DEPARTMENT OF TRAFFIC AND OPERATIONS

Traffic Flow in Tunnels

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In the absence of a suitable deterministic traffic flow model, capacity of individual sections of single-lane roadways must be inferred from the observed characteristics of the traffic flowing through the sections. In this case, the flow-concentration characteristics of kinematics are used. Various flow-concentration relationships have been presented in traffic engineering literature, and observations in several tunnel roadway sections also produced various relationships. It is suggested that these changing relationships are related through the effect of bottlenecks. The kinematic wave analogy of Lighthill and Whitham is compared with empirical deviations from the theory. Finally, the importance of stimulating further theoretical research on traffic flow is emphasized.

• HIGHWAY and traffic engineers and others concerned with the design and operation of roadway systems are facing the pressure of increasing traffic congestion on the one hand, and high construction costs on the other. Under these pressures, much work has been done to improve traffic flow by operational means. But in this work, an inadequate understanding of traffic flow is a handicap. Lack of traffic flow theory limits the ability to identify needed operating and design changes, to predict the results of such changes, or even to measure the results with accuracy.

This lack assumes a particular importance at The Port of New York Authority because underwater tunnels such as the Lincoln and Holland Tunnels are among the most expensive of all roadways. As the operator of these tunnels, the Port Authority is under obligation to the public to insure that all feasible steps are taken to encourage optimum traffic flow. The problem is to find out what flow is optimal, and what can be done to bring it about. The experimental approach to this problem, with which this paper is primarily concerned, has concentrated first on what relationships among flow, speed, and concentration exist in tunnel traffic, and on how they vary at different points in the tunnel. These relationships are then used to locate those portions of the tunnel roadway which are limiting flow and to determine what maximum flow would be attainable at other sections without existing limitations. The relationships will be used also to measure the effect of various experiments in a program to increase maximum flow.

The traffic engineering literature includes several apparently conflicting reports of flow, speed, and concentration relationships. Some observers have reported increasing flow with increasing speed; others, increasing flow with increasing concentration; and still others have reported no relationship between the amount of flow and either speed or concentration. In the light of these conflicts, the first effort has necessarily been to determine whether consistent relationships among these parameters exist for traffic flow in tunnels. The observations of tunnel traffic presented in this paper suggest that the apparent inconsistencies can be resolved for single lane, no passing, no junction flow by considering the effect of bottlenecks.

BACKGROUND

In the Holland and Lincoln Tunnels there has been for many years a continuing program of improvement in traffic flow through operational changes arrived at largely by intuition and experience. As a part of this program, analytical studies have been made as an aid to intuition, and two in particular have had a significant bearing on the present work. In 1953, Olcott (*1*), referring to Greenshields (*2*), confirmed that the straight line relationship between speed in miles per hour and concentration in cars per mile existed in the speed and headway data newly collected. Accordingly, Olcott based his analysis of tunnel roadway performance on this relationship. Speeds and concentrations which produce maximum flow in cars per lane per hour were determined by conversion of a speed-concentration regression line to a flow-concentration parabola. Estimates of the maximum hourly flow to be expected derived by this method compared closely with actual peak-hour flows. The limited resources available to Olcott precluded extensive development of this methodology in his study; however, he clearly illustrated the applicability of the method to the measurement of maximum flow attainable through the entire length of a tunnel lane.

A more extensive survey, reported by Strickland (*3*), using different observing methods and analysis was undertaken in 1954 by the Traffic Engineering Division of the Port Authority. Speeds and headways were independently sampled at 9 locations concurrently in each of two tubes at the Holland, Lincoln and Queens-Midtown Tunnels, and more than 82,000 samples of peak-hour speeds and headways were recorded. The results of this study were presented in speed and spacing profiles for each tube from which deductions about bottlenecks were made. Analysis at that time did not extend to the determination of optimal speed and headway relationships at the bottleneck locations and elsewhere, but this is now being done.

These two studies and others contributed to the knowledge of tunnel traffic flow, and significant improvements in operation have been made, but more questions have been raised than answered. Furthermore, the major increases in traffic flow during peak periods which still appear attainable have not yet been achieved.

The present study was initiated early in 1956. It was conceived as a long-range program rather than a one-shot study. The basic aim of the program is to insure that traffic flow on each roadway under Port Authority jurisdiction is optimal under peak demand. This means defining and adopting the optimal operating procedures, equipment, and design criteria to produce maximum flow consistent with safety. It is evident that this requires knowledge of traffic behavior and research.

REVIEW

To explore the potential practical results that might be expected from research seeking to optimize flow, past peak-hour production at the Holland and Lincoln Tunnels was reviewed. Summaries of results since 1951 were compiled, and statistical analyses were made to measure quantitatively the effect of two major changes in operating procedures. The first change altered the method of feeding vehicles into the tunnel from a strictly officer controlled start-and-stop operation to one whereby motorists merge gradually. The controlled operation was originally employed as a means of accident reduction, but gaps of undue length were created in the traffic stream by this method. Although several adjustments were necessary in the free-feed method before accident experience was satisfactory, this method did increase production. Statistical analysis based on four years' experience demonstrated an average increase of 70 vehicles per hour (vph) in peak-hour production with a 95 percent confidence of an increase ranging from 17 to 129. Using only a few months' experience, Strickland (*3*) estimated an increase to 50 vehicles and a range of 38 to 85.

A second operating change permitted commercial vehicles in both lanes of a

tube rather than restricting them to the right-hand lane. Based again on four years of experience, statistical analysis demonstrated that an average loss of 80 vph, with a range of 50 to 110, resulted when commercial vehicles used both lanes. This analysis did not attempt to determine passenger car equivalents for commercial vehicles, however, and it has been suggested that the reduction in number of vehicles might be offset by a greater proportion of heavy commercial vehicles.

These two statistical studies demonstrated that operational procedures can have a significant effect on maximum flow. They also showed that a statistical method of analysis, which requires at least several months of experience, is not a very good one for quickly assessing the effect of an operating change. Furthermore, with statistical methods, there is always the possibility that events which appear to have a causative relationship may be only a coincidence. To overcome these difficulties, better methods of measurement based on flow theories are needed.

SEARCH FOR A MODEL

In a theoretical consideration of traffic flow on a single-lane roadway which has no intermediate entrances or exits, it is apparent that the average flow is the same for all sections of the roadway. Therefore, differences in ability to accommodate peak flow among the many sections of such a roadway cannot be measured by direct count of the maximum attained at each section, but must be inferred from analysis of other characteristics of the traffic stream.

In selecting the characteristics to be studied, the few published theories of vehicular traffic flow covering conditions similar to those existing in these tunnels were reviewed. A limited number of both discrete and continuous theoretical models are available to describe flow on roadways without intersections. The discrete models describe the behavior of individual cars in sequence as each is affected by the car ahead. A mathematical representation of the traffic stream is built up through a series of difference equations and the reaction times of drivers is a significant parameter. An example of this approach is the work by Pipes (*4*).

The continuous models describe the behavior of the traffic stream as an idealized continuum neglecting reaction time lags, queuing, and other behaviors of single vehicles. Greenshields' linear speed density hypothesis describes the traffic stream in a simple continuous model without a particular physical analogy. Lighthill and Whitham (*5*) and Richards (*6*) have derived traffic-flow models from fluid-flow models utilizing kinematic wave properties. The comparative mathematical simplicity of these continuous models led to adopting them to guide and interpret experimental work in the tunnels. Greenshields' model is the simplest of the continuous models, and it was decided to use this to guide initial data collection. Data needed are the speeds and headways maintained by vehicles while passing through the roadway section being studied.

DATA

Much of the speed and headway data which were available from previous studies could be used. However, the Olcott data, in furnishing speeds and headways for all vehicles passing through a survey zone, were more suitable for the initial approach than the 1954 data which recorded speeds of some vehicles and headways of others. Additional speed and headway data of the complete kind were required. Also required was a more efficient instrument for measuring and recording in quantity the speed and headway of each vehicle, the lane in which it traveled and the type of vehicle. Olcott had used the Esterline-Angus twenty-pen recorder for this purpose and, initially, this instrument was used in the current study. As many traffic engineers know from firsthand experience, this machine produces a graphical rather than a numerical record.

After investigating several alternatives, it was decided to utilize a Simplex Productograph machine. This device is essentially a time clock which prints time

to $\frac{1}{10}$ second plus a 6-letter code on standard adding machine tape. Hours, minutes and seconds are printed in figures, tenths of a second by a vernier scale. This machine was adapted by providing two push-button panels to key the printing mechanism and select the assigned code for a particular lane and type of vehicle. Fast lane or slow lane, and car, bus, truck or tractor-trailer were the classifications used. One panel is used by an observer at the entrance to a survey zone, while the other is used by an exit observer. Each push button activates a different combination of letters which identifies the lane and vehicle type, and indicates whether the time is for entering or exiting the survey zone. Time intervals can be determined readily by direct subtraction. This device has proven reliable and accurate and has permitted a large reduction in data processing time compared to a pen recorder. The staff also developed functional specifications for a punched tape device to be used for even faster processing, but the less expensive, more flexible and more portable Productograph appeared the better choice initially in the light of uncertainty as to the amount of speed and headway data that would be needed.

ANALYSIS

Greenshields Model

The Greenshields model is based on a linear decrease in speed as concentration increases. When speed is expressed in miles per hour and concentration in cars per mile, flow in cars per hour is the product of the two. (In these studies, it was convenient to use the fluid flow terminology of flow and concentration rather than the terms volume and density.) As concentration increases from zero, speed decreases and ultimately becomes zero at jam concentration. Thus, flow rises from zero to a maximum and then decreases back to zero following a parabolic curve. With this relation as a model, the maximum flow for each of several sections of tunnel roadways was sought.

The first tube selected for this analysis was the north tube of the Lincoln Tunnel. Previous surveys had concluded that the foot of the downgrade was the bottleneck location in this tube. It was desirable to test data collection methods and analytical procedure by seeing whether results would agree with this conclusion. For this purpose, data were collected at eight points in the tube.

Before analyzing these data, a test was run to determine whether some other simple relation among the three parameters of flow, speed, and concentration might better describe them, but it was found that the linear relation between speed and concentration produced the most accurate description. Accordingly, and because the validity of the Greenshields model had been confirmed previously for entire tunnels by Olcott, this model was retained as the initial basis for analysis.

In plotting the speed-concentration relationship from the raw speed and headway data, it is necessary to choose among several possible ways of summarizing the data, each of which produces a different picture. For example, the average speed of all vehicles traveling at a certain headway can be determined, and the average speeds for each of the many observed headways can be plotted. Or, the average headway maintained by all vehicles traveling at a certain speed can be calculated, and this point plotted for each observed speed. Or again, the average speed and headway maintained by the traffic stream during a relatively short time period, such as 3 minutes, can be determined and one point plotted for each 3-minute time slice.

Since the initial analysis was based on the assumption that, for each speed, the average headway converted to concentration would be directly proportional to the speed, the method chosen initially to summarize the data was to group all vehicles having the same speed and determine their average headway. This average was converted to concentration. Regression lines were then calculated for speed and concentration, and flow was estimated by taking the product of val-

ues read from the regression line to plot a flow-concentration parabola. Capacity, interpreted as the maximum flow given by the flow-concentration parabola, was generally constant throughout the downgrade section. Beyond the foot of the downgrade, capacity gradually increased to a maximum near the exit portal.

This result was generally consistent with previous knowledge and experience, and it appeared that the assumed linear speed-concentration relationship analysis was the answer to the problem of measuring capacity at any location in the tunnel.

Exceptions. The first doubt arose from the different results obtained by the various methods of summarizing the speeds and headways. A second problem was inherent in the uniform speed method initially used, and had a significant effect on estimates of capacity downstream from the bottleneck. This is the problem of the platoon leader who, although he is traveling at the same speed as other people and, in fact, is setting the speed for a group, has a speed-headway relationship which is not characteristic of the roadway section. Since his long headway is not characteristic and has an inordinate effect on the average headway computed for his speed, it is necessary to exclude such headways. Therefore, vehicles having a time headway longer than eleven seconds were excluded. (Forbes (7) also eliminated long headways, but used a flexible rather than fixed value to do so.) But since platooning becomes more and more pronounced as the roadway section under analysis is farther and farther downstream from the bottleneck, elimination of the platoon leaders from the analysis on this basis resulted in eliminating vehicles which were responsible for a progressively more severe capacity loss. Thus, such computations automatically tend to produce progressively higher capacities for points downstream from the bottleneck.

Another factor cast doubt on the validity of the computations for points upstream from the bottleneck as well. Although it was recognized that the average quantity of flow upstream would be constrained by bottleneck capacity, it was hypothesized that the character of the traffic flow upstream from the bottleneck would still indicate any higher capacity these sections might have. The method did not indicate any higher capacity, however, and accordingly it was initially concluded that the bottleneck section extended over the entire downgrade rather than being just the foot of the downgrade. Two other possibilities would also explain this result, however. One is that the character of the flow as well as the amount of the flow observed upstream would be governed by the bottleneck section. The second possibility is that the method of analysis was insensitive to those differences in the character of the flow at the two points which would reveal any higher upstream capacity.

A fourth factor casting doubt on the validity of this first analysis was the marked and consistent deviations of the observed points from those derived from speed-concentration regression lines, particularly at non-bottleneck sections. On flow-concentration coordinates, deviations from a linear speed-concentration relationship are squared and the effect of non-linearity becomes quite pronounced. Figure 1 shows this comparison at a bottleneck, where the empirical data (which are shown as points) differ from the parabola (shown as a dashed line) resulting from the calculated speed-concentration regression line. Maximum flow indicated by the empirical points is 1,400 vph, which agrees with experience, while

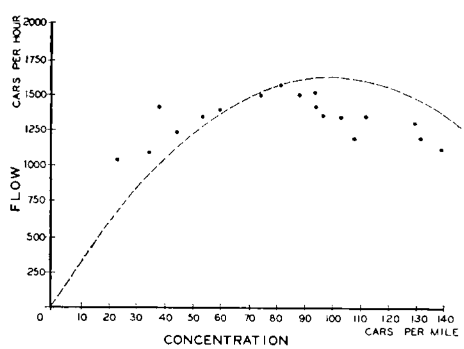

Figure 1. Bottleneck, uniform speed summary.

the maximum from the theoretical curve is 1,600 vph. At non-bottleneck sections, the variance between empirical and theorectical values was much larger and, at some points, the empirical data exhibited no tendency to assume a parabolic form.

Revisions. To resolve these difficulties, the method of analysis was revised in two important ways. One revision was to abandon the calculation of flow on the assumed linear speed-concentration relationship. Instead, flow was plotted directly on flow-concentration coordinates.

This flow-concentration relation is definitely preferred as a basis for analysis rather than one between speed and flow, or between speed and concentration as has been used by other analysts, because it is possible to represent nearly all of the significant parameters of traffic flow on the flow-concentration coordinates with straight lines or simple curves. A specific example is shown in Figure 2. In it flow is shown at 1,200 vph; concentration at 48 veh per mile; speed by the slope of the radius vector as 25 mph; wave velocity by the slope of the tangent to the flow-concentration curve at 14 mph; headway time between vehicles at 3 sec; and clearance time from rear bumper to front bumper at 2.5 sec. Concentration at maximum flow, or at capacity of the roadway section, is called the critical concentration. The speed and headway which produce maximum flow are then optimal from a flow standpoint. Working with the interplay among these parameters, it is possible to surmise the idealized shape of the flow concentration relation over the entire range of concentration. The curve shown here is parabolic from origin to maximum flow, and then elliptical to jam concentration.

The other revision was to abandon the uniform speed method of summing the speed-headway data, and to adopt the method whereby average flow and concentration are calculated for equal time slices. The method whereby vehicles were classified according to headway was also checked, and then average speed for each observed headway was plotted. This failed to produce valid results, since the few vehicles having especially close headways tended to produce points with unreasonably high volumes. Furthermore, both the uniform speed and uniform headway methods fail to indicate graphically the frequency with which various speeds or headways are observed. Determination of the span of the time slice was

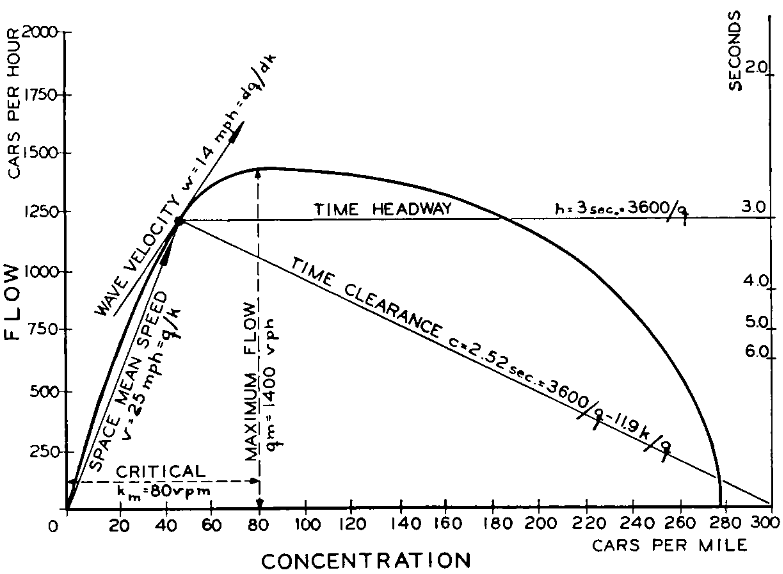

Figure 2. Dimensional analysis of flow on q (k) curve.

made by testing 1-min, 3-min and 5-min spans. The span selected depends on the degree of sensitivity or smoothing effect desired, and on the stability of the actual flow.

Traffic Behavior at Bottleneck. The results produced by the revised analysis of data at the Lincoln Tunnel north tube foot of the downgrade are shown in Figure 3. The empirical data, shown as points, cluster around a parabolic curve drawn as a solid line through the origin and the empirically indicated point of maximum flow. It is apparent, however, that very few data were obtained with which to fix the curve beyond the point of apparent maximum flow. Since the main use made of this curve is to determine maximum flow, observations beyond critical concentration are desirable to make certain that the maximum has been found. Efforts to observe concentrations beyond the critical value were not successful in passenger car traffic. It became evident that passenger car tunnel traffic would not naturally exceed critical concentration at a bottleneck section of relatively short length when the time slices contained, for example, ten or more vehicles. Apparently, protracted slow-downs below critical speed do not normally occur at bottlenecks, but only behind them for this kind of traffic and roadway.

The pattern observed in Figure 3 is typical of a bottleneck and can be used to locate and measure a bottleneck; that is, a section of roadway which is not prevented by adjacent sections of the same

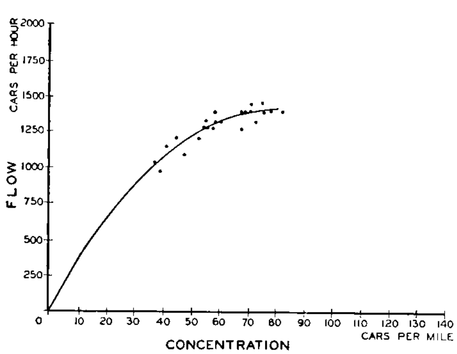

Figure 3. Bottleneck, one-minute summary.

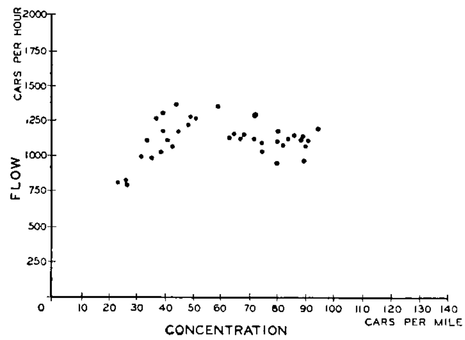

Figure 4. Non-bottleneck observation.

roadway either from receiving or passing all the traffic it can handle. The critical feature about this pattern is the reduction in speed with increasing concentration, producing a leveling off of flow.

These data confirmed the linear speed-concentration relationship for this bottleneck, at least for concentrations up to critical, but data at non-bottleneck sections did not. Figure 4 shows data at a point upstream from a bottleneck, and it is suggested that these data are produced by two separate causes. Data on the left were observed immediately before data on the right. It is evident that there was relatively free flow during the time points on the left were observed; the bottleneck took effect, then points on the right, at slower speeds, were observed. The extent to which these data might be used to infer maximum flow at non-bottleneck sections became the critical question. Without a means of determining flow at non-bottleneck points, it is difficult to determine either the extent of needed improvements or the increase in flow to be expected from them.

Lighthill-Whitham Model

To investigate this question, the hydrodynamic analogy drawn by Lighthill and Whitham in 1955 was used. This analogy produces insight particularly into the wave-like action by which changes in flow are transmitted in the traffic stream, and is useful in relating flow at the observed point to a restriction at another point.

It is an assumption of the kinematic and similar models based on perfect fluids that at a given flow less than the maximum, traffic would tend to vary around either the low concentration or the high one given by the flow-concentration curve and would not fall in between. This assumption permits deductions to be made about flow behavior on each side of a bottleneck (Fig. 5). This figure shows the effect of a bottleneck section with a capacity given by point B of 1,400 vph. Non-bottleneck sections upstream and downstream have capacities of 1,700 vph, as given by point D. As explained by Lighthill and Whitham, when flow upstream from the bottleneck increased above point A, a shock wave coming from the bottleneck would cause a sharp reduction in speed to approximately 8 mph, and an increase in concentration to conditions represented by point C. Both A and C are presumed to fall on the flow-concentration curve for the upstream section of roadway. As traffic reached the bottleneck it would speed up to approximately 15 mph and thin out, moving to conditions represented by point B which lies on the bottleneck flow-concentration curve. This phenomenon is similar to the Venturi effect found in true fluids. Leaving the bottleneck, traffic would speed up to approximately 40 mph, moving to the flow conditions given by point A lying on the downstream flow-concentration curve. This kinematic analogy for wave behavior has been very helpful in providing insight for interpreting observations. The empirical results show, however, that traffic flow upstream and downstream does not follow exactly the patterns suggested.

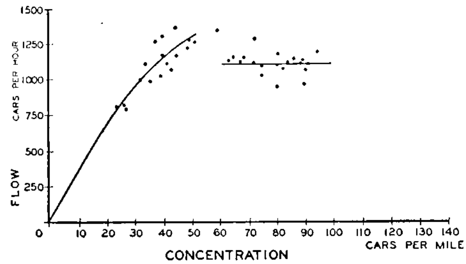

Figure 6. Upstream of bottleneck.

Traffic Behavior Upstream from Bottleneck. Actual behavior upstream from the bottleneck is illustrated in Figure 4. These data are shown again in Figure 6, with two lines through the points. Points on the left are interpreted as indicating the flow-concentration curve for the observed section before flow was restricted

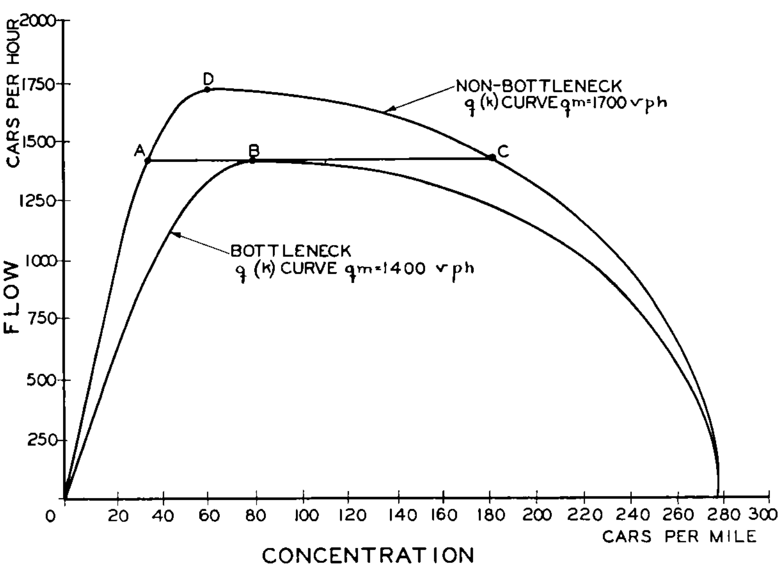

Figure 5. Kinematic behavior of bottlenecks.

by bottleneck capacity. The line generating from the origin is the characteristic flow-concentration curve, but there is only a slight hint of a leveling off with which maximum flow could be determined. Points on the right were recorded during bottleneck-controlled flow. These points do not cluster around the points on the flow concentration curve for the observed section which are at the flow level equal to bottleneck capacity. They assume a range of speeds and concentrations such that flow is equal to bottleneck capacity, as indicated by the horizontal line.

Accordingly, data observed at a location during times when bottleneck flow is controlling do not reflect the performance of the roadway at the observed location, except to establish that it is equal to or higher than the maximum observed flow. This pattern of behavior is typical of those found for flow upstream from a bottleneck. It may be used to locate the bottleneck, set a lower bound on the capacity of the observed section of roadway, and suggest its value even though the capacity cannot be directly observed.

Traffic Behavior Downstream from Bottleneck. Downstream from the bottleneck, values again do not cluster about point A of Figure 5 as suggested by kinematics. Figure 7 shows observations made about 4,800 ft downstream from the bottleneck. Here the upper points have moved slightly to the left and the lower points slightly to the right of the assumed bottleneck curve (shown in dashed line) with flow levels both higher and

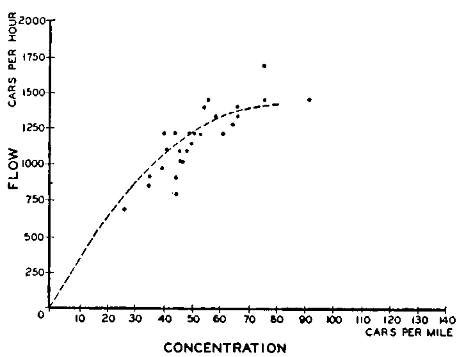

Figure 7. Downstream 4,800 ft from bottleneck.

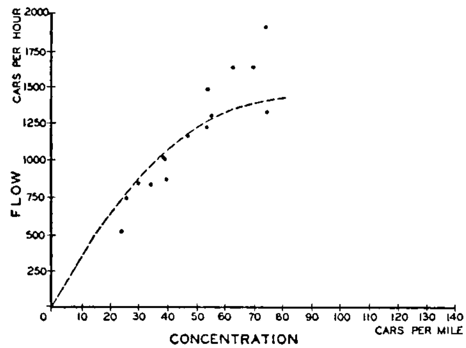

Figure 8. Downstream 5,500 ft from bottleneck.

lower than the bottleneck capacity, but with the same average flow. The general shape of the bottleneck curve is still evident at this location. Further downstream, 5,500 feet from the bottleneck, these trends are continued (Fig. 8). Here the original shape of the bottleneck curve has been lost. The points fall approximately on a straight line, which in this case is the speed line for about 25 mph, instead of on the curve. This pattern is apparently typical of the flow-concentration relationship downstream from the bottleneck.

As in the case of the flow upstream from the bottleneck at times when the bottleneck is controlling, it does not appear that these points downstream represent the flow-concentration curve at the observed section. In this case, the constraint on flow is imposed not by bottleneck capacity (other than in the sense that flows higher than bottleneck capacity cannot be observed except for short periods) but by slow drivers. As distance from the bottleneck increases, these drivers gradually come to control the speed of all other vehicles, which become queued behind them. This interpretation explains the tendency of flow to cluster along one speed line, and a relatively slow speed line at that. Time slices which do not happen to include any platoon leaders should, in their average concentration and flow, reflect the flow-concentration curve for that roadway for that speed. But points at lower concentrations include varying amounts of space be-

tween platoons, and hence are not representative of roadway performance.

SUMMARY

The value of this experimental work to date has been to test the validity of certain continuous models of flow theory and to uncover certain of their limitations. The applicability to single-lane, uninterrupted roadways of two types of continuous traffic flow models has been investigated. Results with the Greenshields model indicate that its usefulness in interpreting flows of this type is limited to low concentration flow where the process of queuing behind bottlenecks or potential platoon leaders has not been carried far enough to be significant. The kinematic theory was found quite useful in interpreting observed flow-concentration data under more conditions, but it did not predict exactly the patterns observed upstream and downstream from a bottleneck. The differences between observed values and those predicted by the kinematic theory result in part because single-lane flow without passing is not as analogous to a fluid as is multi-lane flow with passing, and, probably, in part from the effects of driver reactions and behavior which cause inertia and diffusion. These higher order effects were recognized but not incorporated in the Lighthill-Whitham model.

From a practical standpoint, this work shows that the type of congested flow observed at most sections of the tunnel has relatively little to do with the tunnel environment. It is the consequence of a bottlenecking process or a queuing process. One question which arises is whether the bottleneck itself is a normal consequence of single lane, no passing, no junction flow, possibly arising as a critical point in the transition from relatively constant flow at the input to queued flow at the output. Although this possibility must be investigated further, it is more likely that the bottleneck is environmentally induced, and hence its effect can be ameliorated by improvements in the environment. This estimate relies on observation that the bottleneck generally occurs at a change in grade or at a decision point.

Most important, the work accomplished to date has provided a much better understanding of tunnel traffic flow to guide and stimulate further work.

OUTLOOK

It is evident that the development of theories of traffic flow which will fully describe the behavior of traffic in relation to the factors determining it is an effort that will require different approaches: the theoretical approach concentrating on mathematical models, the empirical and experimental approach concentrating on field work, the psychological approach concentrating on driver perceptions and reactions, and the simulation approach. All are now being followed among the limited number of persons and groups working on this problem.

The need for improved understanding of traffic flow assumes an overriding pertinence to all concerned with the new Federal Highway Program. Over the next fifteen years, expenditures of approximately 100 billion dollars are planned to serve traffic flow. Without detailed understanding of how these roads should be built and operated so as to encourage optimal flow, full advantage cannot be realized from this tremendous construction effort. This problem warrants the kind of all-out approach typified by the AASHO road test, and the kind of inter-disciplinary cooperation being accorded the relationship between highway planning and urban and regional development.

The major contribution the Port Authority can make to this effort is with the experimental approach. The tunnels are, in a sense, a laboratory readily available for the testing of results derived through the other approaches.

In addition to experiments based on continuous models, the staff is also working in a limited way with discrete models. The Massachusetts Institute of Technology is simulating tunnel traffic flow on a 704 computer, and the Port Authority is contributing in this effort by furnish-

ing data and the results of studies to date. Work has also been undertaken to observe directly the action of drivers and vehicles. The review of the literature had disclosed the need for information on driver-vehicle reactions under various environments in order to relate them to flow. Driver-vehicle reactions are one of the distinctive features of vehicular traffic flow which set it apart from fluids or gases. Although experimental work has focussed on the environmental limits imposed on traffic flow, there are also controlling limits imposed by driver-vehicle response patterns. Accordingly, the Port Authority contracted for work in this area with the American Institute for Research (*8*).

Tunnel flow is a particularly suitable subject for developing flow theory. Because such phenomena as vehicle passing, merging, and diverging are excluded from the tunnel flow, and because the tunnel environment is largely controllable and generally constant, tunnel flow represents one of the least complex of all possible flow situations. When behavior of the tunnel traffic stream has been fully explained, more complex cases can be tackled with greater effectiveness.

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