Total Avg Delay					Percentage of Stopped Vehicles				
	Prediction Method					Prediction Method			
Measured	British	Swedish	Australian	NCHRP	Measured	British	Swedish	Australian	NCHRP
26.5	20.4	19.7	21.3	32.3	60.5	73.0	68.9	68.9	67.8
-	Yes	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes
16.8	13.0	8.0	10.4	17.4	22.1	15.7	12.8	12.3	14.5
-	No	Yes	Yes	No	-	Yes	Yes	Yes	Yes
-	8.4	9.3	7.6	12.2	-	15.8	12.7	14.2	12.6
-	12.4	12.4	11.6	15.9	-	19.8	16.5	18.7	15.5
-	9	10	11	20	-	25	22	19	21
-	21	20	19	10	-	5	8	11	9
-	+6.5	-8.2	-1.4	+7.3	-	-12.25	-24.46	-18.85	-21.28
-	+0.98	+1.76	+1.32	+0.59	-	+0.998	+1.234	+1.153	+1.207
-	0.76	0.83	0.82	0.61	-	0.70	0.71	0.64	0.79
-	No	Yes	No	Yes	-	No	No	No	No
-	Yes	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes

We also wish to thank Louis Torregrosa, David Kuan, and Tsutomu Imada for help in the final preparation of this paper.

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Speeds and Flows on an Urban Freeway: Some Measurements and a Hypothesis

V.F. HURDLE AND P.K. DATTA

Speeds and flows were measured in a bottleneck section of a six-lane urban freeway near Toronto, Canada, on three successive mornings. The average capacity flow was 1984 passenger-car units per lane per hour, very close to the traditional value of 2000, but at an average speed of 80 km/h (49 mph), a much higher speed than is usually indicated in textbooks and manuals. Frequency distributions of the observed flows and speeds at capacity are reported and used as a part of a general discussion of the meaning of the term "capacity." In order to study the relationship between speed and flow, measurements were also made before the section reached capacity. At flows less than three-fourths of capacity, the average speed was 100 km/h (62 mph); there was no apparent decrease in speed as the flow increased. Between three-fourths of capacity and capacity, a gradual reduction in speed from 100 km/h to the 80-km/h speed observed at capacity was expected, but no such smooth speed transition was observed. The nature of the data leads to the hypothesis that the average speed on an urban freeway with a speed limit, where neither grades nor curvature is severe and where the traffic is not affected by downstream bottlenecks, may not vary as a function of flow but may depend only on whether the traffic is or is not a capacity flow discharged from an upstream queue.

A good understanding of the way in which speed varies with flow is an essential prerequisite to the creation and use of any level-of-service concept for freeways. Unfortunately, misinformation about this relationship abounds. In this paper, we present some data and some ideas that we hope will help to combat some of the misinformation. As we studied the data, however, we found ourselves questioning not just the things we had intended to challenge, but also some of the things we ourselves believed. What was intended to be a straightforward presenta-

Figure 1. Typical speed-flow relationship.

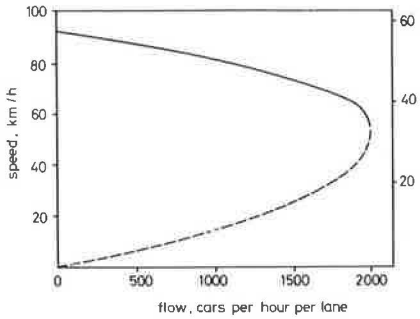


Figure 2. Speed-flow relationships and data points.

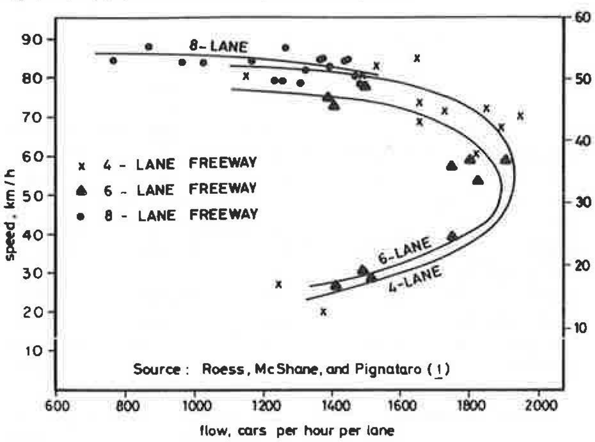
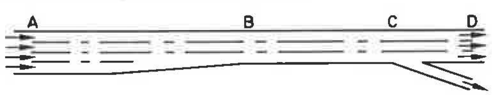


Figure 3. Simple freeway bottleneck.



tion of a simple empirical study gradually became instead an essay that asks more questions than it answers.

As an introduction to both the data set and the unanswered questions, consider Figure 1. The speed-flow relationship shown there is not based on any data set but is our impression of conventional wisdom, the sort of curve one often finds in books and papers or on the blackboard in transportation engineering classes.

That Figure 1 is not entirely correct is immediately obvious. The upper branch of the speed-flow relationship cannot have a negative slope at all points but must be horizontal at very low flows; anyone who drives knows that the first car on a multilane road does not slow down just because a second car appears. It would also seem to be obvious that the speed does eventually drop. What is not obvious, however, is how large the flow becomes before the drop begins or how far the speed drops. Some theorizing may be possible, but these questions must ultimately be answered by making measurements.

Over the years, many measurements have been made and various curves have appeared in the literature or have been circulated privately. Some indicate a rapid drop-off in speed near capacity, whereas others do not; some show a single, continuous curve, whereas others show the upper and lower (dashed) branches as separate curves. No attempt will be made here to summarize this large number of reports (although we will pause to bemoan the fact that many are of limited use because detailed information about the locations and traffic conditions is not readily available). One recent report (1), by Roess, McShane, and Pignataro, is of particular interest here, however, because it shows high speeds at flows of at least three-fourths of the roadway capacity. A speed-flow relationship from this report is reproduced in Figure 2.

This curve is a major step in the right direction; we hope it will lay to rest forever the myth that speeds on North American freeways vary as a function of flow even at moderate flows. [On freeways without speed limits or with speed limits well above 100 km/h (62 mph), the situation may be quite different. Thus the applicability of some of what we say must be limited to the North American scene, where the fact that it becomes increasingly difficult to drive at very high speeds as the flow increases is not a serious issue.] However, we were still not satisfied when this curve appeared. We did not believe that capacity flows on urban freeways typically move at speeds of the order of 50 km/h (30 mph) but rather that they move at something like 70-80 km/h (45-50 mph). This disbelief was based primarily on the personal experiences of one author as an engineer and on extensive examination of speed and density contour charts for California freeways [2; reports on various Los Angeles and San Francisco area freeways by the California Department of Transportation (Caltrans)]. The Ontario data in this paper were gathered in the hope that they would confirm this view. This they do, but they also raise some new questions that we had not forseen.

SOME PRELIMINARIES

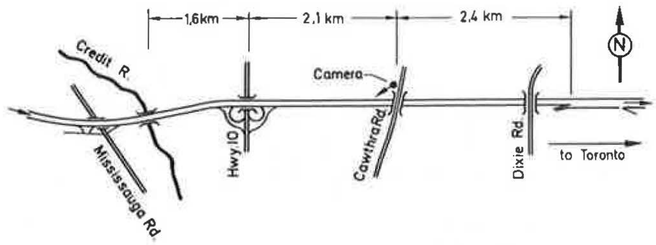
Before the data are presented, it is essential that authors and readers agree on just what they represent or at least that the readers understand the authors' intentions. Therefore it is necessary to explain what we mean by capacity, speed-flow curves, etc. We shall do this by considering what happens at the very simple freeway bottleneck shown in Figure 3. Traffic enters from the left at some rate λ. Between B and C, however, the freeway is narrower, so it is possible that λ vehicles per unit time cannot get through but only some smaller flow, say, 3μ vehicles per unit time, where μ is the average of the capacities of the three individual lanes.

The remaining $\lambda - 3\mu$ vehicles per unit time will queue up behind point B and await their turns to pass through the bottleneck. Needless to say, they will not move at high speeds while waiting but will travel very slowly or in a stop-and-go fashion and the drivers and passengers will complain about the congestion. [This condition is known as level-of-service F (2-4).]

Much of what would happen on this stretch of freeway can be represented by a speed-flow curve like Figure 1 if we measure the flows in vehicles per lane per hour rather than in vehicles per hour. Then the flow at the nose of the curve must be μ, the capacity of one lane, and the lower, dashed curve obviously represents the congested conditions encountered within the queue.

The conditions in section BC, the bottleneck, can be anywhere on the upper part of the curve but never on the lower (unless an accident or other incident occurred downstream, in which case BC would no longer be the controlling bottleneck). Conditions in section AB, on the other hand, can be on either branch, depending on whether the point observed is

Figure 4. Location of observations.



within or behind the queue, but can never lie to the right of $3\mu/4$ on the lower branch, since it is physically impossible for the average total flow within the queue to exceed the bottleneck capacity (3μ).

It is, of course, possible to observe average lane flows between $3\mu/4$ and μ behind the queue in section AB but not for very long, since the queue would then grow and the conditions at the observation point would abruptly change to the lower branch of the curve as soon as the end of the queue arrived.

It should be clear from the preceding discussion that it is very difficult to obtain enough data at any one observation point to plot the entire speed-flow curve. It would seem, in fact, to be virtually impossible unless one regulated the flow by metering ramps both upstream and downstream. In the simple experiment described in this paper, the observations were all taken within the bottleneck section, so all the data points lie on the upper branch of the curve. Furthermore, the flow increased from half of capacity to capacity in about half an hour, so each day of observation provided rather little data at flow levels approaching capacity, the most interesting region of operation.

The two branches of the speed-flow curve in Figure 1 join to form a single, smooth curve. It should be noted, however, that the nose of the curve is not necessarily smooth nor even continuous. The two branches may be quite separate curves, one the result of driver behavior while in queue and the other the result of quite different behavior when not in queue (5-8).

Whether the two branches form a single, smooth curve is not an issue we wish to address in this paper, but it should be noted that even if they do, one should not expect to see a sequence of observations that traverses around the nose of the curve (7,8). Such a sequence would represent a gradual transition between conditions within and outside of a queue at capacity or near-capacity flows. This is something that could happen on a real roadway only under very extreme conditions, if at all. Certainly it could not happen in the kind of uncontrolled experiment described here.

A second point to be noted is that the data points cannot be expected to lie nicely along some smooth curve but will be scattered about any curve one may draw. Thus, the speed-flow curves we are talking about are really some kind of average. In this paper, we shall presume that the scatter is entirely stochastic, the result of differences between the individual drivers and the vehicles on the roadway. In fact, however, there are probably also systematic departures from "average" behavior because of differences between increasing and decreasing flow conditions, cyclic fluctuations in operating conditions, etc. We shall not worry about such things in this paper; our interest here is the general shape of speed-flow curves and the magnitude, rather than the pattern, of variations in capacity flows. Systematic departures from average behavior may, however, be important to those whose work requires more detailed knowledge of freeway flows. Conversely, the stochastic variations may be sufficiently large to make such detailed knowledge very difficult, if not impossible, to obtain.

DATA GATHERING

The data presented in this paper were collected on the Queen Elizabeth Way, a six-lane freeway in Mississauga, Ontario, Canada (9). All data are for eastbound, weekday morning traffic passing beneath Cawthra Road on May 25, 26, and 27, 1977, bound for Toronto. This location, shown in Figure 4, is near the middle of a long bottleneck section that begins at the on ramp from Highway 10 and ends near Dixie Road, where a fourth eastbound lane is added. The lanes are 3.66 m (12 ft) wide with ample side clearance, grades are minimal, there is no horizontal curvature, and the speed limit is 100 km/h. All observations were made in good weather.

The Highway 10 on ramp is metered but not severely enough to completely eliminate upstream congestion. There is also a secondary bottleneck upstream, where the freeway crosses the Credit River, that sometimes meters the flow sufficiently to keep flows at the observation site below capacity.

Neither the metered ramp nor the secondary bottleneck was desirable for this sort of experiment, since we wanted to observe capacity flows. However, sensors operated just downstream from the Credit River Bridge by the Ontario Ministry of Transportation and Communications usually indicate speeds less than 32 km/h (20 mph) for at least an hour during the morning peak, which indicates that a queue almost always builds up behind the bottleneck where our measurements were taken. Thus, since the flow patterns observed on the three days of data gathering were very similar, we feel confident that we did measure capacity flows. However, future experiments of this type should include observation of upstream and downstream traffic, so that there can be no doubt as to whether the flows observed are capacity flows.

All observations were taken from the bridge or bridge approaches at Cawthra Road. All flow data are based on 2-min counts made by two observers located above the freeway lanes on the sidewalk along the west side of Cawthra Road. These observers were clearly visible to drivers, but they were not particularly conspicuous and the presence of pedestrians on the bridge is not unusual, so we do not feel that the presence of observers had an appreciable effect on freeway speeds. If there was an effect, it would almost certainly have been to slow traffic down, an effect that does not seem likely in light of the experimental results.

Speeds were measured by time-lapse photography by using a 35-mm camera equipped with a motor drive and intervalometer. The camera was set up on the abutment fill at the north end of the bridge, a location where very few drivers would notice it. In order to keep film and data-processing costs low, we took a sequence of four photographs every 2 min. The individual photographs were taken 2.63 s apart. Once the flow reached capacity, the 2-min sampling interval was changed to 5 min; this allowed us to record data from 6:00 to 9:00 a.m. on a single film cassette 10 m (33 ft) long.

The photographs were projected onto a grid and the speed of every vehicle that appeared on the grid in at least two successive pictures was measured. The gridded zone was approximately 88 m (270 ft) long with grid lines at 3-m (10-ft) spacings. The arithmetic mean of the speeds of all the vehicles caught in a single series of four pictures was associated with the count during the 2-min interval immediately preceding, or including, the time when the pictures were taken to give a single data point for the speed-flow relation. The plotted speed was usually the average of the speeds of four to six vehicles but sometimes the speed of only one vehicle at low flows and the average speed of as many as nine vehicles at high flows. It is a space-mean speed rather than the time-mean speed obtained by most sampling methods.

This procedure kept the film cost low and avoided the problem of losing data during film changes. However, more frequent sampling of speed would be desirable.

No formal check on the accuracy of the speed measurements was made. However, a car was driven through the section at various times on another day at speeds consistent with the data. Speeds measured by detectors at other locations on the Queen Elizabeth Way at moderate to high flow levels are also consistent with our data, so we have no reason to believe there was serious error in the speed-measurement procedure. In any case, errors of a few kilometers per hour would not affect the nature of our conclusions unless the error was different at different flows, a problem unlikely to occur with our procedures.

Our primary interest at the beginning of this research was speed, not capacity, so trucks were not counted separately. Later, when we examined the data, we decided that we would like to be able to express the flows in passenger-car units. This was accomplished by counting cars and trucks on the film. Since this is a sampling procedure rather than a continuous count and because there was a very noticeable variation in the truck percentage with time of day, it was necessary to fit a curve to the observed data. The fourth-degree polynomial shown in Figure 5 is therefore only a rough approximation of the actual percentage of trucks, but it seemed adequate for the purpose of estimating equivalent passenger-car flows. Since the roadway is very nearly level, each truck was considered equivalent to two passenger cars (3,4).

FLOW MEASUREMENTS AND CAPACITY

The average flow during each 2-min count interval, averaged over the three days, is shown in Figure 6. In this figure and all that follow, the flow is expressed in equivalent passenger-car units per lane per hour; the raw counts have been averaged over the three lanes and then adjusted on the basis that one truck is equivalent to two passenger cars (3,4). The flows observed on the individual days are shown in the lower parts of Figures 7, 8, and 9.

It can be seen that the flow increases steadily and quite rapidly from about 6:20 until shortly before 7:00 and then levels off and fluctuates about a mean of approximately 2000 PC/(lane•h) until nearly 9:00 a.m. This is what one would expect to see in a bottleneck section: the flow stops increasing when the capacity is reached, not because the demand levels off but because the roadway cannot carry any more traffic.

There is, of course, a good deal of fluctuation evident in the capacity flow observations. The capacity of a roadway is determined by the driving style of the individual drivers, so counts of capacity flows must necessarily be random variables. Some knowledge of their distribution would thus seem to be necessary if one is to understand what the word "capacity" means.

The distribution of the 120 flow observations made between 7:00 and 8:20, the period we feel is clearly and conservatively identifiable as a period of capacity flow, is shown in Figures 10 and 11. A normal distribution with the same mean and variance is also shown in Figure 11.

The mean capacity is 1984 PC/(lane•h); the individual means for the three days of observation are 1927, 2004, and 2020 PC/(lane•h). A 90 percent confidence interval for the mean capacity is 1953-

Figure 5. Approximation of truck percentage used to calculate equivalent passenger-car flows.

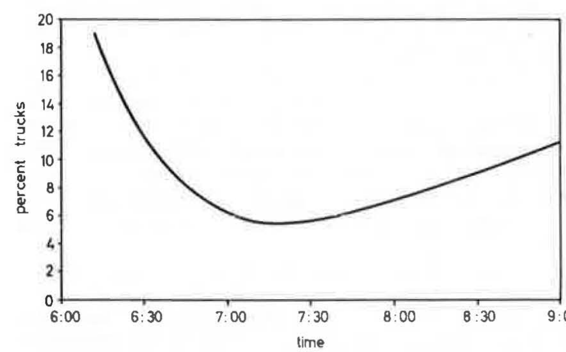
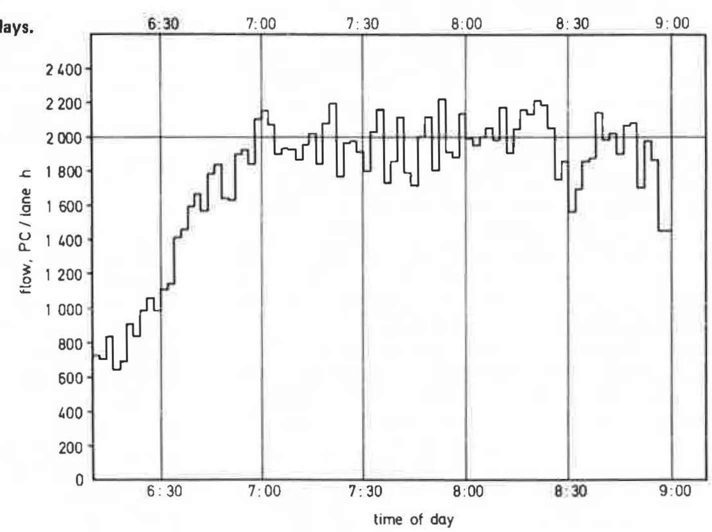


Figure 6. Average of flows measured on three successive days.



2015 PC/(lane•h), a range that includes the commonly accepted value of 2000.

It can be seen in Figures 10 and 11 that flows throughout the range from 1750 to 2200 PC/(lane•h) were frequently observed, whereas flows outside of this range were relatively rare but did occur. It is important to understand that the shape of the distribution was determined not only by the characteristics of the roadway and the drivers, but also by the way in which we made our counts. We chose to

Figure 7. Speeds and flows observed on Wednesday, May 25, 1977.

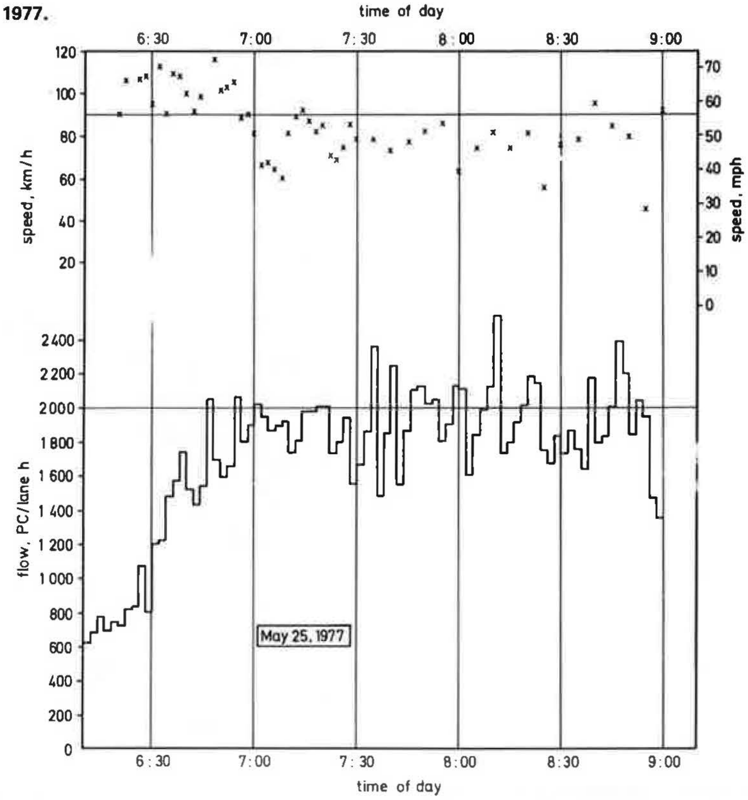


Figure 8. Speeds and flows observed on Thursday, May 26, 1977.

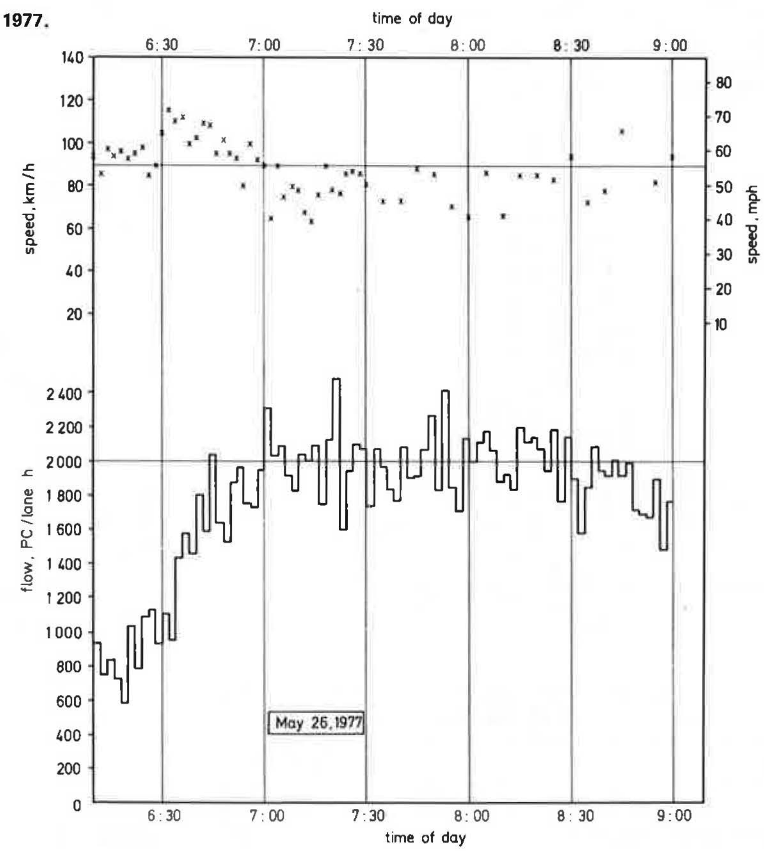


Figure 9. Speeds and flows observed on Friday, May 27, 1977.

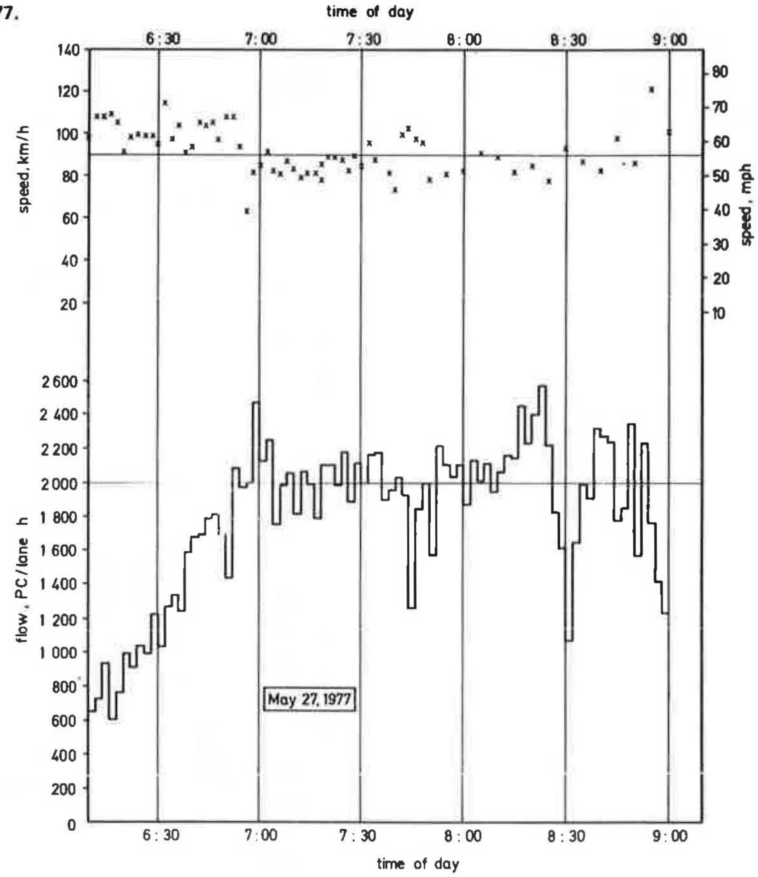


Figure 10. Frequency histogram for capacity flows.

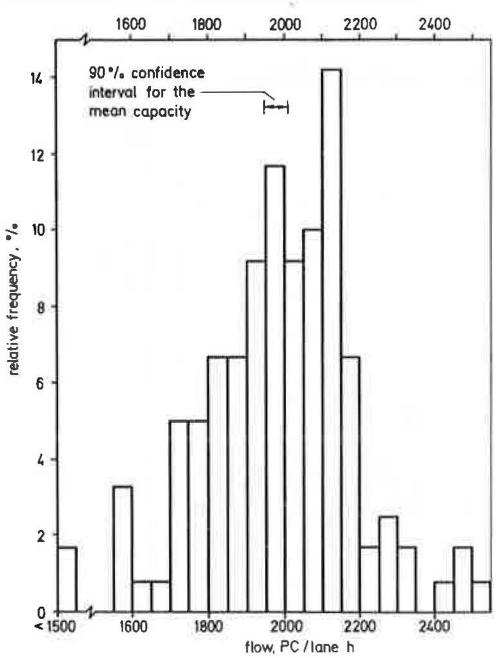
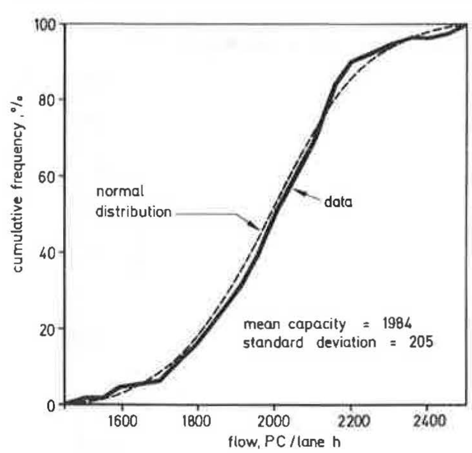


Figure 11. Cumulative frequency polygon for capacity flows.



make 2-min counts and then computed the average flow over each 2-min interval by multiplying the count by 30. (We also made a truck correction, which increased the variance-to-mean ratio of the calculated flows by 11 percent. For the sake of simplicity, the effect of that adjustment will be ignored in the discussion that follows.) Had we instead made 1-min or 5-min counts, the average capacity flow would still have been 1984 PC/(lane•h), but Figure 10 would have had a quite different appearance.

If the counts made during different time intervals are assumed to be independent random variables from the same distribution--a reasonable assumption for capacity flows--it is easy to see the effect of changing the length of the count interval. We made 2-min counts and found that the standard deviation of the flows thus measured was 205 PC/(lane•h). Had we made our counts m times as long, one would expect the standard deviation of the flows to be $1/(m)^{1/2}$ as great, as shown in the second column of Table 1. The implications of this fact are apparent in the right-hand side of Table 1, where we have also assumed that the counts are normally distributed. Here it can be seen that very high flows will be observed rather often if the counting interval is short but almost never if it is long. For example, the average flow would exceed 2200 PC/(lane•h) in about one out of every four 1-min counts but in only one out of every twenty 5-min counts, one out of every five hundred 15-min counts, and in less than one out of every ten thousand 0.5-h counts.

We have defined capacity as the average flow through a bottleneck when a steady supply of cars is assured by the existence of an upstream queue. We think this is a useful definition and that it is compatible with the definition in the Highway Capacity Manual (3). However, it is clearly not the only possible definition. One might say that the capacity is the highest flow ever observed or perhaps the 90th-percentile flow. However, it is clear from Table 1 that such definitions are only usable if the length of the counting interval is specified. Even if a suitable length could be agreed on, we doubt that these are useful definitions.

At the lower end of the distribution, however, there is a more interesting possibility. One might define a "practical" capacity as the flow that will manage to get through at least P percent, perhaps 90 or 95 percent, of the time. Again, the length of the count interval must be specified, but it is easy to see that someone designing a traffic control system might be interested in such a number. Unfortunately, it is also easy to see that a designer interested in short time intervals must either choose a value considerably lower than the average capacity or run a high risk of system failure.

Still another possible definition of capacity is based on the idea that considerably higher flows are possible before a queue forms than can be maintained after it forms. [See, for example, Interim Materials on Highway Capacity (4, p. 256).] Under such a definition, the capacity is that higher flow, not the average flow out of the queue that we have called the capacity.

While this is a conceptually sound definition of capacity, we do not feel that it is a good definition. In the first place, we do not see the usefulness of a capacity that can only be used for an extremely short period of time (unless one can implement far more delicate traffic control schemes than are now in use). In the second place, we question the existence of these considerably higher flows. Certainly they are not evident in Figures 6, 7, and 8. Figure 9 does show a very high flow just before 7:00, but similar flows were observed later as well. To really know whether such higher flows occur prior to the formation of a queue, one would have to have many days' data, not just three. One might also want to use a shorter count interval than 2 min. On the basis of the data presented here, we can only say that we see no reason to be believers.

Table 1. Effect of counting-interval length on observed frequencies of high flows.

Interval Length (min)	SD of Flow Measurements	Percentage of Flow Measurements Exceeding Q PC/(lane·h)			
		Q = 2100	Q = 2200	Q = 2300	Q = 2400
0.5	410	39	30	22	15
1	290	34	23	14	8
2	205	28	15	6	2
5	130	18	5	0.7	0.07
10	92	10	0.9	0.03	x[a]
15	75	6	0.2	x	x
30	53	1.4	x	x	x
60	37	0.1	x	x	x

[a]x indicates less than 0.01 percent.

SPEED-FLOW RELATION

Figure 12 shows the average speed and the corresponding flow for each of the 144 observations made between 6:10 and 8:20 on the three days. As was expected, the speed seems to be virtually constant until the flow reaches at least 1500 PC/(lane•h). In fact, if one tries to fit a straight line to the data by linear regression, the slope turns out to be positive, not only for flows up to 1500 PC/(lane•h), but even if all flows up to 1700 PC/(lane•h) are included. For flows above 1850 PC/(lane•h), however, the speeds are clearly lower; in only one of the 78 observations at a flow of more than 1850 PC/(lane•h) was the speed as high as 100 km/h, the speed limit and the average speed observed when the flow was less than 1700 PC/(lane•h).

This research was undertaken with the primary purpose of studying the pattern of speed reduction that occurs as freeway flows increase. One might reasonably expect such research to lead to a speed-flow curve, but none appears in Figure 12. One reason is that we want readers to examine the data themselves, uninfluenced by any curve we might draw. There is, however, another more basic reason: We simply do not know how to draw a curve that satisfactorily represents the data shown in Figure 12.

To illustrate the difficulties, we have drawn four candidate curves in Figure 13. The lower, congested branch has been omitted in each case,

Figure 12. Speed and flow observations.

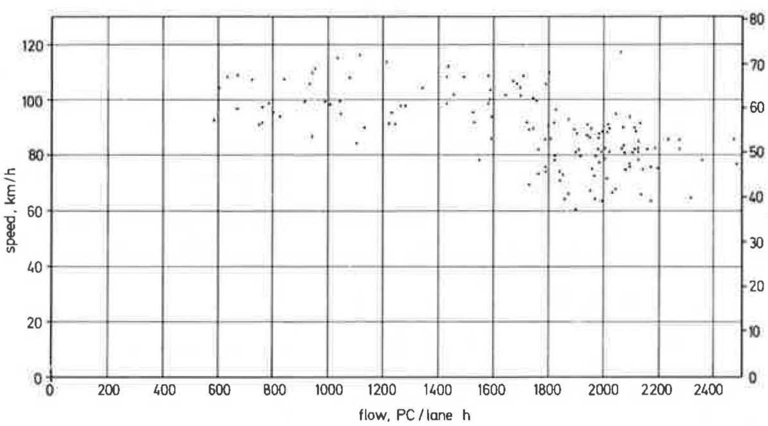
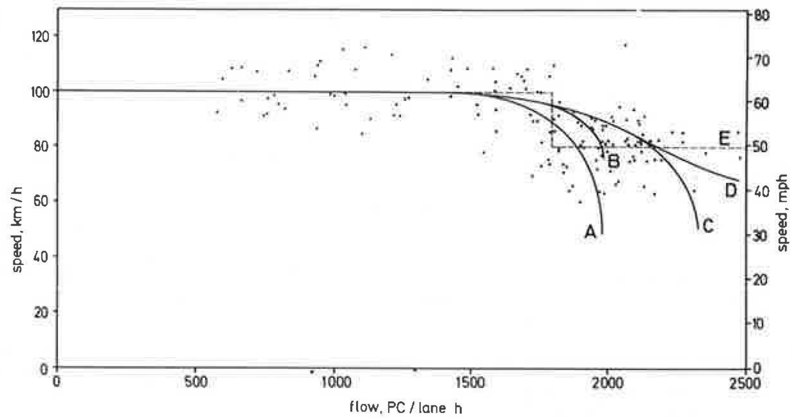


Figure 13. Some possible shapes for a speed-flow curve.



since we have no data for congested flows. Curves A, B, and C are all of the same general shape as those in Figure 2: a horizontal line up to about three-fourths of capacity and then a sharp bend. Each curve becomes vertical at some flow that might be regarded as the capacity. For curves A and B, this capacity is the average capacity flow observed in the experiment; i.e., it is the capacity of the roadway as we have defined the word. In curve C, on the other hand, a higher capacity has been used, a flow closer to the maximum flow that was observed.

Obviously none of these three curves adequately represents the data; an analyst with no a priori ideas about the shape of the curve would surely draw a curve more like D. This did not bother us; our prejudices favored a curve like D anyway.

What did bother us, however, is the fact that curve D does not reflect the nature of the data very well either. If one examines curve D closely, it becomes apparent that the curve systematically predicts speeds higher than those actually observed at flows between 1830 and 2000 PC/(lane•h). There are 30 observations in this range but not a single one lies above the curve. Furthermore, if one were to lower the curve enough to obtain reasonable predictions in this range, the resulting curve would systematically predict speeds that were too slow at flows greater than 2000 PC/(lane•h) and/or less than 1700 PC/(lane•h). Ultimately, we came to the conclusion that no reasonably smooth curve does an adequate job of representing the data. If one must have a curve, it must look more like "curve" E.

Curve E, in fact, fits the data quite well, certainly better than any conventionally shaped curve one might draw. This is disturbing; one must ask why it should be true.

A partial explanation lies in the way in which the data were gathered. Each speed measurement represents only what was happening during a particular 8 s within the 2-min count interval, not an average over the entire length of the count interval. In retrospect, we recognize this as a defect in our experimental procedure. Clearly we could have reduced the scatter in the data by averaging the speeds measured on several pairs of photographs taken at regular intervals throughout the 2-min count interval.

However, this defect in the experimental procedure is clearly not an adequate explanation for what happened. If the speed really dropped significantly as the flow increased, we should have observed more low speeds during intervals with high counts than during those with low counts. Except for the sudden drop in speed at about 1800 PC/(lane•h), Figure 12 shows absolutely no evidence of such a phenomenon. In fact, the average speed for the 42 observations made during intervals with flows in excess of 2000 PC/(lane•h) was faster than the average for the 35 observations made during intervals with flows between 1800 and 2000 PC/(lane•h). This surprising result was almost certainly a matter of chance rather than a thing likely to be observed in all such experiments (though one could hypothesize that clusters of risk-prone drivers produce both high speeds and high flows). It seems very unlikely, however, that we would have obtained such a result if any of curves A, B, C, or D represented the true mean speed. That the true mean speed at capacity was in the neighborhood of 50 km/h (30 mph) seems even more incompatible with the data.

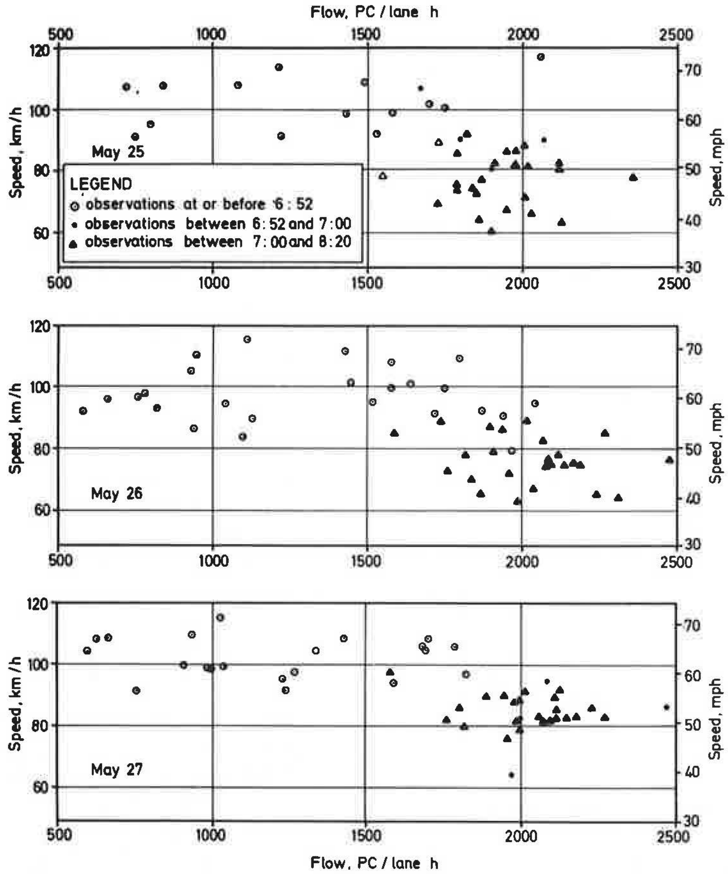
A HYPOTHESIS

Looking at Figure 13 and frustrated by the data's seeming misbehavior, we found ourselves drawn to a radical suggestion. Perhaps the whole notion that freeway traffic slows down as the flow increases is false. Maybe drivers who are able to approach the bottleneck at the speed limit just drive right on through at that speed, regardless of how high the flow may be, whereas those who have to slow down to wait in the queue only accelerate to about 70 or 80 km/h (45-50 mph) when they enter the bottleneck.

This hypothesis did not in fact arise from study of Figures 12 and 13 but from Figures 7, 8, and 9, where the observed speeds and flows are both plotted as functions of the time of day. In general, the pattern seems to be that the speed remained high until shortly before 7:00--about the time the flow reached capacity--and then dropped suddenly and remained lower until the queue vanished. (An obvious exception is the group of high speeds and some low flows observed between 7:40 and 7:50 on May 27. This group of observations could be the result of an upstream disturbance and hence not really representative of capacity flows, but we have no way of knowing.)

The hypothesis is explored further in Figure 14, where observations made at or before 6:52 are indicated by open circles and those made after 7:00 by solid triangles. The supposition is that the queue formed sometime between 6:52 and 7:00 on each of the three days, so the circles represent the situation before the queue formed and the triangles the situation after it formed. Observations made between 6:52 and 7:00 are represented by small dots; this period is not to be regarded as a transition period but as a period during which we are unable to make any statement about whether or not there was a queue. That the period of uncertainty is so long is the result of our data-collection methods, not of traffic conditions.

Figure 14. Speed and flow observations (those made while queue present shown as triangles).



The dichotomy works surprisingly well as a means of explaining the variation in speeds. On each of the three days, the triangles form a distinct group below the circles, with amazingly little overlap. If it were not for the speed of 97.5 km/h (58.5 mph) observed at 7:45 on May 27 at a flow of 1260 PC/(lane•h) and a few low speeds observed on May 26 at flows in the neighborhood of 1000 PC/(lane•h), the separation of the triangles and circles at 90 km/h (55 mph) would be very nearly total.

Particularly interesting is the small group of observations made before the queue formed but at flows in excess of 1700 PC/(lane•h), the open circles that lie above the triangles on the right-hand side of Figure 14. This group of points would seem to provide the key to testing the hypothesis that freeway bottleneck speeds are not a function of flow but only of whether there is or is not a queue up-stream. If the speeds of such points are of the same magnitude as those observed at lower flow levels and consistently higher than the speeds observed at high flow levels when there is a queue, then the hypothesis is a good one; otherwise it is not.

In our data set, there are only nine such points plus two at flows just under 1700 PC/(lane•h). One of these 11 points has a speed of 93 km/h (58 mph); the others are all faster than 95 km/h (59 mph). Thus all 11 are the sort of data points that tend to confirm the hypothesis.

To make a really convincing argument, one would need many more such data points. Unfortunately, they are difficult to obtain. The flow increases so rapidly that only a very few observations can be made on any given day at high flow levels in the absence of a queue. A first step in obtaining more such data points is to carefully observe upstream conditions in order to positively identify the presence of a queue; one really cannot afford to throw away 8 min of prime data as we have done (the small dots in Figure 14). It is probably also better to observe in the evening rather than the morning; theory (10-13) predicts that evening flow levels should increase less rapidly. It would also be possible to increase the data yield by careful ramp metering, but this approach has its own problems. Not only is such tight control physically impossible in many locations, but the need for data at high flow levels both with and without an upstream queue is likely to be incompatible with the normal operating objectives of the metering system.

Still another difficulty is likely to arise if the hypothesis is tested on a freeway with an enforced 55-mph speed limit. Presumably, the no-queue speeds would then be lower, but the speeds downstream from queues would be similar to those we observed. Thus the two groups of points would overlap a great deal and it would be much more difficult to distinguish the hypothesized situation from one in which the average speed decreased with increasing flow in the way indicated by curve D in Figure 13. On the other hand, some locations may have somewhat lower queue discharge speeds than we observed. This would make the analysis easier. For example, the data (1) shown in Figure 2 might represent locations with no-queue speeds of about 85 km/h and queue discharge speeds of about 70 km/h.

AN ALTERNATIVE EXPLANATION

A second possible explanation for the sudden drop in speed at about 1800 PC/(lane•h) has been suggested to us by R. Wiedemann. The capacity at some downstream point within the bottleneck section may be very slightly lower than at the point where our observations were made. If so, the triangles in Figure 14 could lie on the lower branch of the speed-flow curve rather than on the upper branch as we have presumed.

To decide between these two explanations, one would have to have data from at least one more point, at the downstream end of the bottleneck section, and we do not. The second explanation, however, conflicts with conventional wisdom in almost the same ways as the first. If either explanation is correct, the triangles in Figure 14 represent a different condition than the circles. It follows that one cannot draw a smooth curve like A, B, C, or D in Figure 13 but must treat the two groups of points separately. Furthermore, if the triangles do lie on the lower branch of the speed-flow curve, the upper branch must have very high speeds at flows approaching capacity--the same conclusion one reaches if our hypothesis is accepted.

It could, of course, be argued that some of the triangles lie on each branch of the curve and that the upper branch does drop at high flows. If this is the case, however, the abrupt disappearance at 1830 PC/(lane•h) of points with speeds between 95 and 110 km/h (66 mph) becomes very difficult to explain, as does the virtually total separation of the circles and triangles. The seemingly random variation of the flows and speeds in Figures 7, 8, and 9 and the unimodal speed distribution we shall see in Figure 15 also seem incompatible with the idea that some of the observations made between 7:00 and 8:20 lie on one branch of the speed-flow relationship and some on the other. We cannot say that it is not true, but we find it far less likely than either of the two explanations offered above.

Figure 15. Frequency histograms for observed speeds.

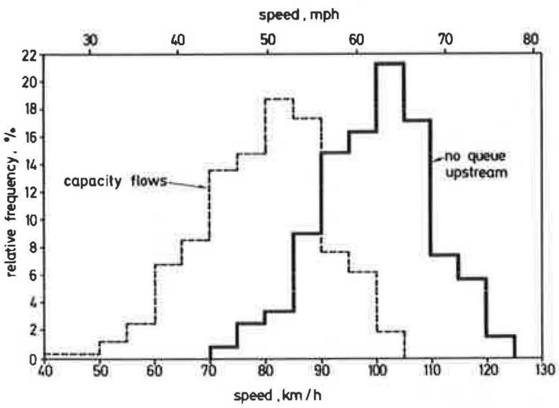


Figure 16. Cumulative frequency polygons for observed speeds.

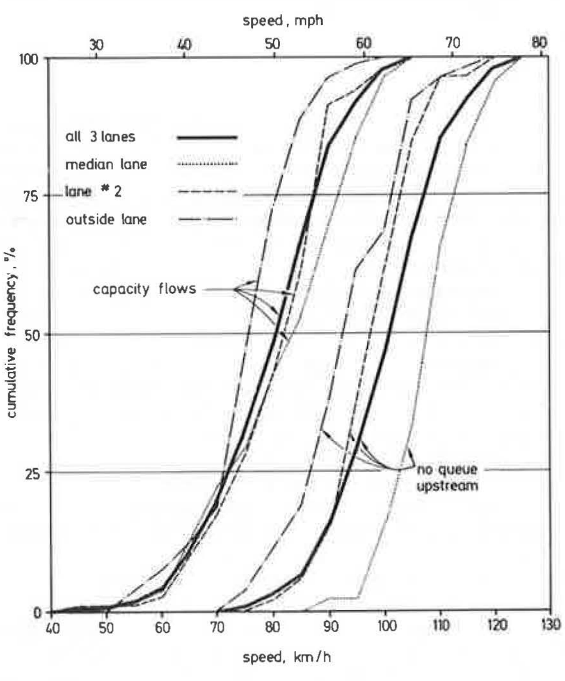


Table 2. Summary of speed observations.

Item	With Queue Upstream (Capacity)[a] (km/h)	No Queue Upstream[b] (km/h)
Mean speed ($\bar{x}$)	79.5	100.2
SD	11.0	10.0
95 percent confidence interval for mean	$78.3 \leq \bar{x} \leq 80.7$	$98.4 \leq \bar{x} \leq 102.0$

Note: 1 km/h = 0.6 mph.

[a]Number of observations = 324. [b]Number of observations = 122.

DISTRIBUTIONS OF SPEEDS

Under either our hypothesis or the alternative described at the beginning of the last section, there are two speed distributions: one for the condition when no queue exists upstream and the other for either capacity queue-discharge flows or for the speed within a very high-speed queue at near-capacity flow. Distributions of the speeds observed in these two situations are shown in Figures 15 and 16; the means, standard deviations, and 95 percent confidence limits on the means are given in Table 2. Figure 16 also shows the speed distributions for the three individual lanes. In Figures 15 and 16 and Table 2, and in the remainder of the paper, the speeds measured when a queue existed upstream are described as the speed of capacity flow, in accordance with our hypothesis. It should be noted, however, that if the alternative explanation is correct, the actual speed of capacity flows is higher than we have indicated.

Each speed plotted in Figures 7 through 14 was the average speed of the group of vehicles observed in a single set of four photographs. Figures 15 and 16 and Table 2, however, are based on the speeds of individual vehicles. It should be noted that the distribution for the no-queue situation is based on a sample that includes more observations at some flow levels than at others. This makes no difference if our hypothesis is correct. If, however, the speed really does vary with flow, the sample is biased. It is also biased with respect to time of day and truck percentage, since the later observations consistently included more vehicles than the earlier ones. Fewer problems arise with the capacity flow distribution, since all observations were made under reasonably similar conditions.

SUMMARY AND CONCLUSIONS

The data presented here tend to confirm other reports that urban freeway speeds remain high until the flow reaches at least 75 percent of the roadway capacity and that 2000 PC/h is still a good estimate of the capacity of a North American freeway lane under ideal conditions (2). On the other hand, we found an average speed of almost 80 km/h (50 mph) for capacity flows, much higher than the 50 km/h (30 mph) that is so often given in traffic engineering books.

Furthermore, and much to our surprise, our data led us to hypothesize that the speeds on uncongested freeway sections and in bottlenecks are not a function of flow but only of whether the vehicles are or are not being discharged from an upstream queue.

Our experiment was both simple and small, so our conclusions cannot be firm but must be checked by further experiments. If either our hypothesis or the alternative explanation that the true bottleneck was downstream is correct, however, the data indicate that the level-of-service concepts of the 1965 Highway Capacity Manual (3) need to be revised to an even greater extent than has been proposed by Roess, McShane, and Pignataro (1) and that the conclusions to be found in the large body of transport economics literature that assumes freeway speeds vary with flow in the manner indicated in Figure 1 or 2 all need to be reexamined.

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