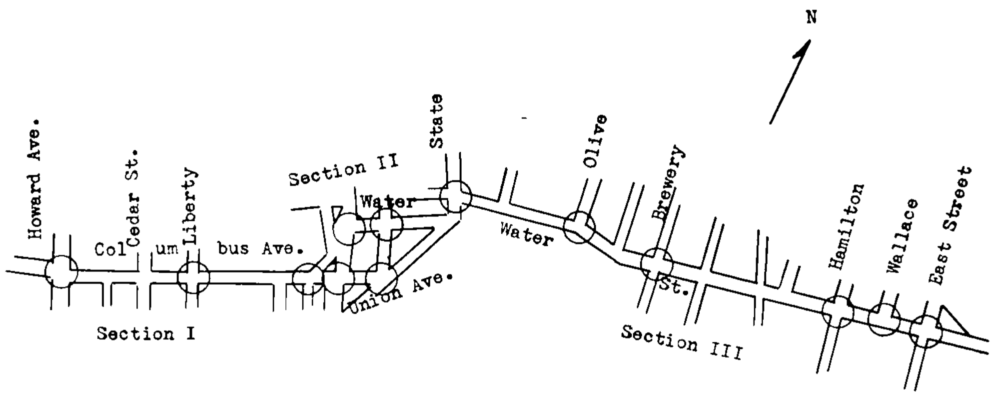


Figure 7. Route L, New Haven, Conn. Overall length, 1.47 miles. Signals at points indicated. Parking on north side of Columbus Ave. at Cedar St., but no parking at Meadow. Parking on both sides of Union St. Parking on north side of Water St. at Olive. No parking at East St.

The east portion of the streets extending from 2nd Avenue to 7th Avenue, a distance of 4,740 feet, had higher Q values. The range was from 0.583 to 7.916.

Arithmetic mean	= 2.54
Standard Deviation	= 1.98
Q'	= 1.98
Deviation from Q'	= 2.05
Error of Q'	= .388

The Q values for 1st and 2nd Avenues from 59th to 110th Streets, a distance of 13,440 feet, ranged from 3.27 to 126.37. The other pertinent values were:

Arithmetic mean	= 26.16
Standard Deviation	= 25.85
Q'	= 16.26
Deviation from Q'	= 27.16
Error of Q'	= 4.61

These streets showed an unusual range in behavior. The average speeds ranged from 7.5 to 23.02 m.p.h., while the speed changes ranged from 64.83 to 373.6 per mile. These ranges indicate the highly variable traffic conditions. Drivers could make time only at the expense of high speed and sudden stops.

Q Values Obtained from Aerial Pictures

A few Q values were calculated from aerial pictures first to determine the practicability of the method and second to find out if the results were comparable to those obtained by the recording speedometer. In suburban and rural areas where the traffic control methods have less influence on the behavior and each driver has more freedom of movement, the test car method becomes less representative.

The data from three runs made over King Street, Alexandria, Virginia (see Figure 8), gave the following Q values: 1.31, 1.41 and 1.50. The corresponding speeds were 7.38, 5.72 and 7.96 m.p.h.

The length of the section from Union to Harvard Streets is 4,913 feet. The width is 37 feet between curbs. The blocks are about 313.0 feet with signals at each intersection. These short blocks together with crowded conditions and parking cause low Q values. During the time that the aerial pictures were being taken, as already mentioned, a test car furnished by Markel Service Inc. was making check runs over the route. The average speeds obtained by the Markel car were within 2 miles per hour of those obtained from the pictures.

Q Values for Duke Street, Alexandria

Duke Street in Alexandria with one signal in the 3,897 foot length observed gave for the 9 runs much higher values than King Street. The Q values ranged from 6.42 to 16.04. The arithmetic mean of these Q values was 11.06. The number of vehicles involved ranged from 11 to 29, and the speeds ranged from 15.24 to 20.09.

Q Values for Route 236

Q values were calculated for 6 aerial runs over route 236, a rather typical 2-lane rural road. This road was marked every 250 feet with a readily visible white mark. This marking was done by J. L. Thomas of the Virginia State Highway Department. The plane from which the pictures were taken was furnished and flown by the Virginia State Police Department, while the film was supplied by the U. S. Signal Corps. Signal Corps photographers also took some of the pictures. The range of Q values was from 20.66 to 98.49.

It will be noted that the Q values show very clearly the differences in the quality of flow for the downtown street, the higher speed street and rural conditions. Route 236 is not a high speed road.

Q Values for the George Washington Bridge

Pictures were taken from both the east and west towers of the George Washington Bridge. It was thought that this bridge would give higher Q values since the flow is not restricted except for maximum speed.

Fifteen Q values were calculated. It was decided that the data for each Q value would consist of data for vehicles sufficient to make a ½ mile run. Each vehicle was in view for about 500 feet. Thus, about five cars were involved in the data for each Q value.

The range of Q values was from 92.93 to 1344.4. The arithmetic average was 480.1 while the true mean was 367.0. Other values were not calculated due to the small size of the sample.

Q Values on the George Washington Bridge from Test Car Runs

In order to compare test car runs with time-motion data, 34 test car runs were made on the

George Washington Bridge. The range of Q values was from 214.02 to 6705.0. The arithmetic mean was 1331.54 and the true mean was 872.79.

A comparison of 8 Q values obtained from pictures with 8 test car runs during which the traffic volumes were about the same, gave the following:

	Test Car	*Picture Method*
Average speed, mph.	40.21	40.19
Average Q value, mph.	673.13	625.25

These results were surprisingly close considering the difference in the methods. They indicate that one method may be substituted for the other. In rural traffic where there is greater freedom of movement for individual vehicles, the aerial pictures should give more consistent results, for the behavior of all vehicles is measured. This method is not recommended for city conditions, since the analysis is much more tedious.

THE EFFICIENCY INDEX

Let us now discuss very briefly the measure of the efficiency of traffic flow. The efficiency of a street in transmitting traffic is measured by the quantity and quality of traffic flow. The greater the quantity and the higher the quality, the greater the efficiency for a given street area. Expressed as an equation, if V_m = vehicle miles per mile per hour, the efficiency $E = V_mQ$. The logical unit area is a lane one mile long and ten feet wide. With this length the volume per hour and the vehicle miles are numerically equal. Also, if the efficiency is desired for any other width, such as one foot, the calculation required is very simple.

The method of calculating an efficiency index may be shown by an example. The section of Chapel Street, New Haven, Connecticut over which the test runs were made extends from Park to Olive Streets and is 4270 feet long. Of this distance, 1530 feet is 41 feet wide, 970 feet is 54 feet wide, and 1770 feet is 37 feet wide. The average width for the entire length is 42.3 feet. This amounts to 4.23 lanes of 10 feet width or 2.12 lanes in each direction.

The Q for one run was 11.79 and the volume 237 vehicles per hour or $237/2.12 = 111.79$ vehicles per lane. $E = V_mQ = 11.79 \times 111.79 = 1318$ vehicle miles per hour per mile.

Efficiency may be thought of as the ratio of input to output. The input in this example was 237 vehicles per hour per 2.12 lanes. The total width of street from curb to curb is used in the calculations. This enables the efficiency of a street of any width to be compared with any other street. The question to be answered is how efficiently is the total street area being used in transmitting traffic.

For the thirty test runs on Chapel Street, the efficiency varied from 261 to 1470. The average was 677.

The efficiencies for Route 1, New Haven, Connecticut varied from 839 to 8111 vehicle miles per hour per mile.

The average $E = 6761$. The volume of flow varied from 565 to 964 v.p.h. for one direction.

The Efficiencies for Whitney Avenue, New Haven, ranged from 7070 to 60,326 vehicle miles per hour per vehicle. The average was 13,590.

Other efficiencies might be calculated but they would apply only to a particular street and it is believed that the method is now clear. The meaning of the efficiency index becomes clearer if it is transformed into cost index.

THE EFFICIENCY INDEX IN TERMS OF COST

The efficiency index E provides a measure of efficiency, but perhaps the most acceptable and easiest understood measure of efficiency of moving traffic is the cost-benefit factor. The more vehicle miles achieved for a given cost, the more efficient is the operation. In expressing the efficiency index, $E = V_mQ$, in terms of cost, it is necessary to assign cost figures to the factors of Q—namely speed, and the combined factor, the sum of the speed differentials times the square root of the frequency of changes, $\Delta_s\sqrt{f}$. We may think of this latter factor as a measure of annoyance or frustration. It is also a measure of the turbulence or uneveness of flow. In assigning cost values to Q we should recognize that exact cost figures do not exist and that the figures used are only approximate. It is judged, however, that they are accurate enough to indicate relative efficiencies.

In assigning cost values to speed we will assume that the value of time is $1.35 per hour or 2.25 cents per minute. This cost figure is from *A Policy on Road User Benefit Analyses for Highway Improvements*, a report issued in April of 1953 by the Committee on Planning and Design Policies of the American Association of State Highway Officials. Truck time was valued at $3.00 to $4.50 per hour. But we are more interested in the method than exact values which will depend upon the composition of traffic.

For the cost of operation we will assume a cost varying from 5 to 8 cents per mile, the higher value being for the lower Q rating. Operating costs for trucks are of course higher. It is believed that there is a close correlation between Q and gasoline consumption, but to date no data has been obtained.

There is very little known about the cost of annoyance. The AASHO report *A Policy on Road User Benefit Analyses For Highway Improvements* assigns one cent per vehicle mile as the "comfort" cost in "restricted operation".

This constant cost does not take account of varying degrees of "restriction"; for an estimate of this varying cost, one may use a different approach.

In Highway Research Board *Bulletin 61* in the paper "Comparative Traffic Usage of Kanawha Boulevard and Alternate City Arteries at Charleston, West Virginia", by C. H. Rothrock and E. Wilson Campbell, Planning Division, State Road Commission of West Virginia, we find that 35 to 40 percent of the drivers chose the boulevard when they did not save time and definitely traveled further. This may be interpreted to mean that the cost

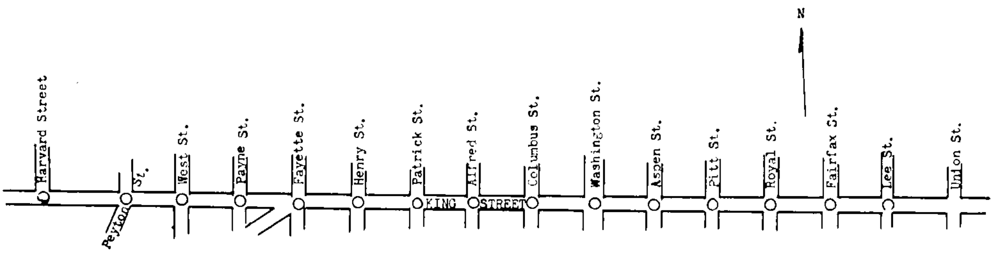
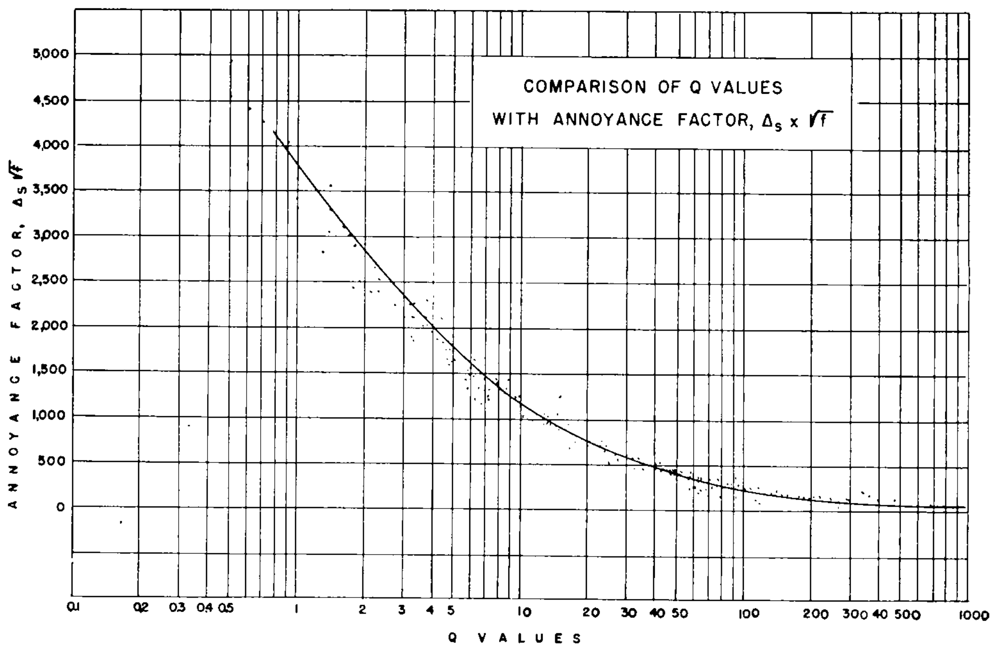


Figure 8. King Street, Alexandria, Virginia. Length of street from Union to Harvard Streets, 4,913 feet. Traffic signals at all intersections.



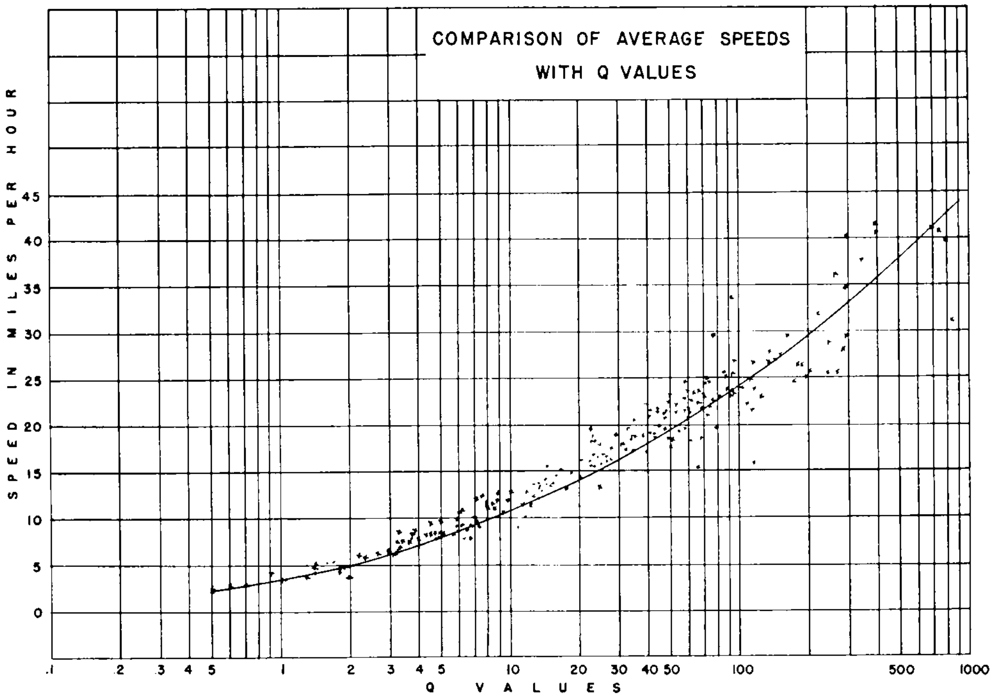


Figure 10

value of annoyance is at least 35 per cent of the value of travel time.

At optimum average speed of, say 35 m.p.h., the annoyance cost would be zero. At a speed of 2.0 m.p.h., about the average speed likely to be experienced, the cost would be equal to 35 percent of the time cost or $.35 \times 30 \times 2.25 = 23.62$ cents.

The next step is to find the ratio of Q to the annoyance factor $\Delta_s\sqrt{f}$. This ratio is shown in Figure 7. The ratio of speed to Q is shown in Figure 8.

With the cost of operation, assumed to vary on a straight line relationship with Q, and with the relationship of speed with Q and $\Delta_s\sqrt{f}$ with Q as shown in Figures 7 and 8, it becomes possible by adding the cost figures for operation, time, and annoyance to obtain the cost versus Q curve shown in Figure 9.

It is clear that similar curves for any given composition of traffic could be developed.

These approximate costs of transportation corresponding to any Q value make the efficiency index more understandable and usable.

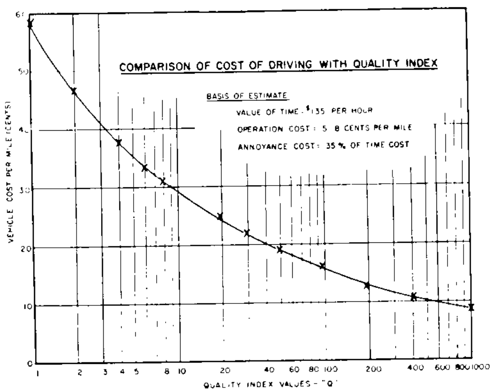


Figure 11

CONCLUSION

The quality of flow index number together with the efficiency index derived from it makes it possible to compare the flow of traffic on two streets or on the same street at different times.

Once sufficient studies have been made to determine just what qualities of flow may be expected under certain conditions, it will be possible to estimate accurately what may be accomplished by improvements. The cost benefits accompanying these improvements may also be estimated.

In presenting these results, it is realized that other methods of measuring the quality of traffic flow may be derived. In fact several have been considered and rejected. One of these was:

$$Q = \frac{\text{overall speed}}{\text{running speed}}$$

another was:

$$Q = \frac{\text{Actual travel time}}{\text{Legal travel time}}$$

a third consisted of three parts:

$$Q = \frac{\text{crest speed}}{\text{running speed}} + \frac{\text{moving time}}{\text{elapsed time}} + \frac{1}{3\sqrt{f}}$$

wherein f = frequency of speed changes per mile. There is also the ratio of average speed to the standard deviation. This too is a dimensionless number and it is a measure of the variance in speed and therefore a measure of turbulence of flow.

In any case it is hoped that this presentation will serve to stimulate thought and to hasten the time when quality and efficiency indices may be used to achieve better design for improvements and better control of traffic movements.

Study of Traffic Flow by Simulation

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THE paper embraces certain philosophies and approaches in the utilization of modern high-speed automatic computers to solve traffic problems. Individuals and research groups in both the United States and England have applied their efforts in this direction. Under the policy of cross-fertilization of fields of specialization at the University of California, a Communication Systems Research team undertook certain traffic studies. It is concluded that computers, used as simulators, offer considerable promise in the solution of such traffic problems as investigating the effects of traffic control devices in advance of installation and predicting the effect of proposed changes on the capacity of a facility.

The concept of vehicle flow rate or, alternately distribution of gaps, finds general utility in approaches of both analysis and simulation. Ideally, the behavior of a physical model (simulator) resembles that of the real situation under study by virtue of the postulates laid down by the investigator. Such a model encompasses both the structure (fixed facility) and the dynamics of the movement of intersecting streams of vehicles in terms of flow paths, queuing, waiting, proceeding ahead and turning subject to delays caused by cross traffic and pedestrians. Computers can be programmed to simulate such structure and dynamics.

Activity to date at the University of California has been as follows: Formulation of a trial problem for solution on a general-purpose discrete-variable computer, Standards Western Automatic Computer (SWAC), completion of the logical design of a special-purpose discrete-variable computer, and considerable progress on the construction of accessory equipment to permit the use of a general-purpose continuous-variable computer.