Two-Capacity Phenomenon at Freeway Bottlenecks: A Basis for Ramp Metering?

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The issue of whether ramp metering can increase the capacity of freeway bottlenecks by prevention or delay of flow breakdown on the freeway main line is considered. A summary of the results of four case studies of metered bottlenecks in San Diego is presented. The hypothesis that flow decreases when it breaks down is confirmed, provided the hypothesis applies to individual lanes. Flow decreases ranging from 10 percent to less than 1 percent were observed in the left lane at the various study sites. When averaged across all lanes, flow decreased by about 3 percent at one site; there was no significant change at the other sites. It is concluded that this phenomenon is unlikely to provide a basis for metering at more than a few locations, because decreases in flow across all lanes are very small, sometimes nonexistent. Even where there are decreases in total flow, there is risk that metering will be counterproductive if it is too restrictive or begins too early.

A previous paper (*1*) presented a study of flow processes in the vicinity of a high-volume freeway bottleneck in San Diego. Detailed detector data were analyzed and compared with videotapes of traffic flow. Evidence supported the hypothesis that capacities at this bottleneck decrease when queues form. In addition, it was found that queues formed about 1,500 ft upstream of the merge point, rather than at the merge point. This situation occurred despite merge rates of approximately 2,500 to 2,800 vehicles per hour (vph) and flows downstream of the onramp that commonly exceeded 2,400 vehicles per lane per hour (vplph) and sometimes reached 2,600 vplph.

The overall objective of this study was to determine whether ramp metering can increase the capacity of freeway bottlenecks by preventing flow breakdown. The project eventually included case studies of three additional bottlenecks. The results of the entire series of case studies are summarized in the following paragraphs, and the potential of the so-called "two-capacity" phenomenon (the existence of which was confirmed by all the case studies) is explored as a basis for ramp metering. A companion paper in this Record focuses on the process by which congestion was initiated at these locations and addresses the question of why capacity should decrease when flow breaks down.

BACKGROUND

Past case studies of ramp metering have indicated that even crude metering systems can sometimes achieve significant reductions in total travel time with no significant reduction in total vehicle-miles of travel (*2,3*). One common explanation is that maximum flow rates at bottlenecks decrease when queues form; hence, metering increases the capacity of the bottlenecks by preventing queueing on the freeway.

This two-capacity hypothesis is found in several standard works (*4,5*) and was previously used as a basis for a ramp metering strategy by Athol and Bullen (*6*). The hypothesis has often been related to two-regime or dual-mode traffic flow theories (*6–9*), but questions have been raised as to whether such theories might represent a misinterpretation of the data (*10–12*). Recent attempts to verify the two-capacity hypothesis were undertaken by Hurdle and Datta (*13*) and Persaud (*14*) but were proved inconclusive because of insufficient data.

Hurdle and Datta (*13*) and Persaud (*14*) took the proof of the two-capacity hypothesis to be a flow pattern in which the mean flow rate at the bottleneck drops abruptly just as the queue forms. Banks (*1*) extended this approach by considering how the distribution of short-term counts just downstream of the bottleneck should be affected by queue formation. Two situations were contrasted: one in which there is no change in capacity and one in which capacity decreases. It was assumed that individual lanes might have separate capacities and concluded that, if even one lane is found in which the mean flow rate is less after the queue forms or in which high counts are less frequent after queue formation, this finding would tend to confirm the two-capacity hypothesis. Increases in flow in noncritical lanes or in total flow across all lanes do not negate the hypothesis, however, because these increases might happen as a result of shifts in lane use. On the basis of these tests, it was concluded that the two-capacity hypothesis was confirmed at the first bottleneck studied.

The test of the two-capacity hypothesis, as a proposition about the facts of traffic flow, depends on decreases in flow in individual lanes. Its value as a basis for ramp metering, however, depends on the existence of a decrease in flow across all lanes when queues form. At the first study site, flow averaged across all lanes did decrease in eight of nine cases. One issue to be addressed by the remainder of the study was the extent to which this situation is typical.

In addition to the question of how often total flow decreases when queues form, there are other concerns related to the exploitation of the two-capacity phenomenon by ramp metering. In his previous paper, Banks (*1*) introduced a model relating the potential benefits of metering (i.e., time savings)

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to several details of the metering strategy. The model clearly indicated that the potential benefit of metering depended, among other things, on (a) the relationship between flow and the time to flow breakdown, (b) the difference between the time metering begins and the time flow would have broken down without metering, and (c) the relationships between the metering rate and the maximum unmetered prequeue flow and queue discharge rates. This model is further developed here, and evaluated by means of sensitivity analyses, to provide a better idea of whether and how metering could take advantage of the two-capacity phenomenon.

METHODOLOGY

The study methodology involved comparison of detailed detector data taken in the vicinity of the various bottlenecks with videotapes of traffic flow. Analysis of detector data was based on an extension of the event-based averaging technique described by Allen et al. (*15*). Characteristics of 30-sec count distributions (including means and standard deviations) were determined for 12-min periods before and after flow breakdown. In addition, regressions of 30-sec count versus time were performed for these same time periods to determine whether flows were increasing or decreasing significantly, and frequency polygons of the count distributions (aggregated over all days included in each case study) were plotted to determine their shapes. Further details of the study methodology are documented elsewhere (*1,16*).

STUDY SITE CHARACTERISTICS

The following four bottlenecks were selected for study. In each case, the exact location of the bottleneck was determined as part of the field study.

1. Westbound Interstate 8 at College Avenue, morning peak period;
2. Northbound Interstate 805 at El Cajon Boulevard, morning peak period;
3. Eastbound Interstate 8 at College Avenue, evening peak period; and
4. Southbound State Route 163 at Washington Street, morning peak period.

Figures 1–3 show schematic diagrams of these sites, and selected characteristics of the sites are presented in Table 1. Further details can be found elsewhere (*1,16*).

As can be seen, all sites involve volumes (both on the main line and at the ramp terminals) that are considerably in excess of those that would be predicted by the *Highway Capacity Manual* (HCM) (*4*) for similar circumstances.

All sites were metered to some extent, although the effectiveness of the metering varies widely. Metering upstream of Site 1 is extensive, so that virtually all vehicles on the main line approaching the bottleneck have passed a meter. At Site 4, only vehicles entering from the Washington Street ramp itself are metered, and there is no attempt to control mainline flows approaching the bottleneck. Some metering exists

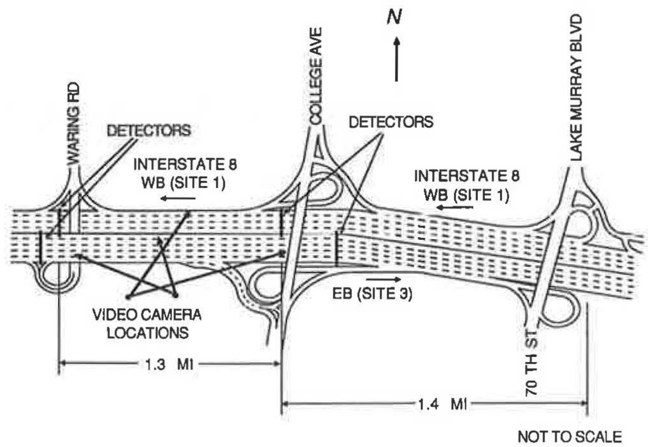

FIGURE 1 Schematic diagram of Sites 1 and 3.

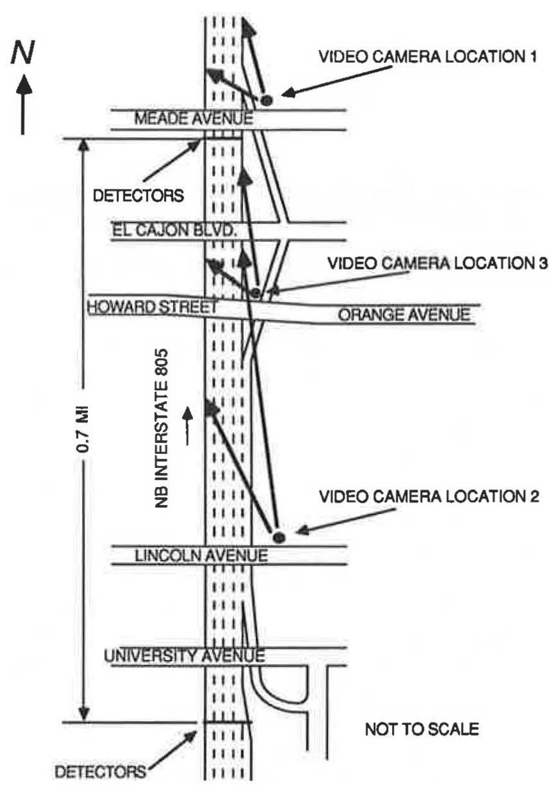

FIGURE 2 Schematic diagram of Site 2.

upstream of Sites 2 and 3, but it is less extensive than at Site 1; that at Site 2 is probably more effective than that at Site 3.

Other important characteristics distinguishing the sites are grades, horizontal curves, and the presence of ramp terminals. In general, the severity of the grades increases from a downgrade at Site 1 to an upgrade of 6 percent at Site 4. There are also critical horizontal curves at Sites 1 and 4. At Sites 1, 2, and 4, maximum volumes per lane occur just downstream of onramp junctions; at Site 3, the maximum volume per lane occurs just upstream of an offramp junction.

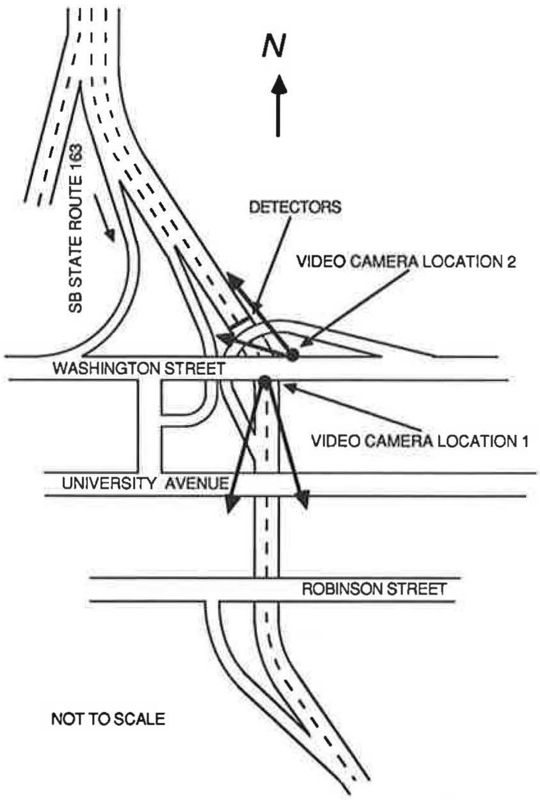

FIGURE 3 Schematic diagram of Site 4.

RESULTS

Table 2 presents a comparison of the changes in the flow process that were observed to occur at the onset of congestion. Further details are given elsewhere (*1,16*).

Table 2 indicates that, in a majority of cases, the following changes occurred at each site:

- The mean flow in the left lane decreased. Flow decreases (averaged over all days) ranged from 10.5 percent at Site 1 to 0.6 percent at Site 4. On the basis of the sign test (i.e., assuming that the probability of an increase or decrease is 0.5 and determining the probability of occurrence, as given by the binomial distribution, of at least the number of decreases observed), all the decreases except that at Site 4 were significant at the 5 percent level.
- The mean flow across all lanes decreased. In this case, however, the flow change (averaged over all days) was actually positive in three of four cases, ranging from −3.2 percent at Site 1 to +1.2 percent at Site 4. On the basis of the sign test, only the decrease at Site 1 was significant at the 5 percent level.
- Where regression slopes of flow versus time tended to have positive slopes before the onset of queueing (thus indicating that flow was increasing despite the metering), the value of the regression line just before the onset of congestion was greater than that just afterward.
- The relative frequency of the highest counts decreased, whether left-lane counts were considered individually or counts for all lanes were averaged together.

TABLE 1 STUDY SITE CHARACTERISTICS

Characteristic	Site 1	Site 2	Site 3	Site 4
Number of Lanes, One Direction	4	4	5	2
Mainline Flow, VPHPL				
Critical Point	2250	2175	2100	2325
Maximum	2400	2300	2100	2450
Critical Ramp (VPH, 6-min. Flow)				
Merge	2500-2800	2500-2800	n.a.	2500
Diverge	n.a.	n.a.	2000-2600	n.a.
Heavy Vehicles	4.0%	4.0%	4.5%	1.9%
Critical Upgrade				
Length, Mi.	n.a.	1.8	1.5	1.0
Average Grade	n.a.	1.7%	2.9%	4.9%
Steepest Grade	n.a.	2.0%	3.0%	6.0%
Critical Horizontal Curve Radius, Ft.	2000	n.a.	n.a.	600

- The percentage of flow in the left lane decreased, whereas that in the right lane increased.
- The variances of the 30-sec counts decreased. Variances and coefficients of variation varied considerably by site and from day to day. Typical coefficients of variation ranged from around 0.1 at Site 1 to 0.2 at Site 3.

In addition, in every case in which the typical point of flow breakdown could be seen, it was somewhere other than at the merge or diverge point (i.e., the right lane just upstream of the offramp or just downstream of the onramp), which would have been identified as critical by Chapter 5 of the HCM. In the three cases in which the merge point would have been expected to be critical, the actual point of flow breakdown was upstream. In the other case (Site 3), flow breakdown occurred both upstream and downstream of the apparently critical diverge point. In all cases, this situation occurred even though the merge or diverge rates in question were far in excess of the merge and diverge capacities reported in the HCM.

At all sites, flow breakdown was observed to be associated with unstable speeds in large and dense platoons of vehicles that formed in high-volume, noncongested flow. At the three sites involving upgrades, the critical platoons were normally associated with the presence of slow-moving heavy vehicles.

The results of all the case studies supported the two-capacity hypothesis, but the degree to which they supported it varied. In general, support for the hypothesis was strongest at Site 1 and weakest at Site 4. For instance, Figure 4 shows a comparison of the relative frequency distributions of 30-sec counts for the left lane of each site, before and after queue formation, and Figure 5 shows similar information for flow averaged across all lanes. The tendency for high counts to occur more frequently in the critical lane before queue formation is obvious at Site 1 and questionable at Site 4.

TABLE 2 COMPARISON OF RESULTS OF CASE STUDIES

Response to Flow Breakdown	Number of Occurrences/Total Days			
	Site 1	Site 2	Site 3	Site 4
Mean Flow Decreases (Decreases/Total Days)				
Left Lane	9/9	12/14	11/14	10/17
All Lanes	8/9	7/14	8/14	9/17
Average Flow Change (Percent, All Days)				
Left Lane	-10.5%	-4.0%	-4.8%	-0.6%
All Lanes	-3.2%	+0.7%	+0.1%	+1.2%
Count Distribution Shifts Down				
Left Lane	yes	yes	yes	yes
All Lanes	yes	yes	yes	yes
Regression Value Decreases (Decreases/ Total Days)	n.a.	13/14	13/14	n.a.
Relative Use of Left Lane Decreases (Decreases/Total Days)	9/9	13/14	13/14	13/17
Relative Use of Right Lane Increases (Increases/Total Days)	9/9	11/14	13/14	13/17
Variance Decreases (Decreases/Total Days)	7/9	11/14	8/14	16/17

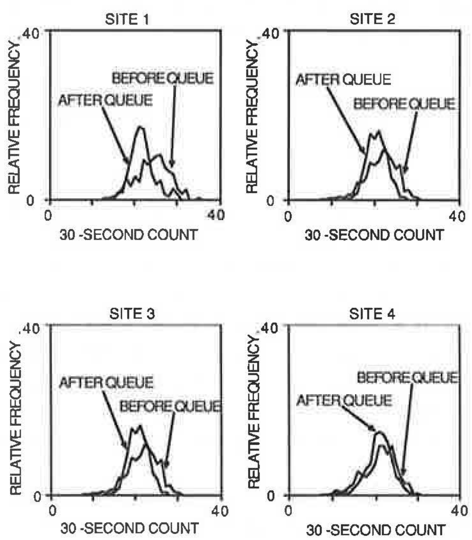

FIGURE 4 Comparison of frequency polygons for left-lane counts.

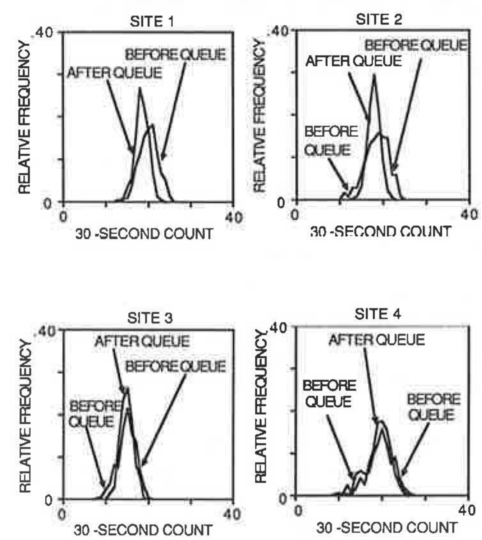

FIGURE 5 Comparison of frequency polygons, mean count, all lanes.

To some extent, this finding may have been the result of using too long an averaging interval at Site 4, where queues sometimes cleared up spontaneously in less than 12 min. Reduction of the averaging interval from 12 to 6 min at Site 4 increased the number of cases in which flow in the left lane decreased when flow broke down from 59 percent (10 out of 17) to 76 percent (13 out of 17). Still, the strength of the two-capacity phenomenon clearly depends on site characteristics.

Although flows averaged across all lanes decreased at least half the time at all sites, they decreased consistently (when averaged over 12 min before and after queue formation) only at Site 1. Thus, even though the existence of the two-capacity phenomenon was confirmed, it is unlikely that the hypothesis can be of value as a basis for metering at more than a small fraction of all bottlenecks.

IMPLICATIONS FOR METERING

There is need for caution even in cases in which the two-capacity phenomenon might be exploited as a basis for metering. Athol and Bullen (*6*) have discussed the relationship between the two-capacity phenomenon and metering strategy. A modification of their analysis was presented previously (*1*) as a conceptual basis for evaluating metering strategies intended to exploit this relationship. Following is a further development of that model, including the results of sensitivity analyses. From these analyses, certain features of the metering strategy were identified as being of special concern in attempts to exploit the two-capacity phenomenon.

Athol and Bullen (*6*) assumed that the probability of flow breakdown during some short time interval is a function of flow. They then considered the probability of flow breakdown over a number of successive time intervals and found the expected time to flow breakdown (after the beginning of the peak) to be a declining function of prequeue flow. They selected an optimum flow (to be produced by metering) to maximize the expected value of uncongested flow for the peak period.

An alternative objective of minimizing total delay in the system has been proposed (*1*). Figure 6 shows a queueing diagram that compares delay for metered and unmetered conditions. In the diagram, the cumulative demand function represents the cumulative flow that would arrive at the bottleneck in the absence of queues or metering. It is assumed that no traffic is diverted, so this diagram is the same regardless of the metering rate.

Any shift in cumulative discharge to the right of this line represents delay, either in a main-line queue or in the queues at the ramp meters. It is assumed that the discharge rate decreases when the queue is formed and that the time it takes the queue to form is a function of the prequeue flow rate. Hence, limitation of the prequeue flow to the metering rate delays queue formation from t_1 to t_2. Area A represents delay experienced because the metering rate is initially less than the unmetered flow; Area B represents delay experienced without metering because the queue discharge rate is less than the metering rate, and metering delays queue formation. Thus, neglecting the effects both of ramp queues and of main-line queues on vehicles not passing through the bottleneck, the

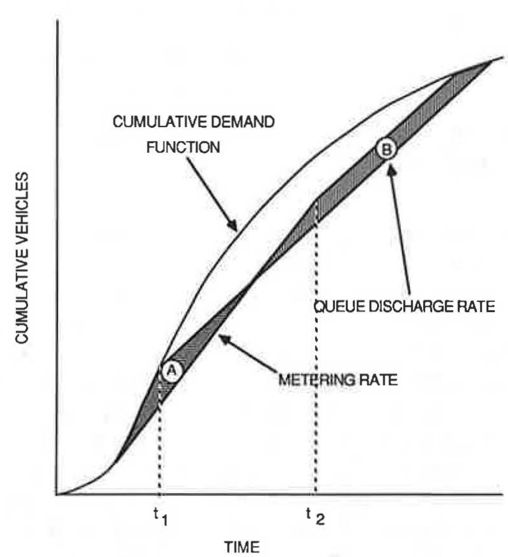

FIGURE 6 Comparison of delay with and without metering (*1*).

expected benefit of metering (i.e., total time saved) is Area B minus Area A.

Figure 6 indicates that the total time saved by metering should be sensitive to the metering rate, the difference between the maximum unmetered free flow rate and the queue discharge rate, the relationship between flow and time of breakdown, and the difference between the time metering starts and the time unmetered flow would normally break down (referred to as anticipation time). In this model, the metering rate is actually the composite of metering rates at several ramps, and the time metering starts is actually the time the first metered vehicle reaches the bottleneck. It is assumed that the beginning of metering at various ramps is so offset that the first metered vehicles from each ramp reach the bottleneck at approximately the same time.

Calculation of the areas in Figure 6 can be simplified by assuming that the arrival function is linear where it bounds either Area A or Area B. This assumption is conservative; normally it would be assumed that the arrival rate is increasing just before breakdown and decreasing at the time the queue clears. Thus, Area A is overstated and Area B is slightly understated. With this simplification, the expressions for the areas (as functions of the time to flow breakdown), the duration of the peak, the anticipation time, and the arrival, queue discharge, and metering rates are straightforward (because they are combinations of triangles and trapezoids) but somewhat messy. They do not lend themselves to sensitivity analysis by inspection and hence are omitted here; however, they do lend themselves to rather simple numerical analysis.

To carry out these sensitivity analyses, assumptions were made about reasonable ranges for the values of the various parameters of the model and about the nature of the flow-breakdown-time relationship. Important parameters are the ratios of the various flow rates to one another and the ratio of the anticipation time to the duration of the peak, where the peak was defined as the anticipated time that a queue would be present without metering.

Let q_0 be the maximum nonmetered free flow rate (assumed to exist just before flow breakdown in the unmetered case), q_c be the queue discharge rate, q_d be the arrival rate at the end of the peak (which is assumed to be less than q_c because the queue eventually vanishes), and q be the metering rate. With the possible exception of Site 4, it was not possible to observe the values of q_0 directly; however, on the basis of the case study results, the ratio of q_0/q_c would not be expected to exceed about 1.05. Thus, a range of values of 1.00 to 1.05 was assumed for q_0/q_c. Values of q_d/q_c were assumed to range from 0.85 to 0.95, and anticipation times were assumed to range from 0.05 to 0.20 of the duration of the peak.

The flow-breakdown-time relationship posed further difficulties because the form of the relationship is unknown. For Site 1, mean prequeue flow rates were plotted against the time of queue formation to see whether a clear pattern would emerge, but none did. The only conclusion that could be drawn was that the time of flow breakdown varied widely (when compared with the duration of the peak) over a fairly narrow range of flows.

Given this uncertainty, a relationship was assumed that was simple, somewhat flexible, and followed Athol and Bullen's assumption (*6*) that the expected time to flow breakdown is a declining function of flow. The model actually used in the sensitivity analysis involves an instantaneous failure rate of

$$Z(t) = k[(q_0 - q_c)/(q_0 - q)]^m \quad (1)$$

where q_0, q_c, and q are as defined previously and k and m are scale and shape parameters, respectively. For $k = -T/\ln(0.5)$, where T is the normal duration of queueing in the unmetered case, this equation leads to an expected time to flow breakdown of

$$E(t) = T[(q_0 - q)/(q_0 - q_c)]^m \quad (2)$$

which varies from 0 at $q = q_0$ to T at $q = q_c$. The shape parameter m expresses the relationship between $E(t)$ and q, with $m = 1$ corresponding to a linear relationship between q and $E(t)$ and $m > 1$ to various relationships that are convex to the origin. Figure 7 shows the effects of parameter m. Again, this particular relationship has no support other than that it is plausible, meets the criteria outlined previously, and is obviously analogous to the failure function resulting from the Weibull distribution.

Given the uncertainty surrounding the flow-breakdown-time relationship and the high probability that there would be considerable scatter in breakdown times in any case, the sensitivity analysis was conducted in two stages. In the first stage, a number of combinations of flow parameters and anticipation times were assumed; for each, the expected benefit was calculated as a function of metering rate, assuming the flow-breakdown–time relationship given by Equation 2 and values of m ranging from 1 to 3. Figure 8 shows an example of the resulting plots of benefit versus metering rate. In the second stage, the expected benefit was calculated as a function of breakdown time for a variety of metering rates. Figure 9 shows an example of the plots resulting from this calculation. Thus, the first stage allows identification of an optimum metering rate, given assumptions about the flow-breakdown–time relationship, whereas the second stage shows the sensitivity of the expected benefit to scatter in the breakdown time for a given metering rate.

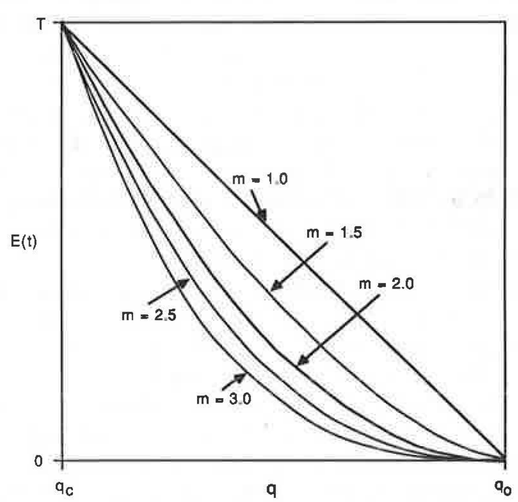

FIGURE 7 Effect of shape parameter *m* on expected time to flow breakdown.

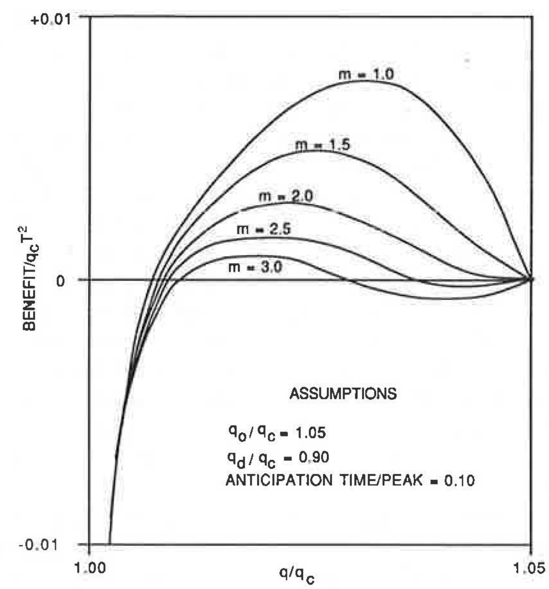

FIGURE 8 Benefit of metering versus metering rate.

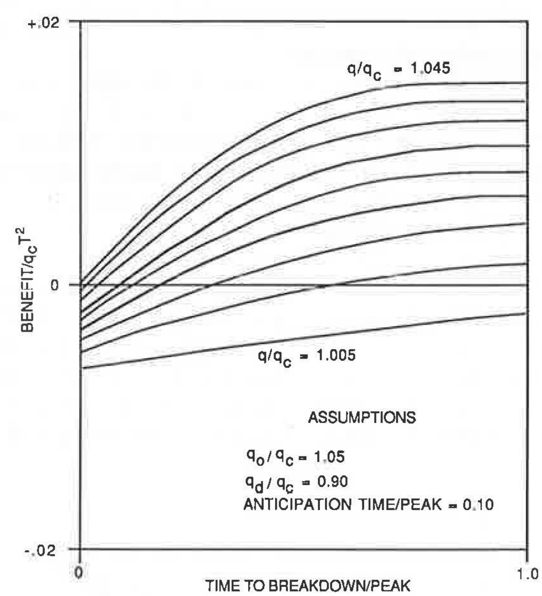

FIGURE 9 Benefit of metering versus time to flow breakdown.

Overall, the sensitivity analyses showed that the expected benefit is a function of the square of the duration of the peak and the volume passing through the bottleneck during the peak (represented here by the queue discharge rate because other flows were expressed as fractions of this). The expected benefit is sensitive to the ratio of q_0/q_c and the duration of the peak, which limit the possible benefit of metering; the anticipation time, which is responsible for the time loss represented by Area A in Figure 6; the metering rate; and shape parameter m. Optimum metering rates are primarily sensitive to shape parameter m. For $m = 1$ (assuming no scatter around the expected breakdown time), the rates are remarkably stable at about $q_c + (2/3)(q_0 - q_c)$. For larger values of m, they decline and are also sensitive to the anticipation time, increasing as it increases. Optimum metering rates appear to be relatively insensitive to scatter in breakdown times, but time savings will be overstated if this scatter is neglected.

From these sensitivity analyses, it appears that, in most cases in which flow across all lanes decreases when queues form, the optimum strategy is to delay metering as long as possible and then meter at a fairly high rate. The major practical dangers appear to lie in beginning metering too soon or setting too low a metering rate because these errors can lead to situations in which metering is counterproductive.

Key practical issues are whether it is possible to (a) anticipate the onset of queueing in the absence of metering well enough to begin metering at a number of different locations just in time to prevent flow breakdown, but not a great deal before, and (b) thereafter hold arrivals at the bottleneck within the fairly narrow range between q_0 and q_c.

The existing metering system in San Diego probably cannot provide the necessary precision. Certainly, the data indicated that there was considerable variation in metered flow arriving at the bottlenecks studied before flow breakdown. This variation was true at Site 1, where flows are extensively metered, as well as at the other sites, where upstream metering was less extensive or nonexistent.

To some extent, this finding may be the result of the details of the current metering strategy; consequently, it may be possible to improve the performance of the system. Work is currently under way to try to improve the precision of the metering provided by the San Diego system by considering the effect of metering rates at upstream locations on subsequent downstream flow. It is expected that one result of this study will be a better understanding of the extent to which target flows can actually be met at bottlenecks. At present, however, whether the system can provide the necessary precision by any conceivable control strategy is not clear.

CONCLUSIONS

The issue of whether ramp metering can increase maximum flow rates through freeway bottlenecks by preventing (or delaying) flow breakdown on the freeway main line has been considered. A test of the hypothesis that bottleneck capacities decrease when flow breaks down has been conducted.

On the basis of evidence from four bottlenecks in San Diego, it was concluded that the two-capacity hypothesis is confirmed, provided it applies to the capacities of individual lanes. The decrease in capacity is not great (at most, about 10 percent for left lanes and 3 percent for flow averaged across all lanes); in three out of the four cases studied, there was no consistent decrease in flow averaged across all lanes when data were aggregated over 12 min before and after flow breakdown. Hence, the two-capacity phenomenon is unlikely to provide a basis for a metering strategy at more than a few locations.

It also appears (on the basis of sensitivity analyses) that, even when there are decreases in total flow, there is substantial risk that metering will be counterproductive unless it is precise, and there is reason to doubt that the necessary precision is possible.

These somewhat pessimistic conclusions about the potential of ramp metering to exploit the two-capacity phenomenon do not rule out the possibility that metering can increase the capacity of freeway bottlenecks in other ways. One of the more startling findings is that merge conflicts were almost never the direct cause of flow breakdown, despite merge rates at three of the sites that far exceeded the supposed capacity of the merge point. Merge conflicts are more likely to lead to general flow breakdown at unmetered sites, especially those at which ramp vehicles arrive at the merge point in bunches. If such is the case, metering may increase bottleneck capacity by eliminating merge conflicts as a cause of flow breakdown. To settle this question, it would be desirable either to study the flow breakdown process at a bottleneck before and after the initiation of metering or to compare breakdown processes at metered and unmetered sites.

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