

**EXAMINATION OF FEATURES OF A FREEWAY
BOTTLENECK SURROUNDING A LANE DROP**

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ABSTRACT

In order to gain a greater understanding of freeway traffic dynamics, traffic features were studied both upstream and downstream of a lane drop bottleneck on a motorway near London, United Kingdom. This study was possible due to the availability of archived loop detector data, where the passage times of individual vehicles and their speeds were recorded in each lane over a 4.1 km (2.5 mile) section. Both the bottleneck location and the time of activation were reproducible from day to day. The average bottleneck discharge flows were also reproducible and were found to be 9.7% lower than the flow observed before the queue formation. Travel times and shock speeds were also evaluated. Flow reductions occurring sequentially in time and space showed the passage of a backward moving shock accompanied by reductions in speed. The analytical tools used in this study were rescaled curves of cumulative vehicle arrival number versus time and rescaled cumulative time mean speed versus time. The findings reported herein will contribute to a greater understanding of traffic dynamics, which will aid in improving the way freeway traffic is modeled.

KEY WORDS:

Freeway Capacity, Freeway Bottleneck.

INTRODUCTION

In order to gain a greater understanding of freeway traffic dynamics, it is shown that a freeway bottleneck became active near a lane drop from three to two lanes on the M4 motorway near London, United Kingdom. The activation of the bottleneck was marked by the formation of a queue that propagated several kilometers upstream, and resulted in a reduction in average discharge flow. The bottleneck location was reproducible from day to day, and the average discharge flow measured after bottleneck activation did not vary substantially on the days analyzed. It is also shown that shock velocities were nearly constant as the queue propagated upstream from the bottleneck.

In earlier studies, traffic conditions have been examined upstream and downstream of a freeway bottleneck located near a busy on-ramp (1, 2, 3, 4). To promote the visual identification of time-dependent features of the traffic stream, these previous studies used curves of cumulative vehicle count and curves of cumulative occupancy constructed from data measured at neighboring freeway loop detectors (5). These cumulative curves provided the measurement resolution necessary to observe the transitions from freely flowing to queued conditions and to identify a number of notable, time-dependent traffic features in and around the bottleneck.

Cumulative curves were also used in this study, which adds to the previous findings by reporting on observations taken during five morning peak periods both upstream and downstream of a freeway lane drop. These observations were made possible via the use of cumulative curves of vehicle arrival versus time and cumulative curves of speed versus time, using archived vehicle actuation times and time mean speeds obtained from inductive loop detectors. Through the use of these curves, it has been possible to verify that the bottleneck became active, guaranteeing that vehicles discharged from an upstream queue and were unimpeded by traffic conditions from further downstream (6). It was also possible to observe that certain bottleneck features were reproducible from day to day. These observations will contribute to a greater understanding of traffic dynamics, which will aid in improving the way freeway traffic is modeled.

First, a brief background discussion will be provided, followed by a description of the study site and the loop detector data used for this analysis. Next, a detailed description of the bottleneck's location and discharge features will be presented for one study day, followed by a summary of features found to be reproducible on four additional days. Finally, some concluding comments will be provided.

BACKGROUND

Understanding traffic behavior at a freeway bottleneck provides a foundation for understanding how a freeway system operates. A bottleneck is any point on the network upstream of which one finds a queue and downstream of which one finds freely flowing traffic. Bottlenecks can be static (e.g., a tunnel entrance) or dynamic (e.g., an incident or a slow moving vehicle). A bottleneck is considered active when it meets the conditions described above and is deactivated when there is a decrease in demand or when vehicles are impeded by a spillover from a downstream bottleneck (6). Bottlenecks are important components of freeway systems, since the queues that develop upon bottleneck activation may propagate for several kilometers, causing delay and potentially blocking ramp facilities.

While discussing the state of traffic flow theory in 1965, Gordon Newell (unpublished lecture) stated that "the main object" of traffic research should be "to study time-dependent flows, to determine velocities of propagations of disturbances," and to determine "how...traffic

adjusts to some time- or space-dependent influences such as traffic lights, bottlenecks, etc.” In a later review of the evolution of traffic flow theory, Newell (7) explained that in the early 1960s, it was expected that “new experimental observations would soon resolve some of the deficiencies of existing theories.” Newell returned to the study of basic traffic flow principles in the 1990s since new surveillance systems “offered some hope that new experimental techniques may soon resolve some of the deficiencies of existing theories.” (7) Therefore it is appropriate to study and understand freeway bottlenecks of all kinds—including merges (1, 2, 3, 4, 8), diverges (9, 10), lane drops and other configurations. This study will contribute to a greater understanding of bottlenecks arising in the vicinity of a freeway lane drop.

DATA

The observations that follow were taken during a morning peak of one (November 16, 1998) of the five study days from a segment of the eastbound M4 motorway near London, United Kingdom, as shown in Figure 1. This is part of the main connection between London and Heathrow Airport. Inductive loop detectors recorded individual vehicles’ actuation times and time mean speeds in each lane; thus the loop detector data were available in their most raw form and were not aggregated over any arbitrary periods. In contrast to many loop detection systems, occupancy data were not recorded. The loop detectors are labeled 1 through 9 as shown in Figure 1. The lane drop is located at kilometer 17.1 (mile 10.6). When these data were collected the motorway speed limit was 112 km/h (70 mi/h) upstream of station 9 and 80 km/h (50 mi/h) downstream of station 9.

It is noted that the M4 motorway now includes a high occupancy vehicle lane at this site, installed in 1999. However, the observations contained in this study were taken during the period prior to these modifications of the motorway lane markings.

OBSERVATIONS

In order to gain a macroscopic view of traffic conditions over the morning peak, Figure 2 shows a speed contour diagram for an extended section of the eastbound M4. In this figure the horizontal axis is time (hours—5:30 AM until 11:00 AM) and the vertical axis is distance. Note that on this day detector data were not available for station 9. The variations in gray scale represent changes in speed, from a very dark color for lower speed to a lighter color for higher speed. As noted above, the speed limit for the segment shown was 112 km/h (70 mi/h). The speed contours indicated that a queue may have arisen in the vicinity of station 6 and appears to have propagated upstream for several kilometers beginning at around 6:45 AM. This led to lower vehicle speeds and resulting delays. It is also apparent that the queue began to dissipate beginning near station 1 at about 8:45 AM.

To confirm this and reveal more details, Figure 3 shows rescaled curves of cumulative arrival number of vehicles versus time, $N(x, t) - q_o(t - t_o)$, constructed from counts measured across all lanes at detectors 1-8 and collected during a 30-minute period surrounding the activation of the bottleneck between detectors 6 and 7. The curves were constructed by taking linear interpolations through the individual vehicle arrival times, so that a 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 so all curves describe the same collection of vehicles. Each curve was shifted horizontally to the right by the average free flow trip time from its respective x to station 8, the downstream most detector. Any resulting vertical displacement is the excess vehicle accumulation between stations due to vehicular delays.

In order to magnify the curves' features, an oblique coordinate system was used, where $N(x, t)$ was reduced by $q_0(t-t_0)$ where q_0 is a background flow and $(t-t_0)$ is the elapsed time from the passage of the reference vehicle. The q_0 value was chosen by iteration in order to obtain the best visualization to magnify the traffic features of interest. The same value of q_0 was used for all curves and therefore does not affect the vertical separations (5). This rescaling method is described in detail in several references (1, 5).

As shown in Figure 3, curves for all stations are initially superimposed indicating freely flowing traffic throughout the entire motorway section. The curves for stations 8 and 7 remain nearly superimposed for the entire period, indicating that traffic continued to flow freely between these stations. Substantial vehicle accumulations are seen between stations 6 and 7 as a consequence of flow reductions which were observed at stations 7 and 8 at around 6:45:26 AM and 6:45:50 AM respectively.

The divergence of the curve at station 6 from the one at station 7 (at 6:47:28 AM) marks the arrival of a backward-moving queue at station 6. There was a pronounced flow reduction at station 6 that accompanied this divergence. The inset in Figure 3 contains a re-scaled curve of cumulative vehicle speed, $V(x,t)-V_{ot}'$, versus time, measured at station 6. A sharp reduction in speed is seen at 6:47:28 AM, verifying the arrival of the queue. The presence of freely flowing traffic between stations 7 and 8 (as evidenced by the superimposed station 7 and station 8 curves in Figure 3) accompanied by excess accumulation of vehicles upstream of station 7 reveals that the bottleneck was located somewhere between stations 6 and 7 where the transition from three lanes to two lanes takes place.

Figure 3 also traces the propagation of the queue beyond station 6. As shown in the figure, a reduction in flow at station 5 was observed at 6:50:08 AM, when the curve at station 5 deviated from the upstream curves. This indicates excess vehicle accumulation upstream of station 5. Further deviations are visible, indicating that the queue arrived at station 2 at 7:01:46 AM. This procedure has made it possible to visually diagnose the bottleneck's location (between stations 6 and 7), as well as the time it became active (around 6:47:28 AM).

In order to determine the length of time that this bottleneck remained active, Figure 4 shows rescaled $N(x,t)-q_0t'$ for station 2 and 8 for a longer period of time. As indicated by the continued vertical displacement, the queue between stations 2 and 8 persisted until around 9:07:56 AM when N -curves became superimposed. This shows that the vehicles were traveling at their free flow speeds after this time. The insets in Figure 4 contain re-scaled curves of cumulative vehicle speed at stations 2 and 8. As shown in the lower inset, a speed increase was observed at station 8 around the time that the queue dissipated. Queue dissipation occurred several minutes after a decrease in flow at station 2 (around 8:48:40 AM) signaled the end of queuing at that station. The upper inset verifies the timing of the end of queuing at station 2 by showing that an increase in speed also occurred around 8:48:40 AM.

Figures 3 and 4 have verified the bottleneck's location, the time it became active, and the time that it was deactivated. Now it is possible to examine the active bottleneck's discharge features in detail.

Cumulative curves from station 8 (downstream of the bottleneck) will be used to examine the bottleneck's discharge features. Figure 5 shows a rescaled curve of $N(8, t)-q_0t'$ curve along with a rescaled curve of $V(8,t)-v_0t'$ also measured at station 8. These curves reveal that traffic conditions at this location were not influenced by downstream spillover effects. Figure 3 showed that the arrival of a queue from downstream was marked by a reduction in N accompanied by a reduction in speed. Since the curves in Figure 5 do not display any abrupt reductions in the N

accompanied by reductions in speed, it is apparent that there was no disruption of bottleneck discharge caused by a queue from further downstream.

Turning to the bottleneck's flow features shown in Figure 5, it is shown that between 6:28 AM and the beginning of queue discharge (6:45:50 AM) a flow of 3,690 vehicles per hour (vph) prevailed in this two lane section downstream of the bottleneck. Upon queue discharge, a lower flow of 3,470 vph was observed, which prevailed for about 50 minutes. This was followed by a series of sequences of nearly constant flow that continued until queue dissipation. The average discharge flow is also labeled on the figure, with a value of 3,300 vph. From the perspective of modeling queue evolution, this sequence of flows does not deviate much from the average discharge flow, which was 10.6% lower than the flow that prevailed prior to bottleneck activation. This average discharge flow prevailed over a period of 2 hours 22 minutes. These data are summarized in Table 1.

Table 2 shows the shock speeds recorded upon bottleneck activation. The shock speed was computed by dividing the station-to-station distance by the mean shock travel time. When the backward-moving queue reached a particular station, a transition from freely flowing to queued conditions was observed. In Figure 2, shock speeds can be identified as the slope of the boundary of the congested area (low speeds represented by dark colors). As shown, the shock moved upstream at a speed between 6.4-12.8 km/h (4-8 mi/h), which is somewhat slower than reported elsewhere (9, 10). It is noted that the wave speed recorded between station 7 and station 8 is a downstream moving expansion wave of lower flow and lower density.

The upstream shock velocity is verified by the flow vs. density diagram shown in Figure 6. This figure shows observed flow and calculated densities from 6:00 AM to 8:00 AM on November 16, 1998. Time periods with nearly constant flow are identified using the rescaled N -curve for station 2. The average speed is calculated for each of the same time periods using the reported speed data. From the flows and speeds, and using the speed-flow-density relationship, it is possible to plot a flow vs. density curve for station 2. Note that the queue reaches this station at 7:01:46 AM marking the change from freely flowing to queued conditions. The shock speed is determined to be approximately 11.5 km/h (7.2 mi/h).

Figure 7 shows rescaled $N(x,t)$ and $V(x,t)$ for stations 2 and 9 from December 3, 1998. It is clear that during the congested period the speed dropped at both stations, but the reduction for station 2 is greater since the speed limit is 112 km/h (70 mi/h) while at station 9 the speed limit is only 80 km/h (50 mi/h).

REPRODUCING THE OBSERVATIONS

The analyses described in the previous section were repeated using data taken from four additional days on the M4 motorway. Similar traffic conditions were observed, but with some differences. On all five days, the bottleneck arose between stations 6 and 7. Table 1 reports the sustained flow immediately prior to queue formation and the average discharge rate that prevailed subsequent to bottleneck activation. The mean, standard deviation, and coefficient of variation are identified for these flows. The duration of queue discharge is also displayed. Further, the table shows the percentage difference between the higher flow prior to queue discharge and the sustained average flow that followed.

The flow immediately prior to the queue lasted for relatively short periods, consistent with findings in (1, 2, 3, 4). At this site, however, these flows appeared to be relatively consistent, with a mean value of 3,700 vph measured in the two-lane section at station 8. This may be at odds with findings in (1, 2, 3, 4) that revealed possible instability in the higher flow

reported prior to bottleneck activation near on-ramps. The average discharge flow was also consistent from day to day, with a mean value of 3,340 vph. This flow was sustained for much longer periods, ranging from 1 hour 30 minutes to almost 5 hours. The magnitude of the drop in flow observed upon queue formation was also consistent from day to day. On four of the five days, this percentage drop is between 10 and 11 percent, while on December 2, 1998 the percentage difference was between 6 and 7 percent.

Table 2 shows that the mean shock speeds (calculated from the speed at which the backward-moving queue traveled from one station to the next upstream station) ranged between 4.8-6.4 km/h (3-4 mi/h as they traveled upstream from the bottleneck. There were only slight differences observed between the shock wave speeds from one section to another. This would appear to confirm the validity of a linear $q-k$ relation for predicting queue propagation (9, 12), but confirmation of this is part of ongoing research.

CONCLUDING COMMENTS

It has been shown that a bottleneck arose in the vicinity of a freeway lane drop in a predictable way. The flow increased above some threshold, a queue formed and propagated upstream until a reduction in demand led to queue dissipation later in the morning. The bottleneck's location was reproducible from day to day. Also, the flow dropped substantially following the formation of the upstream queue, followed by discharge flow exhibiting nearly stationary patterns. The higher flow prior to queue formation was sustained for relatively short periods and the discharge flow that follows prevailed for much longer periods. The values of both of these flows appeared to be reproducible from day to day.

As mentioned earlier, the shock velocity observed is slower than reported elsewhere in the literature. To what extent this is related to drivers' familiarity with the roadway geometry and/or the speed limit change at station 9 is the subject of ongoing research. Further analysis of oscillations propagating upstream from the bottleneck is also underway in order to assess whether these oscillations vary with prevailing flow (11, 13).

This research is only an initial step toward understanding bottleneck behavior in relation to lane drops. Thus, further analyses are being conducted at this site in London as well as at other lane drop sites in the United States.

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TABLE 1 Summary of Traffic Features

Date	Day	Flow Immediately Prior to the Queue		Average Discharge Rate		Percent Difference %
		Rate (vph)	Duration (hr:min)	Rate (vph)	Duration (h:min)	
16-Nov-98	Monday	3,690	0:17	3,300	2:22	10.6
18-Nov-98	Wednesday	3,690	0:14	3,300	2:19	10.6
30-Nov-98	Monday	3,840	0:08	3,430	2:06	10.7
2-Dec-98	Wednesday	3,750	0:11	3,500	1:33	6.7
3-Dec-98	Thursday	3,510	0:13	3,150	4:52	10.3
	Mean	3700		3340		9.7
	Standard Deviation	121		135		
	Coefficient of Variation	3.26		4.04		

TABLE 2 Shock Characteristics

Stations	Distance km (mi)	16-Nov-98			Mean of 5 days		
		Mean Travel Time min:sec	Mean Speed mi/h km/h		Mean Travel Time min:sec	Mean Speed mi/h km/h	
9-8*	0.5 (0.3)				0:21	+ 53	+ 86
7-8	0.5 (0.3)	0:24	+ 47	+ 75	0:28	+ 40	+ 65
6-5	0.5 (0.3)	3:40	- 5	- 8	7:03	- 3	- 4
5-4	0.5 (0.3)	5:19	- 4	- 6	5:23	- 3	- 6
4-3	0.5 (0.3)	3:58	- 5	- 8	4:09	- 4	- 7
3-2	0.5 (0.3)	2:21	- 8	- 13	5:46	- 3	- 5

*9-8 was measured on December 3, 1998

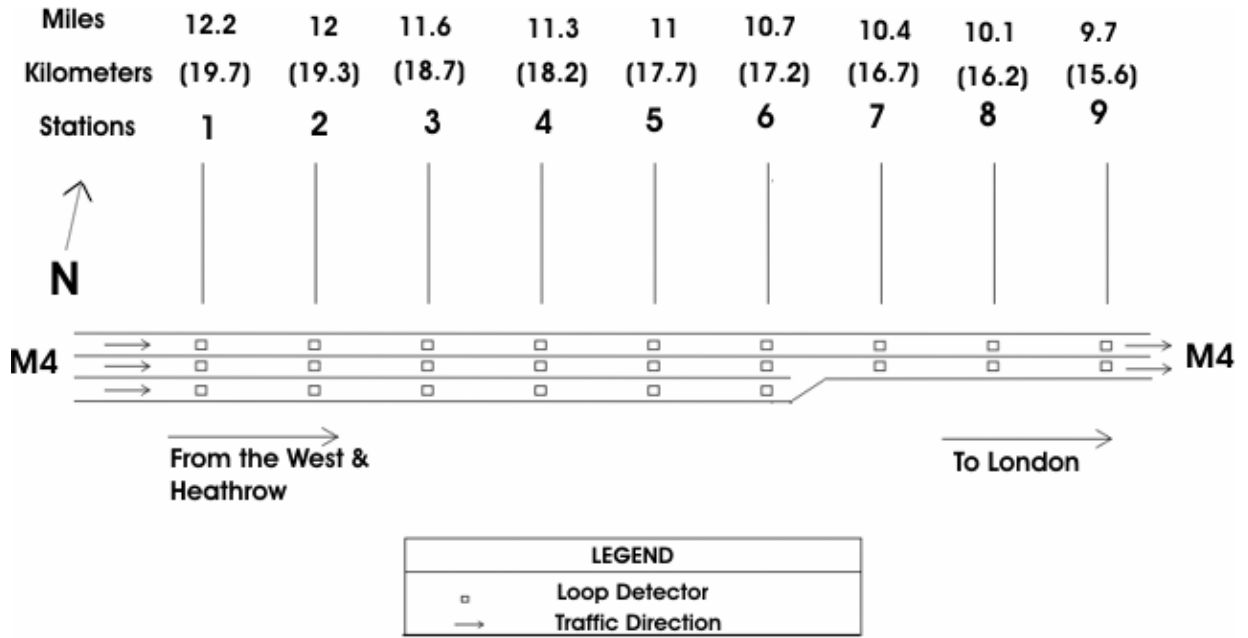


FIGURE 1 Site Map

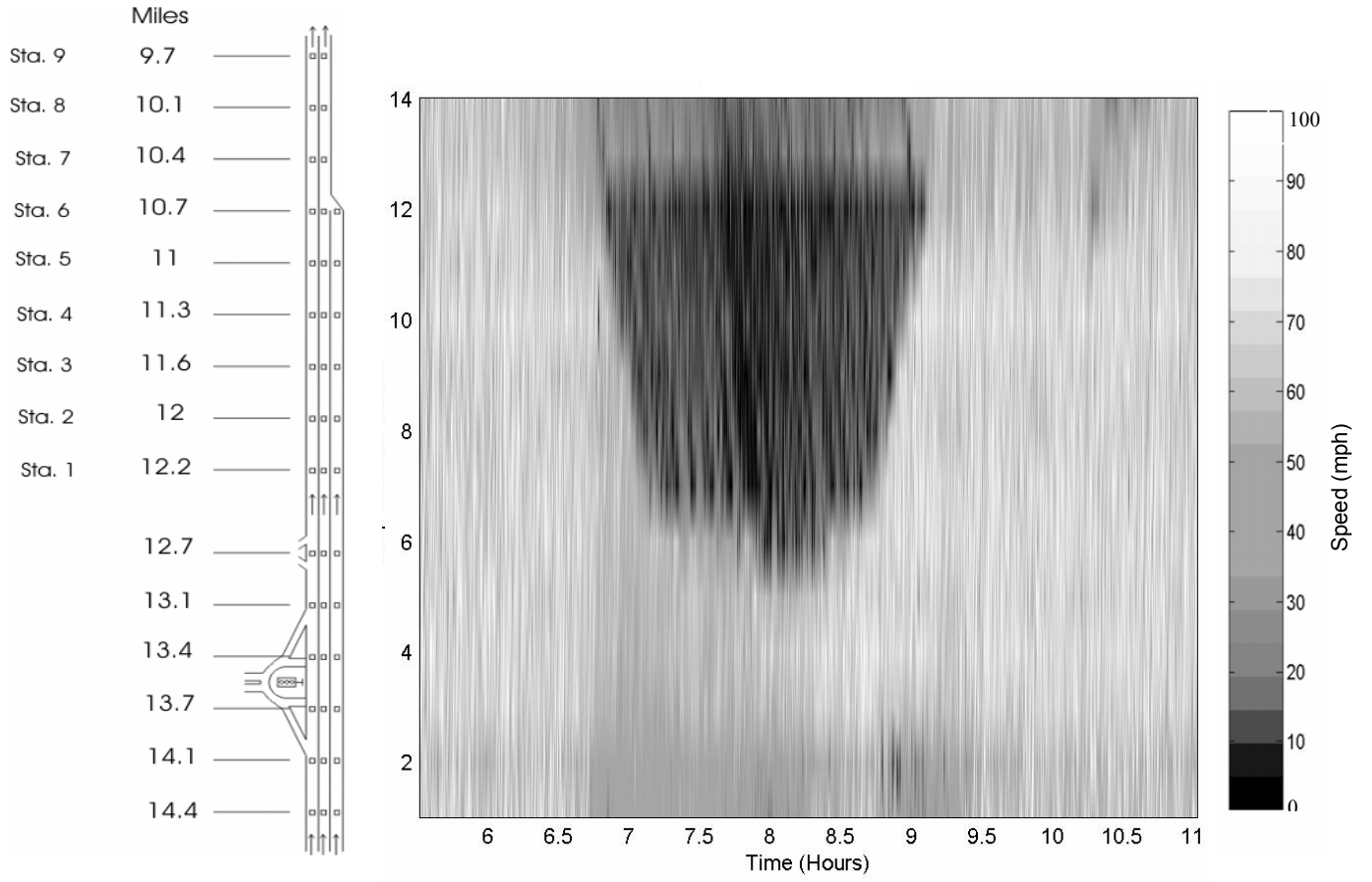


FIGURE 2 Speed Contours – November 16, 1998

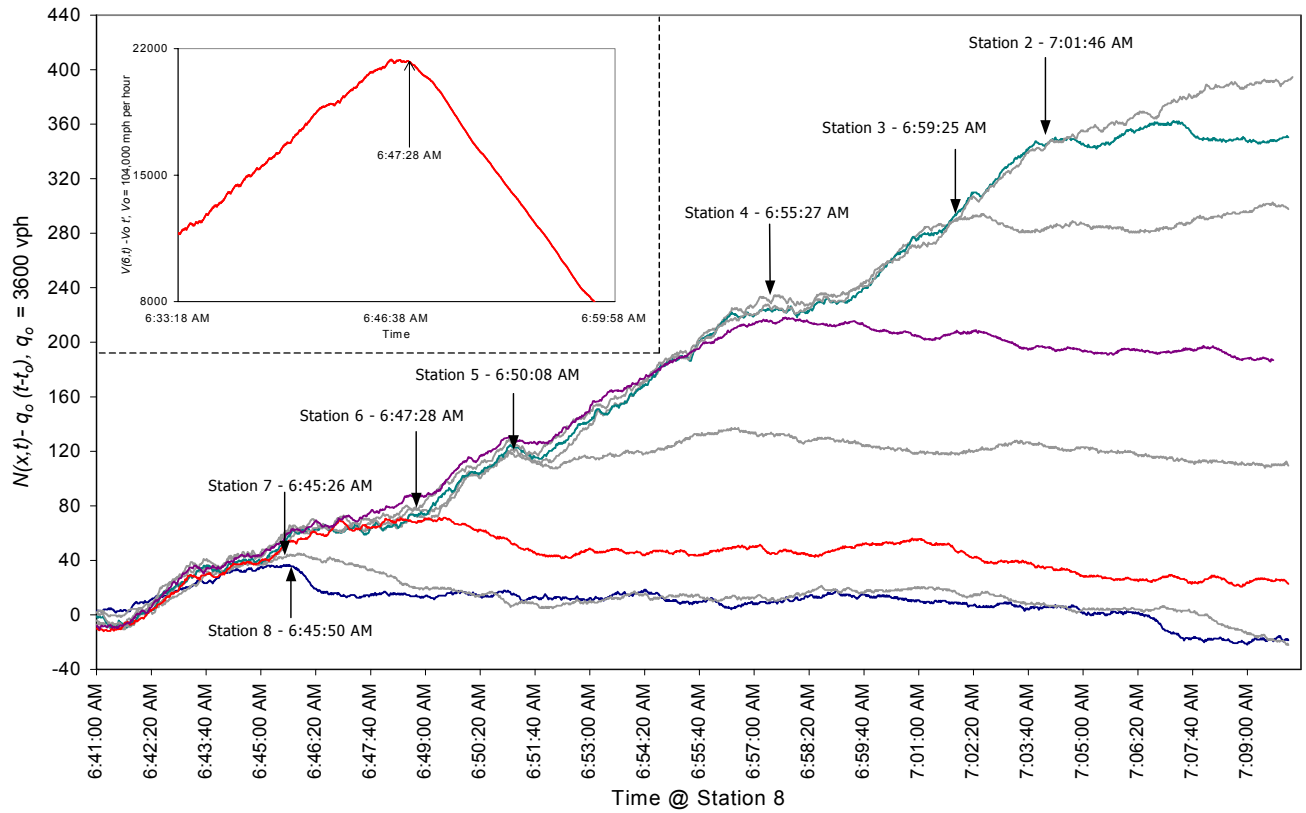


FIGURE 3 Rescaled Cumulative Curves - November 16, 1998

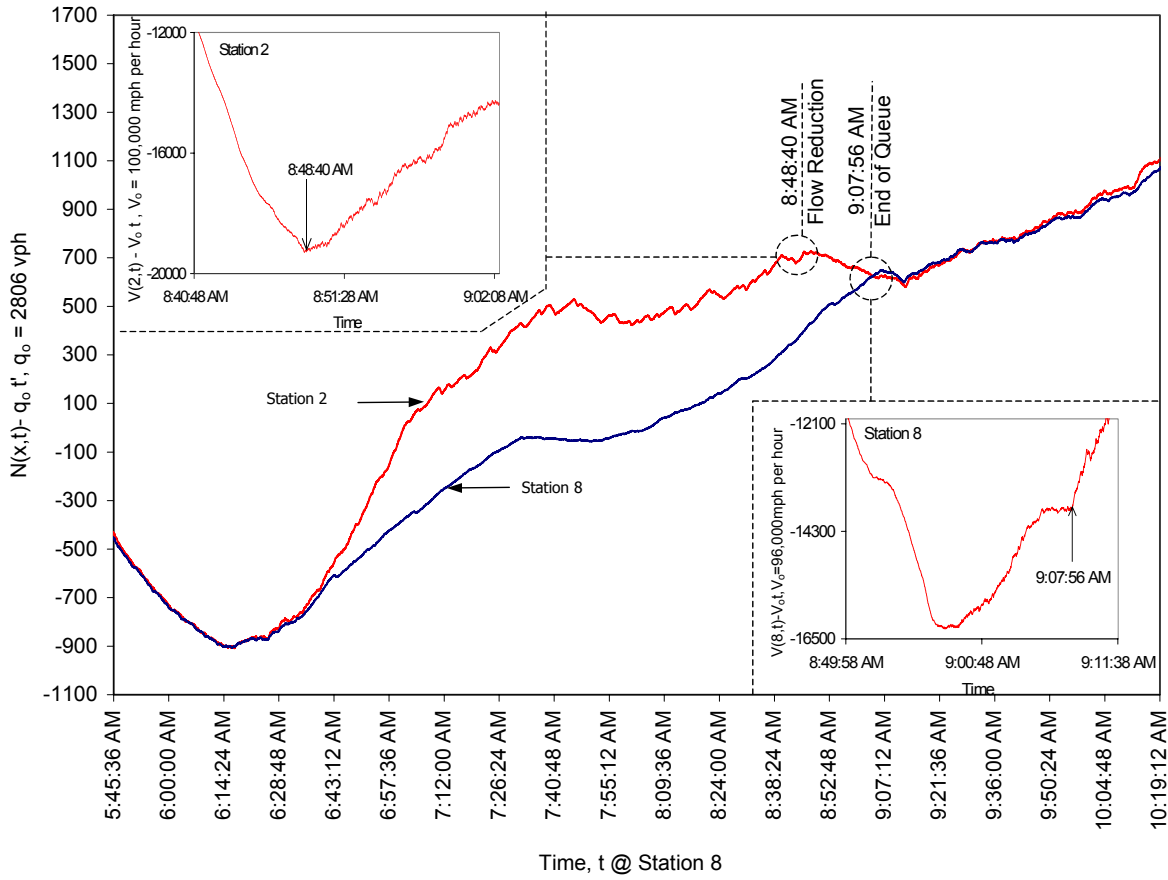


FIGURE 4 Upstream and Downstream Cumulative Curves - November 16, 1998

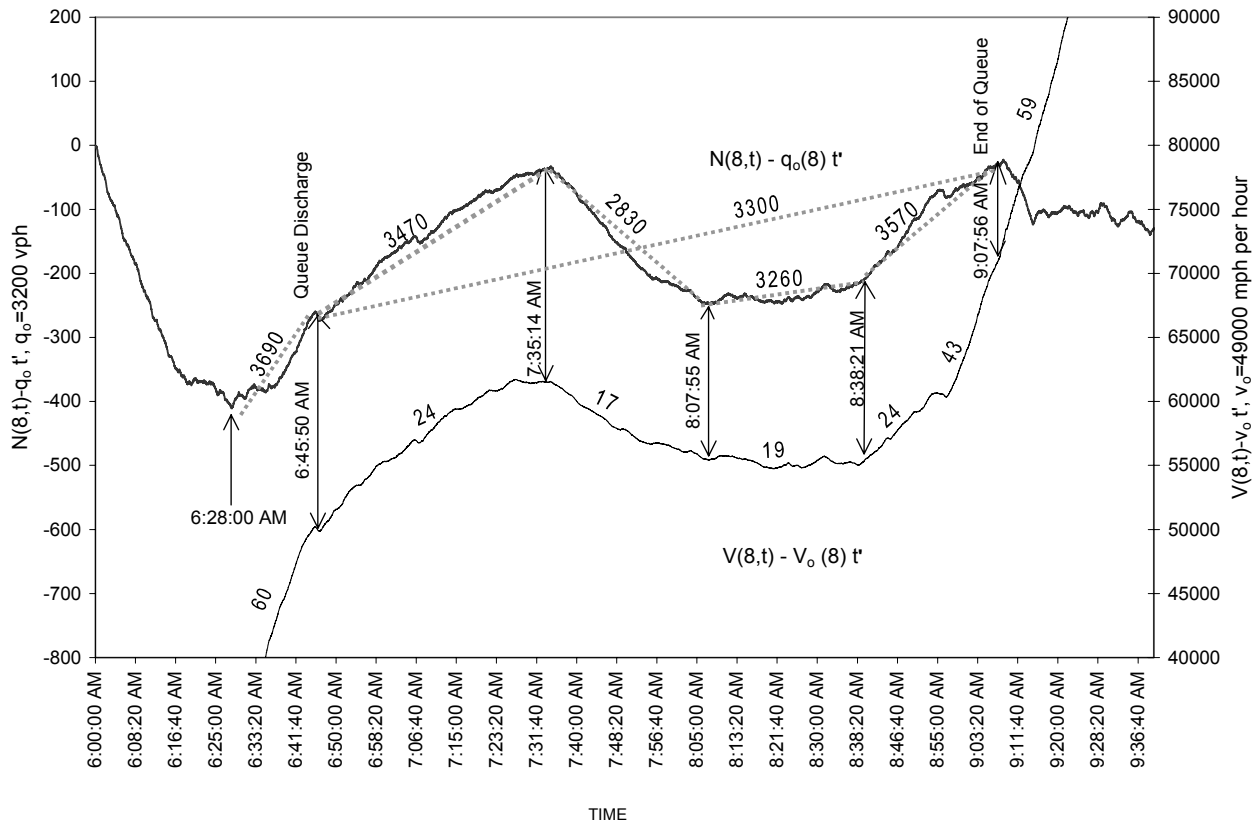


FIGURE 5 Rescaled N-curve and V-curve at Station 8 - November 16, 1998

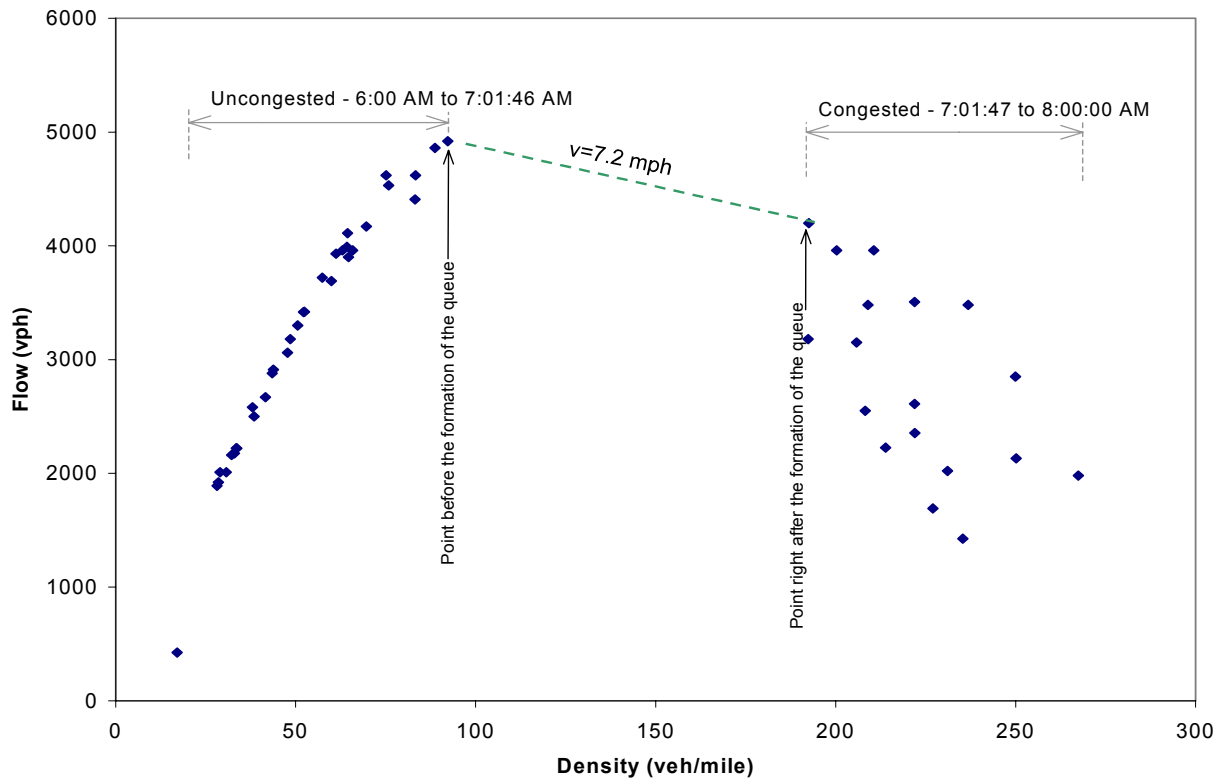


FIGURE 6 Flow Density Curve for Station 2 - November 16, 1998

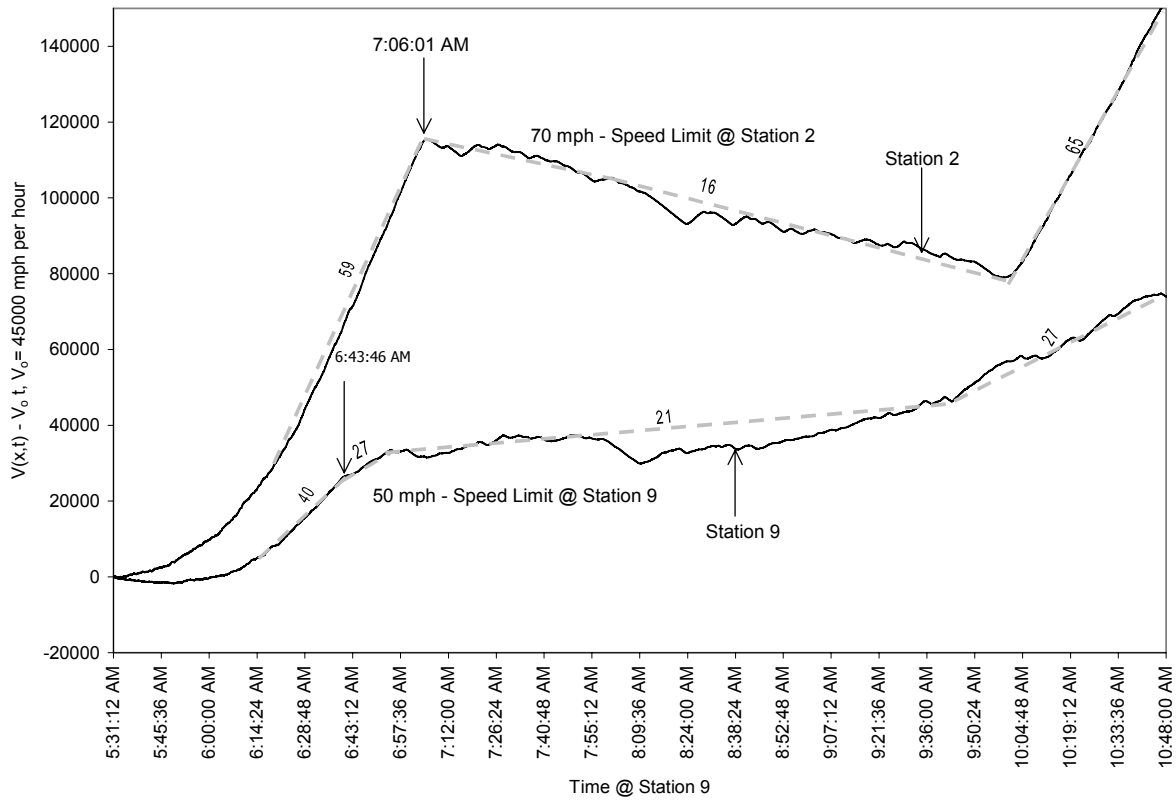


FIGURE 7 Rescaled V-curve at Stations 2 and 9 – December 3, 1998