Empirical Analysis of Traffic Sensor Data Surrounding a Bottleneck on a German Autobahn

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The objectives of the project described here are to conduct an empirical analysis of features of traffic dynamics and driver behavior on a German Autobahn. Because bottlenecks are the building blocks of a freeway system, it is important to understand their details. Improved and repeated empirical evidence of how bottlenecks form and dissipate in the spatial and the temporal dimensions will contribute to future improved traffic flow models and freeway operational strategies. The use of archived freeway loop detector data to examine reproducible bottleneck characteristics on freeways of various types and in various countries is an important step in this direction. In that spirit, this paper describes a study that has sought to carefully diagnose bottleneck activations along a 14-km section of northbound German Autobahn 9 (A9) outside of Munich. It is hoped that other researchers will consider similar studies, possibly even using the same data.

Many earlier studies have analyzed congested traffic conditions both upstream and downstream of freeway bottlenecks located near busy on-ramps (1–5) and near a lane drop (6). To enhance the visual identification of key time-dependent traffic flow features, some of these previous studies used curves of cumulative vehicle count, curves of cumulative occupancy, and velocity constructed from data obtained from freeway loop detectors (7, 8).

The analysis tools used in this study were curves of cumulative vehicle arrival number versus time and curves of cumulative time-averaged velocity versus time. Several references provide excellent tutorials on this approach (9, 10). The archived inductive loop detector data required to construct these curves were available at 1-min levels of aggregation (dual loops were used to measure vehicle speed directly). As illustrated in this paper, these cumulative curves were transformed to provide the resolution necessary to reveal important details of the evolution of traffic flow features. These transformed curves (at their lowest possible level of temporal resolution) have made it possible to identify several bottleneck activations located near a busy on-ramp during the afternoon peak period. This bottleneck’s location and discharge flows were reproducible from day to day. Bottleneck discharge flows also appeared to be relatively stable.

The next section contains some brief background, followed by a short description of the diagnostic tools used in this study. The freeway site analyzed and the available archived data are described next. The diagnosis of the bottleneck’s location and the activation and the deactivation times are provided next for 1 study day. This is followed by a summary of the features found to be reproducible on 5 additional days. The paper ends with some concluding remarks.

BACKGROUND

The development of an improved understanding of how freeway systems operate in different countries with different control strategies, geometric standards, and driver characteristics requires further empirical analyses with archived sensor data. The improved understanding of various forms of freeway bottlenecks is another important priority for improving the understanding of traffic dynamics. Some key network elements that require further research include long, homogeneous freeway sections as well as merge areas, diverge areas, and segments containing other geometric features. As key building blocks of freeway operations, bottlenecks often occur near merge and diverge areas. This paper considers a bottleneck to be a point on the freeway that separates upstream queued traffic from downstream unrestricted traffic (11). Because traffic sensors are typically spaced at discrete intervals, usually only the segment containing the bottleneck can be identified. Bottlenecks can be static (e.g., because of a tunnel entrance, a lane drop, or a diverge area) or dynamic (e.g., because of an incident or a slowly moving vehicle). A bottleneck is defined as “active” when it meets the definition presented above and is deactivated either when there is a decrease in the upstream demand and the queue upstream from the bottleneck has been fully discharged or when a queue spills back from a downstream bottleneck (11). When the presence of an active bottleneck (including its activation...
and deactivation times) is guaranteed, its discharge flow can then be measured, which is sometimes considered that bottleneck’s capacity. Furthermore, if the bottleneck’s activation was preceded by freely flowing traffic conditions, it is possible to measure the flow that prevailed before the queue’s formation and compare it with the discharge flow. In the past, some researchers have found that bottleneck activation can be accompanied by reductions in flow; if this is true, then it might explain the hypothesis that discontinuous fundamental relationships exist in traffic flow.

With the proliferation of traffic management systems that include the deployments of inductive loop detectors (primarily used for real-time traffic control and traveler information), a rich resource that can aid in the understanding of traffic phenomena is now available. By taking advantage of such systems throughout Germany, numerous empirical analyses of freeway dynamics have reported on phenomena observed on German Autobahns and have been presented in the literature (12–14), but raw data from those studies were not available to other researchers. In the spirit of this exciting opportunity to further study traffic conditions on German freeways, the objective of this paper is to carefully diagnose the activation and deactivation of a bottleneck on one freeway site over multiple days and examine some of its notable features that are reproducible from day to day.

DATA

The study site, as shown in Figure 1, is a 14-km section of northbound Autobahn 9 (A9) near Munich, Germany. The freeway is equipped with 17 vehicle detector stations (labeled here as Stations 160 through 630). Dual loop detectors are located in each lane and on most of the ramps, with main-line spacing ranging from 410 to 1,480 m. The data were analyzed for 6 days in 2002: Wednesday, June 27; Thursday, June 28; Monday, July 2; Tuesday, July 3; Wednesday, July 4; and Thursday, July 5. As part of the overall freeway management strategy deployed at this site, there are also five changeable message signs along this corridor, as shown in Figure 1. Figure 1 shows the loop detector station numbers as well as the distance between the stations, measured in meters.

A detailed analysis was conducted by using the data recorded on Wednesday, June 27. The data were available for the entire day, but the analysis focused on the 5-h period between 15:00 and 20:00 h. During this period, the weather was reported to be clear with light winds and temperatures ranging from 24°C to 27°C (15). Each detector site records the vehicle counts and average vehicle speeds over 1-min periods for two vehicle types. The two vehicle types, segregated by length, are reported as cars and trucks.

OBSERVATIONS

To gain an overall picture of traffic conditions on June 27, 2002, in the dimensions of space and time, Figure 2 shows a speed plot for the entire 14-km segment of northbound A9. In Figure 2, the horizontal axis is time (from 15:00 until 20:00 h), the vertical axis is distance, and the variations in shading represent the changes in the speeds measured (in kilometers per hour), from dark gray for lower speeds through medium gray for moderate speeds to light gray for higher speeds. The raw speed data were averaged across all main-line lanes and were interpolated between detector stations for each 1-min interval. It is apparent from this plot that substantial changes in speed occurred near Stations 380 and 390 for almost the entire 5-h period, spilling back more than 4 km and extending outside of the study area.

A potential bottleneck activation was suspected between Stations 380 and 390. Later in the afternoon, a short disturbance was visible in the vicinity of Stations 320 and 340. It appears that after this short disturbance, a bottleneck or bottlenecks were again activated until nearly 20:00 h. Some annotations have been added to Figure 2; the steps taken to identify these times are described in the following paragraphs.

Figure 3 shows a set of transformed oblique curves [definitions and tutorials are provided elsewhere (9, 10)] of cumulative vehicle arrival number (N) versus time (t) at location x, N(x,t) - q0t (where the value q0 is an oblique scaling rate chosen iteratively, and t’ is the time that has elapsed from the beginning of each curve) obtained by using data from Detectors 420, 390 and 380 measured between 14:45 and 15:50 h on June 27, 2002. Each curve contains counts measured across all freeway lanes at each station. The curve from Station 380 includes data recorded at the adjacent Garching-South off-ramp, so that each curve describes the same collection of vehicles. Because the available archived detector counts were aggregated.

![Figure 1: Site map of Autobahn A9 (FrankF. Ring = Frankfurter Ring).](attachment:figure1.jpg)
FIGURE 2 Northbound speed diagram, June 27, 2002.

FIGURE 3 Oblique $N(x,t)$’s and $V(x,t)$ values for Stations 420, 390, and 380, June 27, 2002.
over arbitrary 1-min periods, an unaltered \( N(x,t) \) would be a step function with equal time steps. To create the \( N(x,t) \)'s shown in Figure 3, linear interpolations through the near-side top of each step were used so that the curve’s slope at time \( t \) would be the flow past location \( x \) at that time.

The counts for each curve were started \( (N = 0) \) relative to the passage of a hypothetical reference vehicle such that all curves describe the same collection of vehicles. Given that vehicle conservation exists between measurement locations, each upstream curve was shifted horizontally to the right by the average free-flow trip time from its respective location to Detector 380, the downstream-most detector of the three. As a result of these shifts, any resulting vertical displacements between curves would be the excess accumulations of vehicles between each detector pair, and the resulting horizontal displacements would be the delay or excess travel time between the detectors \( (16) \).

Furthermore, each \( N(x,t) \) was plotted by using an oblique axis, whereby \( q_0 \) was subtracted from each \( N(x,t) \) to amplify the curve's features. Several previous reports have described this procedure in more detail \((3, 9, 10)\). The reason for making these transformations is to avoid any further arbitrary data aggregations (such as 5- or 15-min data aggregations) and, thus, retain the data in their rawest form. Furthermore, these transformations provide the resolution necessary to diagnose the bottleneck activations directly from the loop detector data by making it possible to identify a bottleneck’s location, to guarantee that there is a queue present upstream, and also to ensure that there is not a queue further downstream that restricts the bottleneck’s flow.

The three curves shown in Figure 3 (for Detectors 380, 390, and 420) were initially superimposed and indicated freely flowing traffic throughout the study area from 14:45 until approximately 15:20 h. All times listed on Figure 3 refer to the times measured at particular detector stations, yet for clarity, only the time scale for Station 420 is shown. Therefore, the times measured at upstream stations are to the left of the time scale shown. In Figure 3, excess vehicle accumulations between Detectors 380 and 390 were visible after the two curves diverged, and this divergence was marked by a flow reduction measured at downstream Station 380 at approximately 15:21 h. The divergence between the curves reveals that a queue had formed somewhere between the two stations. The divergence of the curve at Detector 390 from the one at Detector 420, marked by a flow reduction measured at Station 390 at 15:21 h, marked the arrival of the backward-moving tail of the queue at Detector 390. Note the visible flow reduction measured at Detector 380 (emphasized by the light line added to the figure) and Detector 390 that accompanied this first divergence. Figure 3 also helps map the propagation of the tail of this queue upstream of Station 420. As shown, the \( N(x,t) \) for Station 390 deviated from the \( N(x,t) \) for Station 420 after 15:21 h. This deviation reveals the increasing vehicle accumulation between Stations 390 and 420. By using the curves described below (and some not shown here), it is shown that the tail of the queue passed Station 420 at 15:24 h.

To verify the arrival of the backward-moving tail of the queue at each measurement station, cumulative curves of time-averaged velocity versus time \( (v(x,t)) \) were constructed for each detector. Oblique \( v(x,t) \) plots are used to identify trends in the mean measured velocity and to identify clearly the times at which notable velocity changes occurred \((6)\). The advantages of the use of the oblique \( v(x,t) \) are similar to those found when the oblique \( N(x,t) \) is used. These oblique plots consist of curves of \( v(x,t) = b_0 \) versus time \( t \), where \( b_0 \) is the oblique scaling rate and \( t \) is the elapsed time from the beginning of the curve. The \( v(x,t) \) ordinate is established by plotting cumulatively the time-averaged velocity for each averaging period \((i.e., 1 \text{ min in the case of the A9 data})\). The \( v(x,t) \) values nominally have the dimension of velocity, since they represent a cumulative total of velocity values. However, the \( v(x,t) \) values increase at a rate that is inversely proportional to the duration of the averaging period. For example, if the averaging period were 1 h, the cumulative total would equal the average speed over this hour; yet, if the averaging period were 1 min, the average hourly velocity would be obtained by multiplying the cumulative total by 1/60 h. Thus, the \( v(x,t) \) values have the dimensions of speed \( \times \) time. With a construction process similar to that used for oblique \( N(x,t) \)'s, the \( v(x,t) \) values were then plotted on an oblique axis by subtracting a value \( b_0t \) from each value.

Figure 3 contains eight insets that show the oblique \( v(x,t) \) values for Stations 380 through 630. On each inset, the value of \( b_0t \) is labeled on the \( y \)-axis, and linear approximations of prevailing average speeds are shown with light lines and are labeled in kilometers per hour. The times marking notable speed reductions are indicated with vertical arrows. To confirm the passage of the tail of the queue at 15:21 h at Station 390, the inset for Station 390 shows a speed reduction from 80 to 41 km/h at 15:21 h. The \( v(x,t) \) for Station 420 shows a speed reduction from 92 to 65 km/h at approximately 15:24 h, verifying the passage of the tail of the queue at that time. The remaining \( v(x,t) \) values for Stations 540 through 630 help to map the continuing propagation of the tail of the queue. As shown, the queue reached Station 630 at approximately 15:58 h, more than 37 min after the bottleneck was activated downstream. The queue’s passage time was corroborated by additional \( N(x,t) \)'s (not shown here). The times marked by the queue’s propagation (speed reductions) labeled on \( v(x,t) \) are also labeled in Figure 2.

Figure 3 has so far indicated that queuing was present between Stations 380 and 390 but has not confirmed the presence of freely flowing traffic downstream of these locations. Figure 4 consists of a set of transformed oblique \( N(x,t) \)'s for Stations 380, 350, 340, and 320 constructed from data measured across all lanes. The curve for Station 380 includes the vehicle counts from the Garching-South on-ramp, and the curve for Station 320 includes the counts recorded on the Garching-North off-ramp to maintain vehicle conservation between the \( N(x,t) \)'s. For comparison purposes, Figure 4 uses the same value of \( q_0 \) and the same vertical scale used in Figure 3. As all four curves are superimposed, Figure 4 shows that traffic remained freely flowing between 14:45 and 15:50 h. The flow reduction measured at Station 380 at 15:21 h was passed forward and measured at downstream Station 350 at 15:23 h, Station 320 at 15:27 h, and Station 340 at 15:26 h. These times were corroborated by the \( N(x,t) \)'s and the \( v(x,t) \) values measured in individual lanes but not shown here. The presence of freely flowing downstream conditions is verified by the insets for the \( v(x,t) \) values that indicate the continuing relatively high speeds (labeled in kilometers per hour) subsequent to the flow reductions (shown with vertical arrows).

Figures 3 and 4 have made it possible to diagnose the bottleneck’s location (between Detectors 380 and 390) at the time that it became active (approximately 15:21 h) and the propagation of the backward-moving tail of the queue as far as Detector 630.

To determine the length of time that the bottleneck between Detectors 380 and 390 remained active, Figure 5 consists of transformed oblique \( N(x,t) \)'s for Stations 380, 390, and 420 for the 6-h period between 14:00 and 20:00 h. The activation at 15:21 h is visible on the left side of Figure 5. Also included in Figure 5 is an oblique \( v(x,t) \) for Station 390, just upstream of the bottleneck. As shown in Figure 5, the queue between Stations 380 and 390 was sustained until 17:35 h, indicating that the bottleneck was capable of serving vehicles at a
Bottleneck activated between 380 and 390 at 15:21; deactivated at 17:35 due to downstream spillover.

Bottleneck between 390 and 420 activated.

Bottleneck between 380 and 390 reactivated at 18:45, deactivated at 19:18.

Queue from bottleneck between 320 and 340 reaches station 380 at 17:35.

Demand Reduction

Time @ Station 380

FIGURE 4 Oblique $N(x,t)$'s and $V(x,t)$ values for Stations 380, 350, 340, and 320, June 27, 2002.

FIGURE 5 Oblique $N(x,t)$'s for Stations 380, 390, and 420 and oblique $V(x,t)$ values for Station 390, June 27, 2002.
maximum rate. Although they are not shown here, the $N(x,t)'$s for the downstream stations remained superimposed. To determine the precise length of time that the bottleneck remained active, it is shown that the $N(x,t)'$s for Stations 380 and 390 again became superimposed at 17:40 h.

Figure 6 consists of oblique $N(x,t)'$s for Stations 380, 350, 340, and 320 between 17:00 and 18:00 h. Figure 6 shows that all four curves were superimposed between 17:00 and 17:27 h. The curve for Station 320 diverged from the curve for Station 340 for 8 min (17:27 to 17:35 h), after which the two curves remained superimposed. Thus, as shown in Figure 6, there was an accumulation of vehicles between Stations 320 and 340 for this short period. This is visible in Figure 2. The curves for Stations 340 and 350 diverged at 17:28 h, marking the passage of this backward-moving disturbance at Station 340. Figure 6 maps the passage of this queue past Station 350 (at 17:33 h) and Station 380 (at 17:35 h). These times were verified by using the $V(x,t)$ values (not shown here). All four curves again became superimposed at 17:46 h.

The combination of Figures 5 and 6 has identified the end of the first active period for the bottleneck between Stations 380 and 390; therefore, at 17:35 h the queue discharge for this bottleneck could no longer be measured. In Figure 5, the discharge flow of 5,370 vehicles per hour (veh/h) is noted between 15:21 and 17:35 h. As shown, this discharge flow appears to be nearly constant, although there were some fluctuations in flow around this nearly constant rate. By using the scale on the $y$-axis, however, the deviations between the $N(380, t)$ and the straight line do not appear to exceed approximately 25 vehicles.

The analysis thus far has confirmed the activation of two bottlenecks: the first between Stations 380 and 390 from 15:21 to 17:35 h and a short disturbance between Stations 320 and 340 from 17:35 to 17:40 h. As mentioned above and as shown in Figures 5 and 6, the $N(x,t)'$'s for Stations 380 and 390 became superimposed at 17:40 h; however, the queue remained upstream of Station 390. This indicates that a short disturbance emanated from between Stations 390 and 420 at 17:40 h and moved upstream until it was swallowed in the upstream queue. The analysis has shown [by using $N(x,t)'$'s; not shown here] that there was a surge in flow at the Garching-North off-ramp (Station 320) at approximately 17:29 h. At this time there was a surge of 60 vehicles that exited using the Garching-North off-ramp during the 7-min period from 17:29 to 17:36 h, representing a 60% off-ramp flow increase.

It is also possible to see in Figure 5 that the speed at Station 390 increased from an average of 53 km/h to one of 84 km/h, since the vehicles had a longer distance to accelerate after coming out of the queue. As shown in Figure 5, this condition remained until 18:45 h [the $N(x,t)'$'s for Stations 380 and 390 remained superimposed during this period], when a deviation between the curves $N(380, t)$ and $N(390, t)$ occurred. Thus, the bottleneck between Stations 380 and 390 was reactivated at 18:45 h, and the speed at Station 390 downstream returned to approximately the same level as before (61 km/h),
as vehicles were only beginning to accelerate after they discharged from the queue.

The bottleneck remained active for the second time until 19:18 h, when the peak period ended. This is shown in Figure 5 as a flow drop first visible at Station 420 and then at Station 390, followed by its arrival at Station 380 at 19:18 h. Therefore, the measurement of the discharge flow was concluded at this time. As shown in Figure 5, when the bottleneck was activated the second time, it immediately adopted its discharge flow of 5,410 veh/h. The lower flows measured at other times were governed by the capacities of other bottlenecks. Therefore, for this analysis on June 27, 2002, the bottleneck between Stations 380 and 390 was examined while it was active for two distinct periods: from 15:21 to 17:35 h and again from 18:45 to 19:18 h. Figures 3 to 6 have verified the bottleneck’s location, the times at which it became active, and the times that it was deactivated. Figure 5 also shows the bottleneck discharge flows, which were estimated to be 5,370 veh/h during the first active period and 5,410 veh/h during the second active period. Before the first activation, there was a sustained flow of approximately 5,509 veh/h beginning at 14:39 h and ending upon queue formation. The reduction in flow observed here was approximately 2.5%. This is consistent with past research that has found flow reductions upon bottleneck activation ($q_0$). The results from Wednesday, June 27, 2002, are listed in Table 1. Table 1 includes measures of the standard deviation of the individual count reports during the prequeue period and the queue discharge periods. As expected, the prequeue flows exhibited higher variability than the discharge flows.

Thus far, it has been shown that bottlenecks arose in a rather predictable manner along this site. Increasing flows were followed by queue formation and propagation upstream until demand reductions led to queue dissipation. Consistent with past research at other sites in North America (1–3), it has also been shown that reductions in bottleneck outflow accompanied queue formation and that queue discharge outflows were relatively stable and reproducible from day to day.

An investigation of prequeue flows did not reveal an absolute maximum flow preceding queue formation. Therefore, the extent to which changes in flow at the München-North on-ramp (Station 420) and the Garching-South on-ramp (Station 380) may have influenced the initial bottleneck activation at 15:21 h was explored. Figure 7 shows a cumulative curve of oblique $N(x,t)$’s for both on-ramps between 14:30 and 16:00 h. The $N(x,t)$’s have been annotated with piecewise linear approximations, such that the trend lines do not deviate very much from the oblique curve. The annotations have been added (in vehicles per hour) to indicate the flow trends over time. As shown, 4 to 5 min before the bottleneck’s activation, both on-ramps exhibited flow increases. The München-North on-ramp flow increased from 2,370 to 2,660 veh/h at 15:16 h, a 12% increase. While relatively low on-ramp flows were reported for the Garching-South on-ramp flow, the flow increased from 320 to 540 veh/h, a 69% increase. In addition to the possibility that the flow increases from the on-ramp raised the flow past some unsustainable level, it is possible that these ramp-related occurrences influenced driver behavior and exacerbated lane-changing behavior, leading to the bottleneck’s activation. The effects of the Garching-South off-ramp (Station 380) were also studied, but no surges in flow were apparent during the time from 14:40 to 15:29 h.

In general, the rules of the road in Germany require trucks to remain in the right lane on the freeway. Because trucks have vastly different performance characteristics than automobiles, a detailed analysis of truck flow and velocity patterns was conducted just upstream of the bottleneck, with a focus on the activation at 15:21 h. By use of the separate truck count and speed data, Figure 8a shows an oblique $N(x,t)$ plot for each lane at Station 420, a measurement location more than 1.2 km upstream of the bottleneck. The curves were annotated with linear approximations, which are labeled to the nearest 10 veh/h. The linear approximations were constructed such that the vertical deviation between the straight line and the curve was small. The truck counts from each detector were plotted by using an oblique axis, with different values of $q_0$ (thus, one cannot compare the slopes of the individual curves). This reveals that, indeed, trucks remained to the right both on the München-North on-ramp and on the main line. Notice that at several minutes before the queue formation there were three surges in truck counts. First, over a 2-min period, nine trucks passed Station 420 in the main-line median lane. Next, a 120% increase in truck flow was observed in the main-line shoulder lane, and almost simultaneously, a 190% increase in the truck counts was observed in the right lane of the on-ramp.

Figure 8b contains an oblique $V(x,t)$ plot for each lane at Station 420. Similarly, different values of $b_0$ were used. The average truck speeds were also added to Figure 8b and are rounded to the nearest 10 km/h. What is noticeable is that the truck velocities dropped below 100 km/h first in the left lane of the main line, then in the left lane of the ramp, and then in the right lane of the ramp. This may indicate that the surge in trucks counted in the main-line left lane created a blockage for drivers who would have preferred to travel at higher speeds in the left lane, as usual.

Moving downstream toward the bottleneck, Figure 9 shows oblique $N(x,t)$’s and $V(x,t)$ values for trucks only in the individual lanes at Station 390. The values of $q_0$ and $b_0$ are again different for each curve to magnify their features. As shown in Figure 9a, six trucks were counted in the median lane in a 2-min period a few minutes before bottleneck activation. Surges in the truck counts were then observed in both the center lane and the shoulder lane at approximately the same time that the queue passed Station 390 (when all vehicle counts measured across all lanes were examined). The $V(x,t)$ values shown in Figure 9b further indicate that the truck speeds dropped in each lane beginning at 15:17 h, when the average truck speed dropped from 100 to 80 km/h in the shoulder lane, followed 1 min later by the truck speed drop in the center lane and in the median lane 1 min later.

While this evidence is by no means definitive, it seems to indicate that notable truck movements arose just before and upon the bottleneck’s activation.

**REPRODUCTION OF OBSERVATIONS**

The analyses described in the previous section were repeated with data from 5 additional days on the A9 Autobahn. A bottleneck arose between Stations 380 and 390 a total of 11 times over the 6 days. As shown toward the right side of Table 1, the discharge outflows were carefully measured for each activation. The mean discharge outflows appeared to be reproducible from day to day. The mean discharge flow was approximately 5,370 veh/h, with a standard deviation (of the average flows) of 160 veh/h. The discharge duration ranged from 11 min to 3.5 h. The standard deviation of the 1-min counts during discharge outflow ranged from 4.6 to 7.0 veh/h.

Five activations occurred immediately following freely flowing conditions (what the authors have termed a “virgin” activation). The sustained prequeue flows are also listed in Table 1. The duration of these flows ranged from 11 min to 1 h. The standard deviation of the 1-min counts measured during the prequeue periods was somewhat
### TABLE 1  Summary of Bottleneck Features

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FIGURE 7 Oblique $N(x,t)'s$ for on-ramps, June 27, 2002: (a) Station 420 and (b) Station 380.

(a) Station 420 Trucks

(b) Station 380 Trucks

FIGURE 8 Oblique (a) $N(x,t)'s$ and (b) $V(x,t)$ values for trucks at Station 420, June 27, 2002.
higher than that measured during the discharge flow, as one would expect. This ranged from about 5.6 to 11.2 veh/h. Finally, for the five virgin activations, the average prequeue flows were compared with the average discharge flows, and the percent reductions are listed in Table 1. The flow reduction ranged from 2 to 13%.

CONCLUDING REMARKS

This study analyzed the traffic conditions upstream and downstream of a bottleneck that arose near an off-ramp. Oblique curves of cumulative count and time-averaged velocity versus time were used in this study. It has been shown that bottlenecks arose in a rather predictable manner. Increasing flows were followed by queue formation and propagation upstream, until demand reductions led to queue dissipation. Research at this site is continuing and includes further study of the impacts of truck flows on bottleneck formation and also the impacts of the changeable message signs along the corridor. This research is only an initial step toward understanding bottleneck behavior in relation to the geometric features of the roadway. Therefore, further analyses are being conducted at this site and other sites in Europe and the United States.

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