# Capacity and Speed-Flow Analysis of the Queen Elizabeth Way in Ontario 

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#### Abstract

Speed-flow relationships are investigated downstream of a queue and within the queue to identify capacity flows and the effects of formation of an upstream queue on speed and flow. Data were obtained from the Queen Elizabeth Way in Ontario, Canada, on a level three-lane section of freeway. Results show markedly different shapes for the speed-flow curves in the queue and downstream. This result calls into question efforts to develop general speed-flow curves for specific facility types. In a bottleneck downstream of the queue, capacity was found to be approximately 2,300 passenger-car units per hour per lane. Queue formation had no effect on these flow rates but did affect observed speeds.


Ten years ago, Roess et al. ( $1, \mathrm{p} .11$ ) noted the scarcity in the literature of current data for recalibrating speed-flow relations, particularly with regard to knowledge of the underlying conditions. Data that were available appeared in the thencurrent (1965) Highway Capacity Manual (HCM) (2), and in a number of reports from the 1950s and 1960s (e.g., 3,4 ) on which the 1965 HCM was based, but Roess et al. gave these studies the least weight because of their age ( $1, \mathrm{p} .12$ ). The question for Roess et al. was how much both the shape of the curves and the maximum flow rates had changed since those early studies.
The possibility exists that speed-flow curves do change, because they are based on empirical observations of a varying vehicle fleet on roadways that have been continually improved. Driver experience and expectations have also changed. Differences become obvious in the earliest studies, such as Greenshields' 1934 paper (5) on traffic capacity. His paper provides valuable detail on the data collection procedures, including a photograph of one of the vehicles on the roadway in question, which provides a useful visual reminder of how much both components of the system have changed in a halfcentury. Hence, that the shape of empirical curves might also change should not be surprising.
Despite the sparseness of recent data, Roess et al. (1) were able to propose several reasonable speed-flow curves, which have since been included in the $1985 \mathrm{HCM}(6)$. However, the paucity of current data has not changed much in the time since the 1985 HCM appeared. Hurdle and Datta (7) provided additional speed-flow data a few years after the study by Roess et al. (1) was published and one of Hurdle and Datta's figures appears in the 1985 HCM . However, that small amount of additional data is not enough to resolve the question of change in the shape of the curves. Persaud and Hurdle (8) also add some data, but their main focus is on the pitfalls in interpreting

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data obtained, rather than on expanding the data base. Given recent questions that have arisen about the relative capacities of freeways and multilane rural roads, adding some data to the debate seemed appropriate.

Initially, the investigation focused on two questions pertaining to freeway capacity. Do the Ontario data provide good evidence to suggest that capacity is greater than 2,000 passenger cars per hour per lane, or to support that number? And, what is the effect on speed and flow when there is an upstream queue? The larger question then became, what is the nature of the speed-flow relationship for this three-lane section of freeway? As a consequence of this latter investigation, the analysis also provides some comments on conducting research of this kind.

Although the data are from only one freeway system they should be helpful for the debate nonetheless. Further, the system in question is one that has had a freeway traffic management system (FTMS) for a decade, one of the main features of which is ramp metering. Therefore, drivers are accustomed to entrance ramp controls. If such controls are effective in smoothing the merging operation, then a recognition needs to be made at the start that the results may only pertain to a ramp-metered facility.

The source and nature of the data are described in addition to questions that arise in data reduction. Next, speed-flow relationships are plotted from these data. Then locations in the bottleneck (i.e., downstream of the point where the restriction on flow occurs) and in the queue are discussed. The description and definitions provided by Hurdle and Datta ( 7, pp. 128-129) are followed. Finally, the effect on operations when there is an upstream queue and the issue of capacity flows are addressed.

## DATA ACQUISITION AND REDUCTION

The question of where to collect data to identify capacity flows is an interesting one. Obviously, heavily traveled sections of highway are needed but measurements taken in a queue (or stop-and-go situation) will not represent maximum flows. In the context of a section of freeway with a number of heavily used entrance ramps, careful attention needs to be paid to the system to determine where capacity operations occur. If one continuous queue exists that stretches from the farthest downstream ramp back through the other ramp locations, then only measurements taken downstream of the last ramp can represent the maximum rates of flow (assuming the highway geometry does not change and exit ramps are not heavily used at the same time). On the other hand, if separate queues


FIGURE 1 Part of Mississauga FTMS, showing detector station locations.
exist at some of the upstream ramps, capacity flow may occur immediately downstream of these ramps. Flow farther downstream may be constrained by the upstream bottlenecks such that capacity is not reached downstream. Consequently, few of the large number of possible measurement locations can be expected to actually experience capacity flows.

The freeway system used was the Queen Elizabeth Way (QEW) in Mississauga, Ontario, Canada. This facility is a sixlane, limited-access expressway (three lanes in each direction) feeding morning rush-hour traffic into Toronto from the west. Currently, an FTMS is in operation that extends for 16 km $(10 \mathrm{mi})$. Figure 1 shows the relevant portion of the system. Previously, an earlier system covered the present Stations 10 through 18. In the portion of interest, three entrance ramps (Mississauga Road, Highway 10, and Cawthra Road) are metered with metering rates set manually by the system operator in response to traffic conditions. Recurrent (daily) congestion exists on the main line because of the excess of demand (from the ramps and upstream volumes) over the capacity of the facility.

Inspection of data from this system shows that usually the queue from the farthest downstream bottleneck (Cawthra Road) extends back through the upstream bottlenecks (at Highway 10 and Mississauga Road) early during the peak period. For example, in Figure 2, flows at Station 19 kept pace with those at Station 22 until 6:45 a.m., at which time Station 19 flows dropped considerably and remained below those at Station 22. Further, between 8:30 and 9:00 a.m. a brief but drastic reduction in flow rates moved upstream, passing through the three stations in consecutive $5-\mathrm{min}$ intervals. This characteristic provides further support for the idea that the queues for the three bottlenecks coalesced. Hence, analysis will focus on Station 22, the one farthest downstream.

Until recently, the QEW FTMS did not retain data beyond the day acquired, except by special arrangement. As part of


FIGURE 2 Comparison of 870930 flow rates for Stations 16, 19 , and 22.
other work, tapes of data were obtained for a number of days in the autumn of 1987 and for intermittent periods during summer and autumn of 1988. These periods constitute the data for the analysis. Current data cannot be used because of problems with communication lines from Station 22, the main location of interest.

The QEW FTMS is particularly appropriate because most of the stations, including Station 22, have paired loops in all three lanes and provide direct measurements of speed. The ability to measure speed is especially important because previous work has shown that speeds calculated from flow and occupancy data are unreliable (9). The data, which are reported and stored every 30 sec , include volume and occupancy both for the upstream and downstream loops along with the aver-
age speed of vehicles during the interval for each lane at each station. For these analyses, the focus is on the morning peak period, and data from 5:30 to 10:00 a.m. have been used.

Roess et al. (1) call for knowledge of four variables affecting traffic flow in any new data set. Lane widths on the QEW are 12 ft . Lateral clearance is good because the right shoulder is wide enough for a stalled vehicle to pull off safely. However, a 12 -ft-high noise barrier exists immediately adjacent to the shoulder that has caused complaints from drivers of an enclosed feeling. Lateral clearance on the left side is only about 1.3 m to the median barrier. Station 22 is located on a level tangent section, so the design speed can be considered to be better than $120 \mathrm{~km} / \mathrm{hr}$.

Unfortunately, truck percentages were not obtained for these data. However, from observation of many similar days, truck percentages during the period of maximum flow can be estimated to vary between 5 and 20 percent in the shoulder lane, between 5 and 10 percent in the middle lane, and zero percent (because of an operating restriction) in the median lane. Hurdle and Datta (7) used a fourth-degree polynomial to estimate truck percentages by time of day from a small sample. Their results (from 1977) show truck percentages to be below 10 percent for 6:30 to 9:00 a.m. with the lowest percentage just below 6 percent. Data used have not been corrected for truck percentages but are given in vehicles per hour, not passenger-car equivalents. However, Hurdle and Datta's minimum estimates of truck percentages were used for drawing conclusions.
Two concerns are addressed in the data reduction. First is the aggregation issue. Five-minute intervals have been used for the bulk of the discussion. Time periods reported in the data summarized by Roess et al. (1) range from 2 to 15 min (1,p.14). Hurdle and Datta (7) and Persaud and Hurdle (8) report data at 2-min intervals. However, discussions with others involved in freeway capacity issues suggest that the interval of interest is at least 5 min and perhaps 15 min . The 1985 HCM refers to $15-\mathrm{min}$ flow rates in its definition of capacity ( $6, \mathrm{p} .3-3$ ). Five-minute intervals selected reduced most random variation in the data and allowed easy compilation to $15-\mathrm{min}$ data if needed. However, $15-\mathrm{min}$ data are too coarse to allow seeing what is happening within the freeway operations.
For comparability across days, aggregation has been done simply on the basis of clock time. Aggregation might also have been based on natural breakpoints in the operations, such as the onset of congested operation. Tables and figures presented report the end-time for the $5-\mathrm{min}$ interval.

The second concern for data reduction is how to treat missing data. Occasionally, one variable of interest will be missing at one lane in one $30-\mathrm{sec}$ interval during a specific $5-\mathrm{min}$ aggregation. Should the entire 5 min be ignored? Two approaches have been used. For data from a single day, the missing value has been approximated as the average of all of the available observations in that lane for that $5-\mathrm{min}$ interval. This method enabled time-traced speed-flow data to be graphed. In a few instances, all 10 observations were missing, so the graph shows a discontinuity. For summary discussions of capacity values, this interpolation was used only when 1 or 2 of the 10 intervals were missing, but when more than two $30-$ sec intervals were missing, that $5-\mathrm{min}$ observation was omitted from consideration.

## SPEED-FLOW RELATIONSHIPS

## Relationships Within the Bottleneck

Speed-flow data for each of the five available days of data have been plotted in Figures 3-7 and are presented in Table 1 for the period from 6:00 to 10:00 a.m. Data from 870930 (Figure 3) show the smoothest curve. Volumes across the three lanes increased steadily for almost an hour, with minimal decrease in average speeds, dropping from $104 \mathrm{~km} / \mathrm{hr}$ at a flow rate of $1,480 \mathrm{veh} / \mathrm{hr}$ at $5: 35 \mathrm{a} . \mathrm{m}$. to a speed of $89 \mathrm{~km} / \mathrm{hr}$ at a flow rate of 6,530 veh/hr at 6:30 a.m. After 6:30 a.m., speeds fell precipitously, whereas flow rates changed hardly at all, until operations settled into a steady state in the vicinity of $50 \mathrm{~km} / \mathrm{hr}$ and $6,200 \mathrm{veh} / \mathrm{hr}$ up to 9:30 a.m. One brief excursion to lower flows (and speeds) was observed at 8:40 a.m. In total, this diagram of one morning's operations appears to give a full picture of the speed-flow relationship at one location. But, does this diagram describe operations at that specific location, or is it a reflection of operations upstream or downstream? Wattleworth (10) has addressed a similar question for flow-density curves.


FIGURE 3870930 speed-flow data for Station 22 (5-min volumes).


FIGURE 4871001 speed-flow data for Station 22 ( 5 -min volumes).


FIGURE 5871118 speed-flow data for Station 22 (5-min volumes).


FIGURE 6871119 speed-flow data for Station 22 ( $5-\mathrm{min}$ volumes).


FIGURE $7 \quad 880725$ speed-flow data for Station $22(5-\mathrm{min}$ volumes).

Clearly, the cluster of data from approximately 6:50 until 9:15 a.m. is on the lower half of the curve and represents some kind of congested operation. Three possible locations exist to find the cause for this set of points: upstream, downstream, or at the station itself. If the point is the station itself, these data are a direct consequence of susceptibility to breakdown of operations at those high flow rates. If neither the upstream nor downstream traffic causes this drop, then that would be the most plausible explanation. However, possible alternative causes need to be examined.

Three earlier papers $(7,8,10)$ suggest that data similar to this cluster will be obtained downstream of a queue. The argument in all three papers is that once drivers reach the front of the queue, and enter the bottleneck itself, they begin accelerating back toward their desired speed. The average speed observed, then, depends on how far downstream measurements are taken.

The Cawthra Road entrance ramp is roughly 800 m upstream of Station 22 and the queue backs up from the ramp for much of the morning. Station 21 , immediately upstream of the ramp entrance, was unfortunately not working for several of the days for which data was obtained, including 870930 . On these days, Station 20 was used as the indicator of queue formation. Inspection of the $30-\mathrm{sec}$ data at Station 20 indicates that congested conditions occurred intermittently from 6:30 a.m., and consistently from 6:36 a.m. This time is the same that the speed drop begins at Station 22 that day.

However, Figure 3 indicates that an additional 20 min beyond the first small speed drop is required for speeds to stabilize at Station 22. It is not obvious that the effects of an upstream queue should take this long to be felt in their entirety. Persaud and Hurdle's data (8) suggest that at 800 m downstream, the speed drop should be only about 10 to $15 \mathrm{~km} / \mathrm{hr}$.

Results from the other days in the present analysis show operations remaining longer at speeds of 75 to $85 \mathrm{~km} / \mathrm{hr}$. Data from the next day (871001), for example, show that operations remained between 73 and $80 \mathrm{~km} / \mathrm{hr}$ for another 35 min after first dropping to $81 \mathrm{~km} / \mathrm{hr}$ at 6:35 a.m. (Figure 4 and Table 1). At Station 20 on that day, operations began to slow down at 6:35 a.m. and the queue was solidly established by 6:47 a.m. Most likely the queue at the entrance ramp itself was established when slowdowns began at Station 20. On 871118 , the pattern is similar (Figure 5) with 25 min of operation at speeds between 78 and $83 \mathrm{~km} / \mathrm{hr}$ starting at 6:35 a.m. Station 21 was recording that day and showed that the queue started there at 6:31 a.m. On 871119 (Figure 6), the points in question form an even tighter cluster with speeds between 78 and 82 $\mathrm{km} / \mathrm{hr}$ for 30 min starting at $6: 35 \mathrm{a} . \mathrm{m}$., which is also the time the queue formed at the Cawthra Road ramp.

Hence, the upstream queue is the cause of the data that show speeds in the 75 to $85 \mathrm{~km} / \mathrm{hr}$ range. This interpretation is consistent with earlier studies and with the timing of queue formation upstream.

The larger cluster, at speeds between 40 and $60 \mathrm{~km} / \mathrm{hr}$, therefore, would not seem to be a result of the upstream queue. The speeds are too low for the distance from the head of the queue, and there is no obvious explanation for a sudden drop to lower speeds after half an hour of operations at 75 to $85 \mathrm{~km} / \mathrm{hr}$. Hence, the lower-speed cluster is likely caused either by downstream operations or by the nature of operations at Station 22.

TABLE 1 STATION 22 DATA FOR 5 DAYS

| interval end | 870930 |  | 871001 |  | 871118 |  | 871119 |  | 880726 |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | flow | ave | flow | ave | flow |  | flow |  | flow | ave |
| time | rate | spd | rate | spd | rate | spd | rate | spd | rate | spd |
| 6.05 | 3180 | 102 | 2933 | 100 | 2941 | 100 | 3079 | 103 | 3919 | 114 |
| 6.10 | 3792 | 99 | 3816 | 98 | 4027 | 94 | 3792 | 100 | 4073 | 110 |
| 6.15 | 4596 | 95 | 4488 | 97 | 5064 | 96 | 4704 | 98 | 5524 | 107 |
| 6.20 | 4984 | 95 | 5148 | 97 | 5556 | 94 | 5196 | 99 | 5646 | 110 |
| 6.25 | 6387 | 92 | 5892 | 92 | 6468 | 93 | 6168 | 91 | 6233 | 106 |
| 6.30 | 6480 | 89 | 6360 | 88 | 6816 | 89 | 6708 | 90 | 5907 | 108 |
| 6.35 | 6660 | 80 | 6972 | 81 | 6720 | 83 | 6564 | 81 | 6240 | 103 |
| 6.40 | 6648 | 71 | 6840 | 80 | 6648 | 78 | 6648 | 77 | 6168 | 103 |
| 6.45 | 6520 | 66 | 6504 | 78 | 6684 | 78 | 6408 | 82 | 6084 | 109 |
| 6.50 | 6420 | 56 | 6408 | 76 | 6516 | 81 | 6240 | 78 | 6120 | 104 |
| 6.55 | 6432 | 53 | 6672 | 74 | 6180 | 80 | 6372 | 80 | 5772 | 104 |
| 7.00 | 6348 | 59 | 6132 | 78 | 6660 | 58 | 6696 | 80 | 5811 | 101 |
| 7.05 | 6480 | 52 | 6324 | 73 | 6360 | 52 | 6384 | 69 | 5796 | 103 |
| 7.10 | 6096 | 47 | 5820 | 74 | 6012 | 49 | 5904 | 49 | 6456 | 100 |
| 7.15 | 6108 | 48 | 6348 | 59 | 5988 | 55 | 6252 | 47 | 6240 | 103 |
| 7.20 | 6240 | 51 | 5856 | 46 | 6036 | 51 | 5988 | 44 | 5959 | 103 |
| 7.25 | 5964 | 45 | 5869 | 48 | 6267 | 53 | 5856 | 43 | 5964 | 101 |
| 7.30 | 6228 | 51 | 5745 | 47 | 6065 | 47 | 6024 | 47 | 6588 | 95 |
| 7.35 | 6144 | 51 | 5928 | 52 | 5820 | 47 | 5724 | 43 | 6533 | 94 |
| 7.40 | 5928 | 45 | 5781 | 49 | 6228 | 50 | 5700 | 45 | 6204 | 102 |
| 7.45 | 5712 | 45 | 6000 | 52 | 5904 | 43 | 6293 | 50 | 6420 | 98 |
| 7.50 | 5979 | 47 | 5940 | 46 | 5496 | 45 | 5820 | 49 | 6480 | 101 |
| 7.55 | 6180 | 50 | 5856 | 45 | 6036 | 44 | 6180 | 50 | 6072 | 103 |
| 8.00 | 6120 | 51 | 6156 | 56 | 6084 | 47 | 6060 | 49 | 6492 | 97 |
| 8.05 | 6144 | 46 | 5928 | 49 | 5940 | 47 | 6120 | 49 | 6192 | 102 |
| 8.10 | 6360 | 57 | 5772 | 47 | 5784 | 48 | 6192 | 56 | 5728 | 108 |
| 8.15 | 6396 | 57 | 6156 | 52 | 6024 | 49 | 6007 | 50 | 5553 | 104 |
| 8.20 | 6612 | 53 | 6048 | 53 | 6400 | 46 | 6144 | 54 | 5679 | 106 |
| 8.25 | 6360 | 50 | 6372 | 48 | 5916 | 45 | 6492 | 55 | 5904 | 107 |
| 8.30 | 6492 | 48 | 6237 | 50 | 6312 | 49 | 6108 | 50 | 5868 | 107 |
| 8.35 | 6305 | 52 | 6312 | 50 | 5748 | 47 | 6600 | 58 | 5655 | 110 |
| 8.40 | 4340 | 41 | 6108 | 51 | 6300 | 49 | 6132 | 46 | 5616 | 110 |

TABLE 1 (continued on next page)

TABLE 1 (continued)

| interval end | 870930 |  | 871001 |  | 871118 |  | 871119 |  | 880726 |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | flow |  | flow |  | flow |  | flow |  | flow | ave |
| time | rate | spd | rate | spd | rate | spd | rate | spd | rate | spd |
| 8.45 | 5659 | 48 | 6156 | 49 | 6108 | 50 | 5880 | 50 | 5670 | 113 |
| 8.50 | 6288 | 55 | 6108 | 51 | 6077 | 49 | 6792 | 59 | 5827 | 112 |
| 8.55 | 6480 | 57 | 6132 | 52 | 6060 | 49 | 6240 | 51 | 5424 | 115 |
| 9.00 | 6384 | 49 | 6300 | 63 | 6359 | 54 | 6216 | 49 | 4992 | 115 |
| 9.05 | 6684 | 50 | 6648 | 66 | 6156 | 52 | 3696 | 92 | 4871 | 113 |
| 9.10 | 5940 | 47 | 5796 | 83 |  |  |  |  | 5345 | 112 |
| 9.15 | 5976 | 56 | 5688 | 97 | 6600 | 88 | 5600 | 97 | 4875 | 111 |
| 9.20 | 6588 | 68 | 5496 | 97 | 5640 | 97 | 5800 | 94 | 4443 | 114 |
| 9.25 | 5844 | 60 | 5364 | 96 | 5352 | 96 | 6276 | 93 | 4776 | 111 |
| 9.30 | 5532 | 80 | 5052 | 99 | 4764 | 96 | 6228 | 94 | 4549 | 110 |
| 9.35 | 4877 | 99 | 4840 | 99 | 5904 | 98 | 4232 | 109 |  |  |
| 9.40 | 5068 | 97 | 4849 | 100 | 5000 | 98 | 5172 | 101 | 4170 | 106 |
| 9.45 | 4812 | 100 | 4812 | 99 |  |  | 4860 | 102 | 4716 | 95 |
| 9.50 | 4824 | 100 | 4572 | 101 | 4213 | 101 | 5520 | 97 | 4507 | 95 |
| 9.55 | 4344 | 99 | 4733 | 97 | 4680 | 101 | 5004 | 98 | 4596 | 108 |
| 10.00 | 4128 | 105 | 4476 | 101 | 4080 | 102 | 4200 | 103 | 4942 | 110 |

The evidence for a downstream queue as the cause is only indirect, but is nonetheless persuasive. No observations were taken downstream of Station 22 on the 5 days for which data exist. However, three different types of evidence provide support for this interpretation. The most important evidence is the fact that at the present time a queue does form downstream, after about 7:00 a.m., because of a weaving section. If the queue is there now, it is at least plausible that it was present 1 and 2 years ago. The second type of evidence is simply the fact that this type of pattern is consistent with the pattern produced by operation in a queue, as evidenced by many other figures that were inspected for upstream stations in this system (examples will be discussed later). The third piece of evidence is the negative evidence of Figure 7, representing speed-flow data from 880725 . These data show no speeds below $95 \mathrm{~km} / \mathrm{hr}$, although the flows are as high as those on other days when low-speed data were observed. Commuter flows decrease in midsummer, and it is possible that on this day they were just enough below capacity to avoid any queues in this section. Hence, there is a day without congested data, showing that the section of road can operate at high flows without breaking down.

Figure 8 combines the data from all 5 days and provides a good summary picture of the speed-flow relationship. For this
figure, only those $5-\mathrm{min}$ intervals that had complete data have been included-i.e., both speed and flow, for each of the three lanes, for all ten $30-\mathrm{sec}$ intervals. The data are consistent for the 4 days from 1987. However, the data for the one 1988 summer day are consistently above the rest of the data, as if


FIGURE 8 Combined speed-flow data for Station 22 (5 days, 5 -min volumes).
the speeds had been shifted up by perhaps $10 \mathrm{~km} / \mathrm{hr}$. It is hard to know the cause of this difference. Perhaps it accurately reflects conditions on days when there is no queue. Alternatively, the tuning of the loops may have changed over the year, such that the 1988 speed data are not as accurate as the 1987 data.

Despite the appearance of an upward shift in speeds on this one day, the interpretation of the data in Figure 8 is that speeds drop only slightly as volumes increase, and that so long as demand is not in excess of capacity, this speed can be maintained almost to the maximum flow rate (as in Figure 7). However, if demand (in this instance from the combined flows on the ramp and the main line) exceeds this capacity, a queue will form. Then the particular speeds observed at a location in the bottleneck will be a function primarily of the distance from the head of the queue (8), in this case at the Cawthra Road entrance ramp. Hence, the set of points covering the range 70 to $90 \mathrm{~km} / \mathrm{hr}$ may arise as a consequence of a queue having formed upstream of the measurement location. The set of points in the $40-$ to $60-\mathrm{km} / \mathrm{hr}$ range cannot be explained on this basis, and therefore would seem to be a consequence of a downstream queue. The speeds and flows of such data are primarily a function of the net flow available through the downstream queue for the upstream location, and of the speed at which that downstream bottleneck processes traffic.

## Relationships in a Queue

The immediate question that arises from Figure 8 is why the curve does not show a clear rounding of the right-hand end of the curve, like conventional speed-flow curves. Not only do the curves in the 1985 HCM (6) appear rounded, but so also do the data behind them, as shown for example in Roess et al. (1). The working hypothesis was that the type of curve is different upstream, in the queue, than it is downstream, in the bottleneck. This idea is not new. May et al. (3,p.51) noted 25 years ago that the form of relationships between freeway operations variables "depended on the station location relative to a trouble spot." However, this observation is not reflected in the HCM, so it was treated as a hypothesis rather than as something known for certain. To test the idea, data from Station 20 were used, because conditions there have already been described, and from Stations 16 and 17, which are farther upstream.

There is a similarity of Figures 9-11 to the conventional curves. They show a much more pronounced roundedness at high flows than does Figure 8, as well as lower maximum flow rates. For the operations at Station 20 (Figure 9), part of the answer appears in the detailed 30 -sec data scrutinized to ascertain when the queue began. On both days contained in this graph, the arrival of the queue at Station 20 was not simultaneous across the three lanes, nor was it instantaneous in any one lane. The median lane experienced the effects of congestion first, with the shoulder lane showing them last, sometimes as much as 10 min later. Hence, an average of speeds across the three lanes would decrease more slowly than would the speed of any one lane.
Station 16 (Figure 10) is a more interesting one, in that for some of the period it seems to be affected by operations


FIGURE 9 Station 20 speed-flow data on 870930 and 871001 (5-min volumes).

(Thousands)
FIGURE 10 Station 16 speed-flow data on 870930 and 871119 (5-min volumes).


FIGURE 11 Station 17 speed-flow data on 870930, 871118, and 871119 ( $5-\mathrm{min}$ volumes).
upstream (the queue behind the entrance ramps at Mississauga Road), and some of the time it is affected by the queue from the Highway 10 ramps extending back this far. It, too, shows lower maximum flows, and a much more rounded shape.

Station 17 (Figure 11) is the most interesting, as it would appear to exhibit characteristics of both Figures 8 and 9. At flows approaching $6,000 \mathrm{veh} / \mathrm{hr}$, there are some observations for which speeds of $100 \mathrm{~km} / \mathrm{hr}$ are maintained, while there are others for which speeds have dropped to the vicinity of $80 \mathrm{~km} / \mathrm{hr}$. Previously, these speeds would simply have been averaged to get the speed-flow curve. The working hypothesis, however, would suggest that these data represent two types of behavior, and really come from two different curvesfor the same station.

As Roess et al. (1) note, there is not a good description of the conditions behind the data in most empirical studies. This lack is true for details of the study location as well as for other factors that Roess et al. listed. Hence, whether the previous studies were conducted upstream or downstream of congestion is not clear. If those studies contain any congested data, the vehicles must have been in a queue for part of the time, and therefore the flow may not represent capacity operation (as is certainly true for the Station 20 data in Figure 9).
The contrast between Figures 8 and Figures $9-11$ suggests that most of the conventional wisdom regarding the shape of speed-flow curves has been derived from data collected in queues. To know the shape of the relationship in a queue may well be useful for planning purposes, but it would seem not to be appropriate for attempting to determine the capacity of a section of roadway. If a particular location operates in a queue, the flow must obviously be governed by downstream conditions. The place to look for capacity operation, then, is downstream, beyond the queue.

## EFFECTS OF AN UPSTREAM QUEUE

Before addressing the issue of what capacity is, it is necessary to resolve the issue of what happens to operations once a queue has formed upstream. Some studies have suggested that after a queue forms there is a drop in the maximum flow possible through a bottleneck. Wattleworth (10) discusses three such studies. The possibility is also raised in the Interim Materials on Highway Capacity (11). If this effect does happen, then the task of identifying capacity flow is quite different than if there is no such reduction.

The analysis in the preceding section establishes clearly that queues did form immediately upstream of Station 22 on 4 of the 5 days for which there are data. Figures 3-6 indicate that, although there is a clear drop in speeds, there is no easily discernible drop in flow rates at the time the queue forms. In Figure 3, there is no drop in flows from start to end of the upstream queue effect. In Figures 4 and 5, there is a tendency toward decreasing flows over time (from 6,972 to 5,820 veh/ hr in Figure 4), but it is not consistently maintained. In Figure 6 , there seems to be simply random variation between values of 6,240 and $6,696 \mathrm{veh} / \mathrm{hr}$. Hence, a significant flow reduction under such circumstances cannot be deduced from these data. Wattleworth (10) provides a convincing explanation of why this result arises in some studies, whereas others continue to show a capacity reduction.

However, the data do provide strong support for the idea first put forward by Hurdle and Datta (7), and elucidated further by Persaud and Hurdle (8), that speeds drop when a queue forms upstream. The data in Figure 7 help to strengthen the case even further, in that no upstream or downstream queue formed, and the speeds were maintained at roughly $100 \mathrm{~km} / \mathrm{hr}$ right out to $5-\mathrm{min}$ flow rates of $6,500 \mathrm{veh} / \mathrm{hr}$. This is strong support for the hypothesis put forward by Hurdle and Datta ( 7, p.134): "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."

## CAPACITY

Table 2 presents the flow data at Station 22 during the peak 3 hours for the five available days. Given all of these numbers, what is the best estimate of capacity of this three-lane, level section of freeway?
The choice is the bottom line on the table, namely the maximum flow rate during the peak 40 min . On 4 of the 5 days, 40 min seems to be the duration of maximum flow operations before the downstream queue affects flow at Station 22, as shown in Figures 3-6. As discussed in the previous section, there seems to be no change in average flow after the upstream queue affects operations, so those numbers are included in this calculation. Despite the fact that flows after the downstream queue has arrived continue to be at or near $6,000 \mathrm{veh} / \mathrm{hr}$, it is not valid to consider those flows to represent capacity at Station 22. Because they show Station 22 to be operating in a queue, they are a reflection of downstream operations. This condition was obvious in Figures 10 and 11, for stations more clearly in a queue. It is equally valid at Station 22, even though the numbers may look as if they, too, are capacity-type operation.

On the 5th day, no upstream or downstream queue ever formed. In this case, 40 min was the duration for which flows remained consistently above $6,000 \mathrm{veh} / \mathrm{hr}$. Demand dropped off by $8: 15 \mathrm{a} . \mathrm{m}$., when flow was $5,550 \mathrm{veh} / \mathrm{hr}$. Certainly, no speed drop was associated with this reduction in flow (Figure 7), so it cannot be a consequence of congested operations. Hence, it must simply be a reduction in demand. Again, the flows at 7:20 and 7:25 a.m. are just below $6,000 \mathrm{veh} / \mathrm{hr}$, after 10 min above it. Because these flows are not associated with speed reductions, they do not represent flow reductions caused by congestion at the location. Hence, the flows must simply be demand fluctuations, and are therefore not capacity flows.

If these $40-\mathrm{min}$ periods are the best available indicators of capacity operations, then, in round numbers, the capacity at Station 22 is $6,500 \mathrm{veh} / \mathrm{hr}$. With 6 percent trucks, the lowest value estimated for this section of road by Hurdle and Datta (7), this flow would become nearly 6,900 passenger-car equivalents per hour, or 2,300 passenger-car equivalents per hour per lane.

Not only is this number considerably higher than the figure given in the $1985 \mathrm{HCM}(6)$, it is also considerably higher than the value of 1,984 passenger-car units per hour found by Hurdle and Datta (7) in 1977 in the same vicinity. However, since they took their measurements, upstream of Cawthra Road, several major changes have occurred to the freeway at that location. First, a full interchange has been constructed at Cawthra Road, where previously there was no access at all.

TABLE 2 PEAK-PERIOD FLOW RATES (5-min VOLUMES) FOR STATION 22 FOR ALL 5 DAYS ACROSS THREE LANES

| interval |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| end | 870930 | 871001 | 871118 | 871119 | 880726 |
| time |  |  |  |  |  |
| 6.25 | 6387 * | 5892 | 6468 | 6168 | 6233 * |
| 6.30 | 6480 | 6360 | 6816 | 6708 | $5907+$ |
| 6.35 | 6660 | 6972 | 6720 | 6564 | 6240 |
| 6.40 | 6648 | 6840 | 6648 | 6648 | 6168 |
| 6.45 | 6520 * | 6504 | 6684 | 6408 | 6084 + |
| 6.50 | 6420 | 6408 | 6516 | 6240 | $6120+$ |
| 6.55 | 6432 | 6672 | 6180 | 6372 | 5772 |
| 7.00 | 6348 | 6132 | 6660 | 6696 | 5811 * |
| 7.05 | 6480 * | 6324 | 6360 | 6384 | 5796 |
| 7.10 | 6096 | 5820 | 6012 | 5904 | 6456 + |
| 7.15 | 6108 | 6348 | 5988 | 6252 | 6240 |
| 7.20 | 6240 | 5856 | 6036 | 5988 | 5959 * |
| 7.25 | 5964 | 5869 * | 6267 * | 5856 | 5964 |
| 7.30 | 6228 | 5745 * | 6065 * | 6024 | 6588 |
| 7.35 | 6144 | 5928 | 5820 | 5724 | 6533 * |
| 7.40 | 5928 | 5781 * | 6228 | 5700 | 6204 |
| 7.45 | 5712 | 6000 | 5904 | $6293+$ | 6420 |
| 7.50 | 5979 * | 5940 | 5496 | 5820 | 6480 |
| 7.55 | 6180 | 5856 | 6036 | 6180 | 6072 |
| 8.00 | 6120 | 6156 | 6084 | $6060+$ | 6492 |
| 8.05 | 6144 | 5928 | 5940 | 6120 | 6192 |
| 8.10 | 6360 | 5772 | 5784 | 6192 |  |
| 8.15 | 6396 | 6156 | 6024 | 6007 * | 5553* |
| 8.20 | 6612 | 6048 * | 6400 * | 6144 | 5679 * |
| 8.25 | 6360 | 6372 | 5916 | 6492 | 5904 |
| 8.30 | 6492 | 6237 * | 6312 | 6108 |  |
| 8.35 | 6305 * | 6312 | 5748 | 6600 | $5655+$ |
| 8.40 | 6108 | 6300 | 6132 | 5616 + |  |
| 8.45 | 5659 * | 6156 | 6108 | 5880 |  |
| 8.50 | 6288 | 6108 | 6077 * | 6792 |  |

TABLE 2 (continued on next page)

TABLE 2 (continued)

| interval |  |  |  |  |  |
| ---: | ---: | ---: | ---: | ---: | ---: |
| end | 870930 | 871001 | 871118 | 871119 | 880726 |
| time |  |  |  |  |  |
| 8.55 | 6480 | 6132 | 6060 | 6240 |  |
| 9.00 | 6384 | 6300 | $6359 *$ | 6216 |  |
| 9.05 | 6684 | 6648 | 6156 | 3696 |  |
| 9.10 | 5940 | 5796 |  | $5600 *$ |  |
| 9.15 | 5976 | 5688 |  | $5800^{*}$ |  |
| 9.20 | 6588 | 5496 | 5640 |  |  |
| $6: 20$ to $7: 20$ | 6402 | 6344 | 6424 | 6361 | 6066 |
| $7: 20$ to $8: 20$ | 6147 | 5932 | 6004 | 6010 | 6198 |
| $8: 20$ to $9: 20$ | 6287 | 6113 | 6068 | 5960 |  |

The asterisk (*) indicates periods for which one 30 -second interval was missing data. The missing value was estimated as the average of the other 9 intervals for that lane. The plus sign ( + ) indicates that two intervals in one lane have been estimated. If more than two intervals were missing, the 5 -minute observation has been left blank.

Second, as part of that reconstruction, lengthy exit and entrance ramps were added, giving the appearance of a wider roadway. Third, downstream of Cawthra Road, where Station 22 is located, noise barriers have been constructed on both sides of the road.
Any one of these changes may be the cause of the difference, but the most likely is the first, together with the recognition that the two studies were in somewhat different places. The Cawthra Road interchange clearly adds more traffic. The flow Hurdle and Datta (7) measured was constrained by the Highway 10 interchange, and was in the bottleneck from that. Cawthra Road creates a new bottleneck, as Figure 2 indicates, which handles the Highway 10 bottleneck plus entrance ramp traffic. The second possible explanation is related: the improved design of the Cawthra Road interchange over the old one at Highway 10 has led to higher capacity. The noise walls may even help improve traffic flow, by removing a source of roadside distractions. Similarly high numbers for maximum flows have been found in other locations, for example at half a dozen locations reported in the $1985 \mathrm{HCM}(6$, Table $2-1)$, or by Banks (12) near San Diego.

## CONCLUSIONS

Two conclusions relate to capacity. These data suggest that capacity flow at Station 22 on the QEW is roughly 6,900 passenger-car units per hour, across three lanes of a level expressway. The data also show that there is not a reduction in this flow rate when there is an upstream queue, although there is a speed reduction.

The more difficult but perhaps more important conclusions relate to the study of speed-flow relationships. There may not be just one speed-flow curve for a specific freeway type (e.g., for a six-lane expressway with a $112-\mathrm{km} / \mathrm{hr}$ design speed). The comparison of speed-flow relationships upstream and downstream of a restriction raises the interesting possibility that speed-flow curves will be fundamentally different in the two kinds of location. This possibility was hinted at by May et al. (3), but seems not to have been developed. If this is correct, then upstream of a capacity restriction, the sideways $U$-shaped curve may be drawn in conventional shapes. The maximum observed flow in the queue will depend on the net rate of flow at the downstream bottlenecks.

Downstream of a queue, in the extreme case a sideways Lshaped figure, with constant speeds until the queue formed upstream, and then a vertical drop to lower speeds at roughly the same flow rates, are expected. If this interpretation is correct, then any speed-flow curve other than a horizontal line at nearly constant speed may be a reflection of upstream or downstream operations, or both. However, some of the upstream conditions, such as a queue, may arise because of the capacity at the location under study which may be less than the demand for it. In that sense, the speed-flow curve describes not only the site under study, but also the (demand) conditions upstream. Wattleworth reached a similar conclusion (10,p.20): "It may not be possible to obtain empirically a true volume-density curve for a bottleneck since part of the observed curve may merely be reflecting the influence of conditions upstream of the bottleneck."

If these suggestions are correct, it may be that one particular descriptor in the HCM of levels of service needs rethinking. In particular, the notion of unstable flow in Levels of Service $D$ and $E$ is potentially misleading. Unstable flow suggests that operations can break down at a particular location specifically because of the flow there. Although a stoppage wave can develop in very dense traffic without the prior occurrence of any accident, the stoppage wave propagates rapidly upstream, and does not continue to characterize operations at the specific measurement location at which it started. Thus, breakdown flow at any particular location arises as a consequence of downstream operations (which is exactly what the HCM says about Level of Service F, although it implies otherwise in the discussion of Levels of Service $D$ and $E$ ).

It would appear necessary, then, to identify two speed-flow curves for a given facility type, one in the bottleneck and one in the queue. For locations downstream of the head of the queue, in the bottleneck, one curve could serve to identify both operations expected before upstream breakdown (a horizontal line), and the speeds expected (at that same maximum flow) at different distances downstream of the head of the queue, as indicated by Persaud and Hurdle (8). No congested operation would be indicated on this curve. For locations in the queue, the conventional $U$-shaped curve is still appropriate.

Implicit in this proposal for a new set of speed-flow curves is a set of strictures for any empirical approaches to identifying such curves. One must know where, with respect to queue formation, the data have been collected. No one location will be likely to provide data for both types of curves. For operations in queues, it may be possible (and necessary) to combine data from several different locations to arrive at a complete representation of the lower portion of the curve. On a freeway system, the flow rates seen in the queue at a particular location will depend on the net entering flows between that location and the primary bottleneck. Hence, one location cannot be expected to provide a large range of congested flows.

Perhaps most important, the speed-flow relationship cannot be simply ascertained at a congested location nor can capacity be identified. These relationships are not straightforward.

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