AN EXPERIMENTAL VALIDATION OF VARIOUS METHODS FOR OBTAINING RELATIONSHIPS BETWEEN TRAFFIC FLOW, CONCENTRATION, AND SPEED ON MULTILANE HIGHWAYS

A. V. Gafarian, R. L. Lawrence, and P. K. Munjal, System Development Corporation, Santa Monica, California; and J. Pahl, University of California, Los Angeles

Three methods frequently reported in traffic literature for obtaining flow-concentration-speed relationships were selected for an experimental validation study. In the first method, data are grouped into short successive time intervals for computations; in the second, cars are classified by computed virtual concentration; and in the third, cars are classified by their speeds. A standard method was developed against which these 3 methods were compared. The method used as a standard is based on the isolation of periods of constant traffic flow. The data used for the study were collected by the Federal Highway Administration's traffic analyzer and were taken at 12 unidirectional two-lane sites. Results show substantial agreement between the methods based on short time slices, constant flow intervals, and speed classes. However, the method based on virtual concentration disagrees with all of these in the high concentration range. Because the method based on virtual concentration yields flows much higher than any ever observed in practice, it should not be considered a valid method for obtaining flow-concentration-speed relationships.

•ALTHOUGH the idea of functional relationships between the quantities of flow, concentration, and speed is one widely used in traffic literature, no uniformity of opinion exists as to how the related values of flow, concentration, and speed should be derived from data taken at a fixed point in the roadway. This lack of uniformity is probably due in part to the fact that such data consist of measurements of the arrival times of cars and their speed from which flow and speed—but not concentration—can be directly derived. Concentration must be derived by some indirect method from the observed values of time headways and speeds. The necessity of deriving a value for the concentration from observed data has led to varying approaches in converting the raw data of headways and speeds to values on flow-versus-concentration and speed-versus-concentration curves. Differences in categorization of the raw data based on various theoretical assumptions about the nature of traffic flow, e.g., the theory advanced by Wardrop of independent streams of cars (1), have also led to divergent methods of calculating values for flow-concentration and speed-concentration curves.

In this study the results of 3 different methods commonly mentioned in traffic literature are compared: (a) The observed data are divided into small time intervals (on the order of a minute) and flow, space mean speed, and concentrations are calculated for each interval; (b) cars are classified by the computation of a virtual concentration for each car, and speed is calculated for each concentration class; and (c) cars are classified by speed, and an average virtual concentration is calculated for each class. All of these methods are applied to the same raw data taken from a multilane facility, and the resulting values are graphed.

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Whatever the backgrounds, 2 questions must be asked of these different methods in order to clarify this presently ambiguous problem of data reduction: Although different in methods of classifying raw data and deriving the related values of speed, concentration, and flow, do the methods give substantially the same results? If the methods do not give the same results, is there any reason for the rejection of one or more in favor of another?

In order to help us answer the first of these questions and to avoid a proliferation of graphical comparisons, we wished to develop a method that could be used as a standard against which we could compare other methods. The method developed was based on isolating from the observed data long time slices during which the flow remained constant (in the sense of the passage times of cars being indistinguishable from a stationary point process). The selection of these constant flow periods is fully described elsewhere (2). The rate of flow, space mean speed, and concentration for these time slices are then computed. To some extent this method represents an expansion of the method of short time slices, but differs in that (a) periods during which the flow of vehicles is changing rapidly are excluded, as they do not represent a steady-state condition; and (b) the estimates of flow, concentration, and space mean speed for the constant flow intervals are much more reliable than those for the short time interval because the number of cars included is substantially increased. The small amount of scatter in the estimates produced by the constant flow method makes it a useful standard for graphical comparisons.

The second of these questions dealing with the rejection of one method in favor of another is harder to answer. However, in the application of some methods, anomalies arise that indicate that the methods may not be valid; obviously, we prefer methods that do not have such anomalies.

The conclusions of this study are as follows:

1. There is substantial agreement among the methods based on short time slices, constant flow periods, and speed classes. The method based on virtual concentration disagrees with all of these in the high concentration range.

2. The method based on virtual concentration yields flows much higher than any ever observed in practice and should, therefore, not be considered a valid method.

THE VARIOUS METHODS STUDIED

The data available for this study were collected by the traffic analyzer and were obtained by measuring the times and speed at which cars passed a fixed point on the highway. These data were recorded for each lane. The passage times were recorded in units of $\frac{1}{10{,}000}$ hour, that is, 0.36 sec. The speeds were determined by measuring the time τ each car traveled a speed trap distance L. This time was measured in units of 0.01 sec. In this study, the value of L was 30 ft for the lighter traffic flow and 15 ft for the heavy traffic flow conditions.

From these data, values of flow, concentration, and speed were computed by 3 basically different methods published in the literature, and plots of flow versus concentration and average speed versus concentration were prepared. For an examination of the resulting relationships in graphical form, a standard was developed against which the relationships would be compared. In this study, a method based on constant flow periods, fully described elsewhere (2), was considered as the standard. This method and the 3 methods to be validated are described in detail in the following.

The Method Used as Standard

For the purposes of this study, traffic flow can be regarded as a statistical process generating passage times and associated values of speed in each lane. Average flow and average speed are 2 parameters describing some of the properties of this process. Estimates of such parameters will fluctuate with time. These fluctuations can be due to one or two causes, depending on the properties of the generating process. The first cause, the purely statistical fluctuations around the mean, is always present. The second cause, fluctuations of the mean, adds to the fluctuations of the first one only if the flow is not stationary in time. A good statistical estimate of parameters describing the process is obtained by selecting periods of flow that are stationary in time, i.e., periods in which the passage times of cars can not be distinguished from a stationary point process.

For each period thus obtained, the parameters flow

$$q = N/T \tag{1}$$

space mean speed (harmonic mean of observed speeds)

$$\bar{v} = \frac{N}{\sum_{i=1}^{N} 1/v_i} \tag{2}$$

and concentration

$$k = q/\bar{v} \tag{3}$$

were computed, where T is the time length of the constant flow period, N is the number of cars passing the point of measurement in this time period, and v_i is the measured speed value for each car.

These parameters were computed for each lane separately, as well as for both lanes superimposed, whereby the superimposed case was obtained by superimposing the statistical processes measured separately for each lane.

The Methods To Be Validated

$1/50$ Hour Groupings—The entire time period of data acquisition was divided into successive time intervals of the length of $1/50$ hour each (3). This was a more convenient length than 1 min, which is most frequently used, because passage times of cars were measured in units of $1/10{,}000$ hour for each time interval. The quantities

$$q = 50\,N$$

in cars/hour,

$$\bar{v} = \frac{N}{\sum_{i=1}^{N} 1/v_i}$$

in miles/hour, and

$$k = q/\bar{v}$$

in cars/mile were computed, where N is the number of cars passing the point of measurement in the particular time interval under consideration ($1/50$ hour). These computations were performed for each lane separately, as well as for both lanes superimposed.

Virtual Concentration—A value of virtual concentration (3) was computed for each car as the inverse of its space headway. Because only time headway and speed of each car were measured, the space headway in this case had to be estimated. It was assumed that the speed of the n - 1 car, v_{n-1}, remained constant for a time period t_n, which is equal to the time headway of the nth car after it had passed the point of measurement. The space headway was then computed as the product of v_{n-1} and t_n. This yields the virtual concentration in cars/mile

$$k_n = 1/(v_{n-1} t_n) \tag{4}$$

for the nth car. The space headways for all cars were classified into intervals of 5 ft. For each such interval, the quantities

$$k = \frac{N}{\sum_{n} v_{n-1} t_n} \tag{5}$$

$$\bar{v} = \frac{N}{\sum_{n} 1/v_n} \tag{6}$$

$$q = k\bar{v} \tag{7}$$

were computed, where N is the number of cars in the concentration interval under consideration. These computations were performed for each lane separately. In this case, computation could not be made for both lanes superimposed because then the spacings obtained between cars do not correspond to their real spacings. As a matter of fact, the time headway—and thus the spacing—can be zero for some cars, leading to an infinite value of virtual concentration for these cars. Instead, both lanes were added together; i.e., the computations were not altered but, disregarding lane number, all cars of both lanes were classified into the concentration intervals.

Classification by Speeds—Cars were classified by their speeds (3, 4) into the speed intervals determined by increments of 0.01 sec in time through the speed trap (5). For each such speed interval, a value of concentration was computed in analogy to Eq. 5 with the only difference being that here N is the number of cars in the speed interval under consideration. With the computed values of concentration for each speed interval, corresponding values of flow were computed by using Eq. 7, where $\bar{v}$ in this case is the midpoint of the speed interval. In analogy to the computations in the method of virtual concentrations, these computations were performed for each lane separately, as well as for both lanes added together.

COMPARISON OF THE METHODS

The methods described in the previous section were implemented for data taken at a two-lane unidirectional half of a highway in Virginia. The data were acquired by measuring the passage times and speeds of cars in each lane from 3:50 to 6:30 p.m. The resulting experimental values of flow concentration and speed given by the method based on constant flow periods are given in Table 1.

Figures 1 through 18 show the speed-concentration and flow-concentration relationships resulting from the use of the methods of $1/50$ hour groupings, virtual concentrations, and classification by speeds (classes containing less than 5 cars were not plotted). The

TABLE 1

CONSTANT FLOW PERIODS

Flow (cars/hour)			Concentration (cars/mile)			Speed (mph)		
Lane 1	Lane 2	Lanes 1 and 2 Superimposed	Lane 1	Lane 2	Lanes 1 and 2 Superimposed	Lane 1	Lane 2	Lanes 1 and 2 Superimposed
916	1,120	2,035	16.5	16.8	33.3	55.5	66.7	61.2
1,308	2,003	3,311	26.0	35.4	61.3	50.4	56.6	54.0
1,441	1,613	3,053	58.9	73.0	131.9	24.5	22.1	23.2
1,544	1,779	3,323	63.2	64.7	127.9	24.4	27.5	26.0
883	1,169	2,052	15.8	17.7	33.4	56.1	66.2	61.4

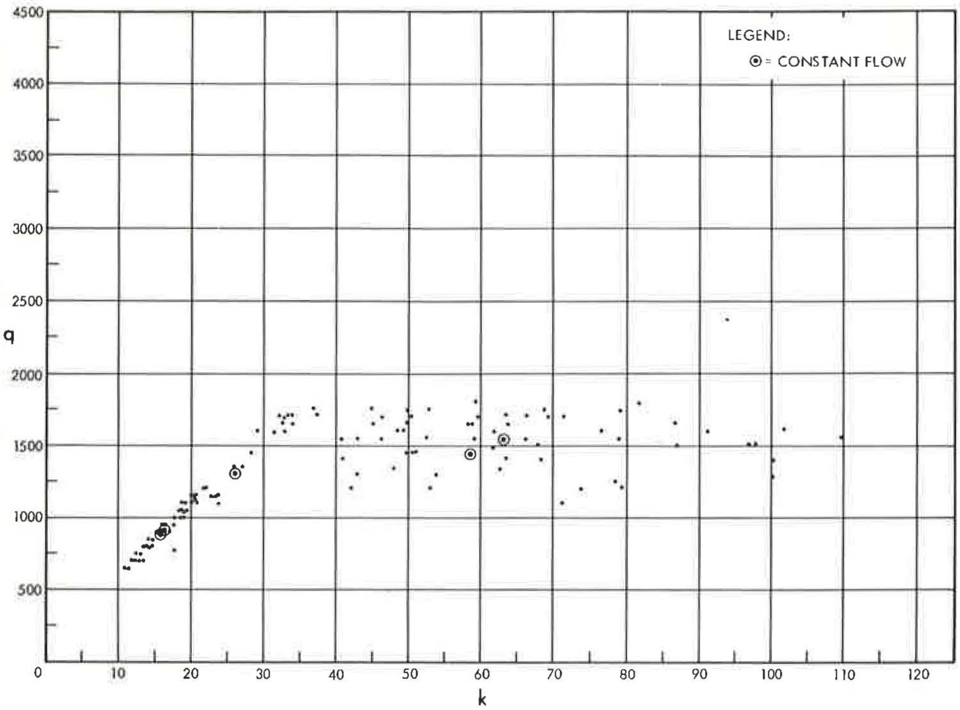

Figure 1. Lane 1, q - k plot, $\frac{1}{50}$ hour groupings.

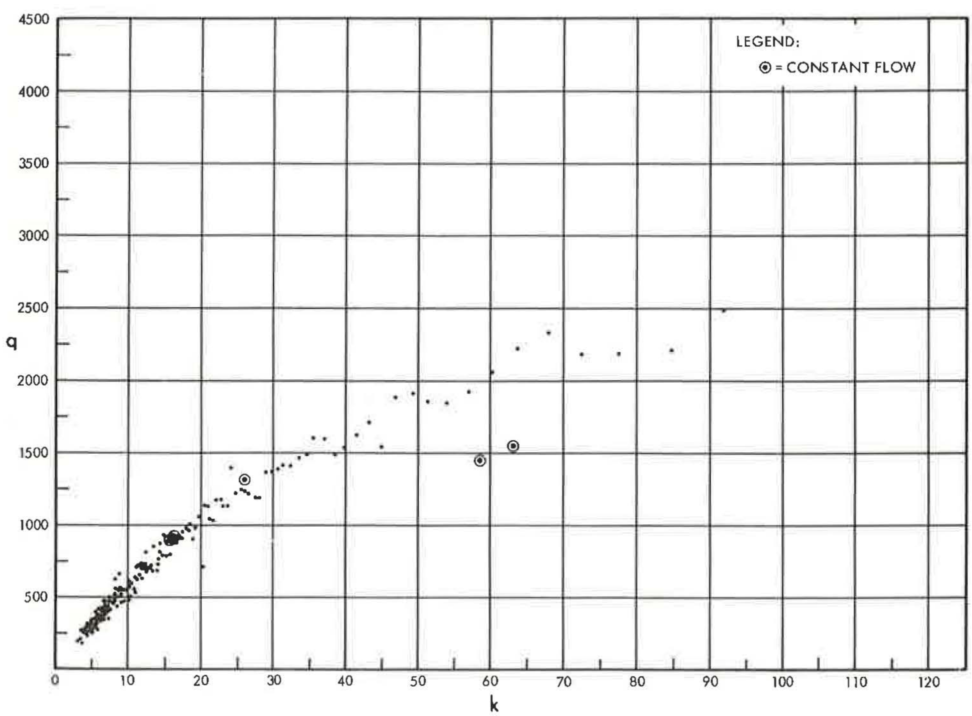

Figure 2. Lane 1, q - k plot, cars classified by virtual concentration.

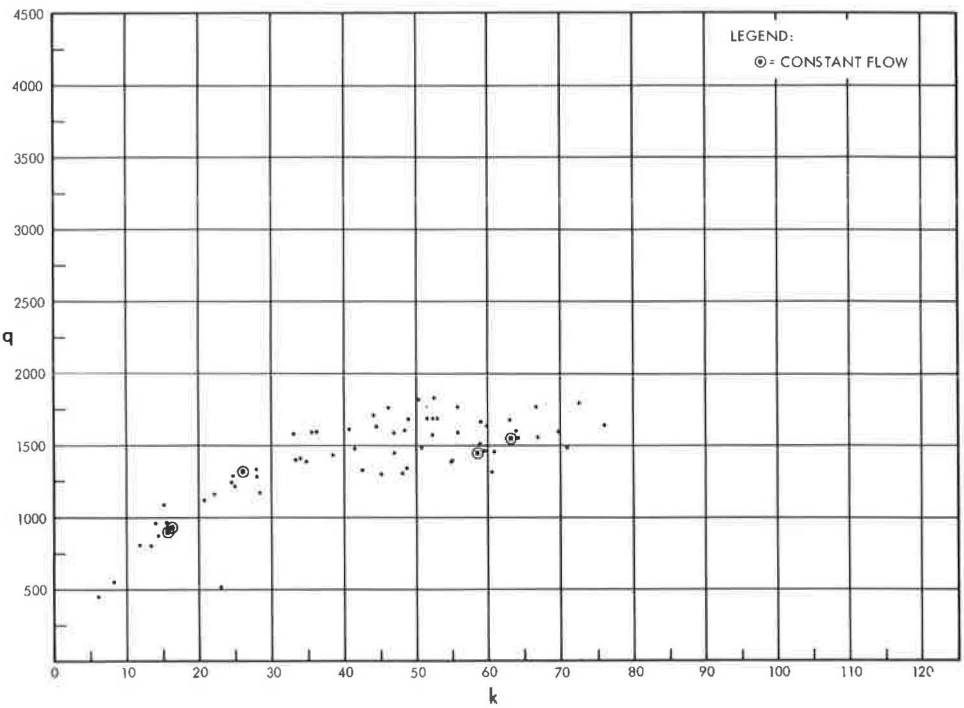

Figure 3. Lane 1, q - k plot, cars classified by speed.

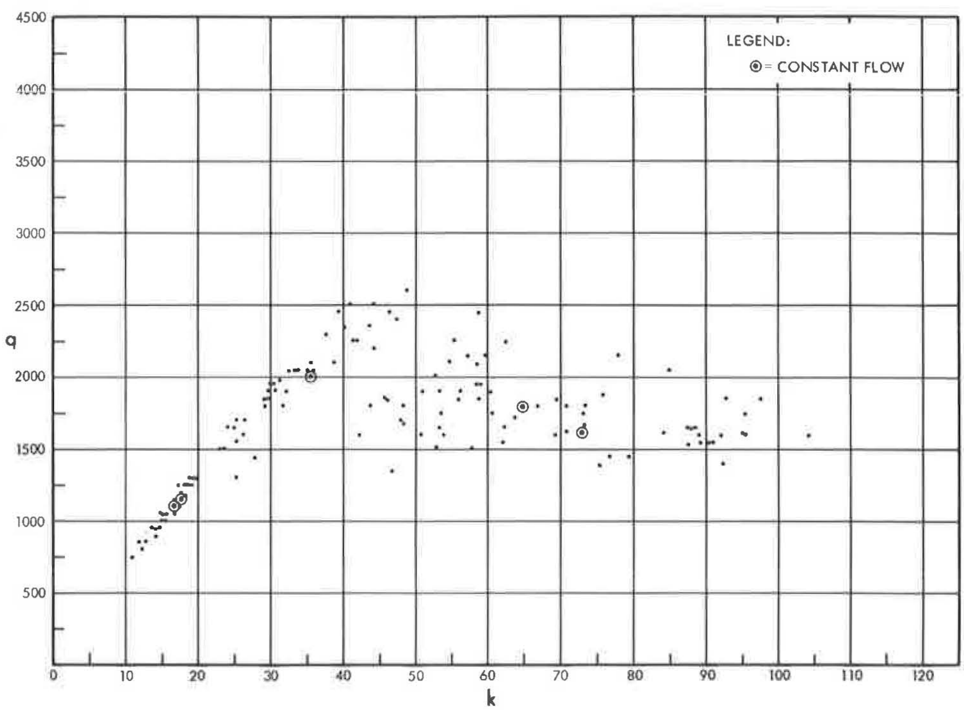

Figure 4. Lane 2, q - k plot, $^1\!/_{50}$ hour groupings.

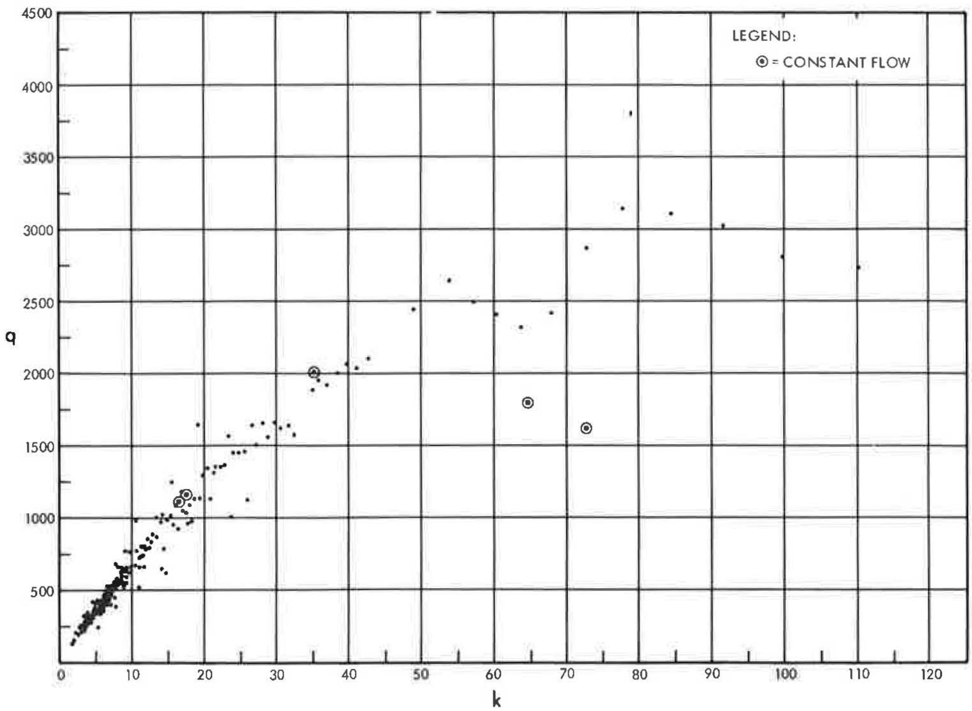

Figure 5. Lane 2, q - k plot, cars classified by virtual concentration.

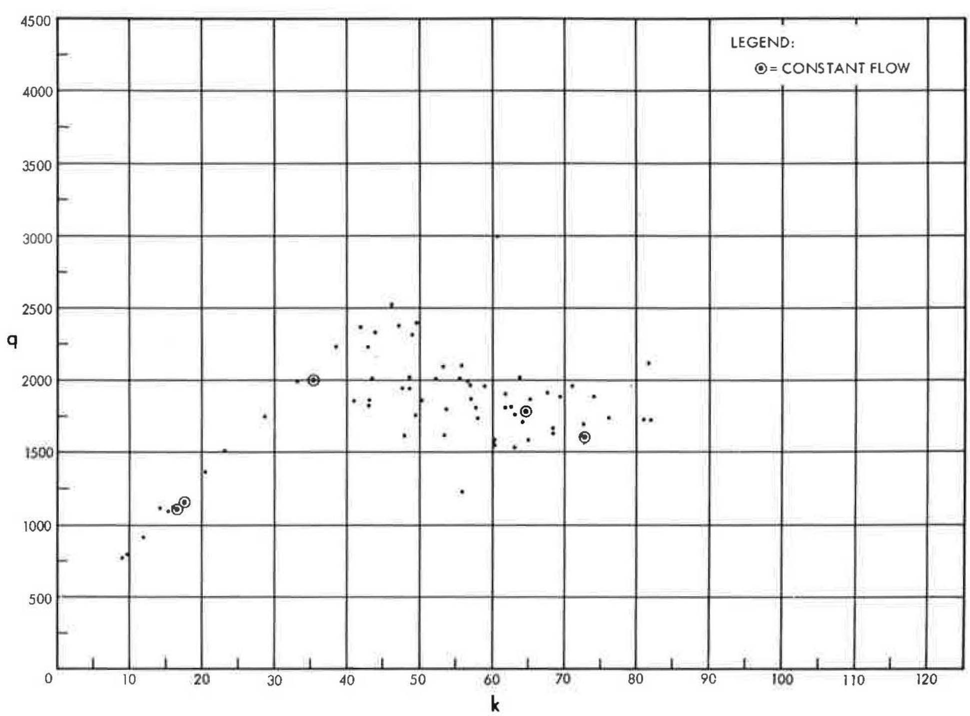

Figure 6. Lane 2, q - k plot, cars classified by speed.

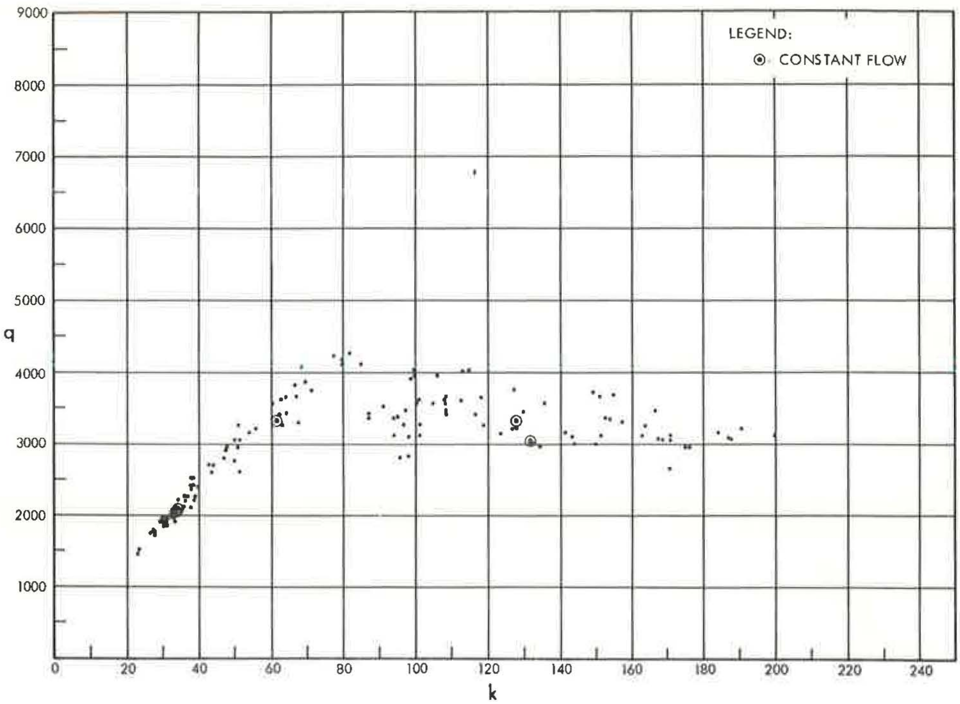

Figure 7. Lanes 1 and 2 superimposed, q - k plot, $\frac{1}{60}$ hour groupings.

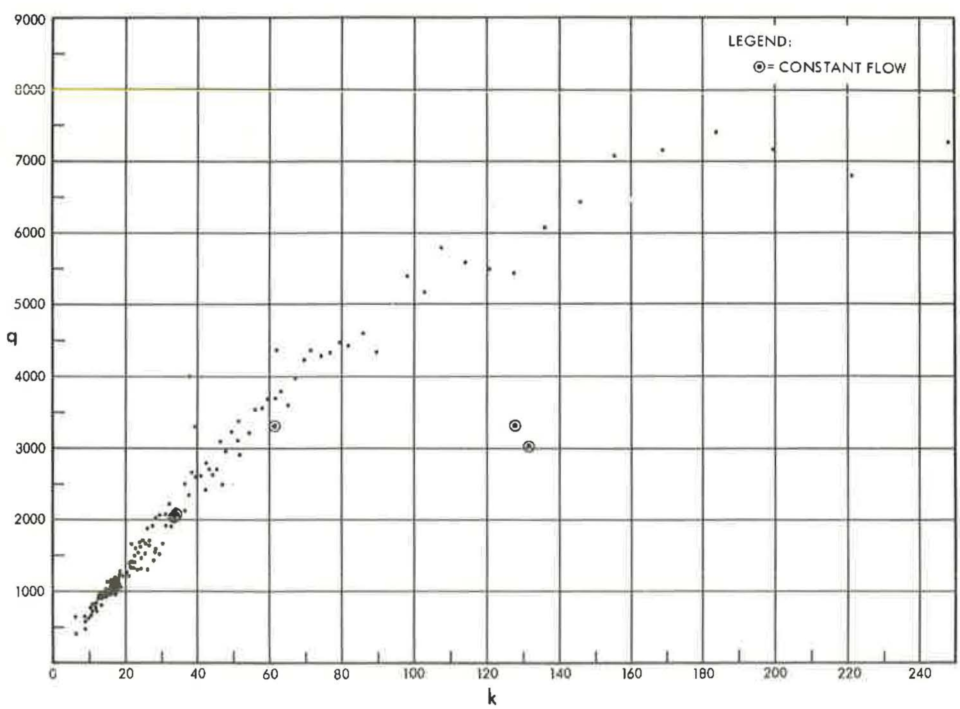

Figure 8. Lanes 1 and 2 added together, q - k plot, cars classified by virtual concentration.

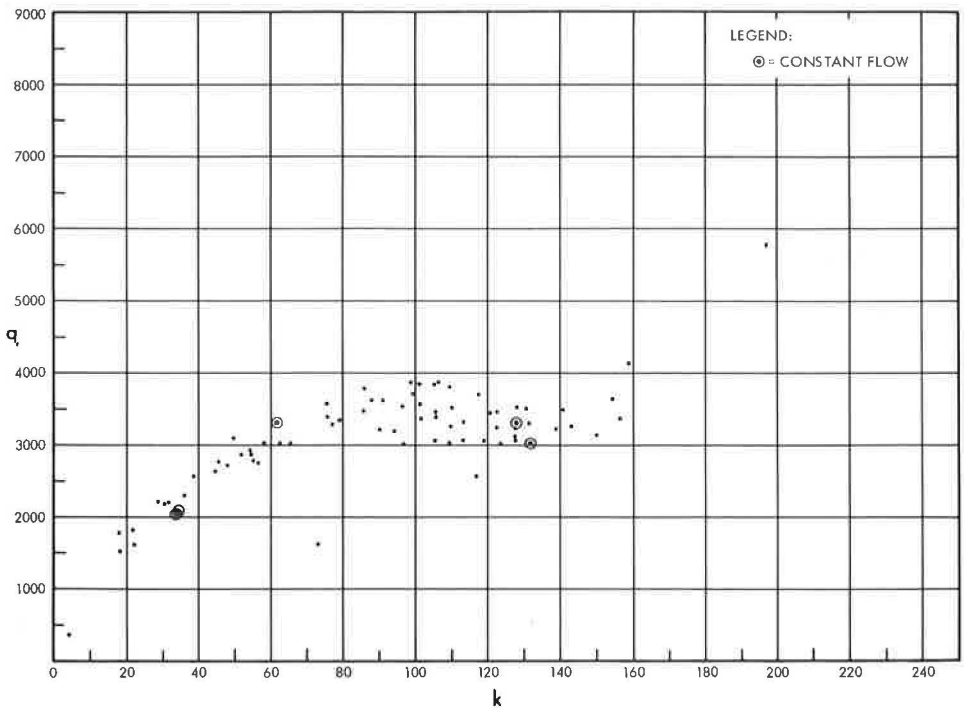

Figure 9. Lanes 1 and 2 added together, q - k plot, cars classified by speed.

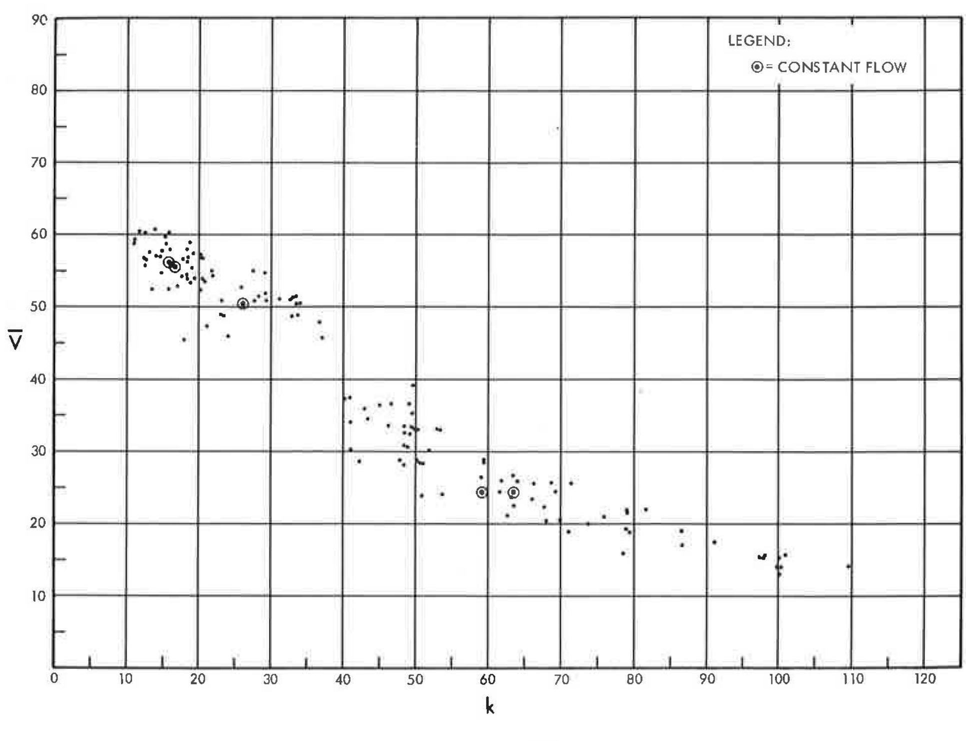

Figure 10. Lane 1, $\overline{v}$ - k plot, $\frac{1}{60}$ hour groupings.

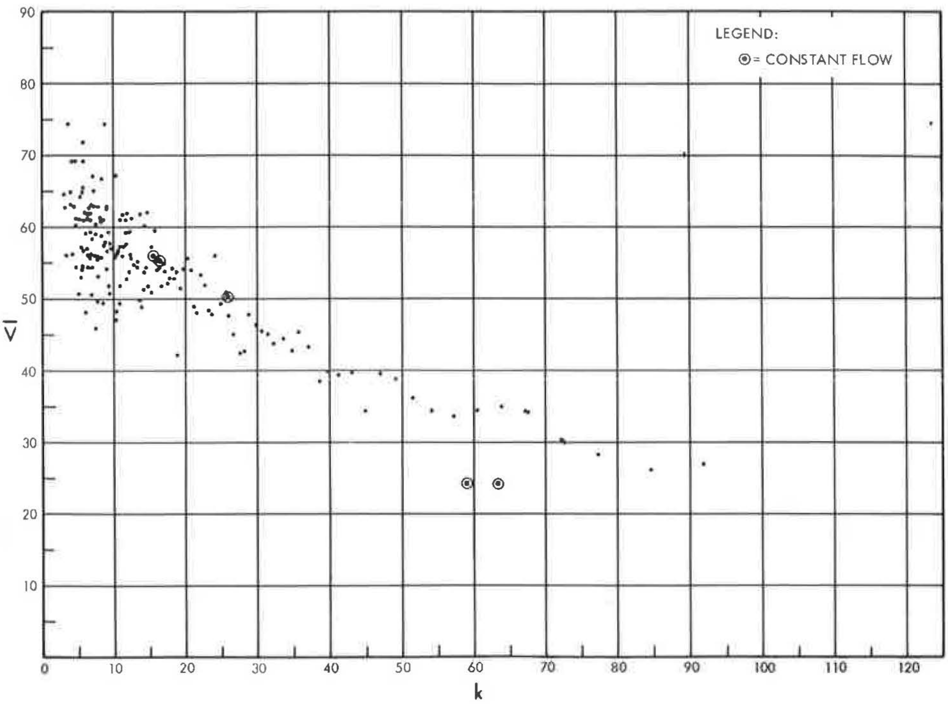

Figure 11. Lane 1, $\bar{v}$ - k plot, cars classified by virtual concentration.

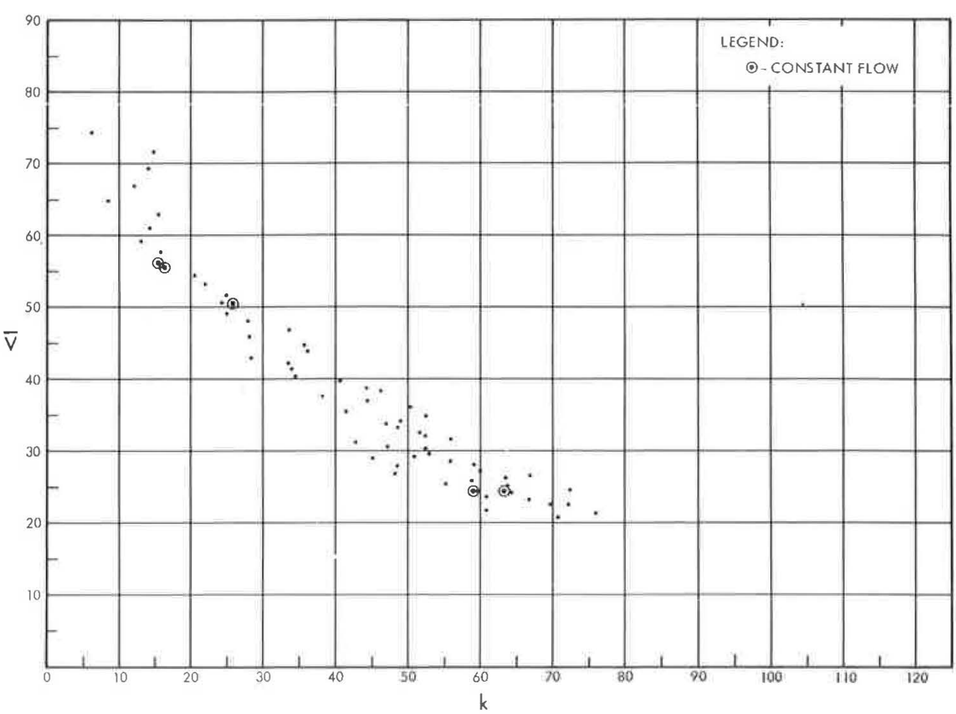

Figure 12. Lane 1, $\bar{v}$ - k plot, cars classified by speed.

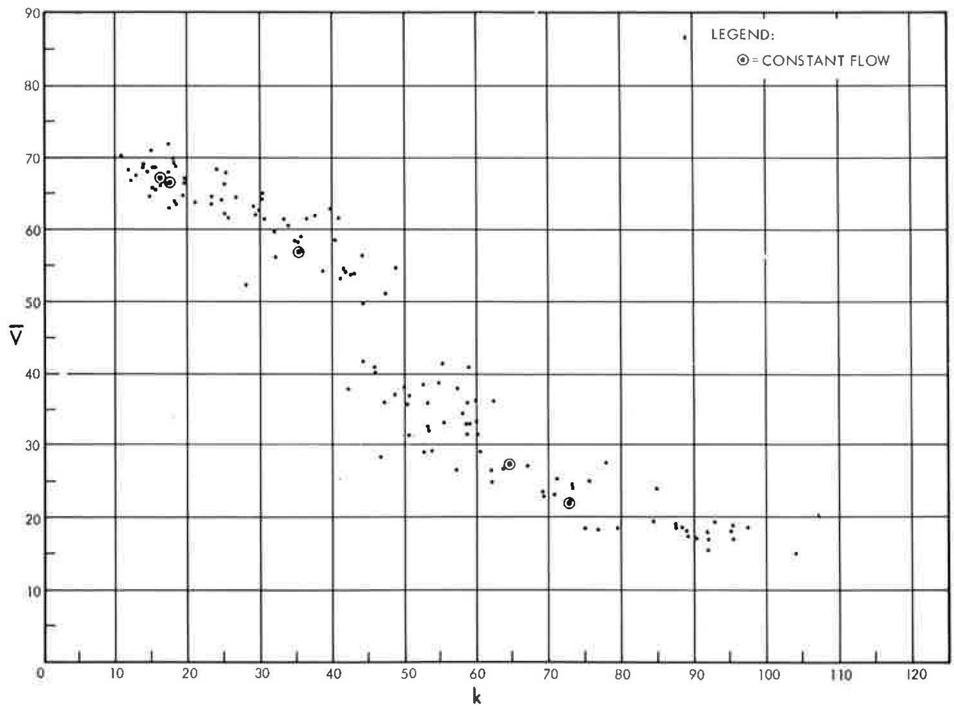

Figure 13. Lane 2, $\bar{v}$ - k plot, $\frac{1}{50}$ hour groupings.

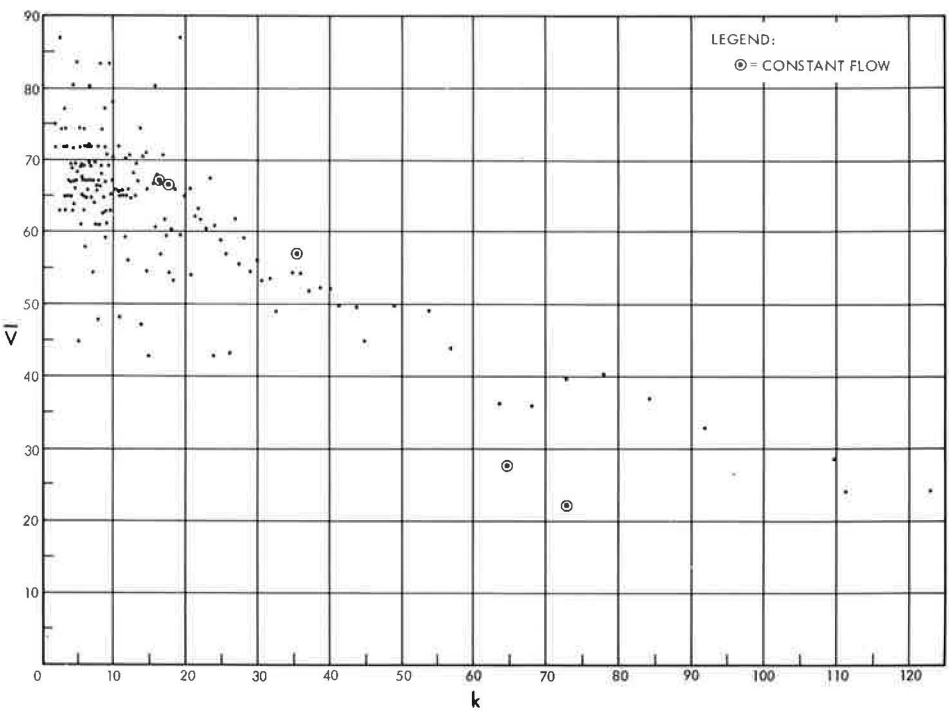

Figure 14. Lane 2, $\bar{v}$ - k plot, cars classified by virtual concentration.

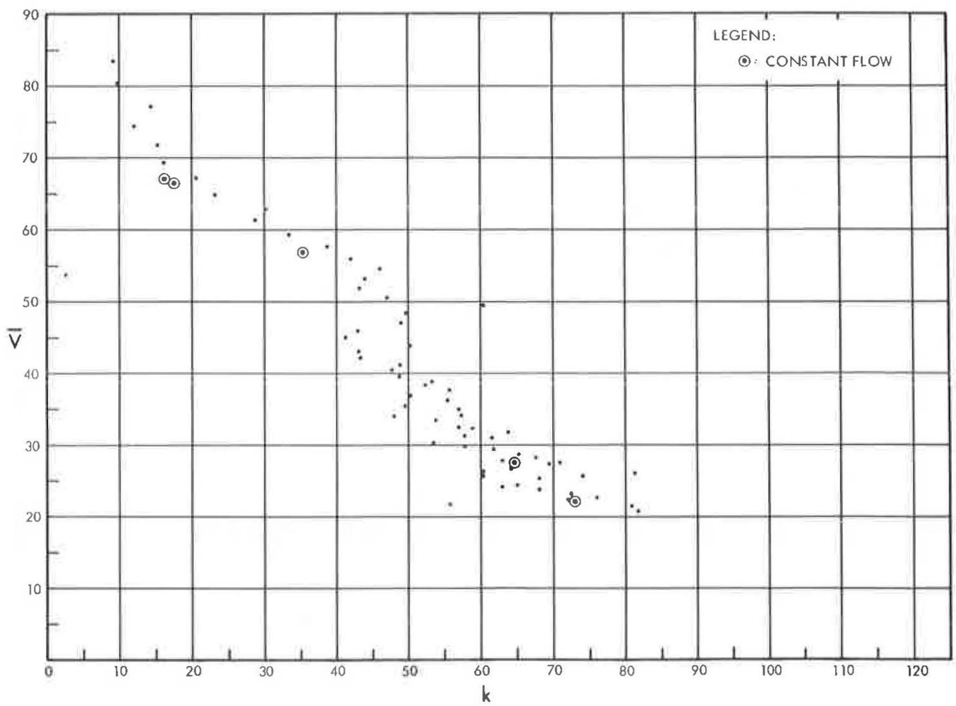

Figure 15. Lane 2, $\bar{v}$ - k plot, cars classified by speed.

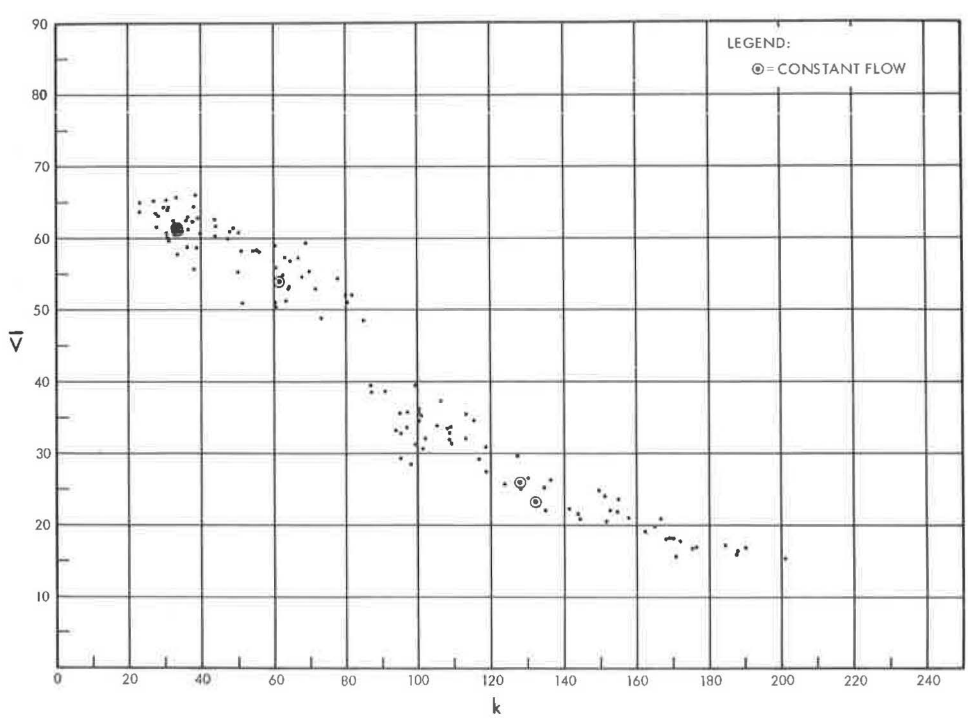

Figure 16. Lanes 1 and 2 superimposed, $\bar{v}$ - k plot, $\frac{1}{50}$ hour groupings.

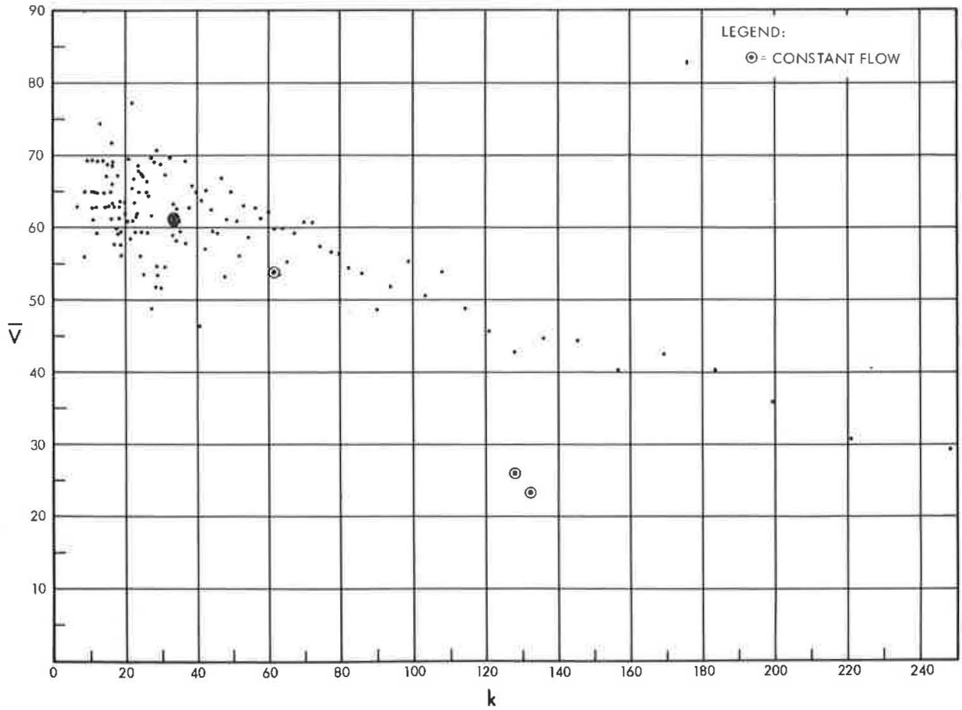

Figure 17. Lanes 1 and 2 added together, v̄ - k plot, cars classified by virtual concentration.

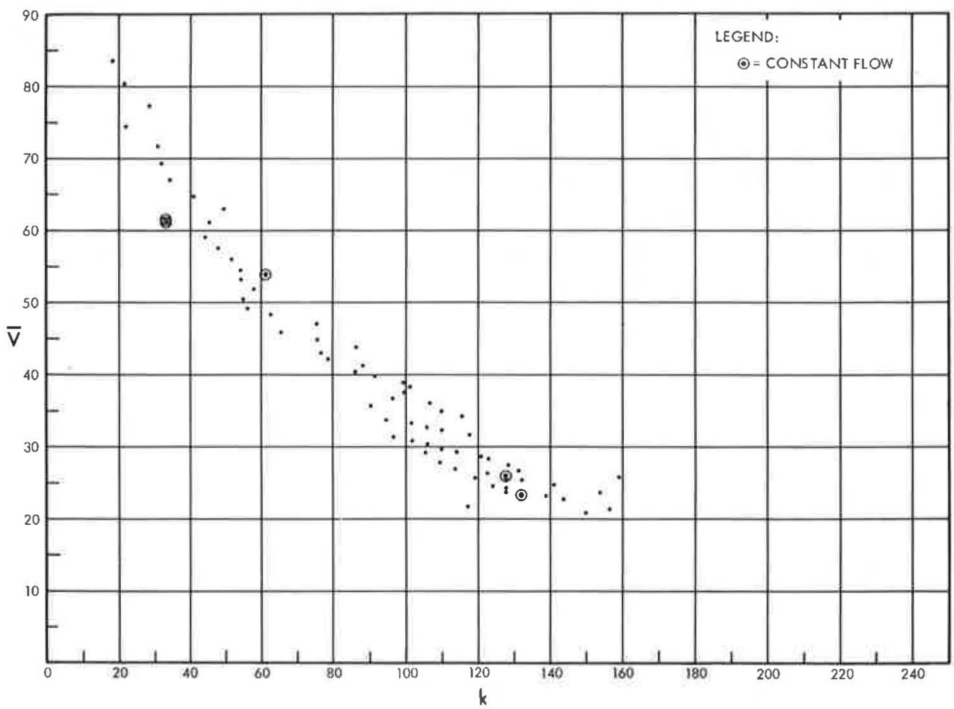

Figure 18. Lanes 1 and 2 added together, v̄ - k plot, cars classified by speed.

TABLE 2
COMPARISON OF METHODS

Plot	Lane	Concentration Range	Methods to Be Validated		
			1/50 Hour Groupings	Virtual Concentration	Speed
$\bar{v}$ - k	1	Low	Agreement	Agreement	Agreement
		High	Agreement	Too high	Agreement
	2	Low	Agreement	Agreement	Agreement
		High	Agreement	Too high	Agreement
	1 and 2 superimposed or added together	Low	Agreement	Agreement	Slightly too steep slope
		High	Agreement	Too high	Agreement
q - k	1	Low	Agreement	Agreement	Agreement
		High	Agreement	Too high	Agreement
	2	Low	Agreement	Agreement	Agreement
		High	Agreement	Too high	Agreement
	1 and 2 superimposed or added together	Low	Agreement	Agreement	Slightly too steep slope
		High	Agreement	Too high	Agreement

points resulting from the constant flow method are superimposed on each graph. Table 2 gives the results from the comparison of the 3 methods to be validated with the method of constant flow periods.

The method of $1/50$ hour groupings gives satisfactory agreement with the standard method. For low concentrations, the virtual concentration method tends to agree with the standard method; for the higher concentration, however, this method yields very high values of flow and speeds relative to the standard. We note that the values of flow are higher than ever reported for flows in a two-lane facility. The method of classification by speeds tends to agree with the standard at the higher concentrations and at low concentrations for the single-lane case. At the low concentrations for both lanes taken together, however, this method results in slightly too steep a slope of the $\bar{v}$ - k curve, and a slightly low slope of the q - k relationships.

The fact that the method of classification by speeds agrees with the constant flow method for the lanes taken by themselves and disagrees somewhat with the constant flow method for both lanes taken together leads us to believe that the speed classification method should perhaps not be extended to the derivation of q - and $\bar{v}$ - k relationships for both lanes taken together.

Analogous procedures were repeated for 11 other two-lane, one-way sites. The concentration range of the data for these sites was smaller in each case than for the site presented. However, within these smaller concentration ranges the comparison of all 3 methods with the standard resulted in the same conclusions as obtained for this site. Therefore, only this site was selected for the purpose of demonstrating the results of this study.

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Discussion

JOSEPH A. WATTLEWORTH, Civil Engineering Department, University of Florida, Gainesville—The authors have presented the results of quite an interesting study. These results will be important to many people who are involved in research on traffic stream flow or in real-time surveillance and control of traffic flow. Frequently some of the measurements that are used by traffic engineers have a somewhat mysterious air to them and are not completely understood. Scientific analyses of these measurements, such as the analyses conducted by the authors, are welcome and important.

The authors have demonstrated that the methods used to obtain data for a particular variable are quite important as well as the variable itself. In the reported study, one of the three data collection procedures that was used (the virtual concentration technique) was rejected because of the inconsistency of data obtained by this technique with the data obtained by the other methods.

Three methods of obtaining flow, speed, and concentration data were compared to a standard method. The standard method involved the use of data for periods in which the flow rate remained relatively constant. Flow was measured directly and speed-trap travel times were used to calculate the space mean speed for the period. Concentration was then calculated from the basic stream flow equation, $q = kv$, where q = flow rate, k = concentration, and v = space mean speed.

In the first method, these same data were collected for time periods of $\frac{1}{50}$ hour, and values for q, k, and v were calculated for each time period. In the second method, the virtual concentration of each vehicle was calculated from the measurement of travel time in the speed trap. Space mean speed for the time period was also calculated from the travel time measurements. Flow rate was calculated from concentration and space mean speed. The periods of analysis were periods of constant concentration. The third method involved the classification of data into groups in which the speeds were essentially constant. In this method, concentration for each period was determined from the travel time samples and the midpoint of the speed interval was used as the speed. Flow rate was then calculated from these values.

The authors found that the results of the first method correlated most closely to the standard method. This, perhaps, should not be surprising because of the similarity of the data collection techniques. One would expect more variation in the test method data because of the smaller time periods used. For this method the optimal density agrees well with values of 40 to 60 vehicles/lane-mile obtained in previous studies (6, 7). This method depends on speed measurements in which the speed trap travel time has an accuracy of ±0.01 sec. For a speed of 60 mph, the travel time over the 30-ft trap is about 0.33 sec. The speed measurements, then, have an accuracy of ±3 percent.

The virtual concentration method yielded flow values that were unreasonably high (2,500 to 3,000 vehicles/hour). This possibly is due to some extremely short time periods included in the analyses. The report did not discuss this possibility. In addition, this method is heavily dependent on headway measurements. Arrival times of each of the vehicles constituting a particular headway have a measurement error that falls in the range from -0.36 sec ($-\frac{1}{10,000}$ hour) to zero. Therefore, the headway has an accuracy of ±0.36 sec. For a headway of 2.0 sec, the accuracy of its measurement is ±18 percent. Because flow rates are based on the inverse of the measured headways, the measured flow rates would tend to be biased somewhat on the high side. These measurement errors would not appear to account entirely for the extremely high flow rates that were obtained in the virtual concentration method.

Some of these same comments apply to the third method, that in which the time slices were based on constant speed values. Flow rate in this method is also determined by headway measurements.

The conclusions of the authors would appear to be valid. The method of constant time slices is the most accurate of the 3 methods tested.

The authors have made an important contribution to the understanding of the measurements of some of the basic variables of traffic stream flow.

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RICHARD ROTHERY, General Motors Research Laboratories, Warren, Michigan—Three methods that have been used for calculating estimates of speed, concentration, and flow on individual lanes of a multilane highway by previous investigators are compared to a fourth technique. Because this latter technique is used as a standard, it is of value to focus attention on it here.

The procedure that the authors have used is well known in the field of time series analysis (8). In the analysis of a time series of events (in this case, vehicle arrival times), a primary objective is to determine the existence of trends or deviations from a constant mean flow that may be present in the data. One particularly effective technique that reflects this gross property is a graphical presentation of the data where the total number of vehicles that have passed an observation point at or before a time, t, is plotted against t. Examples of this graphical technique in analyzing traffic flow may be found in the literature (2, 9, 10).

The data presented and analyzed by the authors are of particular interest because they use this approach to establish periods during which the mean flow may be regarded as constant. Five such constant flow periods were obtained from the data and these 5 estimates of flow together with the corresponding estimates of concentration form the skeleton of a flow-concentration "curve." Possibly the most interesting facet of this paper is that the estimates of flow and concentration using the method of constant time intervals or constant speed classifications agree with this curve. Such agreement implies that flow and concentration fluctuations follow the same relationship around the mean.

The method denoted as using virtual concentrations deserves special comment. Virtual concentration is a misnomer because the data in this case are classified into groups according to their spatial headway in intervals of 5 ft. That this technique leads to speed estimates that are biased has been known. The bias is inherent in the technique. It results directly from dispersion in the distribution of spacings for a given speed even if such dispersion were to be symmetrical and speed-independent. The effect is to bias speed estimates toward higher values at high concentrations and lower values at low concentrations. The inadequacy of this approach has also been pointed out by Edie and Foote (3).

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SIDNEY WEINER, Federal Highway Administration—This paper presents a rather simple, although useful, technique in the exploratory validation of seemingly diverse methods for obtaining joint measurements on freeway characteristics, namely, flow, concentration, and speed. This is accomplished by first establishing a standard method that isolates periods of constant traffic flow. Thus, if q can be considered to be constant, the observed concomitant variables, speed and concentration, can then be regarded as properly identified.

Actually, as is indicated by Breiman and Lawrence (2), one desires as reliable a measurement as possible for flow rate. If the measurements were based on a short period, then fewer samples are involved leading to a considerable variation in the calculated quantity whether it be flow, speed, or concentration. To reduce such "short-scale" variations, the standard method first isolates those time periods during which traffic flow data exhibit a stationary behavior. This then permits one to form an estimate of q based on a longer stretch of the stationary flow than otherwise possible. The statistical variation of such an estimate is thereby reduced, and our reliance on this figure is accordingly increased. Concomitant measurements on such a flow rate give us a useful representation of the overall behavior of the freeway. It is noted that this method yields only 5 data points to be used as bench marks as given in Table 1 and plotted on each of the 18 figures. It is remarkable that only these few points result from 160 min of observation.

In the next step, the authors plot the set of points obtained by each of the frequently employed methods on separate graphs and visually compare each set with the standard set. This comparison is clearly given in Table 2 indicating that the method of categorizing traffic flow data by virtual concentration for each car is invalid because it yields very high values of flow and speed at higher concentrations. For measurements taken on individual lanes, the 2 other methods, one based on $\frac{1}{50}$ hour groupings and the other based on speed interval classification, were both found to be in agreement with those points presented by the constant flow or standard method.

On the face of it, one gets the clear impression that the 3 methods, the constant flow, the categorization by $\frac{1}{50}$ hour interval, and the categorization by speed interval, exhibit qualitative agreement. However, it is implicit that there is certainly a distinction among the underlying models. If we examine the q - k curves, for example, the constant flow method considers the flow to be approximately constant for certain ranges of the concentration, while those based on the other 2 methods consider the concentration to be approximately constant for a relatively small time interval or small speed interval. The assumptions underlying the other 2 models are not in disagreement with the assumption underlying the standard model—they are merely less stringent. It may be desirable to develop a theoretical analysis to examine these methods so as to determine to what extent any method may underestimate or overestimate the underlying relationships or to establish appropriate criteria in their selection.

One final remark may be added. This study was based on traffic analyzer data measuring traffic variables past a point for a given time period. At present we are obtaining spatial data involving one-half mile or more of traffic. We, thus, can obtain direct estimates of the concentration and better estimates of the other parameters. With such improved data, more valid estimating procedures can be provided for these traffic parameters.

A. V. GAFARIAN, R. L. LAWRENCE, P. K. MUNJAL, and J. PAHL, Closure—The authors would like to thank Rothery, Wattleworth, and Weiner for their discussions and suggestions concerning this paper.

In their discussions both Rothery and Weiner focus on the standard method that uses data from periods of constant traffic flow. We note that the technique used to isolate these periods represents a statistical analog of the graphical technique discussed by Rothery. This nonstandard statistical testing procedure that was developed by Breiman and Lawrence (2) consists of a sequential test of the hypothesis that there is no change in average flow and an estimation of where the change in flow occurred when the hypothesis is rejected. The advantages of this procedure over the original graphical technique are that it could be used easily on large amounts of data, it was reproducible, and the constant flow intervals chosen did not tend to exclude occasional large random fluctuations in flow.

As Rothery mentions, the inadequacy of the virtual concentration method has been pointed out by Edie and Foote in their experimental studies of traffic flow in tunnels. However, their study concerned a single lane with no passing situation, and it was felt by the authors that a test of this method on a multilane facility would be of interest. It is clear that, if the distribution of spacings were speed independent, a bias would result from this method; however, if such independence does not hold, it is not readily apparent that the method is biased.

Wattleworth's error analysis is appreciated and forms a useful addition to the paper as presented. We feel there are 2 points that should be clarified: (a) The error figures presented in the analysis represent the maximum possible error, and in general, the measurement error is considerably smaller; and (b) for the most part we are concerned with mean values of the measured variables, and the errors in the estimations of these means are, of course, substantially smaller than the errors of the individual measurements.

Weiner's comment on the desirability of developing a theoretical analysis of the accepted models to determine potential biases is well taken. Such analysis, in combination with spatial data now being obtained by the FHWA, may lead to establishing the relative accuracy of the accepted methods.