Measurement of Urban Traffic Congestion

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This paper is an extension of one presented by Rothrock at the 33rd Annual Meeting of the Highway Research Board, entitled: "Urban Congestion Index Principles." It presents the results of a special study financed by the Yale Bureau of Highway Traffic, in which careful and precise measurements were obtained, during a period of 8 hours, of the progress of all vehicles in a lane of traffic through a test section subject to congestion.

Analysis and tabulation revealed certain characteristics which were developed into a concept of vehicle time-of-occupancy as a measurement of the degree of congestion. The basic concept is presented by a simple assumed example, and then applied to the data obtained on the test section. The possibility of developing a more practical and economical method of securing field measurements for general application is discussed.

● THE problem of the objective measurement of the degree of urban traffic congestion, and a method of comparing the measurements for different locations so as to obtain an index of relative degree of congestion, was the subject of a previous paper by Rothrock (1).

As a result of that paper, the Yale Bureau of Highway Traffic authorized and financed a field study by Rothrock to investigate the possible application of a concept for the evaluation of congestion expressed in terms of total vehicle time-of-occupancy for any given period. This concept is actually an application of the "operational-characteristics" concept, as it was termed and discussed in the 1954 paper.

During his attendance as a member of the 1955 class of the Yale Bureau of Highway Traffic, Keefer analyzed the data from the field study and applied the concept in a thesis (2), from which most of the material in the present paper is adopted.

Theory

The concept as developed may be simply expressed by a statement that traffic congestion consists of too many vehicles occupying space in a lane of highway for too long a time. This conception leads directly to the idea of total vehicle time-of-occupancy as an expression of the vehicular use of any given space of roadway for any given period of time.

The total vehicle time-of-occupancy will increase only directly as the volume of traffic increases, as long as there is no increase in the unit time-of-occupancy, or, stated differently, when any number of vehicles in traffic can move through a section of highway in the average optimum travel time, there is no congestion. From this it may be concluded that when the volume of vehicles composing traffic is so great as to impede their freedom of movement, and thereby increase the unit time-of-occupancy beyond the optimum travel time, there is congestion.

The degree of congestion for any such volume may be taken to be the amount by which the actual total vehicle time-of-occupancy exceeds what the vehicle time-of-occupancy would have been if the vehicles had been able to attain the optimum travel time.

To illustrate: Suppose a set of observations taken on a section of a single lane of road, considering travel in one direction only. Suppose that the driver of a vehicle, with due regard to speed limits, safety and prudent driving, can travel through this section in 10 seconds. Suppose also that during another similar period of observation, two such vehicles can each traverse the section in an average of 10 seconds, and suppose that during other periods of observation, up to six vehicles can each traverse the section in an average of 10 seconds. Arraying these observations by time period in the order of the vehicular volumes, the total vehicle time-of-occupancy for each is found to be as in Table 1.

TABLE 1

Number of Vehicles in Period	Average Time-of-Occupancy Per Vehicle (seconds)	Total Vehicle Time-of-Occupancy During Period (vehicle-seconds)
1	10	10
2	10	20
3	10	30
4	10	40
5	10	50
6	10	60

TABLE 2

Number of Vehicles in Period	Average Time-of-Occupancy Per Vehicle (seconds)	Total Vehicle Time-of-Occupancy During Period (vehicle-seconds)
7	11.5	80
8	13.5	108
9	16.0	144
10	19.0	190
11	23.0	253
12	28.0	336

Because the average time-of-occupancy is constant, there has been no vehicular delay, and plotting the data with the volume (number of vehicles) as abscissa and the total vehicle time-of-occupancy as ordinate results in a straight line as shown in Figure 1.

Now suppose further that during another period of observation seven vehicles traversed the section with the effect that the average time-of-occupancy for each was increased from 10 seconds to 11.5 seconds, and that during similar periods of observation the volume of traffic increased to the extent that the average times-of-occupancy were correspondingly increased, approximately as shown in Table 2. These data also have been plotted in Figure 1. This, of course, is a "manufactured" and somewhat exaggerated case, devised solely for the purpose of illustrating the theory of this one method of congestion measurement.

Referring to Figure 1 again, a dotted line has been extended to the right from the straight line representing the data from Table 1. This straight line is what would have been obtained if the average time-of-occupancy for the 57 vehicles represented in Table 2 had remained at the optimum of 10 seconds, in which case there would have been no congestion.

The concept of excess vehicle time-of-occupancy as an indication of congestion, aside from its use in calculating an index, is a useful value for direct comparison, as it is actually the measurement of time lost by vehicles due to congestion. Thus a value per vehicle-minute can be placed upon it and the cost of congestion readily computed. It may even be practicable to estimate an annual congestion loss for a given space of highway by the application of appropriate traffic factors.

Application

The calculation of the vehicle time-of-occupancy is not difficult. There are at least two relatively simple ways of obtaining it, as follows:

1. For the given section of street during any time period of observation, say for the peak hour, the vehicle time-of-occupancy is simply the average density multiplied by the time of observation. If instantaneous counts of density could be made during the hour frequently enough to get a true average of density (that is, the number of vehicles in the section at any instant) the vehicle time-of-occupancy would be the average density multiplied by the length of the period of observation or, where the period of observation is an hour, the average density is the same as the vehicle time-of-occupancy expressed in terms of vehicle-hours. To be expressed in minutes, the average density would be multiplied by 60.

2. For any section of street during any time period of observation, say for the peak hour, the vehicle time-of-occupancy is simply the volume count of vehicles entering the section multiplied by the average travel

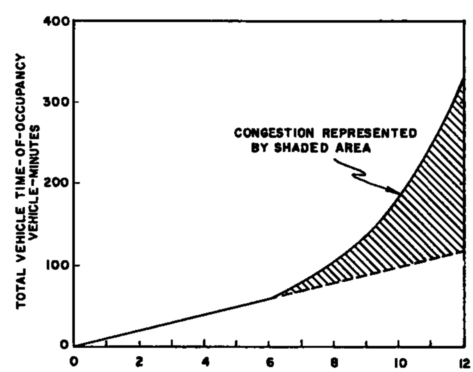

Figure 1. Hypothetical vehicle times-of-occupancy during congested and uncongested time periods of observation.

time through the section for those vehicles, as may be obtained by test car runs during the period. In this method the count of vehicles is not an instantaneous one of density, but a continuing count of volumes.

To illustrate how the foregoing calculations might be made for a selected sample: Suppose observations are made during the peak hour on a section of street with one travel lane in each direction, with observations confined to a single lane, the direction of which is toward a traffic-signalized intersection at one end. Suppose the length of the section to be three blocks between ends, totaling 1,200 feet, the beginning and intermediate intersections not being signalized.

At times during the observations, made during the peak hour, it is probable that the lane would be completely filled with cars queued up, especially during the red phase of the signal. At other times it is also probable that the lane will contain freely moving vehicles, especially during the latter seconds of the green phase of the signal.

Suppose a series of instantaneous counts of the number of vehicles in the lane be made, such as might be taken from a series of instantaneous photographs, so spaced in time that the average of the counts gives a true average density. Suppose this average is found to be, say 25 vehicles. Then, from the foregoing, the total vehicle time-of-occupancy is found to be 25 vehicle-hours, or 25 by 60 = 1,500 vehicle-minutes.

Now suppose that during the same hour of observation, time and delay runs had been made with a test car, with sufficient number and spacing to give a reasonably accurate average of the travel times through the section, including necessary stops, for all the the vehicles entering. Suppose also that a volume count had been made of all vehicles entering the section.

Assuming that the test runs give a calculated average travel time of 2.7 minutes, and that the volume count is 570 vehicles per hour, the value for the vehicle time-of-occupancy is obtained by multiplying 570 vehicles times 2.7 minutes, or 1,539 vehicle-minutes; practically the same value as that obtained by the previous method.

If the purpose of the observations is to obtain a concrete measurement of congestion they must be made for the predetermined times for which the congestion is to be assessed. Probably the peak hour of travel (or hour of most congestion) would be the most useful period, because designs for capacity are generally based on volumes for that time.

Having an expression for the vehicle time-of-occupancy during the peak hour, a comparison may be made with what may be termed the normal vehicle time-of-occupancy, during an off-peak hour of uncongested traffic. This may be the maximum such figure obtainable during an hour when the average travel time per vehicle is not in excess of that to be found at any time for free moving vehicles.

In the foregoing case, this may be assumed to be during the maximum volumes of traffic counted at the signal when no vehicles are necessarily stopped by more than one red phase of the signal cycle. If the cycle is 50 seconds, for instance, of which the red phase is 25 seconds against traffic in the lane under consideration, the probable maximum volume which could pass without undue hindrance would be 8 vehicles per cycle, which could conceivably account for 600 vehicles per hour.

In any continuous hour, however, it is not probable that an average frequency in one lane of 1 vehicle per 3 seconds of green could be maintained without some periods of congestion, due to the uneven spacing and speeds of vehicles.

Suppose that it had been found by tests under the conditions here assumed, with an allowable speed of 25 mph, that the largest volumes of traffic that did pass such a signal without restriction of movement except from the signal was approximately 275 vehicles per hour. This volume was passed at an average running time of 47 seconds, which accounts for an average speed of about 20 mph. This condition, for the purpose of discussion, will be here assumed as the optimum criteria by which to compare the vehicle time-of-occupancy figures.

If it should be found that the average travel time for vehicles under volumes less than 275 vehicles per hour is maintained at approximately the same average travel time (that is, 47 seconds), and that at volumes greater than this the average travel time increases substantially above 47 seconds, the 215 vehicle-minutes of occupancy may be assumed to be the optimum normal.

On this assumption there is one method of comparison available by which it may be said that the congestion during the peak hour of travel amounts to the vehicle time-of-occupancy during the peak hour, less the vehicle time-of-occupancy during the optimum hour, or 1,539 - 215 = 1,324 vehicle-minutes. This could be expressed as a ratio, or $\frac{1,539}{215}$ = 7.16, which may thus be considered as one way of expressing an index of the relative congestion per lane, per given section of street.

It is possible, however, that both of these values, the one for the index and the one for the amount of congestion, may be false or misleading.

In the first place the optimum, or standard of comparison, might be taken as the time-of-occupancy calculated for the volume of traffic found to be the practical capacity. If this is established, the question remains as to what value to use for the average travel time through the section.

It would be difficult to find an hour during which the traffic volume was almost exactly the practical capacity and in which there would not be some sort of deviation from the average spacings and speeds. Perhaps a series of short time counts and travel time runs, say for intervals of 6 minutes, could be obtained and the average travel time of several most nearly equal to 1/10 the volume of practical capacity taken as the optimum travel time. In the following example 400 vehicles per hour is assumed as the volume representing practical capacity.

Now suppose that the average time during such counts turned out to be 47 seconds, as before. The index found by comparing the peak hour time-of-occupancy with the time-of-occupancy computed by multiplying the practical capacity by the optimum average travel time would be 400 by 47 seconds = 312 vehicle-minutes, and the index would be $\frac{1,539}{312}$ = 4.93. The amount of congestion would be 1,539-312 = 1,227 vehicle-minutes.

Then again it may be argued that the optimum should be taken as the volume during the peak hour multiplied by the average travel time for the hour of best conditions of travel. In this case, with a constant volume, the difference between the two times-of-occupancy would amount to time lost by those vehicles.

In such a situation, assume the values used in the previous examples: Peak hour volume = 570 vehicles; average travel time during the peak hour = 2.7 minutes; and average travel time during the optimum hour (hour of best travel conditions) = 0.78 minute. Then for the peak hour the time-of-occupancy = 570 by 2.7 = 1,539 vehicle-minutes, and for the optimum (or standard) the time-of-occupancy = 570 by 0.78 = 445 vehicle-minutes. A measurement of the amount of congestion would be 1,539-445 = 1,094 vehicle-minutes which, of course, would be the same as 570 (2.70-0.78) = 570 by 1.92 = 1,094 vehicle-minutes.

Then the index of congestion would become $\frac{1,539}{445}$ = 3.46.

It is also possible that a "double-barreled" index, showing a comparison with both the practical capacity and the maximum capacity as previously shown would be desirable. A statement that the index of congestion for the section equals 3.46 at the peak hour and 4.93 at practical capacity may be more revealing than a statement of either separately.

It would be necessary, to be able to express the amount of congestion in accord with some predetermined common denominators; that is, it should be expressed as representing the level of congestion per traffic lane per mile or per 1/10 mile. The latter value is particularly useful because it approximates the average urban block length. This step would be necessary to facilitate the comparison of congestion for two or more street sections of different length or number of lanes.

For example, the numbers previously shown represent the amount of congestion for a single traffic lane 1,200 feet long. Inasmuch as 1 mile is 4.4 times 1,200 feet, the values might be stated as 1,227 by 4.4 = 5,399 vehicle-minutes per lane per mile, and 1,094 by 4.4 = 4,814 vehicle-minutes per lane per mile. This would allow a relative comparison with another congested section of different length, whereas with the original index figures the comparison is quantitive, not relative.

The observations in the preceding examples could be expanded in length of section and traffic to cover the traffic on multi-lane streets in both directions, so as to cover the total traffic on any length of section. Normally, the congestion quantity would be obtained for all lanes in both directions for a given section or area, for practical evaluation purposes. Single-lane, one-directional observations were used in the foregoing simply to illustrate the hypothesis.

An area or an intersection would be evaluated by as many counts as necessary on the various legs that contribute to congestion, the various units of occupancy being added together to produce a complete picture without overlap or gaps. This might be termed a "cordon" count technique applied to the measurement of urban traffic congestion. Theoretically, the technique could be expanded to cover almost any area. The method is illustrated in Figure 2.

It is manifest that an index figure does not mean much quantitatively unless the total extent of each case of congestion is known for comparison. For example, an index of 3.46 at one location as compared to an index of 3.46 at another does not mean that they are equal in amount of congestion, because one case may cover only a short distance and the other a much greater distance. If the indexes are intended to denote which of the two cases should be given priority in remedial treatment, no choice is indicated, whereas the case having the greater length should be treated first. The cordon count technique can settle this problem by obtaining the quantity as well as the quality of congestion.

METHOD OF STUDY

When this study was first contemplated, it was decided to confine the field work to a simple type of problem, that of an ordinary two-lane urban street, with parking permitted and travel in each direction. It is probable that a large proportion of existing congestion is found on streets of this type.

Test Section

A section of street in an intermediate urban area of Charleston, W. Va., was chosen as an almost ideal situation, affording in one continuous stretch several different conditions needing appraisal. The street was approximately 40 feet wide throughout the section. It consisted of two lanes of moving traffic, one in each direction, with parking permitted on both sides except at variously-located bus loading zones. The annual average daily traffic of 12,000 vehicles included a large percentage of trucks and busses.

It was decided to break the subject of study into small section units for separate observation, and to define the limits of each in such a way that it would logically remain an integral unit, the characteristics of which could be combined with those of other similarly defined units to add up to the characteristics of the whole facility without overlapping or omission. The total section length of 1,200 feet was therefore divided into four more or less equal segments, with breaks at the two intermediate intersections and at one mid-block location.

The dividing lines between sections were called cordon count lines. These lines were extended across the western or far sides of intersections and across side streets as continuations of curb lines. Subsequent counts were thus made of vehicles as they cleared the intersections or count lines.

A count station was established near each cordon count line, as shown in Figure 3. The five count stations were lettered consecutively from the initial station to the final station, the latter being located at an isolated, signalized intersection.

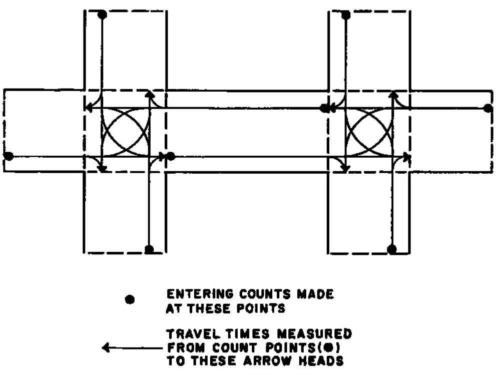

Figure 2. Cordon count concept applied to the measurement of urban traffic congestion.

Field Work

The field work consisted primarily of obtaining a detailed record of the times re-

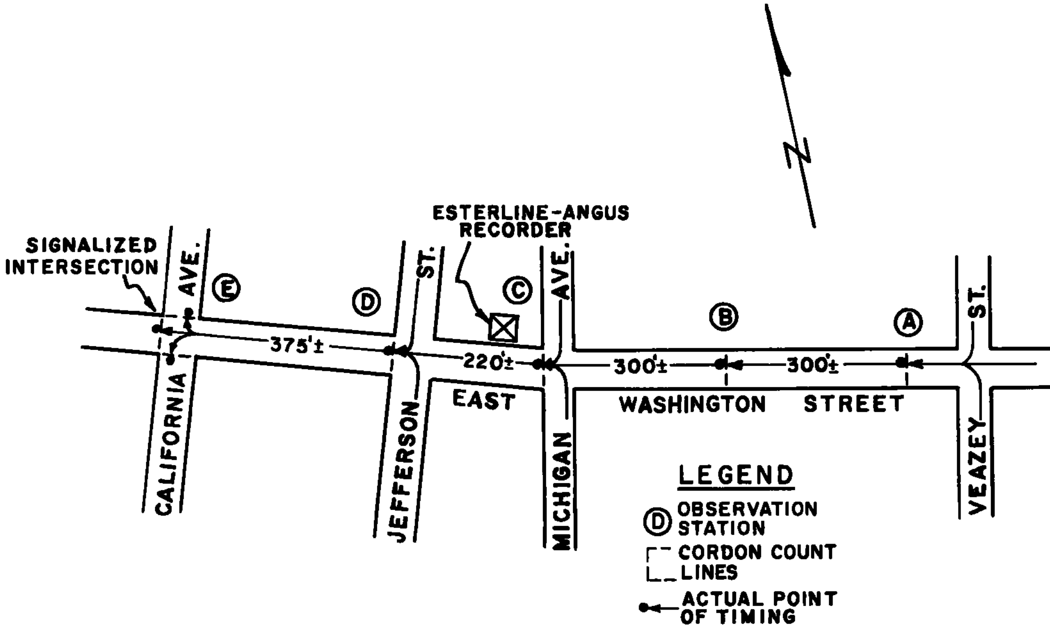

Figure 3. Schematic drawing of the test section.

quired for all westbound vehicles to travel through the section. Records were made of the single westbound lane of traffic from the time that it entered the section at Station A until it left at Station E.

The times were recorded on an Esterline-Angus recorder tape by means of an electrical circuit operated by telegraph contact keys. In addition to recording the times of vehicles entering or leaving the terminal stations, the times that they passed through the intermediate stations were also recorded; at two of these latter, the times of those vehicles entering from the side streets were recorded. To facilitate identification of individual vehicles, the type and last three digits of the license plate number of each vehicle was recorded as it cleared each station.

Details of the operation to be performed by each field worker were explained previous to the days of observation. The number and kind of worker required for each station was as follows: Stations A and B required one key operator, one recorder, and one relief man each; Stations C and D each required one key operator, two recorders, and one relief man; Station E required one key operator, two recorders, one observer, and one relief man. Another man was needed at the recorder to insure its proper functioning at all times. Two general supervisors were active throughout the section.

The observations began at 2:00 P.M., May 21, 1954, and ended at 7:00 P.M. Observations were continued the following day from 7:00 to 11:00 A.M. All the work was done in good weather with no unusual conditions to interfere with the established traffic pattern in the section.

In addition to the observations, a series of time and delay runs was scheduled so that the average travel times could be compared as between the test car and all vehicles. A single test car, with the same driver and observer throughout, made as many runs as practicable each hour through the total section. The "average" car technique was used throughout.

The data collected in the field consisted of several hundred field sheets and three lengthy Esterline-Angus recorder tapes. The initial step in analyzing the data was to match the partial license numbers noted on the field sheets by the recorders to the appropriate "blips" actuated on the tapes by the key operators. Where occasional error in telegraph key operation or license number recording occurred, matching was made difficult but not impossible.

After matching license numbers had been transcribed on the corresponding tapes, it was comparatively simple to follow the course of any given vehicle through the section and to compute its exact travel time from any station to the next in minutes and hundredths of minutes.

The mass of information represented by the completed tapes was then coded and business machine cards were punched, sorted, and tabulated. The final tabulation showed the number and classification of all vehicles entering the test section, and the total times-of-occupancy in the section as well as in each of the subsections, by 6-minute intervals.

ANALYSIS OF DATA

The nature and location of the section selected for the study were such that most of the vehicles recorded entered at the initial station and continued through to the final station. These vehicle trips, termed "through," numbered 4,301 vehicles, or 92 percent of all the vehicles recorded in the section during the observation period.

However, some of the vehicles recorded entered or left the section at the intermediate stations. These vehicle trips, termed "intermediate," numbered 377 vehicles, or the remaining 8 percent of all vehicles recorded in the section during the observation period. Extensive analysis indicates that intermediate trips can be ignored in this presentation without significant loss of detail.

Westbound vehicles entering the section at the initial station followed the typical pattern for an intermediate urban location. Hourly volumes increased rapidly during the morning, with peak arrival periods around 9:00 and 10:30 A.M. Hourly volumes were relatively constant during the afternoon, with peak arrival periods around 3:30 and 4:30 P.M. The highest hour of traffic was 4 to 5 P.M., with 627 entering vehicles. The second highest hour of traffic was 3 to 4 P.M., with 579 entering vehicles.

All vehicles were classified into five convenient groups, as follows:

1. Passenger cars, including panel, pickup, and single-tire trucks.
2. Dual-tire vehicles.
3. Combination vehicles.
4. Busses.
5. Test car.

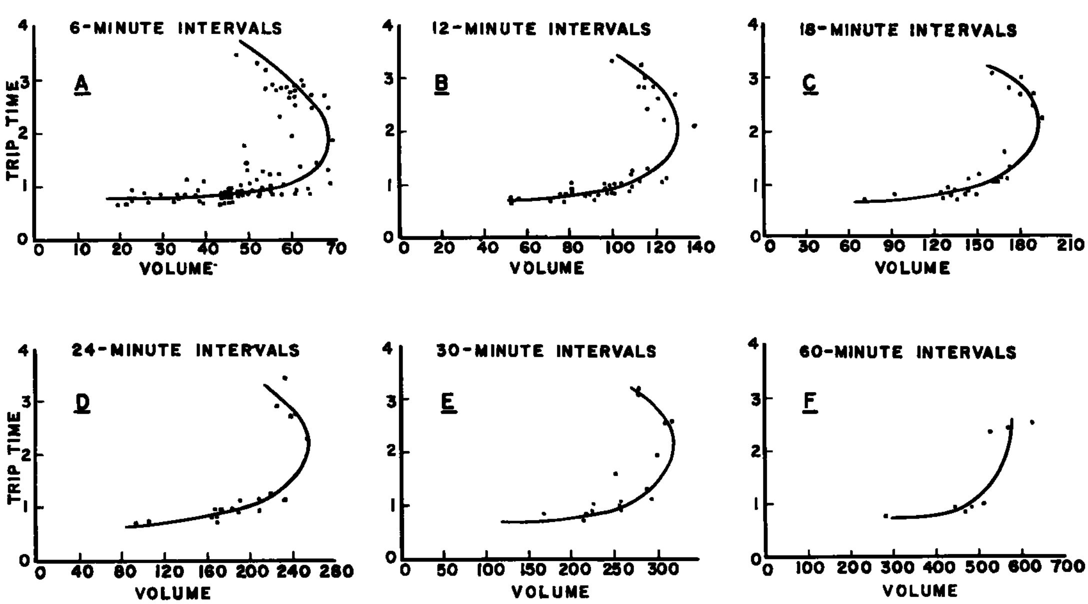

Figure 4. Relation of entering volumes to average trip times-minutes.

Average Travel Times

The average travel time was simply the average time that was required by a given number of vehicles to travel from Station A through Station E of the test section. The average travel times were computed for through trips only, by 6-, 12-, 18-, 24-, 30-, and 60-minute intervals. For the 60-minute interval between 4:00 and 5:00 P.M., for example, the 592 vehicles which passed through the section required an average travel time of 2.56 minutes each.

Travel times for individual vehicles varied greatly. One vehicle was recorded through the section in the minimum time of 0.40 minute, corresponding to an over-all speed of about 34 mph. Another was recorded through the section in the maximum time of 4.90 minutes, corresponding to an over-all speed of about 3 mph, or as slow as a brisk walk.

The average travel times also varied greatly, but not through such a wide range. In general, the average travel times were lowest when the section was experiencing a light volume of traffic, and highest when experiencing a heavy volume of traffic. It is important to note that this function was actually reversed at or near the point of critical density as defined in the "Highway Capacity Manual" (3). At that point, while the recorded volume of traffic decreased abruptly because of congestion and stoppages, the average travel times continued to increase. This is well illustrated in Figure 4.

Good correlation was obtained between the all-vehicle and the test car average travel times. The greatest deviation of average travel times occurred during the hour 7 to 8 A.M. It seems probable that the test car driver at that time may have passed too many vehicles to conform to the "average car" technique, with more frequent opportunities due to lack of opposing traffic. With the exception of that hour, the test car average travel times were within ± 7 percent of the average travel times for all vehicles, on an hourly basis. Computed on a 6-minute basis, the coefficient of correlation was found to be 0.9679.

These results compare favorably with those obtained in a similar study on a 1.45-mile section of urban street in California. Berry (4) stated that on all but one of the test sections, both average and floating test runs yielded mean values within 7 percent of the means obtained by the license-check method. He further concluded that to obtain an accuracy of 10 percent, 8 and 10 test car runs per hour would be needed on two-lane urban uncongested and congested routes, respectively.

The somewhat better results obtained in this study with an average of nine test car runs per hour and using the same "average car" technique, may be due to the relative brevity and substantially uniform conditions of the 1,200-foot test section. Both studies produced test car travel times which were lower than those of the license-check method.

Relation of Average Travel Times to Entering Volumes

The average travel times for all vehicles have been plotted (Figure 4) against the volume of traffic entering the section of the initial station for the corresponding time intervals of 6, 12, 18, 24, 30, and 60 minutes, as a family of scatter diagrams. In each, entering volumes are the abscissas and average travel times are the ordinates. For ease of comparison, scales were made proportionate to the various time intervals represented.

The superimposed curves, which were fitted by visual effect, tend to turn back on themselves. The 12- and 18-minute interval curves (B and C) seem to show the effect best. For example, although many 12-minute intervals reveal an average travel time of about 1 minute, several others with approximately the same entering volumes show an average travel time of about 3 minutes. This could be taken as one simple indication of the amount of congestion present during the latter intervals.

The effect is not entirely unexpected. Greenshields (5) has discussed its theoretical aspects in his recent publication dealing with highway traffic analyses. Although his analysis deals with speed rather than time, the curves presented are quite similar to those in Figure 4.

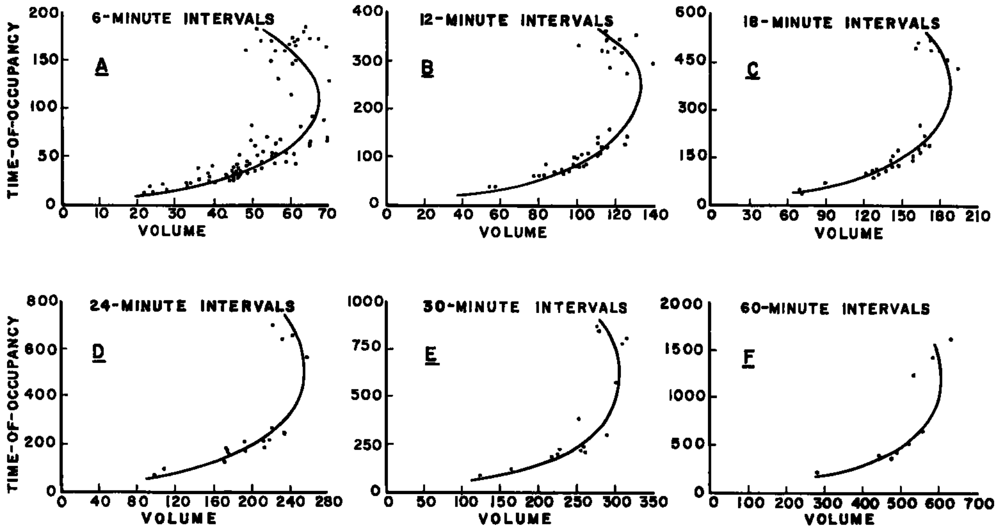

Figure 5. Relation of entering volumes to time-of-occupancy minutes.

Vehicle Times-of-Occupancy

As previously defined, the vehicle time-of-occupancy during a given time period was simply the average density multiplied by the time of observation. From the recorder tapes, vehicle densities were computed at 1-minute intervals for the hour 4 to 5 P.M. Average density in the test section for that hour was found to be 25.5 vehicles. Total time-of-occupancy = 25.5 by 60 minutes (period)of observation) or 1,530 vehicle-minutes. Although this method is relatively simple in itself, it is recognized that more convenient ways may be found to use the average densities concept in obtaining total time-of-occupancy. Greenshields has suggested three ways: a photographic method, an adaptation of the Esterline-Angus recorder method, and a calculating machine method.

Also as previously defined, the vehicle time-of-occupancy during a given time period was simply the volume count of vehicles entering the test section multiplied by their average travel time through the section. The total entering through volume for the hour 4 to 5 P.M. was 592 vehicles. The average travel time for all vehicles during the hour was 2.56 minutes.

In this example, total time-of-occupancy = 592 by 2.56 = 1,516 vehicle-minutes. That compares well with the 1,530 vehicle-minutes obtained from the average densities computation. The present method makes use of the travel time observations recorded on the Esterline-Angus tapes and, therefore, is assumed to be most accurate.

If the test car average travel time is substituted for the all-vehicle average travel time during the same time period, still another measure of the total time-of-occupancy is found. Again illustrating with the peak hour 4 to 5 P.M., with total entering volume the same as before, total time-of-occupancy = 592 by 2.62 = 1,551 vehicle-minutes.

The total vehicle time-of-occupancy as determined from the Esterline-Angus tapes increased rapidly from the morning to the afternoon hours of observation. This was expected, because time-of-occupancy is the product of entering volumes and average travel times, both of which values also increased from morning to afternoon hours.

Relation of Time-of-Occupancy to Entering Volumes

The total times-of-occupancy for all vehicles have been plotted against the volume of traffic entering the section at the initial station, for corresponding time intervals of 6, 12, 18, 24, 30, and 60 minutes, as a family of scatter diagrams (Figure 5). In each, entering volumes are the abscissas and total times-of-occupancy are the ordinates. Scales were again made proportionate to the various time intervals represented for ease of comparison.

The superimposed curves are fitted by visual effect rather than by formulas. As with the family of curves in Figure 4, these tend to turn back on themselves. Thus, the highest entering volumes do not assure the greatest total time-of-occupancy.

Not unexpected, the cause of this phenomenon is largely self-explanatory. As entering volumes increased to the point of critical density, the total time-of-occupancy increased more or less linearly. When that point was reached, the greater delay allowed fewer entering vehicles, but required longer travel times, which resulted in greater over-all time-of-occupancy. It is obvious that the travel times increased at a more rapid rate than the entering volumes decreased.

Congestion Indexes

It was found during the field work that when entering volumes were 282 vehicles per hour, or less, the average travel time for all vehicles was maintained at approximately 0.78 minutes. At volumes greater than this, the average travel time increased substantially above 0.78 minutes. In deriving the Simple Index, the optimum normal time-of-occupancy may be assumed to be 282 by 0.78 = 219 vehicle-minutes.

The actual time-of-occupancy for any given hour of the field work can be taken directly from the travel time observations as recorded on the Esterline-Angus tapes. For the peak hour of 4 to 5 P.M., the actual time-of-occupancy was 1,516 vehicle-minutes. During the peak hour, then, congestion amounted to the vehicle time-of-occupancy recorded for that hour, less the vehicle time-of-occupancy represented by the optimum hour; 1,516-219 = 1,297 vehicle-minutes. This can be expressed as a ratio, $\frac{1,516}{219}$ = 6.92, which may be considered as one way of expressing an index of the relative congestion existing in the single westbound lane of the test section.

The optimum normal time-of-occupancy may also be taken as the time-of-occupancy obtained with the volume of traffic found to be the practical capacity of the test section. In this case, the signalized intersection at Station E was the limiting factor which determined the practical capacity for the entire section.

Using the procedure outlined in the "Highway Capacity Manual" (3), the practical capacity of the intersection was found to be approximately 400 vehicles per hour. Unfortunately, in no single hour of the field work was the traffic volume even roughly equal to 400 vehicles per hour. To overcome this obstacle, the average travel time of several 6-minute intervals most nearly equal to 1/10 of the volume of practical capacity was taken as the optimum travel time.

The average travel time thus arrived at was 0.78 minutes, exactly the same as for the hour previously used for an optimum in which the volume was 282 vehicles per hour. Using this value as the optimum travel time, the optimum normal time-of-occupancy at the practical capacity would be 400 by 0.78 = 312 vehicle-minutes. The index of congestion found by comparing the peak hour actual time-of-occupancy, say, with the optimum time-of-occupancy at the practical capacity would be $\frac{1,516}{312}$ = 4.86.

The optimum normal time-of-occupancy may also be taken as the volume during the peak hour multiplied by the average travel time for the hour of best conditions of travel. The optimum normal time-of-occupancy at the peak hour would thus be 592 by 0.78 = 462 vehicle-minutes. The index of congestion found by comparing the actual peak hour time-of-occupancy with the optimum peak hour time-of-occupancy would be $\frac{1,516}{462}$ = 3.28.

Comparison of the Three Types of Indexes

The same optimum travel time of 0.78 minute was used in the calculation of each of the three indexes. For the Practical Capacity Index, the optimum travel time was the same as for the other indexes, apparently as a matter of chance. It is suspected that future applications of the Practical Capacity Index will find the optimum travel time somewhat higher than for the Simple or Peak Hour Index. The optimum travel time corresponded to an over-all speed through the test section of 17.4 mph.

It has been suggested that the optimum travel time be based on the legal speed limit

(25 mph in the test section). This possibility was rejected on the grounds that (a) the legal speed may be so slow as to impede movement itself, or (b) so high as to be unattainable. In either case, false indications of congestion would appear in the calculation of any index.

It has also been suggested that some constant speed, say 35 mph, might be selected arbitrarily to represent completely satisfactory travel time conditions for urban areas. This concept might even be expanded in use to provide for different desirable speeds in downtown, intermediate, or residential areas. Further research should be devoted to this possibility.

For each index, the same optimum travel time was applied against a different volume level. For the Simple Index, it was applied to the volume above which it could not be obtained (282). This produced the least optimum normal time-of-occupancy and the highest numbers of the three types of indexes.

Making use of a somewhat higher volume level (400), the Practical Capacity Index had a higher optimum normal time-of-occupancy and consequently lower index numbers. Applying the optimum travel time against a still higher volume level (592), the Peak Hour Index had the highest optimum normal time-of-occupancy and the lowest index numbers of the three types of indexes.

The three indexes previously calculated are for the total test section. They could as well have been calculated for any of the subsections merely by substituting whatever optimum travel time was found to be applicable for each, and proceeding according to the method used for the entire section.

Eventually, of course, the congestion quantity would be obtained for all lanes in both directions for a given street section or area by use of the cordon count technique described earlier. This would be possible with any one of the three indexes, because they each possess the property of "additiveness".

Excess Time-of-Occupancy as a Measure of Congestion

As previously stated, the concept of excess vehicle time-of-occupancy as an indication of congestion, aside from its use in calculating an index, is a useful value for direct comparison, as it is actually the measurement of time lost by vehicles due to congestion. The cost of congestion occurring in a given section of street during a given interval of time can be readily computed by placing a value per vehicle-minute upon such lost time.

To illustrate: Using the Simple Index, the excess vehicle time-of-occupancy during the peak hour 4 to 5 P.M. in the test section was 1,297 vehicle-minutes. Placing a value of $0.02 per vehicle-minute upon it, the monetary loss for the single hour was $25.94. Losses due to congestion can be similarly computed for all the hours of the field work during which congestion actually occurred.

SUMMARY AND CONCLUSIONS

The study began with the development of this definition of congestion: "The condition in which traffic, because of impedences from any source, moves at average over-all speeds less than the maximum speed that is tolerable, considering prudence and safety."

From this, the concept of excess vehicle time-of-occupancy as one indication or measurement of congestion was evolved. To illustrate the concept, observations and comparisons were made of the actual and optimum vehicle times-of-occupancy in a selected test section under varying volume conditions.

It was found that the actual total time-of-occupancy in the section increased only directly as the total entering volumes increased, up to the point at which congestion may be said to have begun. Thereafter, as the average vehicular travel times increased because of various impedances, the actual time-of-occupancy increased faster than the entering volumes. As congestion became even more severe, the time-of-occupancy continued to increase while entering volumes remained constant or decreased slightly.

Time and delay runs were made through the test section to determine if the average travel times recorded by the test car could be used to represent the average travel times recorded by all vehicles. A positive answer was found in the resulting coefficient of correlation of 0.9679.

The least obtainable travel time through the test section during one continuous hour, without restriction of movement except from the signalized intersection at Station E, was 47 seconds. This was possible with entering volumes up to 282 vehicles per hour; with greater volumes the average travel time increased substantially above 47 seconds.

The least obtainable travel time was then applied to three magnitudes of entering volumes to produce three optimum times-of-occupancy. In the first case, it was applied to that volume above which it could not be obtained; in the second, to that volume which represented the practical capacity of the signalized intersection at Station E; in the third, to the observed volume in the test section during the peak hour.

The formulas for each of the three congestion indexes developed in this study are based on the ratio of actual to optimum time-of-occupancy. The major formula is:

$$\text{Congestion Index Number} = \frac{\text{Actual Time-of-Occupancy}}{\text{Optimum Time-of-Occupancy}}.$$

In the calculation of an index, the actual occupancy value is as observed in any given space of roadway. The optimum occupancy value may vary, depending on the type of index selected for use.

Assuming equivalent entering volumes, it is evident that the time-of-occupancy required in the test section during periods of congestion, exceeding that required during periods of no congestion, is a direct measurement of lost time by vehicles due to congestion. A value per vehicle-minute can be assigned to it, and the cost of congestion readily computed. It may even be practicable to estimate an annual congestion loss for a given space of roadway by the application of appropriate traffic factors.

It may be possible that under some circumstances the excess time-of-occupancy would be a more revealing measure of congestion than an index number. It is recommended that both measurements be given proper consideration in the evaluation of congested highways.

It should be acknowledged that further research may well uncover a better measurement of congestion. Greenshields (6) has proposed a method of measuring the quality of traffic transmission in urban areas. Conradt (7) has developed a "service rating" for urban streets. Other urban rating scales have been used for many years. Although these have not been ignored, it is felt that the present study offers a method of measuring urban congestion that may have general application until such time as better measures are introduced.

Before embarking on any comprehensive program involving the measurement of urban traffic congestion, various unsolved questions must be resolved. Having proved that the test car method of obtaining time-of-occupancy is valid, thereby assuring future savings in time and money over that method used in this study, there remains to be found for practical uses an even faster and cheaper method.

Experience in usage may be necessary to determine which of the three indexes developed are best suited to particular locations; perhaps different type indexes would be required for different types of urban streets. There may be reason to believe that the Simple Index would be best used on non-signalized sections, for example, while the Practical Capacity Index, because it recognizes a certain delay from adverse signal indications, would be better for signalized sections.

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