

Observed Dynamic Traffic Features on Freeway Section with Merges and Diverges

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Traffic data measured on a four-lane freeway and its on-ramps (with metered flows) and off-ramps were studied for 4 days during the peak hour. Certain features were reproducible from day to day. A bottleneck arose on all 4 days because of traffic merging and diverging at a freeway location. During these times queuing arose in a freeway section with an auxiliary lane some distance downstream of the merge. Corresponding flow reductions were also measured at a downstream off-ramp. Queuing was apparently caused by drivers who had just entered the shoulder lane from the on-ramp and had slowed down to merge. The slowing of vehicles spread to both lanes and propagated upstream. The average discharge flows that accompanied the onset of queuing were 4% lower than flows measured just before the queue's formation. Upon bottleneck activation, flow reductions occurred sequentially in time and space marking the passage of the backward-moving shock. Mean shock velocities ranged from 20 to 24 mph (32 to 40 km/h). The analysis used transformed curves of cumulative vehicle counts and cumulative occupancy to obtain the measurement resolution necessary for studying important traffic features. The site is located in Minneapolis, Minnesota, and data were collected before a ramp meter shutdown experiment conducted in 2000.

Queue features at a freeway bottleneck that became active because of merging and diverging traffic are described. It is shown that the bottleneck became active during the p.m. peak after the influx of traffic rose on an on-ramp. This rise was accompanied by a sudden drop in exit ramp flow downstream of the on-ramp, indicating that queuing arose between the on- and the off-ramps and was apparently caused by drivers who had just entered the freeway at reduced speeds in order to negotiate lane-change maneuvers.

From this study, certain reproducible patterns were observed. For example, the location of the bottleneck and the patterns of flow observed on the nearby ramps were consistent for all days of analysis. The average discharge flow measured after the bottleneck arose did not vary much from day to day either and was 2% to 5% lower than the flows that prevailed before the bottleneck's activation. The onset of queuing was marked by a sudden drop in flow and increase in measured occupancy. The velocity of the backward-moving shock marking the onset of queuing was also similar from day to day.

Some observations reported here remain consistent with earlier studies of freeway bottlenecks. This study used cumulative vehicle arrival curves and cumulative curves of vehicle occupancy measured at neighboring loop detectors, transformed in ways that reveal

traffic characteristics of interest. This method enabled construction of cumulative vehicle arrival curves across merges and diverges that helped identify the bottleneck's location and the times it remained active. Earlier studies on traffic flow have used similar procedures for studying merges (1-6) and diverges (7).

After presentation of some background, the freeway site and the loop detector data used for analysis are described. Then a detailed description of the bottleneck's location and the adjustments that were necessary to ensure conservation of vehicles between the consecutive stations is presented, along with the observations for one study day. Using at least five successive detector stations (three upstream and two downstream of the bottleneck), the analysis includes identification of the bottleneck's location and time it remained active, as well as bottleneck discharge features, merging and diverging ramp flow analyses, and wave propagation upon queue formation. Some findings from repeating these analyses with data from other days are also included in the subsequent section. Finally, some concluding remarks are provided.

BACKGROUND

In order to understand how a freeway system operates, one must understand where its bottlenecks are located and when they are active. An active freeway bottleneck is a location characterized by the presence of queued traffic immediately upstream and unqueued (freely flowing) traffic immediately downstream. Toward an understanding of more details of freeway operations, some previous studies have found bottlenecks near merge and diverge areas (1-7). Also, several empirical studies have shown that bottleneck activation was preceded by certain clear signals like high bottleneck input flows that persist for few minutes (1-4). However, despite the value of these observations, freeway bottlenecks are still an important subject for further research and experimentation. Thus, this research makes a small contribution to the understanding of freeway operations by carefully examining the activation of a bottleneck in a freeway section with an auxiliary lane in Minnesota. With further research in the area of bottleneck prediction, freeway managers, planners, and designers would be able to use this information to improve operations in real time.

DATA

The data analyzed in this study came from northbound highway US-169, located in Minneapolis, Minnesota. US-169 is a limited-access freeway with ramp control and high afternoon peak-period flows. The total length of the freeway is approximately 16 mi (26 km) between I-494 and I-94, and a 3-mi (4.8-km) section was chosen for this study (Figure 1).

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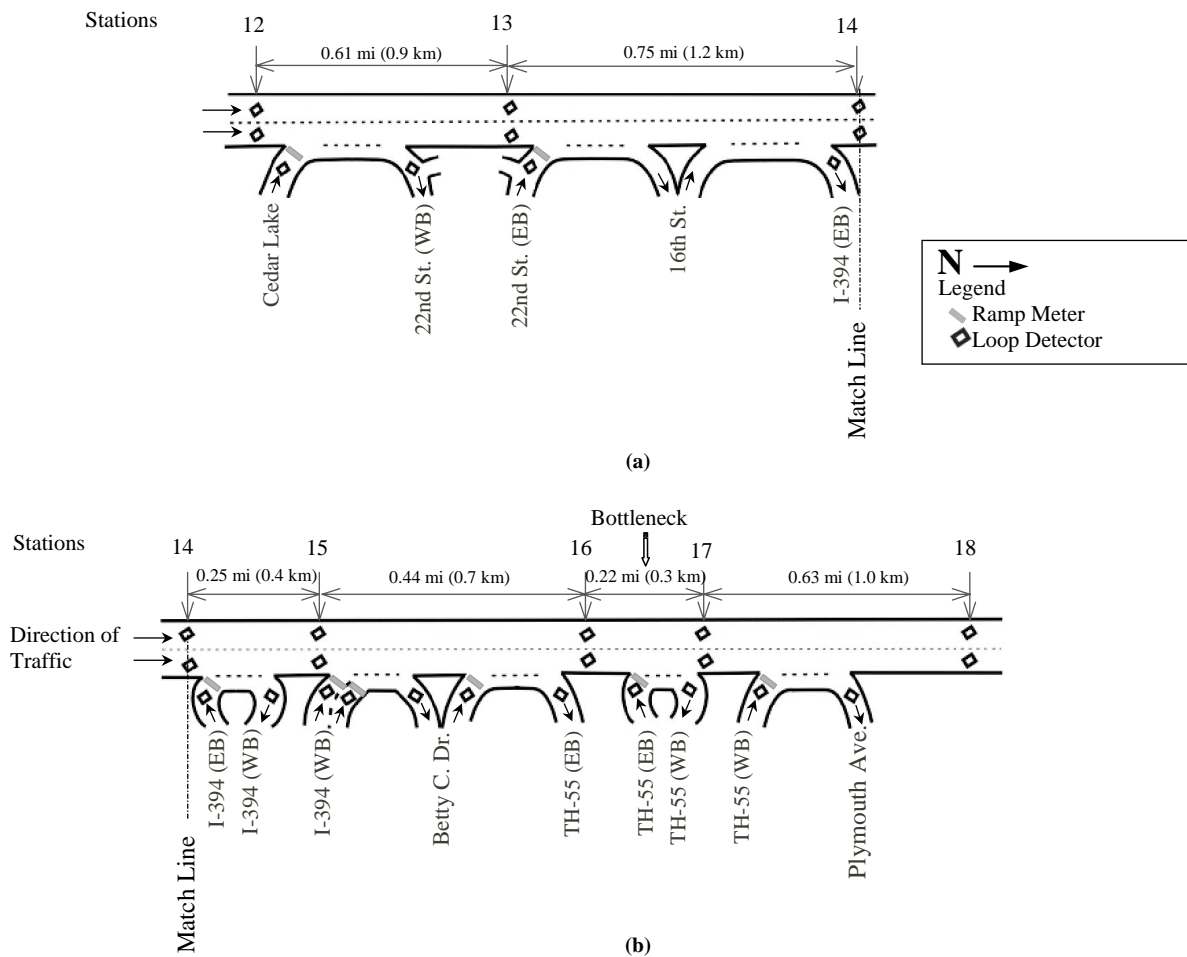


FIGURE 1 Site map, US-169 (not to scale).

The site map shows that there were eight on-ramps and eight off-ramps in the section of interest. The inductive loop detectors, indicated by diamond-shaped symbols, recorded vehicle counts and occupancies (a dimensionless measure of density) over 30-s intervals. For this study, the seven mainline detector stations (one detector is located in each travel lane) were numbered 12 to 18. All on- and off-ramps had detectors except at the 16th Street interchange between Stations 13 and 14. An auxiliary lane is present between each on-ramp and subsequent off-ramp. It should be noted that during the evening peak periods analyzed for this study, all on-ramps were metered and that the posted speed limit was 55 mph (88 km/h).

The data were available for four weekdays between March 20 and 23, 2000. The conditions on this freeway section were suitable for studying queue characteristics since it consisted of two northbound lanes of a four-lane freeway with no lane drops and no obvious inhomogeneities other than the ramps and auxiliary lanes. US-169 is a vital corridor that connects the city of Minneapolis to southwest Minnesota's manufacturing and agricultural centers and carries both commuter traffic and heavy commercial and recreational traffic. Two main highways, I-394 and Trunk Highway 55 (TH-55), included in the study area, also intersect US-169. As will be demonstrated, a bottleneck consistently formed between Stations 16 and 17 on each of four afternoons studied. The weather for all days considered for

analysis was dry and sunny except for March 23, 2000, when light rainfall was experienced (8).

OBSERVATIONS

The observations that follow were taken during an afternoon peak on one of the four study days (March 20). The analysis began by plotting raw occupancy data (Figure 2). In Figure 2, the y -axis is distance, the x -axis is time, and the color variation represents occupancy, from light gray for lower occupancy to dark gray for higher occupancy. As shown, the peak period occurred between 17:00 and 18:00, when the occupancies appeared above normal (dark gray areas). This contour map also verified the extent of congestion and the candidate location of a bottleneck, possibly in the vicinity of Stations 16 and 17. Lower occupancy (indicating higher speeds since it is a surrogate of density) occurred at Stations 17 and 18 during the day except at 16:45 at Station 17, when the occupancy rose to 50% for approximately 10 min. This rise was due to a minor incident that ended before 17:00. Since occupancy values of more than 28% are an indication of congested conditions (9), Figure 2 shows that congestion propagated over several miles upstream of Station 16 and began to dissipate beginning at Station 12. The minor incident that

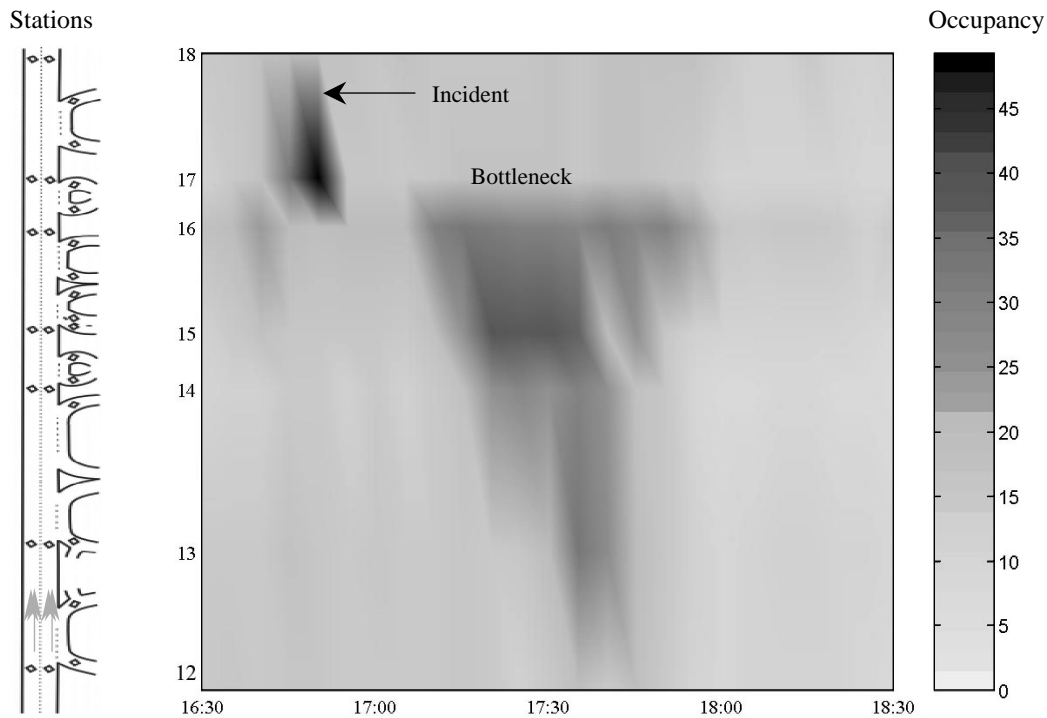


FIGURE 2 Day 1: occupancy contour map.

occurred between Stations 17 and 18 had no impact on the traffic conditions observed later.

The initial findings noted earlier were confirmed by constructing oblique curves of cumulative vehicle arrival number versus time, $N(x, t)$, as shown in Figure 3. The oblique $N(x, t)$ include counts measured across both lanes at Stations 12 to 18. Since the available archived detector data were aggregated over arbitrary 30-s periods, an unaltered $N(x, t)$ would be an increasing step function with even time intervals. To create the smoothed $N(x, t)$, linear interpolations through the near-side top of each step were used so that a curve's slope at time t would be the flow past location x at that time. The counts for each curve began relative to the passage of a hypothetical reference vehicle ($N = 0$) so each pair of curves describes the same collection of vehicles. Each upstream $N(x, t)$ was shifted horizontally to the right by the average free-flow trip time from its x to the respective downstream station. Any resulting vertical displacements between curves would be the excess accumulations of vehicles between the station pairs and resulting horizontal displacements would be the delay between the stations (10). Details of these curves were amplified by using an oblique axis, where q_0 is the rescaling rate (obtained by trial and error). For readers interested in the use of an oblique coordinate system, several authors describe this procedure in detail (1–3, 6, 11).

For the construction of $N(x, t)$ for Stations 12 through 18, on- and off-ramp counts were included so that pairs of curves shown in Figure 3 described the same collection of vehicles. A pairwise approach was adopted in which the interchanges were modeled as single points along the freeway, including on-ramps and off-ramps located at these points. Thus, cumulative vehicles measured upstream should equal those measured at the neighboring downstream station minus the interchange's net inflow. With this methodology for the

site selected, results from station pairs showed that the upstream volume minus the interchange's net inflow did not exactly equal the neighboring downstream volume. During uncongested periods, the vehicle counts for the analysis period indicated a slight loss of vehicles when the upstream and the downstream stations were compared. It appeared that the off-ramp detectors were missing vehicles that did not pass directly over the ramp detectors but rather drove around them.

It is recognized that the study would have benefited from video data for the site. In the absence of such data, minor adjustments were made to the exiting ramp flows in order to maintain vehicle conservation between each pair of neighboring stations. The resulting off-ramp volume adjustments for Stations 12 to 18 ranged between 4 and 38 vehicles over the peak hour. Cumulative curves of measured occupancy, $T(x, t)$, were also constructed for each station. As with the $N(x, t)$, piecewise linear approximations to the $T(x, t)$ were constructed and $T(x, t)$ was plotted on an oblique axis, where b_0 is the rescaling rate. $T(x, t)$ at each station also described measurements across both travel lanes. The oblique $T(x, t)$ improved the resolution of occupancy features at location x .

An example of this procedure is shown in Figure 4, which was plotted for Station 17 (minus net inflow) and Station 18 for March 20, 2000. A schematic sketch of the two stations is shown below the plot. As may be seen, the traffic between the stations had nearly stationary characteristics in which the fluctuations in flow at Station 17 (minus net inflow) were seen at Station 18 a short time later, taking into consideration the free-flow vehicle trip time. This nearly stationary traffic could only have resulted from a state when the traffic was freely flowing (12). Oblique $T(x, t)$ and $N(x, t)$ (Figure 5) confirmed that queuing was not present at this location since the curves do not display any abrupt reduction in $N(x, t)$ accompanied by a rise

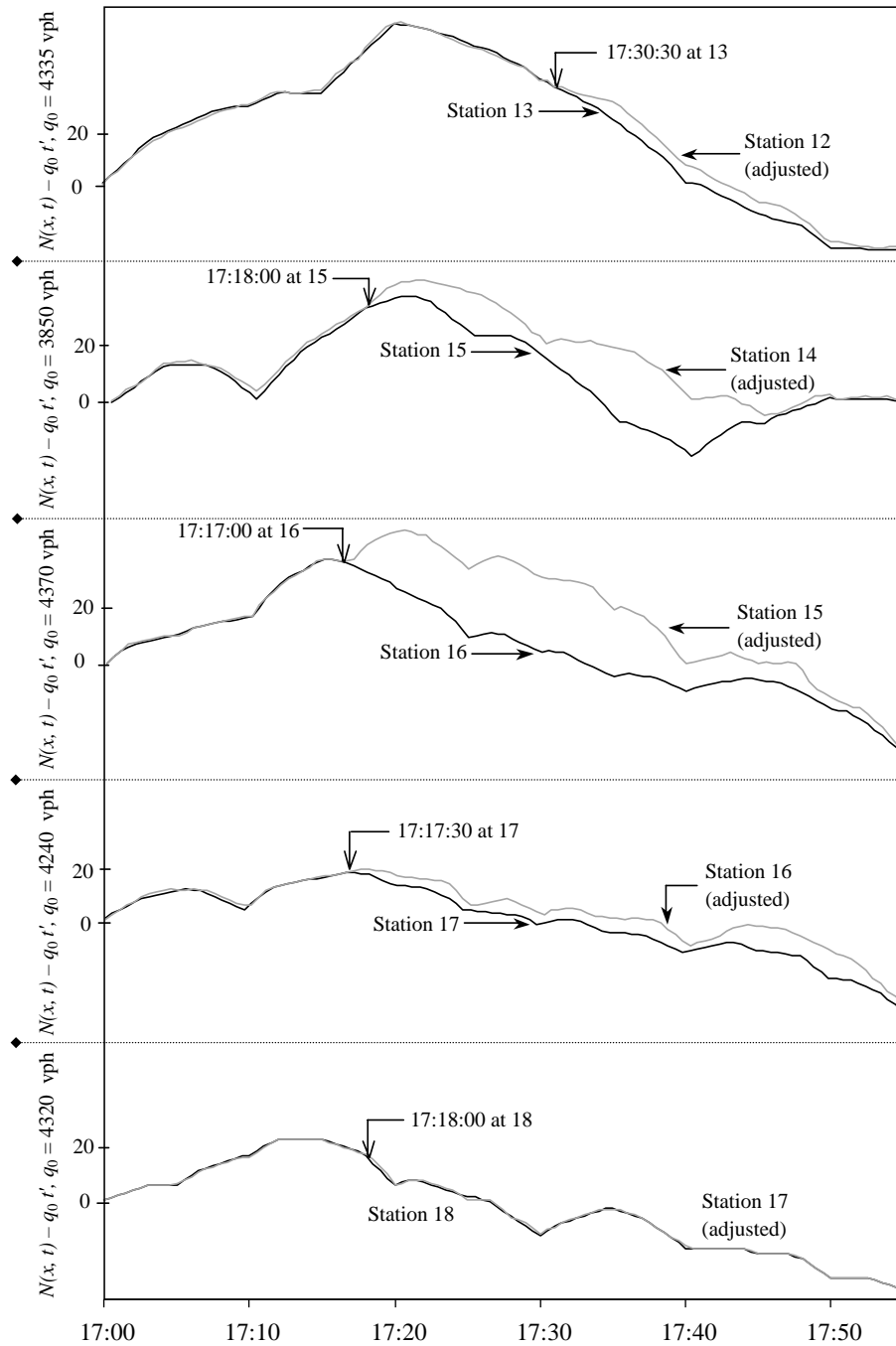


FIGURE 3 Day 1: transformed $N(x, t)$.

in $T(x, t)$, a feature that would mark the arrival of a queue from downstream. In Figure 5, both curves display very similar features, confirming that the stationary traffic state that existed between Stations 17 and 18 was free flow. The vehicle accumulations that appear between the stations are actually due to the undercounting of the number of off-ramp vehicles leaving the system before Station 18. In this case, adding eight vehicles to the off-ramp volume corrected the problem.

Returning to Figure 3, for each pair of $N(x, t)$, the upstream curve includes adjusted off-ramp volumes as discussed earlier. As shown in

Figure 3, the $N(x, t)$ for Stations 17 and 18 remain nearly superimposed, indicating that the traffic remained freely flowing between these two locations. Flow reductions at the two stations were noted at 17:17:30 and 17:18:00, respectively. Figure 3 also shows excess vehicle accumulation between Stations 16 (adjusted) and 17 at around the same time (17:17:30). Evidence from the nearly superimposed $N(x, t)$ between Stations 17 (adjusted) and 18 and the excess accumulation between Stations 16 (adjusted) and 17 indicates that the bottleneck was located between Stations 16 and 17. The divergence of the curve at Station 16 from the one at Station 15 (adjusted) at

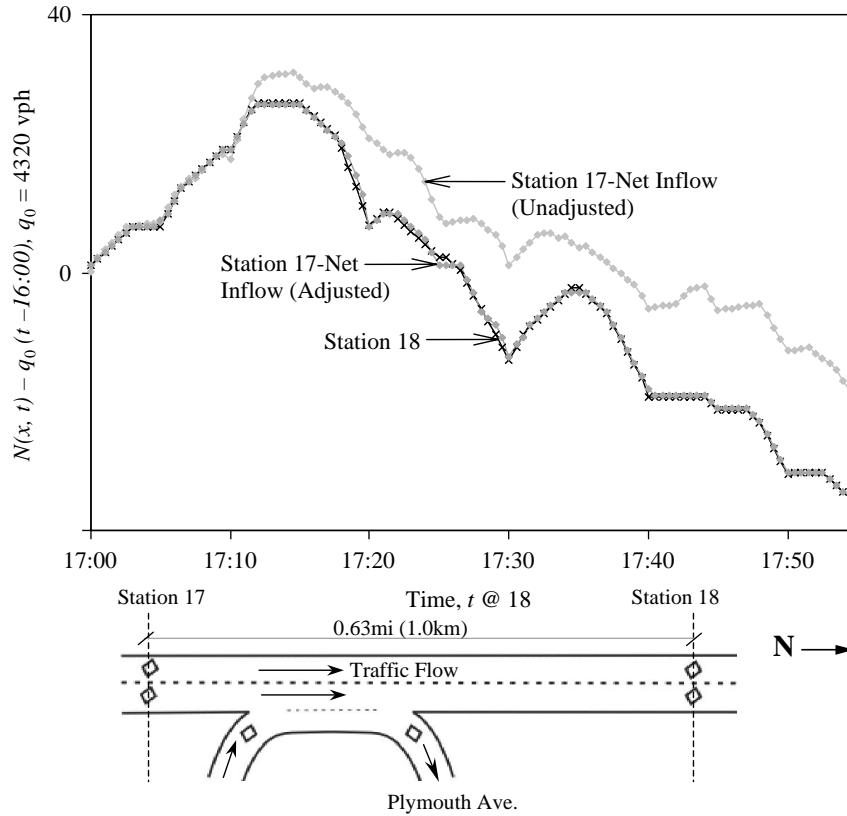


FIGURE 4 Volume adjustment example.

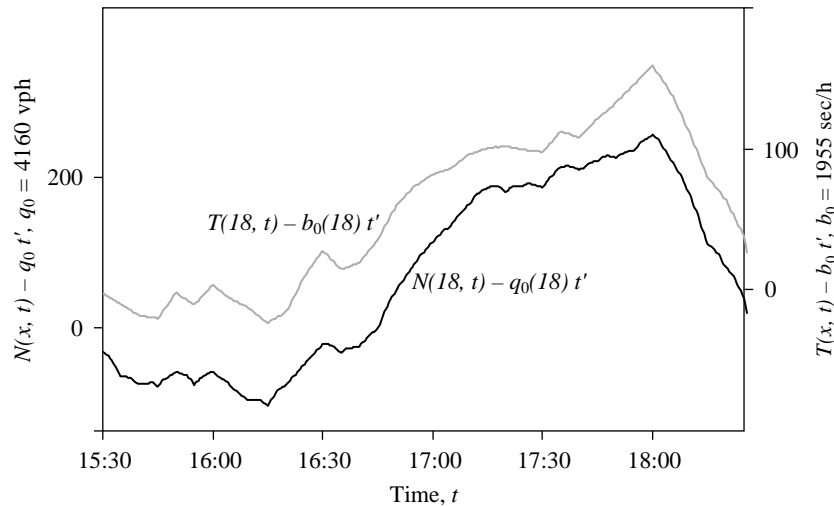


FIGURE 5 Oblique $N(x, t)$ and $T(x, t)$ downstream of bottleneck (Station 18).

approximately 17:17:00 marked the arrival of a backward-moving queue at Station 16. A pronounced flow reduction at Station 16 accompanied this divergence. This finding was confirmed by plotting oblique $N(x, t)$ and $T(x, t)$ for Station 16 as shown in Figure 6a.

Figure 3 also mapped the propagation of the queue upstream of Station 16. As shown, the tail of the queue arrived at Station 15 at 17:18:00 (corroborated by the increase in occupancy shown in Figure 6b). Since the ramp counts were not available for the 16th Street

on- and off-ramps between Stations 13 and 14, the excess accumulation of vehicles between the two stations could not be traced. However, Figure 6c shows that the queue arrived at Station 14 at around 17:19:00, marked by a reduction in flow and a simultaneous increase in occupancy. The backward-moving queue reached Station 13 at around 17:30:00. Until this time, the nearly superimposed $N(x, t)$ for Stations 12 and 13 in Figure 3 show that the traffic had been flowing freely between them. This finding is corroborated

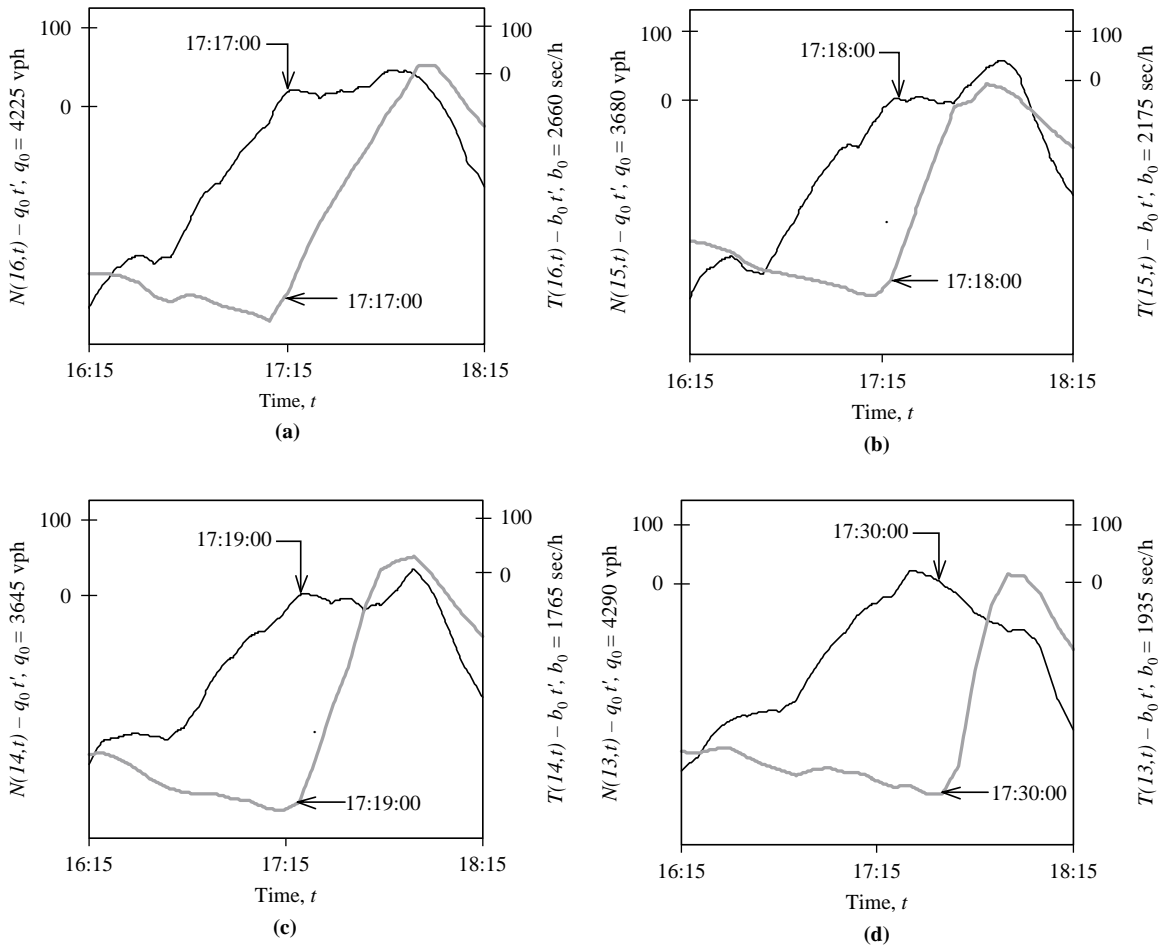


FIGURE 6 Day 1: oblique $N(x, t)$ and $T(x, t)$: (a) Station 16, (b) Station 15, (c) Station 14, and (d) Station 13.

by Figure 6d, which shows an increase in the oblique $T(x, t)$ at 17:30:00.

To understand the traffic flows in each lane, $N(x, t)$ and $T(x, t)$ were constructed for each lane as shown in Figure 7. It should be noted that the backward-moving shock arrived at slightly different times in each lane. The velocity at which the shock propagated (measured using 30-s data) varied slightly between stations. Table 1 presents the shock characteristics recorded on bottleneck activation for Day 1. The bottom row shows the speed and travel time of the wave traveling from Station 17 to 18, which was a downstream-moving expansion wave of lower flow and lower occupancy. On Day 1, the observed backward-moving shock velocities ranged between -15 and -26 mph (-24 and -42 km/h). These velocities were slightly faster than those reported previously (11, 13). Earlier studies benefited from the use of loop detector data archived at a resolution of 1 s.

To confirm the period during which this bottleneck remained active, Figure 8 shows transformed $N(x, t)$ for Station 12 (adjusted) and Station 18. Station 12 was adjusted to account for the total net inflow of all on- and off-ramps between Stations 12 and 18. Figure 8 also shows Station 12 without flow adjustments. Between 17:00 and 18:03, an adjustment of 115 vehicles was required to account for conserved net inflow in the section. Thus, the correction to flow at

Station 12 also accounted for the 16th Street interchange between Stations 13 and 14, which did not have count data available. In Figure 8, the continued vertical displacement between the two curves shows that the queue persisted until around 18:00:30, when the $N(x, t)$ again became superimposed. After this time, vehicles were traveling in free-flow conditions between these stations. The two insets in Figure 8 show the oblique $N(x, t)$ and $T(x, t)$ curves for Stations 12 and 18. At 17:51:00 a reduction in flow and occupancy is visible at Station 12 indicating the dissipation of the queue. Traffic between Stations 12 and 18 became freely flowing after 18:00:30.

Figures 3 to 8 have verified the location and time of the bottleneck's activation. The queue's propagation was traced over five upstream stations over a distance of 2.3 mi (3.7 km). The analyses showed that the bottleneck remained active for almost 43 min. The active bottleneck's queue discharge features could now be examined in detail.

To study the discharge flows while the bottleneck was active, oblique $N(x, t)$ and $T(x, t)$ (Figure 9) were constructed across both travel lanes at Station 18 (downstream of the bottleneck). The time interval, spanning about 2.5 h, includes the period before bottleneck activation, the time it remained active, and a later time after it was deactivated. The curves reveal that the traffic conditions at this location were not influenced by any downstream effects; that is, the curves do not display any abrupt reduction in $N(x, t)$ accompanied

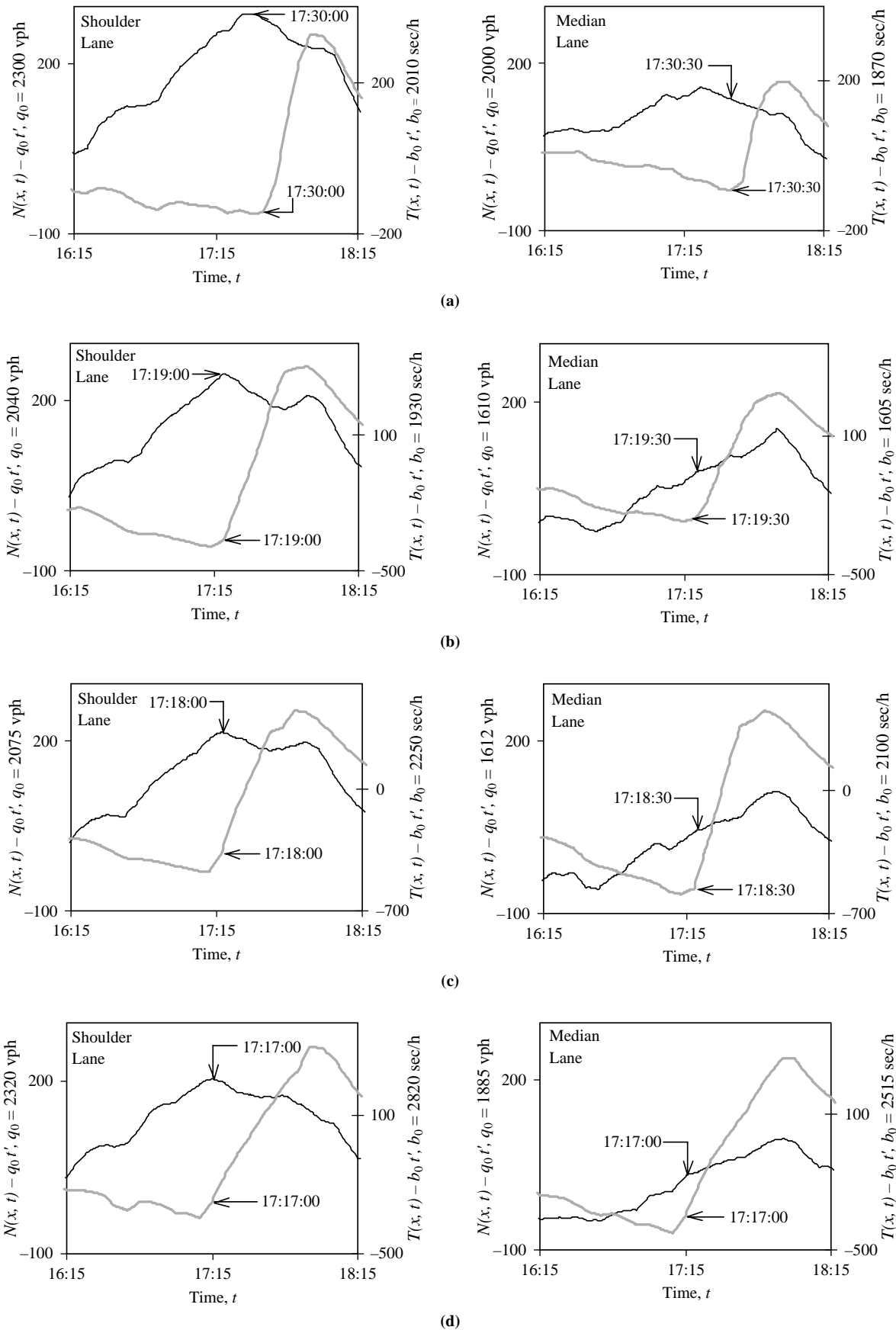


FIGURE 7 Day 1: oblique $N(x, t)$ and $T(x, t)$ per lane: (a) Station 13, (b) Station 14, (c) Station 15, (d) Station 16.

TABLE 1 Shock Velocity Variations

Stations	Section Length		Day 1 Travel Time	Day 1 Velocity		Mean Travel Time	Mean Velocity	
	miles	km	(min:sec)	mi/h	km/h	(min:sec)	mi/h	km/h
13-12	0.61	0.98	2:00	-18	-29	-	-	-
14-13	0.75	1.20	2:00	-23	-36	-	-	-
15-14	0.25	0.40	1:00	-15	-24	0:45	-20	-32
16-15	0.44	0.70	1:00	-26	-42	1:08	-24	-38
17-18	0.63	1.01	0:30	+76	+121	0:30	+76	+121

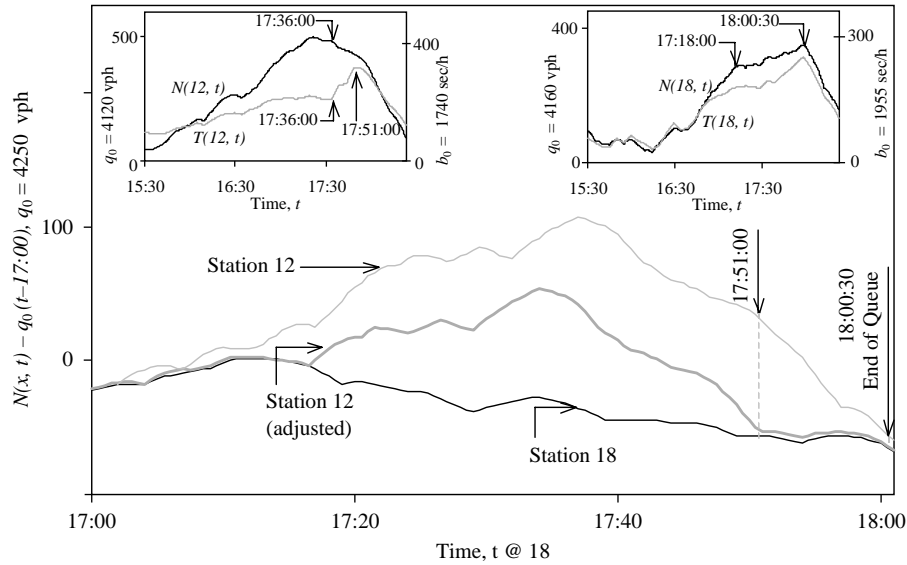


FIGURE 8 Day 1: transformed $N(x, t)$ showing end of queue between Stations 12 and 18.

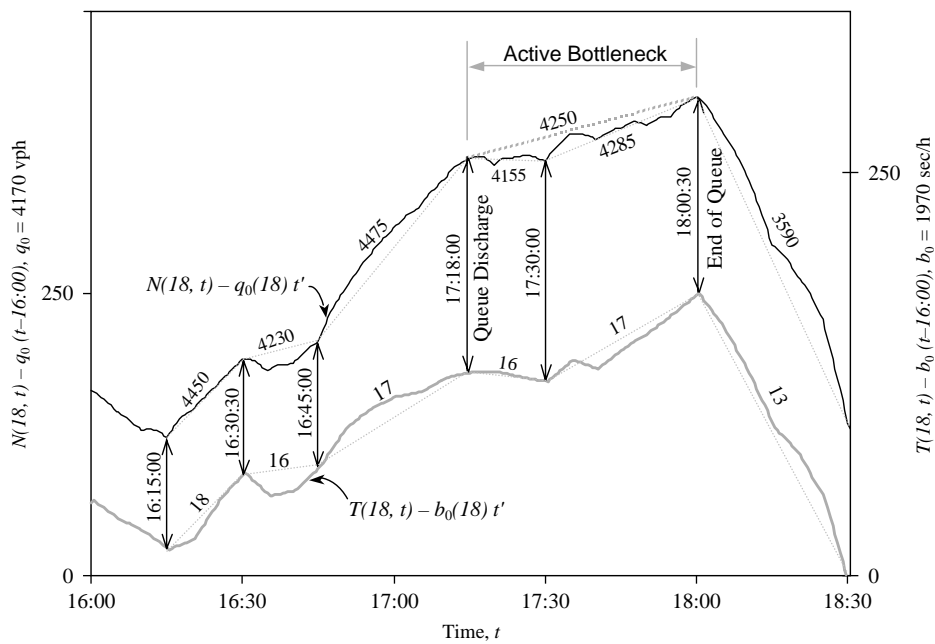


FIGURE 9 Day 1: oblique $N(x, t)$ and $T(x, t)$ at Station 18.

by a rise in $T(x, t)$, a feature that would mark the arrival of a queue from farther downstream. Both curves display very similar features between 17:18:00 and 18:00:30, indicating that discharging vehicles exhibited sequences of nearly stationary traffic patterns with time-dependent flows. The intervals delineated by vertical arrows in Figure 9 are periods when the oblique $N(x, t)$ and $T(x, t)$ exhibited small deviations from linear approximations superimposed on these curves (shown with dashed lines). Each of these intervals was characterized by nearly constant flow and nearly uniform vehicle occupancy, shown in units of vehicles per hour and seconds per hour, respectively, along the dashed lines.

The flow features displayed in Figure 9 show that between 16:15:00 and 18:30:00, Station 18 experienced the highest mean flow just before the queue discharge at 17:18:00, about 4,475 vph. Soon after, the flow dropped to 4,155 vph for about 12 min, reflecting a 7% reduction. This reduction was followed by a discharge flow of 4,285 vph for about 30 min. The mean queue discharge flow measured between 17:18:00, the time when queue discharge began, and 18:00:30, when the queue dissipated, was 4,250 vph. This flow represented a 5% reduction from that measured before queue formation.

Bottleneck activation time having been determined and some of its discharge features having been examined, its correlation with changes in ramp flows can now be analyzed. The on-ramp from TH-55 eastbound (EB) to US-169 is located 370 ft (113 m) downstream of Station 16. It is followed by an off-ramp to TH-55 westbound (WB) at a distance of 580 ft (180 m) from the on-ramp. Figure 10 shows oblique

$N(x, t)$ for both ramps, in which a sequence of nearly stationary flows was observed and is superimposed on the $N(x, t)$ in units of vehicles per hour. It appears that the bottleneck activation time (17:17:30) was preceded by a surge on the off-ramp (at 17:05:00) followed by a surge on the on-ramp (at 17:10:00) that lasted for 7 min. Vehicles were entering the freeway at the relatively low rate of 130 vph for about 12 min before 17:10:00. This rate was followed by an increased flow of 240 vph (~85% increase) until 17:17:30. Comparing the off-ramp flows with these observations, there was a flow reduction from 320 vph to 200 vph (~40% decrease) at 17:17:30. Vehicles entering at 17:17:30 had to merge with the freeway traffic over a short distance (580 ft, or 180 m) by which time there must have been diverging vehicles in the shoulder lane. The lane changing evidently became disruptive, such that periodic slowdowns resulted. The slowdown also led to the apparent restriction of exiting traffic at approximately 17:17:30.

From Figure 10, it is clear that the bottleneck arose because of the conflict between merging and diverging traffic just downstream of Station 16. Figure 7d shows that the flows in the shoulder lane during these times were higher than the flows in the median lane for Station 16. The coincidence of the rise in off-ramp flow, the rise in metered on-ramp flow, and the apparent restriction in the off-ramp flow for the same time period seemed to trigger the bottleneck. This finding was also observed for three other days analyzed. For all days, the same merge and diverge conflict seemed to lead to sustained freeway queuing.

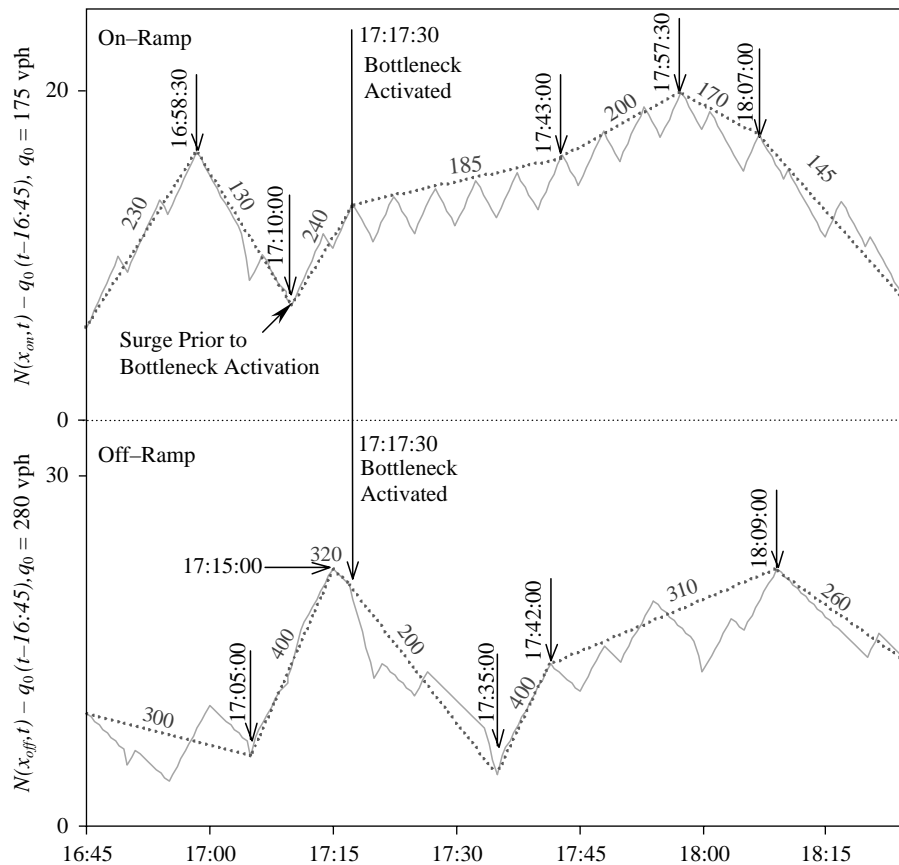


FIGURE 10 Oblique $N(x, t)$ showing ramp flows between Stations 16 and 17.

TABLE 2 Summary of Measured Traffic Features

Day	Date	Flow Immediately Prior to Queue		Average Discharge Rate		Percent Drop (a)-(b) %
		Rate (a)	Duration	Rate (b)	Duration	
		vph	(h:min:sec)	vph	(h:min:sec)	
Monday	20-Mar-2000	4475	0:32:30	4250	0:42:00	5
Tuesday	21-Mar-2000	4440	0:19:00	4230	0:51:00	5
Wednesday	22-Mar-2002	4340	0:10:00	4260	0:25:00	2
Thursday	23-Mar-2000	4530	0:19:30	4290	0:19:30	5
Mean		4450		4260		4
Standard Deviation		80		25		

REPRODUCING OBSERVATIONS

These analyses were repeated using three additional days of data from US-169. It was revealed that on all 4 days, the bottleneck arose between Stations 16 and 17. On each day, the bottleneck activation time coincided with a surge from the metered on-ramp located between Stations 16 and 17. At the same time, the off-ramp just downstream of the on-ramp exhibited a reduction in flow.

Reproducible bottleneck features are summarized in Table 2, which shows the flows immediately before upstream queue formation and the average discharge rates that prevailed while the bottleneck was active. The durations of high flows before queuing were relatively short. The flows during these times and the durations varied somewhat from day to day. The magnitudes and durations of the discharge flows that followed the onset of queuing were consistent with a mean of 4,260 vph. Table 2 also shows that the mean flow before queue discharge was 4,450 vph. The flow reduction measured upon queue formation was also reproducible from day to day, ranging from 2% to 5%.

The shocks that marked the onset of queuing were analyzed for the additional 3 days. The results for 4 days were averaged and are shown in Table 1. On all days analyzed, the observed backward-moving shocks ranged in velocity between -4 and -26 mph. As shown in Table 1, the mean backward-moving shock velocities ranged between -20 and -24 mph. There were only slight differences in the shock travel times between stations from day to day. The forward-moving waves showed a mean velocity of 76 mph. Because of the arbitrary data aggregation at a 30-s level, it was difficult to pinpoint velocities, especially for the forward-moving waves.

CONCLUSIONS

An active bottleneck arose whenever flows from an upstream on-ramp reached a certain peak. The location of the bottleneck was consistent from day to day, between an on-ramp and a downstream off-ramp located between Stations 16 and 17. This conclusion follows from the observation that the bottleneck activation time always coincided with surges from the on-ramp accompanied by apparent flow restrictions on the off-ramp. After the bottleneck became active, the queue propagated to both freeway lanes. A sudden drop in flow accompanied by a rise in occupancy marked the arrival of the queue at each successive upstream station. The onset of congestion sent forward- and backward-moving waves that had nearly constant veloc-

ities for all days analyzed. The bottleneck's activation had marked effects on its discharge flows. Average queue discharge rates were approximately 2 to 5% lower than the flows that prevailed before the bottleneck's activation. It was also observed that these discharge flows in active bottlenecks exhibited near-stationary patterns about a constant rate. The bottleneck's long-run discharge rates were consistent from day to day.

It follows that bottlenecks that arise at fixed reproducible locations can be predicted. As a remedy to recurring bottlenecks that result because of ramp flows, suitable metering techniques should be investigated that consider the mainline flows. In this study no attempt was made to assess the impact of metering rates used by the Minnesota Department of Transportation on bottleneck activation. In an earlier study (14) of the role of ramp metering for averting bottlenecks on freeways, it was noted that service rates at such sites could be increased by (a) eliminating or postponing the bottleneck's activation and (b) mitigating downstream slowdowns if and when the activation occurred. The study further showed that these objectives could be realized by carefully metering an on-ramp to limit the rates at which its vehicles joined the freeway traffic stream. The idea should be to increase flows at locations where a queue would have otherwise impeded traffic, particularly if the queue was kept from propagating past busy off-ramps and starving them of flows. This observation is also true for the site examined on US-169.

These findings are consistent with what has been observed elsewhere in the literature at sites in Canada and the United Kingdom. The study was unique in that it confirmed these results for a freeway in the United States and showed that traffic behaved as if it were passing over links where on- and off-ramps existed. Further experiments will be required that can test the effects of metering rates for postponing (or perhaps eliminating) the bottleneck's activation. Results based on extensive empirical evidence will encourage highway managers to use this information for easing congestion and for the placement of intelligent transportation system-related devices to aid in traveler information and to increase safety.

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