Probabilistic Nature of Breakdown at Freeway Merge Junctions

LILY ELEFTERIADOU, ROGER P. ROESS, AND WILLIAM R. MCSHANE

Observation of field data collected as part of NCHRP Project 3-37 showed that at ramp merge junctions, breakdown may occur at flows lower than the maximum observed, or capacity, flows. Furthermore, it was observed that at the same site and for the same ramp and freeway flows, breakdown may or may not occur. After visual examination of traffic operations at sites where breakdown occurred, it was observed that immediately before breakdown, large ramp-vehicle clusters entered the freeway stream and disrupted traffic operations. It was concluded that breakdown is a probabilistic rather than deterministic event and is a function of ramp-vehicle cluster occurrence. Subsequently, a probabilistic model for describing the process of breakdown at ramp-freeway junctions was examined. The model gives the probability that breakdown will occur at given ramp and freeway flows and is based on ramp-vehicle cluster occurrence. Simulation of a data collection effort was conducted to establish the data requirements for model validation. It was concluded that the amount of data available was not adequate for precise validation of the probabilistic model.

Various mathematical models have been used to describe the relationships among flow, speed, and density on freeways for any given instance. Such models provide the basis for selecting measures of effectiveness and defining level-of-service ranges (*1*). They are also used for estimating capacity and the operating conditions under which capacity is reached. Doing so requires the identification of the maximum volume point on a speed-flow or flow-density curve, a process often questionable because of the vague range of data generally observed before breakdown on most facilities. Because of these inconsistencies in the data, the process of flow breakdown in merge areas has not been documented adequately. The mechanism through which the operation switches from stable to unstable flow has not been modeled effectively.

Existing models predict breakdown as a deterministic function of a given flow rate, or speed, or density. These models generally assume that breakdown will occur at capacity flows only, and therefore capacity can be measured in the field immediately before breakdown. However, it is clear neither what triggers the breakdown, nor when and how the facility will eventually break down. The development of a quantitative model describing the process of flow breakdown around entrance ramps will be very useful for the operational analysis of ramp-freeway junctions. It can also help in establishing freeway control strategies to maximize flow and optimize operations on the freeway.

The probabilistic aspect of ramp merge breakdown was developed through examination and analysis of traffic data at ramp merge junctions. It was observed that breakdown was not the direct result of peak volumes. Data from NCHRP-Project 3-37, Capacity of Ramp-Freeway Junctions (*2*), showed that breakdown often occurs at flows lower than observed "capacity." One of the most interesting observations was that at a site where data were collected during two peak morning periods, breakdown occurred only once while volumes on the freeway and the ramp remained at the same levels. Closer examination of videotapes revealed that when a large cluster of vehicles entered the freeway from the ramp, queues were created on the ramp or on the freeway (or on both). Furthermore, the higher the number of ramp vehicles entering the freeway in platoons, the bigger the impact on freeway operations. On some occasions this series of vehicles caused a shift of freeway traffic to the left lanes, as they tried to avoid the turbulence and conflicts in the merge area.

The unpredictability of breakdown during data collection for NCHRP Project 3-37 led to this attempt to describe breakdown as a probabilistic function. The model that has been developed is based on the occurrence and size of on-ramp vehicle clusters instead of on ramp volume, as is done in common practice. The probability of breakdown is estimated as a function of the clusters on the ramp, which are, however, directly related to the ramp volume. The freeway flow and the respective gaps available on each freeway lane, as well as drivers' actions as they approach the merge area, were considered in developing the model. Some implications in data collection of the existence of a probabilistic model are subsequently examined, and the data requirements for validating the model are calculated.

OBSERVATIONS ON CAPACITY, BREAKDOWN, AND SPEED-FLOW RELATIONSHIPS

Capacity is defined in the 1985 *Highway Capacity Manual* (HCM) (*1*) as the maximum flow rate that can reasonably be expected to pass through a section of a roadway under prevailing roadway and traffic conditions. According to the HCM,

> at capacity there are no usable gaps in the traffic stream, and any perturbation from vehicles entering or leaving the facility, or from internal lane changing maneuvers, creates a disturbance that cannot be effectively damped or dissipated. Thus operation at, or near capacity is difficult to maintain for long periods of time, and the switch from stable to unstable flow occurs rapidly.

This definition of capacity implies that breakdown occurs immediately after capacity has been reached and is a direct consequence of high traffic volumes. The field data for this study, however, show that capacity and breakdown are not necessarily interconnected. Clearly, the way in which the stable and unstable flow branches are joined, and the operational nature of transitions between the

L. Elefteriadou, Civil and Environmental Engineering Department, Pennsylvania State University, 212 Sackett Building, University Park, Pa. 16802. R. P. Roess, Polytechnic University, Six Metrotech Center, Brooklyn, N.Y. 11201. W. R. McShane, Polytechnic University, 901 Route 110, Farmingdale, N.Y. 11735.

branches, must be investigated further. If capacity does not always occur immediately before breakdown, the shape of the speed-flow curve will appear to be discontinuous around capacity. The data presented here demonstrate that breakdown may occur at flows lower than capacity.

Field Observation of Breakdown Conditions

When studying capacity and breakdown issues at ramp-freeway merge junctions, the site selection is critical. The section downstream of the merge should be free of constraints. A downstream bottleneck would cause spillback of queues into the merge section and create the impression that the speed-flow and flow-density relationships are discontinuous near capacity. The merge area must regularly experience breakdown conditions as a direct result of the ramp volume, not because of geometric design deficiencies. Traffic operations are dependent on the specifics of the location, so that the sites selected must be as similar as possible in terms of geometrics and general environment. Taking into account geometric factors would unnecessarily complicate the study of breakdown. The field data were collected using video cameras at various locations along the freeway in the vicinity of the ramp. It was possible to observe directly the number of ramp vehicles approaching in clusters, as well as traffic operations in general. A detailed description of the data collection effort for this study can be found elsewhere (*3*).

Two sites were selected from the NCHRP Project 3-37 data base. At the first one, Site 28, data were collected during one afternoon peak period; at the second, Site 21, data were collected during two morning peak periods (Sites 21 and 59, respectively). Both sites are on six-lane freeways and involve a single-lane on-ramp. The acceleration lane at both junctions is of the parallel type. Both sites are also the middle ramps in an off-on-off sequence of ramps along a freeway.

Data Analysis

The shape of the curves around capacity depends heavily on the time intervals over which the traffic variables are averaged. If the transition period is smaller than the time intervals used, the process of averaging will create some false data points, especially if data from many days are used (*4*). Persaud observed that there is no gradual drop in speeds and flows. He showed that speed-flow observations during breakdown indicate a false pattern because they are averaged over conditions with and without a queue present, which results in a gradual decrease of speeds and flows. A similar study at a metered location undertaken by Allen et al. (*5*), who investigated transitions in speed-flow relationships, resulted in graphs implying a continuous relationship, but the data used came from detectors, so there is no information about the queue. The sudden drop in speeds that Persaud advocates is also in accordance with other researchers' observations (*6,7*) that breakdown is initiated by a slower-moving vehicle. It is also in accordance with the probabilistic model of breakdown, since a ramp vehicle cluster forces lower speeds on the freeway as soon as it occurs. Since one slow-moving vehicle makes the following vehicles reduce their speeds, the result is an overall sudden speed drop. Therefore, for this study, field data were analyzed in 1-min intervals.

Observation of videotapes on a second-by-second basis helped identify transitions and their possible causes, as well as traffic conditions in general. Transitions can best be observed with plots of traffic variables for each period of observation. For these plots the variables of interest are plotted versus the time period to examine how they change during the period of data collection. There appear to be clear advantages to looking at daily traces of traffic behavior rather than relying on scatter diagrams of many days of accumulated data (*5*). The first advantage is that from the daily plots one can obtain some idea of actual behavior of the variables, as well as their relationship in time, which the scatter diagram cannot provide. The second advantage is that inspection of the daily plots along with the videotapes permits one to identify points that represent transition between congested and uncongested flow. Visual examination also helps identify points of localized congestion on the freeway or on the ramp, not easily distinguished otherwise.

Site 28

Site 28 is located on I-290 southbound, at the intersection with Biesterfield Road, in Chicago, Illinois. Data were collected for 100 min at five locations along the freeway. Starting with the 79th min of data collection, there is a temporary disruption of traffic for 5 to 6 min, during which the flow is unstable, and then the facility returns to stable operation. During this disruption, queues form occasionally in Lanes 1 (shoulder lane) and 3 (median lane) along the merge section. The fact that no queues appeared at the last downstream camera confirmed that breakdown was not caused by a downstream bottleneck. Queues form first along the acceleration lane area, and then the disruption spreads upstream. Visual examination showed that during the 79th to 81st min, clusters of vehicles entering from the ramp disrupted traffic at this section and caused temporary breakdown.

Speed-flow time-connected diagrams for Site 28 were constructed for each camera location and lane. Figure 1 shows the speed-flow graph for a location close to the end of the acceleration lane. It can be observed that a relatively flat section representing stable conditions and speed fluctuating between 80 and 97 km/hr and a section where flow decreases somewhat with decreasing speed. After the end of the acceleration lane, on the other hand, speed only drops to 68 km/hr, with a small effect on flow (Figure 2). The numbers on the data points represent the period of observation.

Contrary to common belief, the speed drop shown in Figure 1 does not correspond to the highest observed flows. At this site the breakdown does not occur at capacity flows, when 1-min analysis intervals are used. As shown in Figure 2, flow at this location is stable at all times. There is, however, a slight speed drop (68 km/h) starting with Period 79, approximately 20 sec before the breakdown is observed at the upstream location. No queues are observed at this location, and there is no other noticeable change in operations other than the slight speed drop. This subject is investigated in greater detail in the following section, in conjunction with the observation of clusters at this site.

A general examination of Figures 1 and 2 shows that flows exceed conventional capacity estimates by far, which may be expected since these numbers represent 1-min flows. Freeway flow after the end of the acceleration lane reaches 8,500 passenger cars per hour (pcph). Most of the higher flows occur before the breakdown, but there are several intervals of high flow after the breakdown. The single-lane flows are very high, approaching 3,000 pcph per lane (pcphpl) in some cases. Finally, Lane 3 flow is consistently the highest among the three lanes.

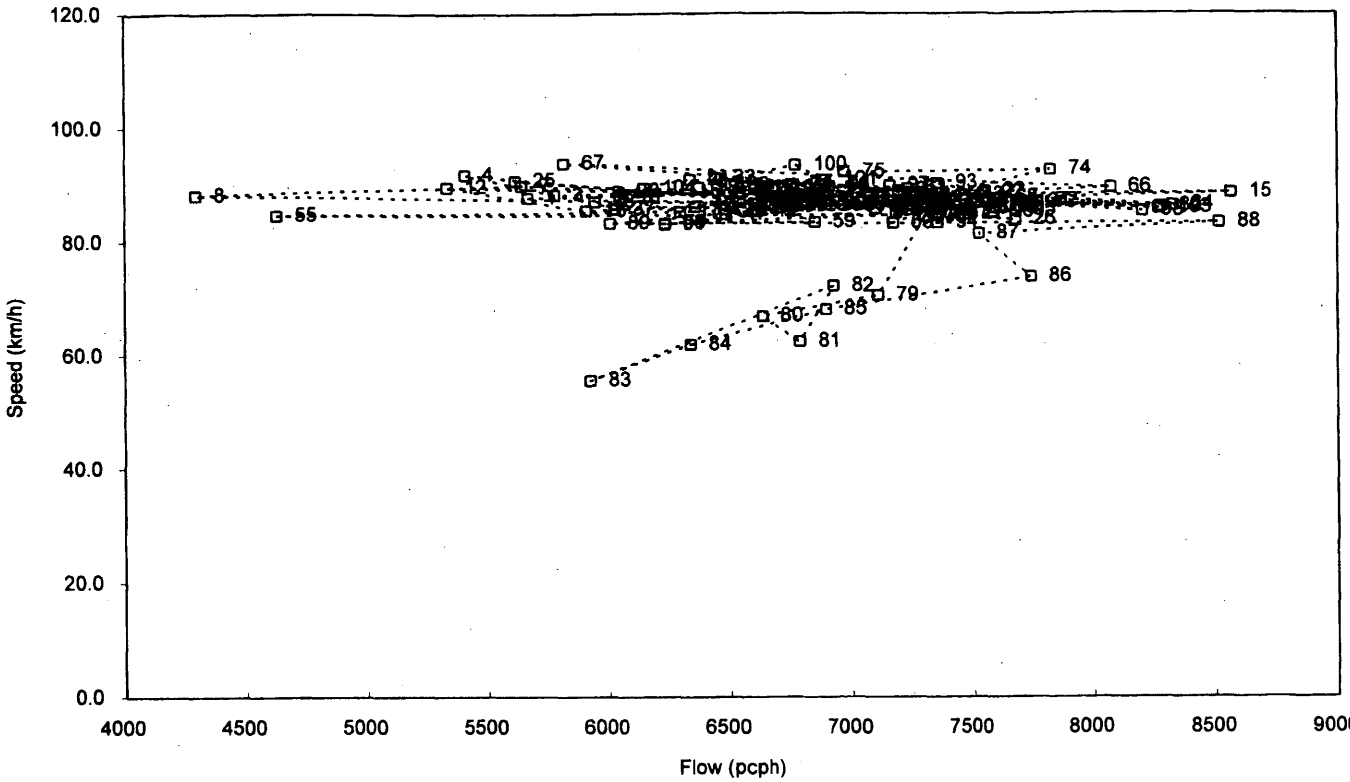

FIGURE 1 Flow versus speed at acceleration lane section, Site 28.

Speed-flow time-connected graphs with 5-min analysis intervals, especially the ones at the downstream end of the acceleration lane area, resemble much closer the conventional curves. However, two intervals preceding the breakdown have higher flows than the breakdown interval. It is also interesting that the flows downstream of the merge exceed the conventional 6,000-pcph capacity throughout the data collection period, including both stable and unstable operations. At the time of breakdown the flow at the last downstream camera is near 7,400 pcph.

Site 21

Site 21 is in Orlando, Florida, at the junction of I-4 eastbound and Princeton Street. Data were collected for approximately 1 1/2 hr at three locations along the freeway. At the beginning of data collection, the flow at the facility is stable; it switches to unstable after 1 hr and remains so until the end of data collection. Observation of the videotapes and the speed data revealed that the first location where speed drops at this site is Lane 3, the leftmost lane, downstream of the end of the acceleration lane. Subsequently, the other lanes are affected, and the breakdown spreads to the sections upstream. At this site queues were also observed downstream of the merge section, but after the formation of queues upstream. However, the last downstream camera is only 61 m from the end of the acceleration lane, whereas Site 28 is 153 m downstream. Therefore, the last downstream camera for Site 21 is closer to the merge, and the operations at this section are much more affected by the turbulence of the merge. It is speculated that at the section farther downstream from the merge area, the speed dropped only slightly, as at Site 28. It is possible that congestion and unstable flow spread downstream, with speeds increasing farther away from the merge.

As at Site 28, the transition from stable to unstable flow does not occur during the interval with the highest flow. The drop in speeds starts during Period 57, during the same interval that a cluster of 12 vehicles enters the freeway. The speed starts dropping when the freeway flow is approximately 7,500 pcph, while flows had reached 8,500 pcph before breakdown.

As expected, curves for 5-min intervals are much smoother than the ones for smaller analysis intervals. Again, the speed drop caused by the breakdown does not correspond to the peak volume.

Site 59

At Site 59 there is no breakdown during the data collection period, even though this is a site that breaks down regularly. This is the same ramp merge location as Site 21 at which breakdown was observed on a similar weekday morning peak period. Several data variables for this site were compared with the previous two sites to identify similarities and differences. The comparisons between Sites 21 and 59 were for the same real-time periods. It was concluded that the flows at Site 59 are as high as, or even higher than, they are at Site 21. The fact that Site 21 breaks down even with lower flows supports the hypothesis that the breakdown is not a deterministic function of freeway flow. The 1-min flow at the last downstream camera at Site 59 reached 9,500 vehicles per hour (vph), whereas the respective number for Site 21 is 8,800 vph. This clearly demonstrates that breakdown does not necessarily occur at

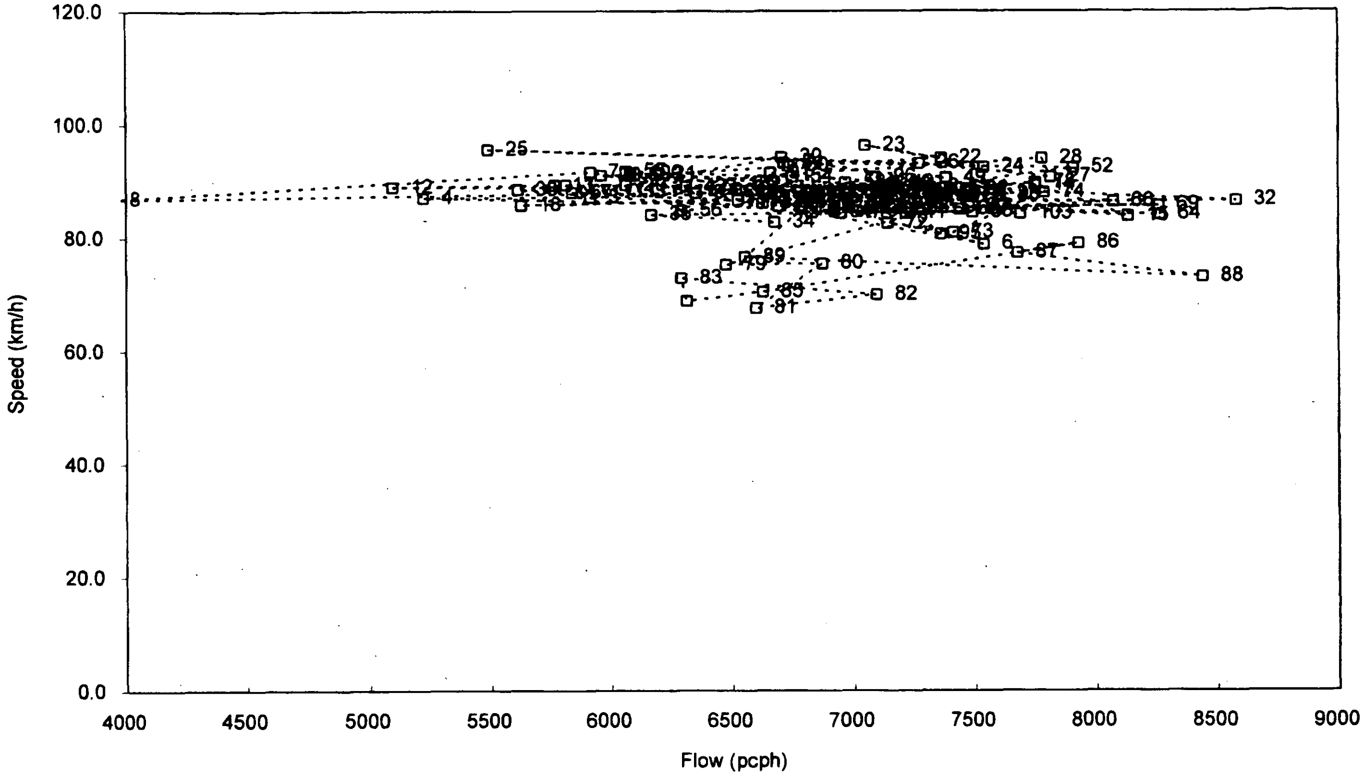

FIGURE 2 Flow versus speed after end of acceleration lane, Site 28.

capacity, therefore, previous assumptions that capacity can be measured immediately before breakdown are not true.

Field Observation of On-Ramp Vehicle Clusters

Observation of traffic operations at the gore/merge area before the breakdown led to the conclusion that when a large number of vehicles in clusters enters the freeway stream, it disrupts traffic and may result in breakdown. Therefore, the clusters were observed at the three sites to document their sizes and establish their relationship to breakdown.

A cluster is defined here as three or more vehicles traveling together so that their headway does not exceed 3 sec, or a spacing of 54 m at a speed of approximately 64 km/h. The vehicles in a cluster entering the freeway from the ramp were counted at each site. The ramp vehicles were observed from Camera 2 as they were approaching the gore area from the ramp. The time that the first vehicle in a cluster crossed the gore was recorded, along with the number of vehicles in the cluster.

Site 28

Clusters at Site 28 were observed starting at real time 3:13 p.m. The size of clusters ranges between 3 and 11 vehicles, up until the 78th min (period) of data collection. During the 78th period the cluster entering the freeway includes 15 vehicles, the largest cluster so far, and breakdown occurs during the 79th period. During the 78th interval the ramp flow is 1,320 pcph and the freeway flow is 6,449 pcph. Note that earlier, during Period 68, the freeway flow was higher (7,080 pcph) and the ramp flow was the same as for Period 78, but there was no breakdown. The only difference in operations was the cluster size, which during the 68th period never exceeded the six vehicles. There appears to be a 1-min interval during which the high-flow, high-concentration cluster must travel downstream to the beginning of the bottleneck, at which point the speed drops. Then the low-speed wave travels upstream, resulting in the temporary disruption of traffic.

As noted, the speed drops somewhat at the section downstream from the end of the acceleration lane, starting approximately 20 sec before the breakdown. Observation of videotapes verified that at the camera located after the end of the acceleration lane, 20 to 30 sec into the 79th interval there is a transition from high-speed low flow to lower-speed higher flow and density. Therefore, at this site, the sequence of events before breakdown is (*a*) entrance of a large cluster to the freeway stream, (*b*) subsequent small speed drop at the beginning of the bottleneck, which (*c*) spreads upstream and creates the breakdown.

At the freeway section along the acceleration lane, the speed starts dropping 40 sec into the interval, with the most notable drop in the shoulder lane during the last 15 sec of the interval. The speed drop at this interval is not justified by the corresponding freeway flows, since there were intervals preceding the breakdown during which flows were higher. Again, the data reinforce the notion of breakdown as a probabilistic variable. After the breakdown, during the 81st period, there is a new maximum of 16 vehicles in a ramp cluster. During this time the ramp flow is 1,020 pcph and the freeway flow is only 5,521 pcph. Operations recover after the 85th period, with the ramp flow dropping dramatically (180 pcph) during several intervals. The size of the ramp clusters does not exceed the 11 vehicles thereafter.

Site 21

Clusters were observed at Site 21, but only until breakdown occurred. Afterward, the speed drops dramatically and a queue is created on the ramp, precluding observation of cluster sizes. In general, at this site, the distances between cars were longer. It was found that the largest cluster was 12 vehicles, and it entered the freeway during the same interval that speed started dropping at the section after the end of the acceleration lane. As at Site 28, as soon as a large cluster of ramp vehicles enters the freeway, the speed starts dropping at the beginning of the bottleneck. After that, it is a matter of time for the wave to reach the merge area and for breakdown to occur. Just as at Site 28, the ramp and freeway flows were not the highest during the time of breakdown. At Site 28, though, operations became stable after 5 or 6 min, because of the low ramp volume at the time immediately following the breakdown. At Site 21, after the breakdown, there is a queue created on the ramp that does not dissipate after the first conflict. This demand on the ramp is not reflected in the ramp flows, which represent discharge flows. The location of the cameras, unfortunately, did not allow for measuring queue length on the ramp.

Site 59

Clusters were observed at Site 59 to compare operations with Sites 28 and 21 and to determine whether there is a different cluster pattern that may be crucial to the breakdown. It was determined that where the largest cluster at Site 21 was 12 vehicles, the largest cluster at Site 59 was 10 vehicles. The difference is small, and it illustrates the point that breakdown is not deterministic—that is, large clusters have a high probability to cause breakdown, but again it is not imperative that they do. Cluster size is a very important factor in causing breakdown, but breakdown is not a deterministic event.

Breakdown As a Probabilistic Event

The data presented here clearly demonstrate that breakdown does not necessarily occur immediately after capacity is reached, and high flows do not necessarily result in breakdown. During the data collection for NCHRP Project 3-37, Capacity of Ramp Freeway Junctions (*2*), several sites recommended by various agencies as frequently experiencing breakdown operated under free-flow conditions during the videotaping. This phenomenon supports the hypothesis that breakdown is a probabilistic event. Taking into consideration the probabilistic nature of merge operations, it can be explained why capacity has not been identified and why breakdown, as a direct result of the merge, is so difficult to observe.

The cluster size of on-ramp vehicles plays a very important role in breakdown. At two of the three sites, large clusters were entering the freeway stream immediately before breakdown occurrence. At the third site breakdown did not occur even though the volumes on both the freeway and the ramp were as high. It was concluded that even a large cluster does not guarantee breakdown; instead, the probability of breakdown increases with increasing cluster sizes. In the following section, a probabilistic model of breakdown (*3*) is examined, and the implications of the existence of a probabilistic model are investigated.

PROBABILISTIC MODEL OF BREAKDOWN

For the purposes of this paper, breakdown is defined as a significant reduction in speed for vehicles traveling on the mainline (i.e., 16 km/h). If vehicles on the freeway must reduce their speeds because of ramp vehicles, a traffic wave is created that propagates upstream and triggers breakdown. A traffic wave can be described as a cluster of vehicles traveling at similar speeds along a highway. In general, traffic flow is not homogeneous, and traffic waves can influence operations at any point or section of a highway.

The development of the model was based on the observation that a large cluster of vehicles entering the freeway from the ramp triggered breakdown, while at the same site, comparable freeway and ramp flows on a similar weekday peak hour had no effect on operations. Even though ramp clusters certainly affect operations, breakdown is not a deterministic function of cluster occurrence. Therefore, the probability of breakdown was computed as a function of the cluster size, which is dependent on the ramp flow rate, and the freeway flow. The objective was to develop a model that gives the probability that breakdown will occur, based on the cluster sizes, and as a function of given ramp and freeway flow rates. A brief description of the model is given in the following section; a detailed analysis can be found elsewhere (*3*).

MODEL DEVELOPMENT

The objective in developing this model was to calculate the probability of a disruption created from the ramp clusters at the ramp merge area of the freeway. The model development process is shown in Figure 3. First, the cluster effect is taken into consideration by calculating the probability of occurrence for all possible cluster sizes; clusters of 3 to 15 vehicles were considered. Then the presence of vehicles in the most critical lane of the freeway, the shoulder lane, is entered into the model with the calculation of the probability that at least one vehicle is present at the critical area of the freeway. The effect of drivers' possible actions is estimated by assigning probabilities to different actions that a driver in the critical area of the freeway may take as the cluster of vehicles approaches the freeway from the ramp. These three factors are taken into account in calculating the probability of breakdown, given that a cluster of a specific size has occurred. It is assumed that breakdown occurs if at least one vehicle on the freeway is forced to reduce its speed by 16 km/h or more. Finally, the probability of breakdown in a 15-min period is calculated, considering the expected number of clusters in the specified interval, as a function of the ramp and freeway flow.

Figure 4 shows the probability of breakdown in 15 min versus ramp flow, for freeway flows ranging from 1,400 to 2,200 vphpl over three freeway lanes. Only clusters of 3 to 15 vehicles were considered in calculating the probability of breakdown. As expected, Figure 4 shows that the probability of breakdown increases with increasing freeway flow, and effect that becomes more pronounced for high ramp flows. For ramp flows of 0 to 600

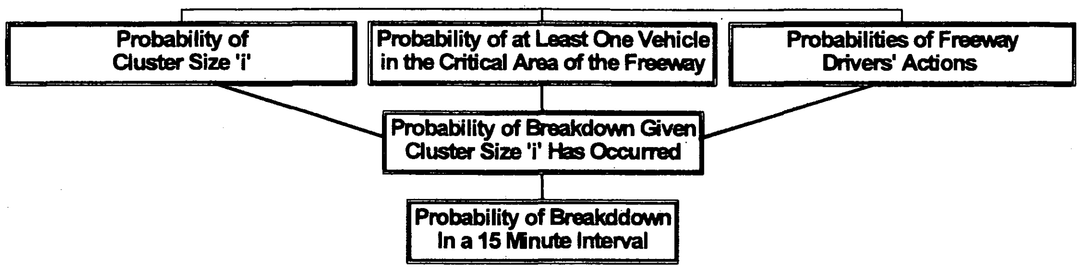

FIGURE 3 Model development flow chart.

vph, the probability of breakdown increases slowly and the effect of freeway flow is minimal. For ramp flows of 600 to 1,200 vph, the increase is sharper, especially for the higher freeway flows. The figure shows what is expected: the probability of breakdown increases with increasing ramp and freeway flows. In light of this, it is understandable why it was thought that high flows are the single cause of breakdown. Even though high ramp and freeway flows increase the probability of breakdown, they are not the direct cause of it.

In Figure 4 the probability of breakdown does not increase much beyond 0.70 for ramp flows approaching 1,500 vph, even for near-capacity freeway flows. This explains why there are few instances in which one can observe breakdown that is a direct result of the merging maneuvers. In most cases, there is a downstream constriction that creates congestion and breakdown, which eventually spreads upstream into the merge area.

Data Implications of Probabilistic Model

The existence of a probabilistic model at ramp-freeway merge junctions implies new considerations for the data collection process. The data requirements for validating the probabilistic model must be examined. In light of the probabilistic nature of breakdown, for future studies examining breakdown, the data collection requirements will change as a function of the expected probability that breakdown will occur. Calculating the sample size required for observing any aspect of breakdown operations must take into account the probabilistic model. These aspects of data collection at ramp-freeway merge junctions are examined here.

The required sample size for estimating the probability of breakdown at a single point, with given ramp and freeway flows, is determined first. The sample size N needed to estimate the true percentage within h is given by the equation

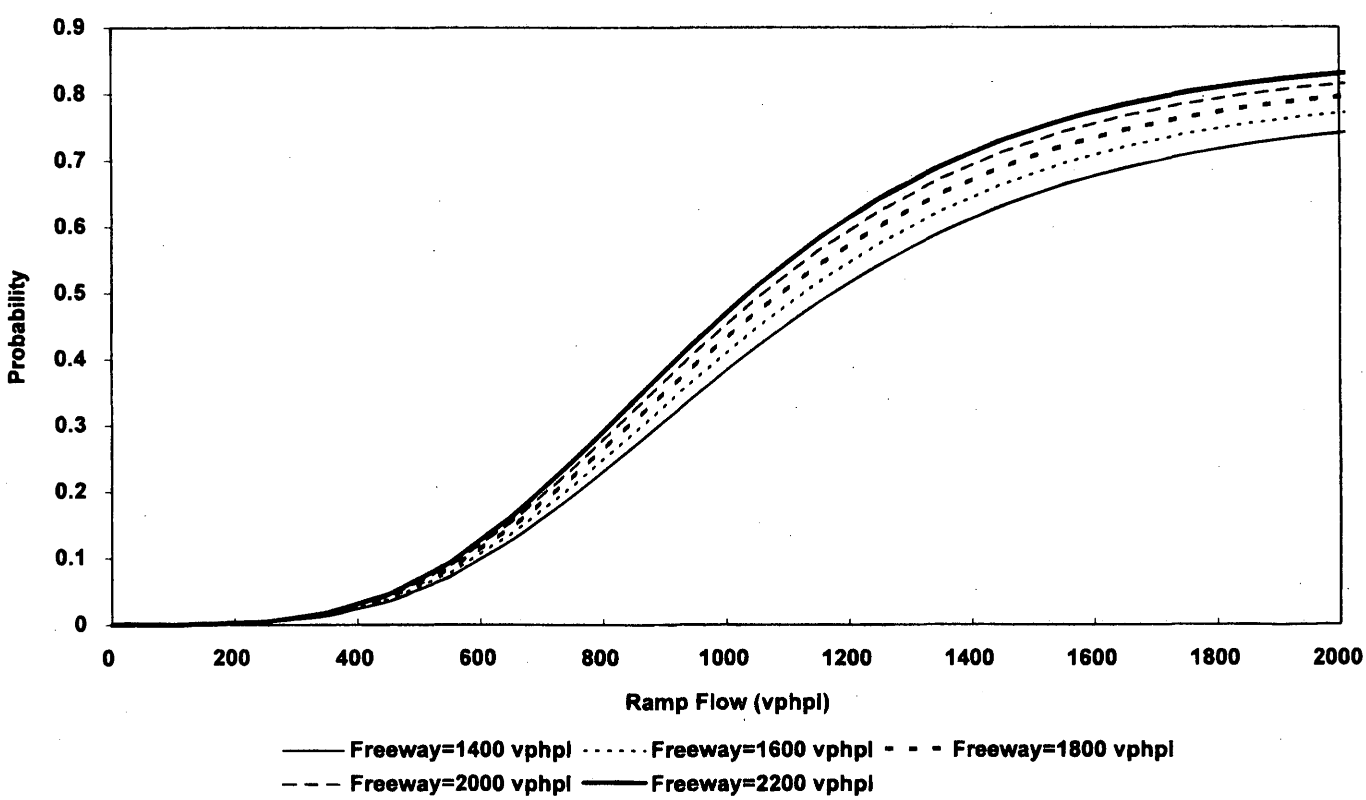

FIGURE 4 Probability of breakdown in 15 min.

$$N = \frac{z^2 p(1 - p)}{h^2}$$

where

p = true percentage,
z = standard normal distribution parameter, and
h = precision requirement, or amount of deviation from true value allowed.

From Figure 4, for a ramp volume of 1,100 vph and a freeway volume of 1,800 vphpl, the probability of breakdown is 50 percent. The normal approximation to the binomial distribution can be used here, since the percentage p is not close to p or 1. For a confidence level of 95 percent and a precision requirement of 5 percent, the required sample size is

$$N = \frac{1.96^2\, 0.5(1 - 0.5)}{0.05^2} \approx 384$$

It is noted that these samples are required to validate one point of the probabilistic curve, corresponding to a particular value of ramp flow and a particular value of freeway flow. Each of these data points represents a 15-min interval. From these calculations, it is obvious that the data requirements for validating the probabilistic model are enormous.

In the preceding example, the confidence intervals for a sample size of 10 are

$$h = z\sqrt{\frac{p(1 - p)}{N}} = 0.310 = 31.0 \text{ percent}$$

They do not provide the desired precision, given that they cover more than half of the range of probabilities.

Demonstration of Data Requirements Using Simulation

After the data requirements for validating each point of the probabilistic model are examined, the corresponding requirements for a linear regression equation fitted to the model are studied. The Far fewer data points are needed for calibrating a linear relationship than are needed to calibrate each point of the x-axis. Assuming that the model and its equation are true, simulated field data are generated and compared with the probabilistic model.

First, regression was performed to derive the equation of the line describing the probabilistic model of Figure 4 for a freeway flow of 1,800 vph per lane (vphpl). This equation is almost a straight line between the ranges of 300 and 1,500 vph. For this range, and for freeway flow 1,800 vphpl, the probability of breakdown is approximated by the linear equation

$$y = -0.29723 + 0.000653\, x$$

Then, using Monte Carlo simulation, it can be shown what the typical data scatter will be in estimating the probability of breakdown from field data. It is assumed that a typical data base will contain 50 data points, each of them representing whether breakdown occurred at a particular ramp flow (yes or no). It is also assumed that these points are divided equally among five ramp flow rates; 300, 600, 900, 1,200 and 1,500 vph.

For the simulation, a random number generator is used for predicting whether breakdown occurs or not. The boundaries established in the probabilistic model are used to distinguish between breakdown and free-flow conditions for each volume. It is assumed that the freeway volume is constant, at 1,800 vphpl. Twenty such experiments were conducted to illustrate the possible outcomes of such an experiment; the resulting probability curves are shown in Figure 5. As shown, a sample of 50 data points can produce drastically different results. Each of the 20 experiments, if seen alone, can give a totally different picture than the others: some of them result in lower probabilities of breakdown for higher flows, others show exactly the opposite. It is clear from the simulation experiment that limited amounts of data will give misleading results.

Regression was used to derive the linear equations that describe each of these experiments, so that they can be compared with the original probabilistic model. For each experiment, the two linear equation coefficients b_0 and b_1 are calculated as follows:

$$b_1 = \frac{\sum x_i y_i - nXY}{\sum x_i^2 - nX^2}$$

$$b_0 = Y - b_1 X$$

where

x_i = ramp flow,
y_i = probability of breakdown, and
X, Y = respective averages.

Subsequently, the regression confidence bounds are calculated by calculating the confidence bounds of the parameters b_0 and b_1. The confidence interval for b_1 is

$$\beta_1 = b_1 \pm z s_{b_1}$$

where z is the normal distribution parameter and the standard deviation for b_1 is calculated as

$$s_{b_1}^2 = \frac{s^2}{N s_x^2}$$

The confidence interval for b_0 is

$$\beta_0 = b_0 \pm z\, s_{b_0}$$

The standard deviation of b_0 is estimated as

$$s_{b_0}^2 = \frac{s^2}{n}\left(1 + \frac{x^2}{s_x^2}\right)$$

The confidence intervals for these parameters are too wide for the accuracy needed in the model. The constant b_0 of the probabilistic model is −0.29723, whereas the ranges calculated vary from −0.30 to 0.10. The b_1 coefficient of the probabilistic model is 0.000653, with ranges between −0.00027 and 0.00080. Figure 6 shows the frequency distribution for b_0 and Figure 7 shows the frequency distribution for b_1. These figures show the variability of the coefficients and demonstrate again the inadequacy of a limited data base to validate the probabilistic model.

As noted, establishing the true probability of breakdown at ramp-freeway merge junctions is required for estimating the sample size needed for observing breakdown. The probability of breakdown must be known before the data requirements can be estimated. For example, if the probability of breakdown is 50 percent, then a sam-

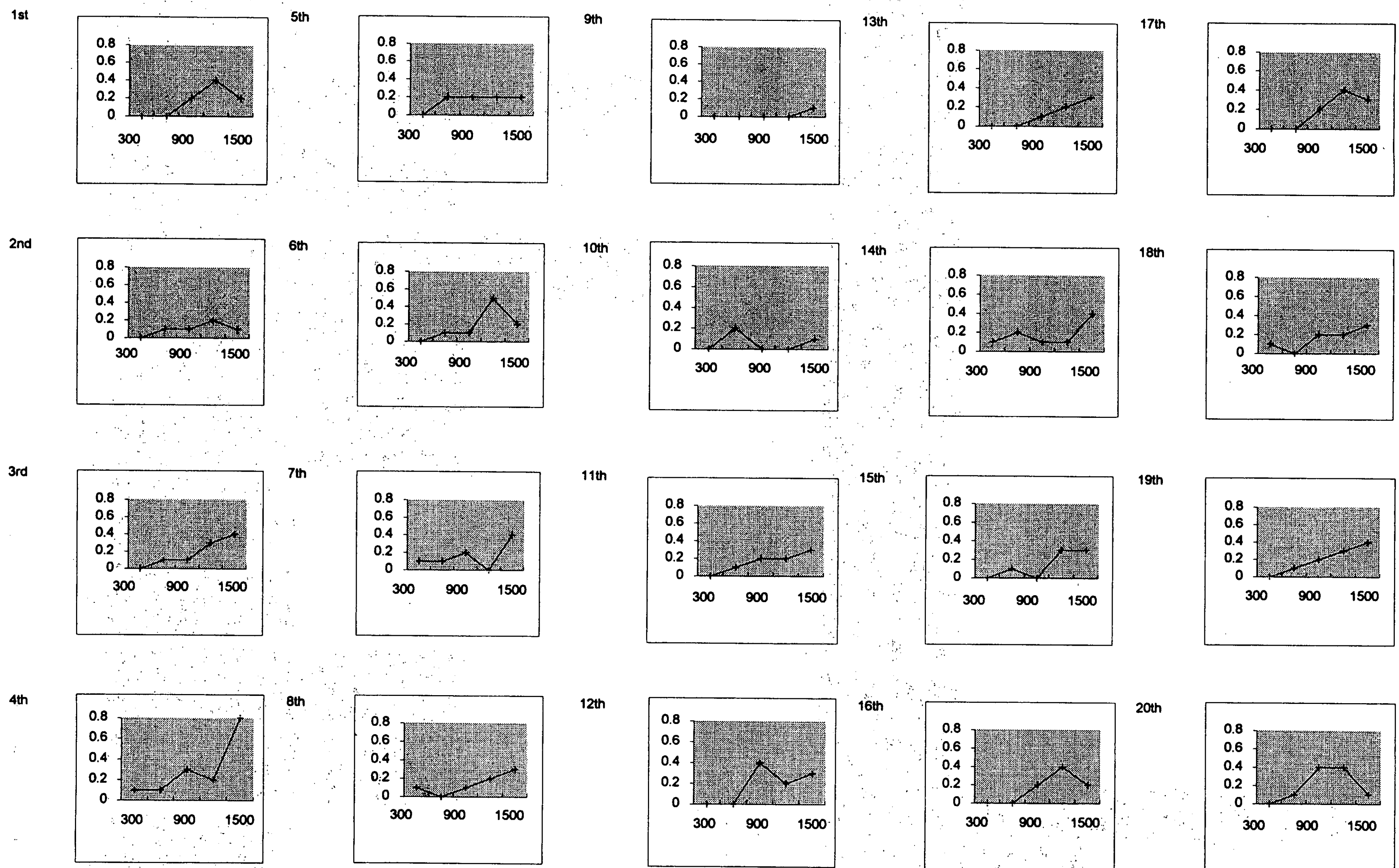

FIGURE 5 **Simulation results (probability is shown on *y*-axis; flow rate in vph on *x*-axis).**

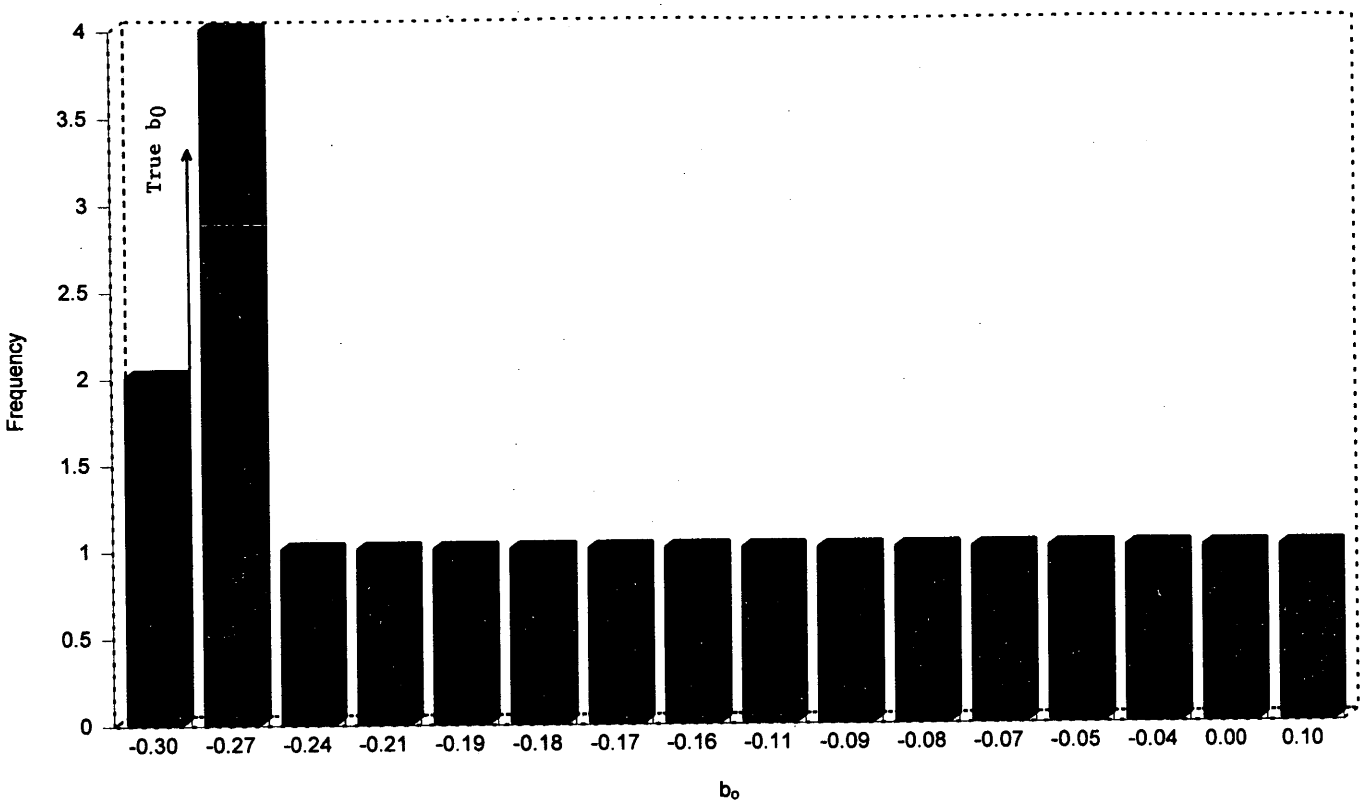

FIGURE 6 **Frequency distribution of b_0.**

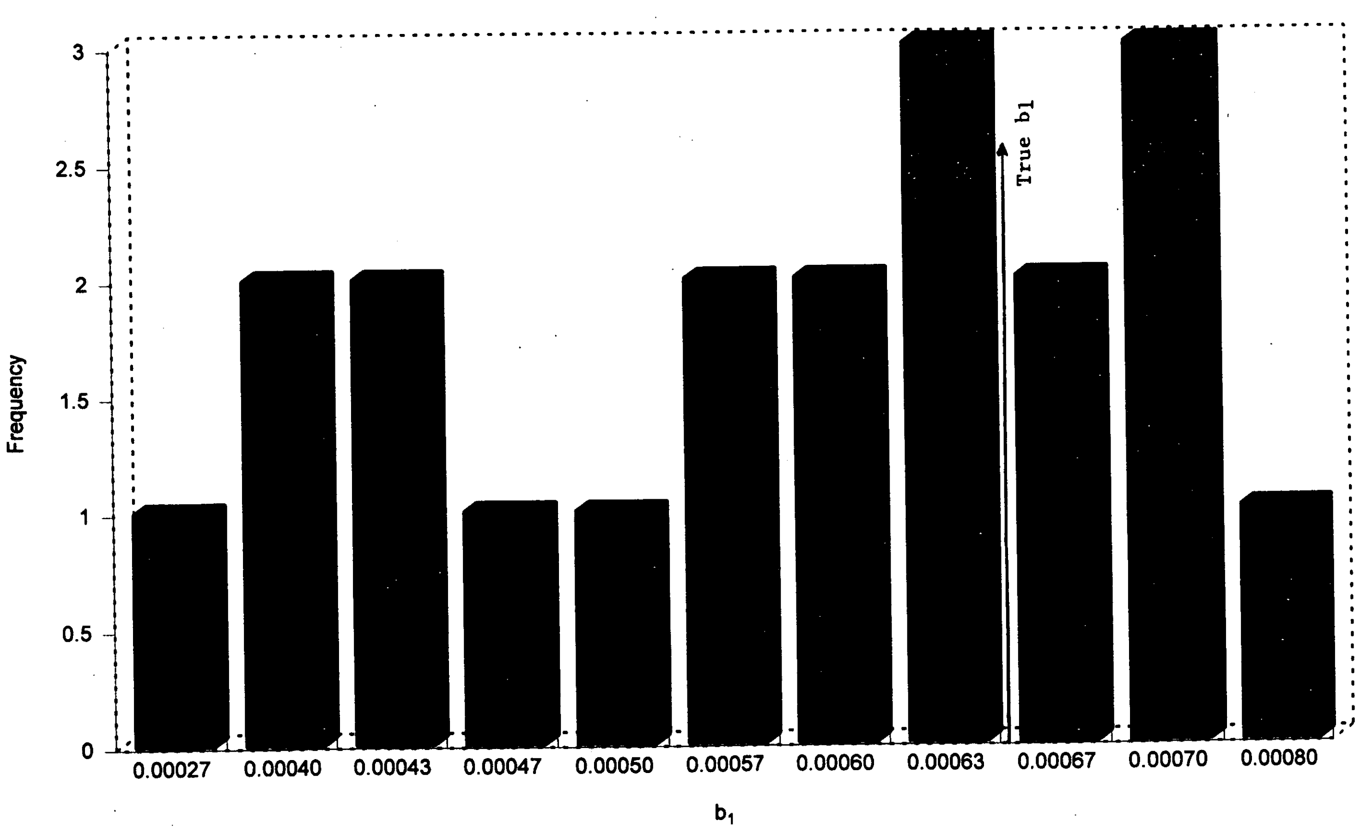

FIGURE 7 **Frequency distribution of b_1.**

ple of size 10 will on the average result in observing only five break-down occurrences.

CONCLUSIONS AND FUTURE RESEARCH

Field data, taken during three peak periods at two merge junctions, were examined to study capacity, breakdown, and speed-flow issues. The first one, Site 28, experienced a disturbance of traffic operations for only 10 min, but it gave valuable information about breakdown conditions. The fact that the speed never drops below 68 km/h downstream of the merge area precludes the occurrence of a downstream bottleneck affecting the section. The flows at the time of breakdown were not the highest observed at this site. Observation of videotapes showed that a ramp cluster entered the freeway stream immediately before breakdown and caused the speed drop at the merge.

At the second site, Site 21, the last camera was not far enough downstream for free-flow conditions to be observed after the bottleneck section. Nevertheless, Site 21 data have many similarities to Site 28 data. The flows were not the maximum observed at this site when breakdown occurred. Again, a large cluster was observed entering the freeway immediately before breakdown. During the second data collection period at this site (Site 59), breakdown did not occur, even though the ramp and freeway flows were at comparable levels. Observation of field conditions verified that there were no large ramp clusters occurring throughout the data collection at this site.

Following these observations, a probabilistic model that was developed to predict breakdown at ramp-freeway junctions as a function of ramp clusters and freeway flow was examined. In general, the following conclusions can be drawn:

- The breakdown at ramp-freeway junctions is a probabilistic variable and not deterministic, as it has been thought. The data showed that breakdown does not always occur at given volumes, even at the same site.
- Capacity does not necessarily occur immediately before breakdown. Data showed that capacity flows are not a prerequisite for breakdown and are not the only factor in breakdown occurrence.
- Clusters of vehicles from the ramp, rather than ramp flow, may cause breakdown. Even though clusters are a function of ramp flow, it is the clusters that affect operations at ramp-freeway junctions.
- Ramp metering, which helps break up the ramp vehicle clusters, improves traffic operations at merge junctions. Even though it is assumed that ramp metering is beneficial because it decreases the ramp volume, in reality its greatest benefit is that it alleviates large clusters. The same effect may be achieved by using small cycle lengths at the signals upstream from the ramp.
- Since the probability of breakdown does not increase much beyond 70 percent for ramp flows of 1,500 vph, it can be explained why there are few instances in which one can observe breakdown that is a direct result of the merging maneuvers. In most cases, a downstream constriction creates congestion and breakdown, which eventually spreads upstream into the merge area.
- Speed remains almost constant at both sites and all camera locations until the breakdown. At the last cameras downstream, there is a relatively gradual speed drop before the breakdown, but it does not occur until operations are about to become unstable.
- More data are needed to validate the probabilistic model developed here with more precision, or to establish other factors that may influence the model. Establishing the true probability of breakdown at merge junctions is required for estimating the sample size needed for observing breakdown.

ACKNOWLEDGMENT

The data used for this paper were obtained from the NCHRP Project 3-37 data base.

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Publication of this paper sponsored by committee on Highway Capacity and Quality of Service.