EMPIRICAL STUDY OF TRAFFIC FEATURES AT A FREEWAY LANE DROP

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Manuscript Number: TE/2003/022979

Submitted August 2003
Revised February 2004

ABSTRACT

Traffic was studied upstream and downstream of a bottleneck that arose near a freeway lane drop near London, United Kingdom using archived high-resolution loop detector data. The bottleneck's location and mean discharge flows were reproducible from day to day. Further, it is shown that the bottleneck's discharge flow was about 10% lower than the prevailing flow observed prior to queue formation. Upon bottleneck activation, flow reductions occurring sequentially in time and space marked the passage of the backward-moving shock. Mean shock velocities ranged between 4.8 to 6.4 km/h (3 and 4 mph) as they traveled upstream from the bottleneck. During bottleneck discharge, oscillations arose in the queue and propagated upstream at nearly constant speeds of 17.6 to 19.2 km/h (11 to 12 mph). Flows measured at locations downstream of the bottleneck were not affected by these oscillations. These findings were corroborated using data from a freeway lane drop in Minneapolis, Minnesota, USA. The analysis tools used for this study were curves of cumulative vehicle count, time mean speed and occupancy versus time. These curves were constructed using data from neighboring freeway loop detectors and were transformed in order to provide the measurement resolution necessary to observe the transitions between freely-flowing and queued conditions and to identify important traffic features.

CE Database Subject Headings:

INTRODUCTION

Understanding traffic behavior at freeway bottlenecks provides a foundation for understanding how a freeway system operates. A bottleneck is a 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) in space and time. A bottleneck is considered active when it meets the conditions described above and is deactivated when there is a decrease in demand or when there is a spillover from a downstream bottleneck (Daganzo, 1997). Bottlenecks are important components of freeway systems, since the queues that develop upon bottleneck activation may propagate for several miles, causing delay and potentially blocking off-ramps and access to other facilities. With the implementation of new traffic surveillance systems, it is possible to study and understand freeway bottlenecks of all kinds—including merges near busy on-ramps (e.g., Bertini, 1999; Cassidy and Bertini, 1999a; Cassidy and Bertini, 1999b; Bertini and Cassidy, 2002; Cassidy and Mauch, 2001; Cassidy and Rudjanakanoknad, 2002), diverges near busy off-ramps (e.g., Windover, 1998; Muñoz and Daganzo, 2002; Cassidy, et al., 2000), lane drops and other configurations. This study contributes to a greater understanding of bottlenecks arising in the vicinity of freeway lane drops, which are variants of freeway merges associated with on-ramps.

LITERATURE REVIEW

Toward understanding the details of traffic flow around locations where traffic streams merge, earlier studies have examined traffic conditions both upstream and downstream of freeway bottlenecks located near busy on-ramps (Bertini, 1999; Cassidy and Bertini, 1999a; Cassidy and Bertini, 1999b; Bertini and Cassidy, 2002). Bertini (1999) also describes other previous studies that were limited by availability of data only upstream of actual bottleneck locations. In earlier studies, oscillations were also found to propagate upstream in freeway queues at nearly constant speeds (Cassidy and Mauch, 2001; Mauch, 2002; Mauch and Cassidy, 2002). These oscillations did not affect flows measured downstream of the locations where queues formed. To promote the visual identification of time-dependent features of traffic streams, these previous studies used curves of cumulative vehicle count and curves of cumulative occupancy constructed from data measured at neighboring freeway loop detectors (see Cassidy and Windover, 1995; Cassidy and Bertini, 1999a; and Cassidy and Bertini, 1999b for tutorials on the use of these cumulative curves). The use of these curves provided the measurement resolution necessary to observe transitions between freely flowing to queued conditions and to identify a number of notable, time-dependent traffic features of the bottlenecks.

Cumulative curves of vehicle count, time mean speed and occupancy were also used in this study, which adds to previous findings by reporting on observations taken during five morning peak periods both upstream and downstream of a freeway lane drop near London and at a freeway lane drop in Minneapolis (Leal, 2002). For the London site, individual vehicle actuation times (to the nearest second) and time mean speeds were obtained from inductive loop detectors located in each travel lane. For the Minnesota site, flow and occupancy data at 30-second intervals were obtained from inductive loop detectors also located in each travel lane. Through the use of cumulative curves, it has been possible to verify that the bottlenecks became active, guaranteeing that vehicles discharged from upstream queues and were unimpeded by traffic conditions from further downstream (Daganzo, 1997). It was also possible to observe certain bottleneck features that were reproducible from day to day.

First, some background will be provided, followed by a description of the study sites and the loop detector data used for this analysis. Next, detailed descriptions of the bottlenecks' locations and discharge features will be presented for one representative day at each site. This is followed by summaries of features found to be reproducible on four additional days at the London site. Finally, some concluding comments are provided.

DATA

It is shown that a freeway bottleneck arose near a freeway lane drop (from three to two lanes) on the M4 motorway near London, United Kingdom. The bottleneck's location and average discharge flow were reproducible from day to day. Further, it is shown that the bottleneck's discharge flow was about 10% lower than the prevailing flow observed prior to queue formation. It is also shown that shock velocities were nearly constant as the queue propagated upstream from the bottleneck. During bottleneck discharge, oscillations arose in the upstream queue; these oscillations propagated upstream at nearly constant speeds. These oscillations were not observed in flows measured downstream of the bottleneck location. These findings were corroborated using data from a freeway lane drop on I-494 in Minneapolis, Minnesota, USA.

The two freeway sites used in this study were the segments of the M4 Motorway near London, United Kingdom and the I-494 freeway in the Minneapolis, Minnesota, USA, illustrated in Figure 1. On this 4.1 km (2.5 mi) segment of the M4, inductive loop detectors spaced approximately every 0.5 km (0.3 mi) recorded individual vehicles' arrival times (to the nearest second) and their time mean speeds in each lane. The loop detector data were available in their most raw form and were not aggregated over any arbitrary periods. The M4 detectors were labeled 1 through 9 as shown in Figure 1, and the lane drop is located at approximately kilometer 17.1 (mile 10.6). When these data were collected in 1998 the motorway speed limit was 112 km/h (70 mph) upstream of detector 9 and 80 km/h (50 mph) downstream of detector 9. We note that in 1999 modifications to the motorway lane markings were installed, creating a bus lane for use by buses and taxes (and as of 2002, motorcycles as well) in the fast (right hand) lane (Rees, et al., 2000). This does not affect the present study's findings. On the 2.4 km (1.5 mi) segment of I-494 in Minneapolis shown in Figure 1, the detectors recorded counts and occupancies in each lane over 30-second intervals. The detectors were labeled 1a through 4 and the lane drop is located between detectors 2 and 3.

The following two sections describe the bottleneck features observed (for single days) on the M4 and on I-494. These observations were reproduced on four additional days for the London site, as described in a later section.

OBSERVATIONS ON THE M4 MOTORWAY

Traffic features surrounding the lane drop on the M4 were analyzed using data from Monday, November 16, 1998, reported to be a cloudy day with no measurable precipitation. Figure 2 shows oblique curves of cumulative vehicle arrival number versus time, $N(x,t)$, constructed from counts measured across all lanes at detectors 2-8 and collected during a 30-minute period. These 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 began (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 detector 8, the downstream most detector in the figure. Any resulting vertical displacements are the excess vehicle accumulations between detectors due to vehicle delays (Newell, 1982; Newell, 1993).

In order to magnify the curves' features, an oblique coordinate system was used where $N(x,t)$ was reduced by $q_0(t-t_o)$ where q_0 was an oblique scaling rate and t_o was the curve's starting time. One can visualize the curves in Figure 2 as depicting the difference between the original

N(x,t) and a line of slope q_0, which merely provides a higher visual resolution of the same data. The same value of q_0 was used for all curves and therefore did not affect the vertical separations (Cassidy and Windover, 1995). The use of this oblique coordinate system is described in detail in several references (Cassidy and Windover, 1995; Cassidy and Bertini, 1999a).

As shown in Figure 2, curves for all detectors were initially superimposed indicating freely flowing traffic throughout this entire motorway section. The curves for detectors 8 and 7 remained nearly superimposed for this entire 30-minute period, indicating that traffic continued to flow freely between these detectors. Excess vehicle accumulations occurred between detectors 6 and 7 subsequent to flow reductions observed at detectors 7 and 8 at around 6:44 and 6:45 respectively (despite the fact that vehicle arrival times were available to the nearest second, times are reported to the nearest minute so as not to imply an undue precision of measurement).

The divergence of the curve at detector 6 from the one at detector 5 (at 6:44) marked the arrival of a backward-moving queue at detector 6. There was a pronounced flow reduction at detector 6 that accompanied this divergence. The presence of freely flowing traffic between detectors 7 and 8 accompanied by excess vehicle accumulation upstream of detector 7 revealed that the bottleneck was located somewhere between detectors 6 and 7 where the transition from three lanes to two lanes occurs.

Figure 2 also mapped the propagation of the queue upstream of detector 6. As shown in the figure, a reduction in flow at detector 5 was observed at 6:50, where the curve at detector 5 deviated from the upstream curves. This indicated excess vehicle accumulation upstream of detector 5. Additional deviations occurred in sequence, indicating that the queue ultimately arrived at detector 2 at 7:01. Figure 2 has made it possible to diagnose the bottleneck's location (between detectors 6 and 7), as well as the time it became active (around 6:45). To further confirm the queue's arrival time at detector 6 at approximately 6:46, the inset in Figure 2 shows a bar chart of the variance of the counts recorded at detector 6, measured over 3-second periods. In order to amplify this feature, the variance is also plotted cumulatively in the figure (see Bertini, 2003), using an oblique axis to magnify the details of the curve. This shows that the variance drops at the beginning of the queue discharge, which is not surprising since vehicles were discharging from a queue.

To verify the arrival of the backward-moving queue at each detector, cumulative curves of time mean speed ($V(x,t)$) were constructed for each detector. $V(x,t)$ was the cumulative time mean speed measured at detector x by time t. As with the $N(x,t)$, piecewise linear approximations to $V(x,t)$ were constructed, where the slope of the V was a "speed rate" measured at location x at time t. An oblique coordinate system was also used where $V(x,t)$ was reduced by $V_o(t-t_0)$, Similar to the use of q_0, V_o was an oblique scaling rate and t_0 was the curve's starting time. The V were plotted using this oblique axis to visually identify periods of nearly constant average speed and times marking changes in average speed.

Figure 3 contains oblique curves of cumulative vehicle speed, $V(x,t)$, versus time, measured at detectors 6 and 7. As shown in the figure, a sharp reduction in speed was seen at detector 7 at around 6:47, confirming the arrival of the forward-moving wave at approximately that time. The $V(x,t)$ for detector 6 reveals a reduction in velocity measured at about 6:46, confirming the queue's arrival at that time. The figure also shows $V(x,t)$ measured in individual lanes at detectors 6 and 7, to indicate that speed reductions occurred at slightly different times in each lane.

Figure 3 also shows oblique $V(x,t)$ for detectors 5, 4, 3 and 2 as measured across all lanes. The times marked by drops in velocity corresponded with the times marked by flow reductions in Figure 2. Table 1 shows the shock speeds recorded upon bottleneck activation for this day. As shown, the shock's upstream velocity was between 6.4 and 12.8 km/h (4 and 8 mph). Note that the wave between detectors 7 and 8 was a downstream moving expansion wave of lower flow and higher velocity.

In order to determine the exact period during which this bottleneck remained active, Figure 4 shows oblique *N(x,t)* for detectors 2 and 8 for a longer period. As indicated by the continued vertical displacement between the two curves, the queue between detectors 2 and 8 persisted until around 9:07 when the *N(x,t)* again became superimposed. This shows that vehicles were traveling unimpeded between these detectors after this time and thus indicating queue dissipation. The insets in Figure 4 contain oblique *V(x,t)* for detectors 2 and 8. As shown in the lower inset, a speed increase was observed at detector 8 around the time that the queue dissipated. Queue dissipation occurred several minutes after a decrease in flow was measured at detector 2 (around 8:48) signaling the end of queueing at that location. The upper inset verifies the timing of the end of queueing at detector 2 by showing that an increase in speed also occurred at 8:48.

Figures 2 and 4 have verified the bottleneck's location, the time it became active, and the time that it was deactivated. Figure 2 also maps the passage of the backward-moving queue. Now it is possible to examine the active bottleneck's queue discharge features in detail.

Cumulative curves at detector 8 (downstream of the bottleneck) were used to examine the bottleneck's discharge features. Figure 5 shows oblique *N(8,t)* and *V(8,t).* In the figure, periods of nearly constant flow and speed were marked with solid lines where the average flows are in vehicles/hour (vph) and the average speeds are in kph (mph). The average discharge flow is marked with a dashed line. Figure 5 shows that the formation of the upstream queue at 6:45 was marked by a reduction in *N(x,t)* accompanied by a reduction in speed. Since the curves in Figure 5 do not display any abrupt reductions in the *N(x,t)* accompanied by reductions in speed between 6:45 and 9:07, it is apparent that there was no disruption of active bottleneck discharge caused by a queue from anywhere further downstream.

Turning to the bottleneck's flow features displayed in Figure 5, it is shown that between 6:28 and the beginning of queue discharge (6:45) a flow of 3690 vph prevailed in the two-lane section downstream of the bottleneck. Upon queue discharge, a lower flow of 3470 vph was observed, which prevailed for about 50 minutes. This was followed by a series of sequences of nearly constant flow until queue dissipation. This sequence of flows did not deviate substantially from the average discharge flow of 3300 vph (marked by a dashed line), which was 10.6% lower than the flow that prevailed prior to bottleneck activation. The cause(s) of these flow changes is not known and is the subject of ongoing research. The bottleneck's discharge flow prevailed over a period of 2 hours 22 minutes. This confirms the measurement of a flow drop upon bottleneck activation and that the queue discharge flow was nearly constant on this day.

Traffic oscillations in queued conditions are characterized by sharp increases in flow followed by sharp reductions in flow. To a motorist in the queue, oscillations appear as stop and go or slow and go driving conditions (Cassidy and Mauch, 2001). Figure 6 illustrates oscillations for about 45 minutes of congested conditions using oblique *N(x,t)* for detectors 1 to 8. The vertical distances between the oblique *N(x,t)* are proportional to the distances between the detectors along the motorway. Using a procedure from Mauch and Cassidy (2002), a moving 10-minute average flow was subtracted from each *N(x,t)*: $N(t)-\left[N(t+5\,\text{min})+N(t-5\,\text{min})\right]/2$ which is shown as $N-\overline{N}_{10}$ in the figure. Therefore, the slopes of the oblique *N(x,t)* in this figure represent observed flow deviations from average flows (Mauch and Cassidy, 2002).

As shown, the oscillations only occurred upstream of the bottleneck (detectors 1 to 6) and each lasted for several minutes. The oblique *N(x,t)* for the detectors downstream of the bottleneck remained smooth (detectors 7 and 8). Thus, oscillations were not observed where traffic was unqueued. The amplitude of each oscillation was less than 70 vehicles as measured across all lanes or about 23 vehicles as measured in individual lanes, as shown in the figure. The largest amplitude of 68 vehicles across all lanes or about 22 vehicles per lane was observed at detector 1. Other findings reported slightly lower amplitudes of less than 50 vehicles (Mauch and Cassidy, 2002).

The peaks of the oscillations were connected by dashed lines, where the slope of the dashed line was the upstream velocity of the oscillation. These lines appear to be parallel, at a nearly constant speed of about 17.6 to 19.2 km/h (11 to 12 mph), independent of the location within the queue. Mauch and Cassidy (2002) reported similar speeds of about 22.4 to 24.0 km/h (14 to 15 mph).

OBSERVATIONS ON I-494 IN MINNEAPOLIS

Traffic features were analyzed on the I-494 freeway using data from Wednesday, October 27, 1999. Figure 7 shows oblique curves of cumulative vehicle arrival number versus time, *N(x,t),* constructed from counts measured across all lanes at detectors 1 to 4 and collected during a 50-minute period surrounding activation of the bottleneck between detectors 2 and 3. The detector 1 curve contains the sum of counts from detectors 1a and 1b and the detector 4 curve is the sum of counts from the mainline (2 lanes) plus the off-ramp.

As shown in Figure 7, curves for all detectors were initially superimposed indicating freely flowing traffic through the whole section. The curves for detectors 3 and 4 remained nearly superimposed for this period, indicating that traffic continued to flow freely between these detectors. Excess vehicle accumulations were seen between detectors 2 and 3 subsequent to flow reductions which were observed at detectors 3 and 4 at around 6:35.

The divergence of the curve at detector 2 from the one at detector 3 (at 6:35) marked the arrival of a backward-moving queue at detector 2. To confirm this, the left inset in Figure 7 shows an oblique curve of cumulative occupancy versus time, $T(x,t)$, for detector 2, where cumulative occupancy was the total vehicle trip time measured over the detectors by time t. Again for the purpose of magnifying details, the $T(x,t)$ shown was the difference between the cumulative occupancy actually measured at detector 2 (across all lanes) and a line $T = b_0 \cdot t_0$, where b_0 was an oblique scaling rate and t_0 was the elapsed time from the beginning of the curve. A sharp increase in occupancy was seen at around 6:35, verifying the arrival of the queue. The presence of freely flowing traffic between detectors 3 and 4, accompanied by excess vehicle accumulation upstream of detector 2 reveals that the bottleneck was located somewhere between detectors 2 and 3 where the transition from three lanes to two lanes occurs. At about 6:40 there was a flow reduction accompanied by an increase in occupancy at detector 1 as shown in the right hand inset in Figure 7. This figure has made it possible to diagnose the bottleneck's location (between detectors 2 and 3), as well as the time it became active (around 6:35).

Table 2 shows the shock speed measured upon bottleneck activation. As shown, the shock moved upstream at a speed of 12.8 km/h (8 mph). Because the data were aggregated every 30 seconds, and the wave's travel time was less than 30 seconds, it was not possible to measure the expansion wave's velocity between detectors 3 and 4.

In order to determine the period during which this bottleneck remained active, Figure 8 shows oblique $N(x,t)$ for detectors 1 and 4 for a longer period. As indicated by the continued vertical displacement between the curves, the queue between detectors 1 and 4 persisted until around 8:25 when the *N(x,t)* again became superimposed. This shows that the vehicles were traveling unimpeded between these detectors after this time. The insets in Figure 8 contain oblique curves of cumulative occupancy at detectors 1 and 4. As shown in the right inset, an occupancy decrease was observed at detector 4 around the time that the queue dissipated. Complete queue dissipation occurred several minutes after a decrease in flow at detector 1 (around 8:10:30) signaled the end of queueing at that detector. The left inset verifies the timing of the queue dissipation at detector 1 by showing that a decrease in occupancy also occurred around 8:10:30. Figures 7 and 8 have verified the bottleneck's location, the time it became active, and the time that it was deactivated.

Cumulative curves from detector 4 (downstream of the bottleneck) were used to examine the bottleneck's discharge features. Figure 9 shows oblique curves of *N(4,t)* and *T(4,t)* also measured at detector 4. In the figure, periods of nearly constant flow and occupancy are indicated by solid lines where the average flows are in vph. The average discharge flow is marked with a dashed line and is also given in vph. Figure 9 shows that the formation of an upstream queue at 6:35 was marked by a reduction in *N(x,t)* accompanied by a reduction in occupancy. Since the curves in Figure 9 do not display any abrupt reductions in the *N(x,t)* accompanied by increases in occupancy between 6:35 and 7:40, it is apparent that there was no disruption of bottleneck discharge caused by a queue from anywhere further downstream.

Turning to the discharge features displayed in Figure 9, it is shown that between 6:20 and the beginning of queue discharge (6:35) a flow of 5040 vph prevailed in the two-lane section downstream of the bottleneck. This was followed by a series of sequences of nearly constant flow until queue dissipation. This sequence of flows does not deviate much from the average discharge flow of 4430 vph (marked by a dashed line), which was 12% lower than the flow that prevailed prior to bottleneck activation. This average discharge flow prevailed over a period of 1 hour and 5 minutes.

REPRODUCING THE OBSERVATIONS ON THE M4

The analyses described in the previous sections were repeated using data taken from four additional days on the M4 motorway. Similar traffic conditions were reproduced during the four days, but with some slight variations. On all five days, the bottleneck arose between detectors 6 and 7. Table 3 reports the sustained flow immediately prior to queue formation and the average discharge rate that prevailed subsequent to bottleneck activation for all five days. The mean, standard deviation, and coefficient of variation are identified for these flows. The duration of queue discharge is also displayed. Also, the table shows the percent 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 other studies (e.g., Cassidy and Bertini, 1999a; Cassidy and Bertini, 1999b; Bertini, 1999; Bertini and Cassidy, 2002). At this site, however, these flows appeared to be relatively consistent, with a mean value of 3700 vph measured in the two-lane section at detector 8. This may be at odds with other findings (e.g., Cassidy and Bertini, 1999a; Cassidy and Bertini, 1999b; Bertini, 1999; Bertini and Cassidy, 2002) that revealed possible instabilities in the higher flow reported prior to bottleneck activation. The average discharge flow was also consistent from day to day, with a mean value of 3340 vph. This flow was sustained for much longer periods, ranging from 1 hour 30 minutes to almost 5 hours. The drop in flow observed upon queue formation was also consistent from day to day. On four of the five days, this percentage drop was between 10 and 11 percent, while on December 2, 1998 the percentage difference was between 6 and 7 percent.

The shock speeds were also analyzed for all days as summarized in Table 4. The mean upstream shock velocities ranged between 4.8 and 6.4 km/h (3 and 4 mph). There were only slight differences observed between the shock speeds from one motorway section to another. This would appear to confirm the validity of a linear *q-k* relation for predicting queue propagation (e.g., Newell, 1993; Windover, 1998), but confirmation of this is part of ongoing research.

Figure 10 shows oblique *V(x,t)* for detectors 2 and 9 from December 3, 1998. It is clear that while a queue was present the speed dropped at both detectors, but the reduction at detector 2 was larger since the speed limit was 112 km/h (70 mph) while at detector 9 the speed limit was 80 km/h (50 mph). This speed limit change could contribute to the observation that vehicle speeds at downstream detectors did not increase as rapidly as expected. It appears that the vehicles did not accelerate very rapidly after passing the bottleneck location because of the drop in speed limit at detector 9. This aspect is the subject of ongoing analysis.

CONCLUSIONS

This study analyzed traffic conditions upstream and downstream of two bottlenecks arising near freeway lane drops. Curves of cumulative count, time mean speed and occupancy versus time were used in this study. Suitably constructed, these curves facilitated the observation of traffic conditions around the lane drop bottlenecks. It has been shown that bottlenecks arose in the vicinity of the freeway lane drops in a generally predictable way. Flows increased above some level, queues formed and propagated upstream until demand reductions led to queue dissipation later in the morning. The London bottleneck's location was reproducible from day to day. Also, it was shown that the flows can drop substantially following the formation of the upstream queues, followed by discharge flows exhibiting nearly stationary patterns. This contradicts Kerner (2000) and Kerner (2002), who found large variations in discharge flows downstream of bottlenecks on a German highway. In this study, the drops in flow were accompanied by drops in speed and increases in occupancy. The higher flows prior to queue formation were sustained for relatively short periods and the discharge flows that followed prevailed for much longer periods. The values of both of these flows appeared to be reproducible from day to day at the London site. The long run queue discharge flows should be considered to be the bottleneck capacities since discharge flows were nearly constant and they were reproducible from day to day.

The shock velocities observed on the M4 were somewhat slower than reported elsewhere in the literature. To what extent this was related to drivers' familiarity with the roadway geometry and/or the speed limit change at detector 9 is the subject of ongoing research. The oscillations on the M4 arose within the queue at the detectors upstream of the bottleneck. Oscillations were not observed at locations downstream of the head of the queue. It was observed that the oscillations displayed a nearly constant upstream speed.

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

ACKNOWLEDGEMENTS

The idea for this study was originally prompted by correspondence with Mr. Stuart Beale, Telematics Group, Highways Agency, Executive Agency of the Department for Transport, United Kingdom. The authors gratefully acknowledge Mr. Beale and Mr. Tim Rees, Project Manager, Transport Research Laboratory, United Kingdom, for generously supplying the London data used herein. The authors also thank Professor David M. Levinson and Lei Zhang, University of Minnesota and the Minnesota Department of Transportation, for providing valuable data used in this study. Roger Lindgren, Oregon Institute of Technology assisted with the data preparation. A portion of this work was funded by the Department of Civil and Environmental Engineering at Portland State University and the Oregon Engineering and Technology Industry Council (ETIC).

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Table 1: Shock characteristics on the M4

			November 16, 1998		
Detectors	Distance		Mean Travel Time	Mean Speed	
	km	mi	min:sec	km/h	mph
7-8	0.50	0.31	0:24	+ 75	+ 47
6-5	0.50	0.31	3:40	- 8	- 5
5-4	0.50	0.31	5:19	- 6	- 4
4-3	0.50	0.31	3:58	- 8	- 5
3-2	0.50	0.31	2:21	- 13	- 8

Table 2: Shock characteristics on I-494

October 27, 1999					
Detectors	Distance		Mean Travel Time	Mean Speed	
	km	mi	min:sec	km/h	mph
2-1	1.0	0.63	5:00	- 12	- 8

Table 3: Summary of traffic features on the M4

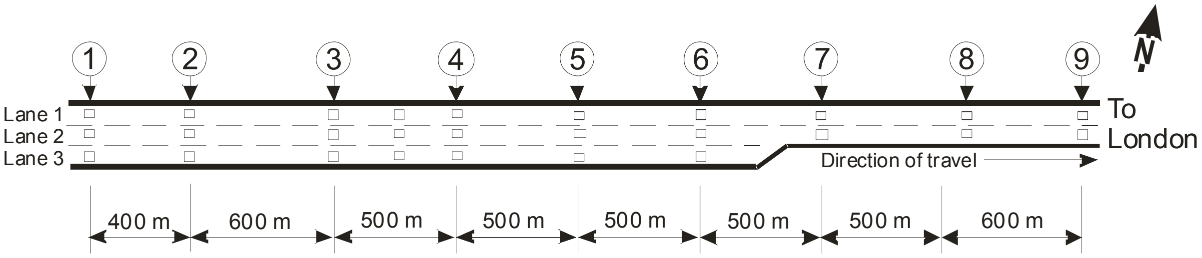
Date	Day	Flow Immediately Prior to the Queue		Average Discharge Rate		Percent Difference
		Rate vph	Duration hr:min:sec	Rate vph	Duration h:min:sec	%
16-Nov-98	Monday	3,690	0:17:50	3,300	2:22:06	10.6
18-Nov-98	Wednesday	3,690	0:14:45	3,300	2:19:25	10.6
30-Nov-98	Monday	3,840	0:08:07	3,430	2:06:09	10.7
2-Dec-98	Wednesday	3,750	0:11:57	3,500	1:33:32	6.7
3-Dec-98	Thursday	3,510	0:13:12	3,150	4:52:22	10.3
	Mean	3,700		3,340		9.7
	Standard Deviation	121		135		
	Coefficient of Variation	3.26		4.04		

Table 4: Shock characteristics on the M4

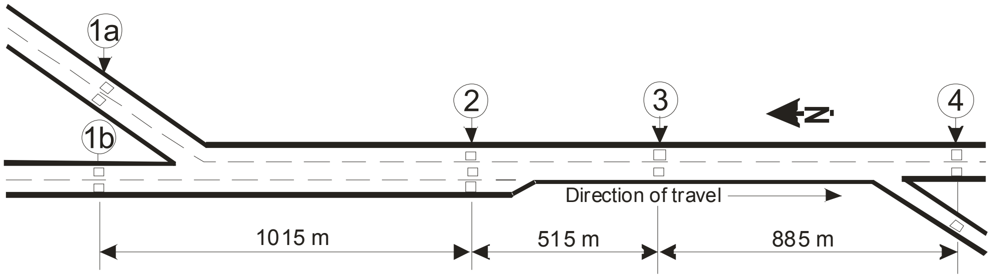
			Mean of 5 days		
Detectors	Distance		Mean Travel Time	Mean Speed	
	km	mi	min:sec	km / h	mph
* 9-8	0.50	0.31	0:21	+ 86	+ 53
7-8	0.50	0.31	0:28	+ 65	+ 40
6-5	0.50	0.31	7:03	- 4	- 3
5-4	0.50	0.31	5:23	- 6	- 3
4-3	0.50	0.31	4:09	- 7	- 4
3-2	0.50	0.31	5:46	- 5	- 3

*9-8 was measured on December 3, 1998

Figure 1: Site maps



M4 Motorway, United Kingdom



Interstate 494, Minneapolis, Minnesota, USA

Figure 2: Transformed *N(x,t)* on the M4

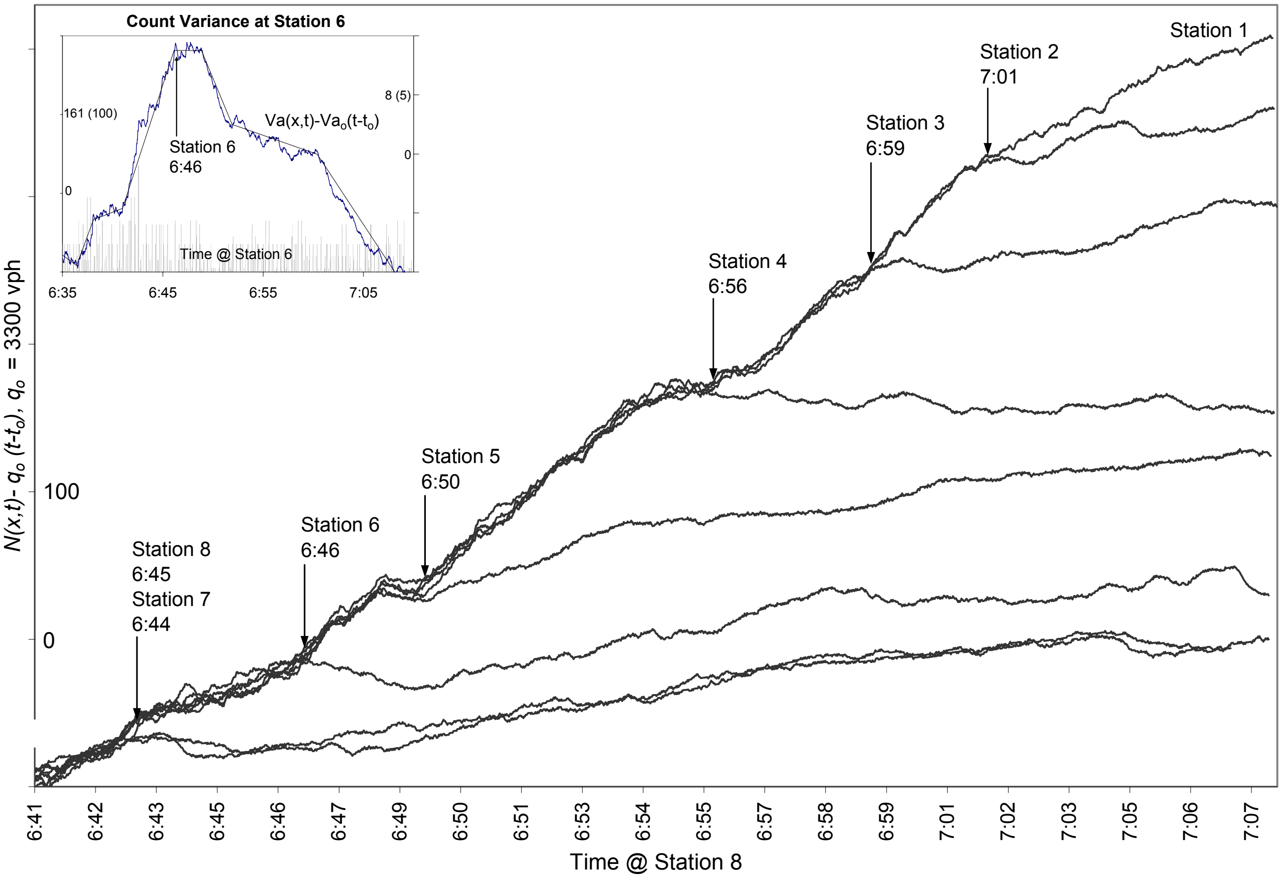


Figure 3: Oblique *V(x,t)* on the M4

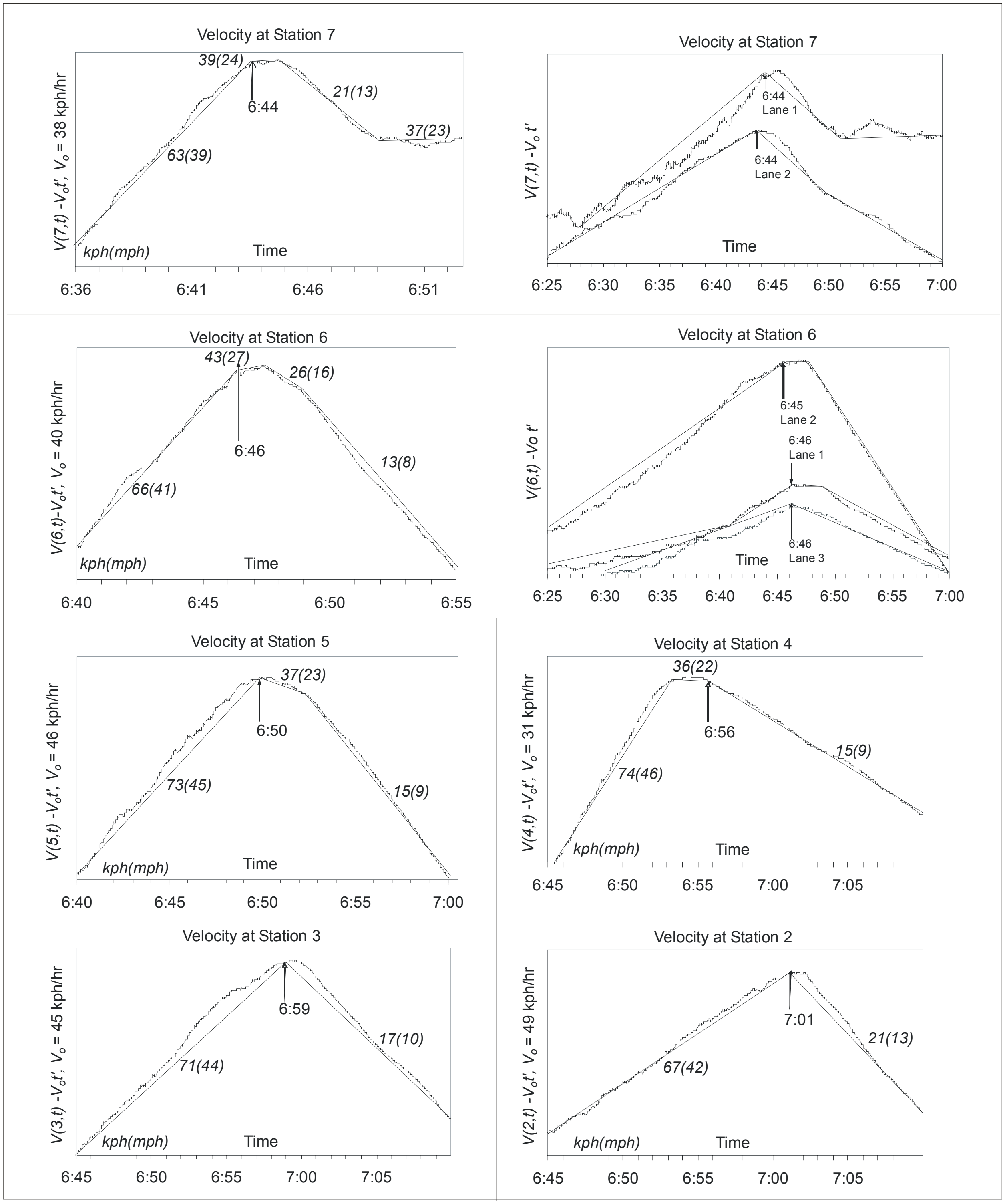


Figure 4: Upstream and downstream oblique *N(x,t)* on the M4

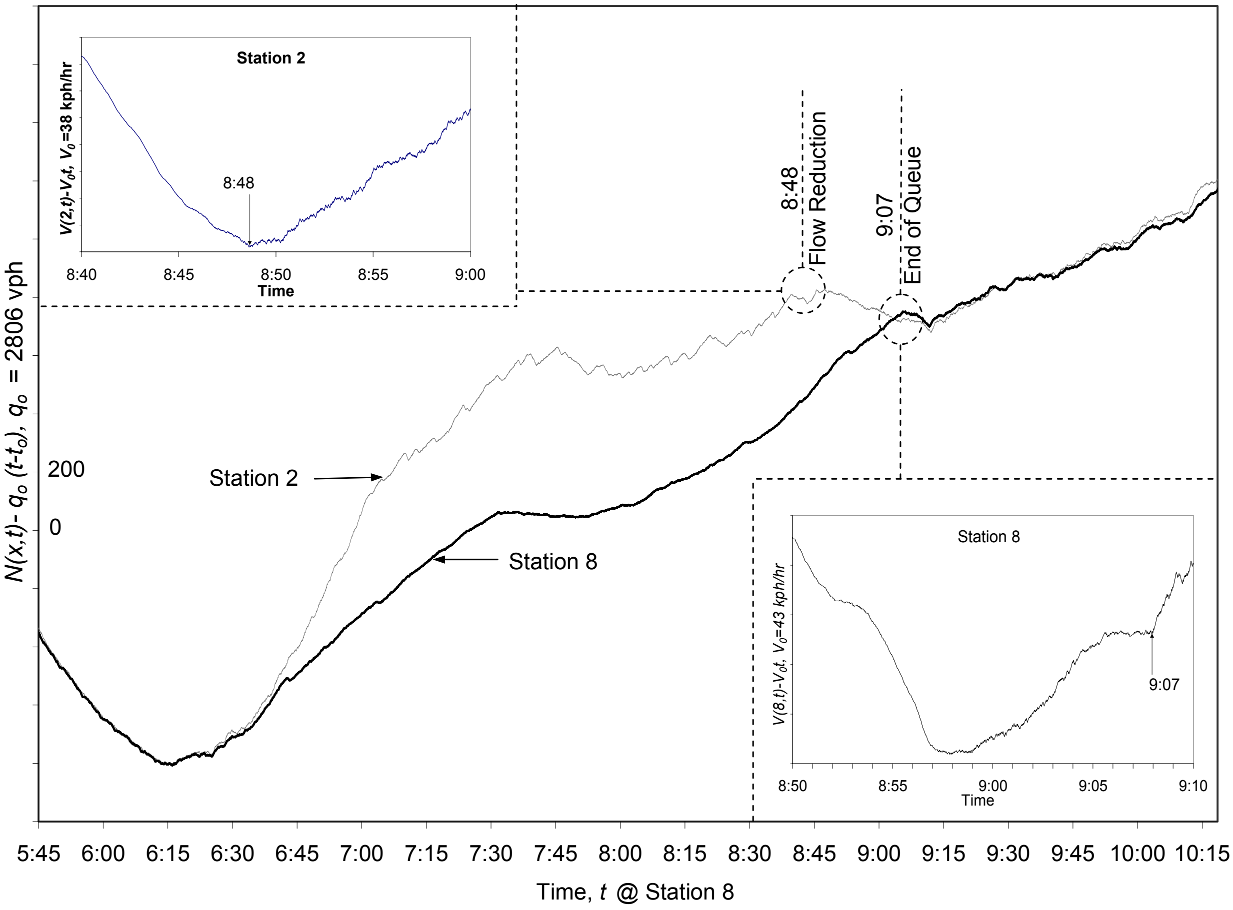


Figure 5: Oblique *N(x,t)* and *V(x,t)* at detector 8 on the M4

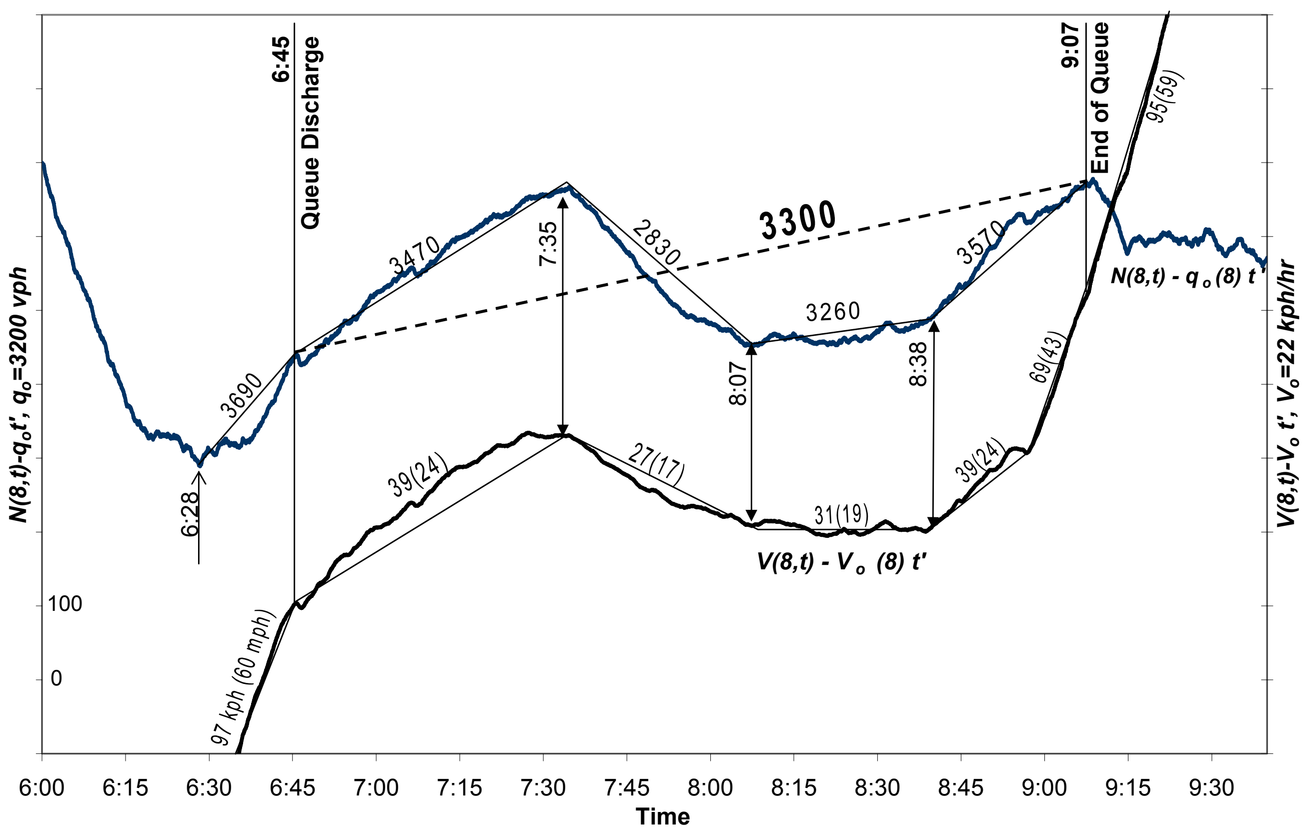


Figure 6: Oblique $N - \overline{N}_{10}$ at each detector on the M4

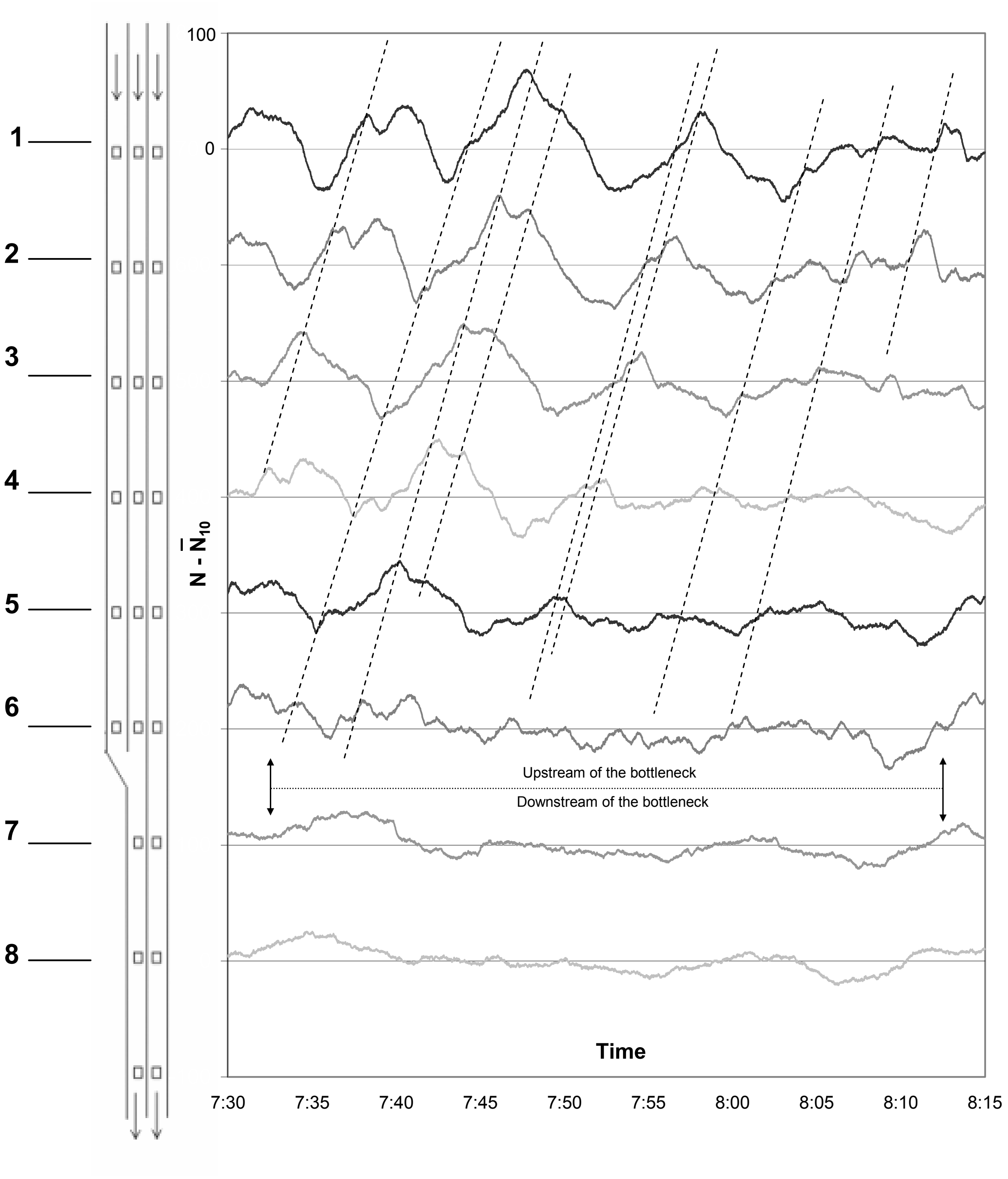


Figure 7: Transformed *N(x,t)* on I-494

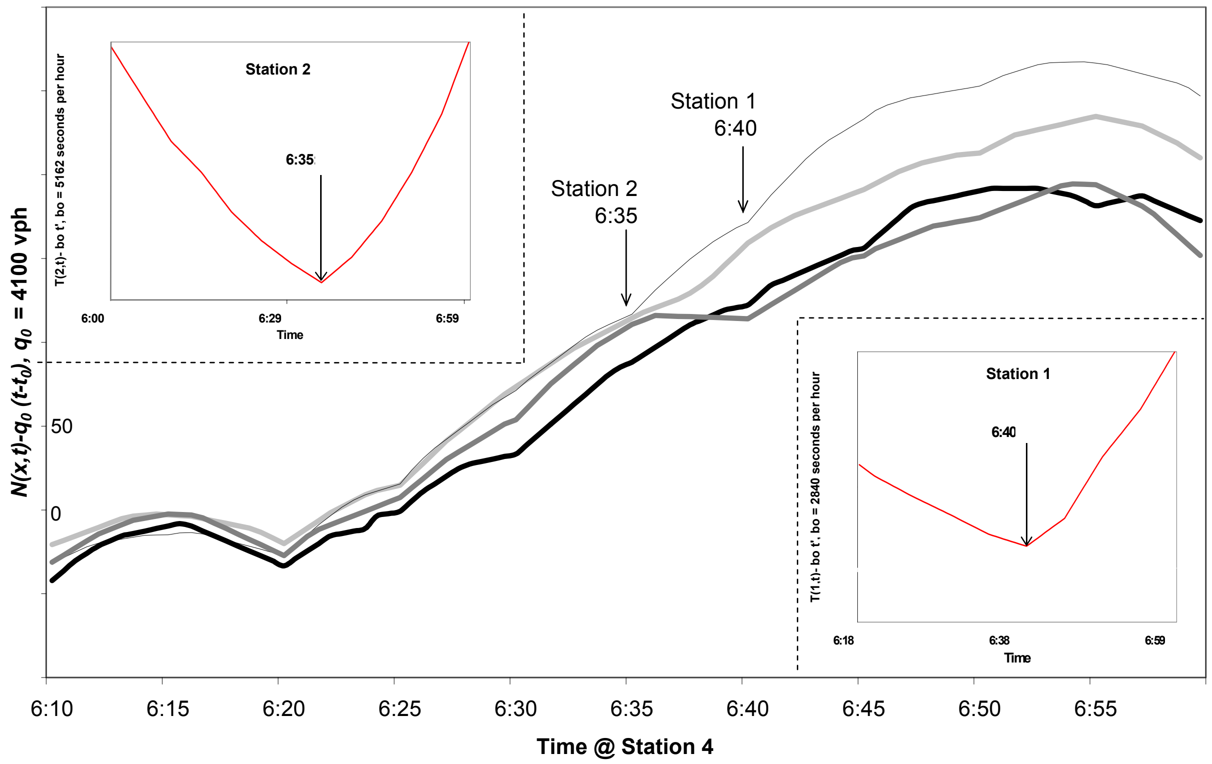


Figure 8: Upstream and downstream oblique *N(x,t)* on I-494

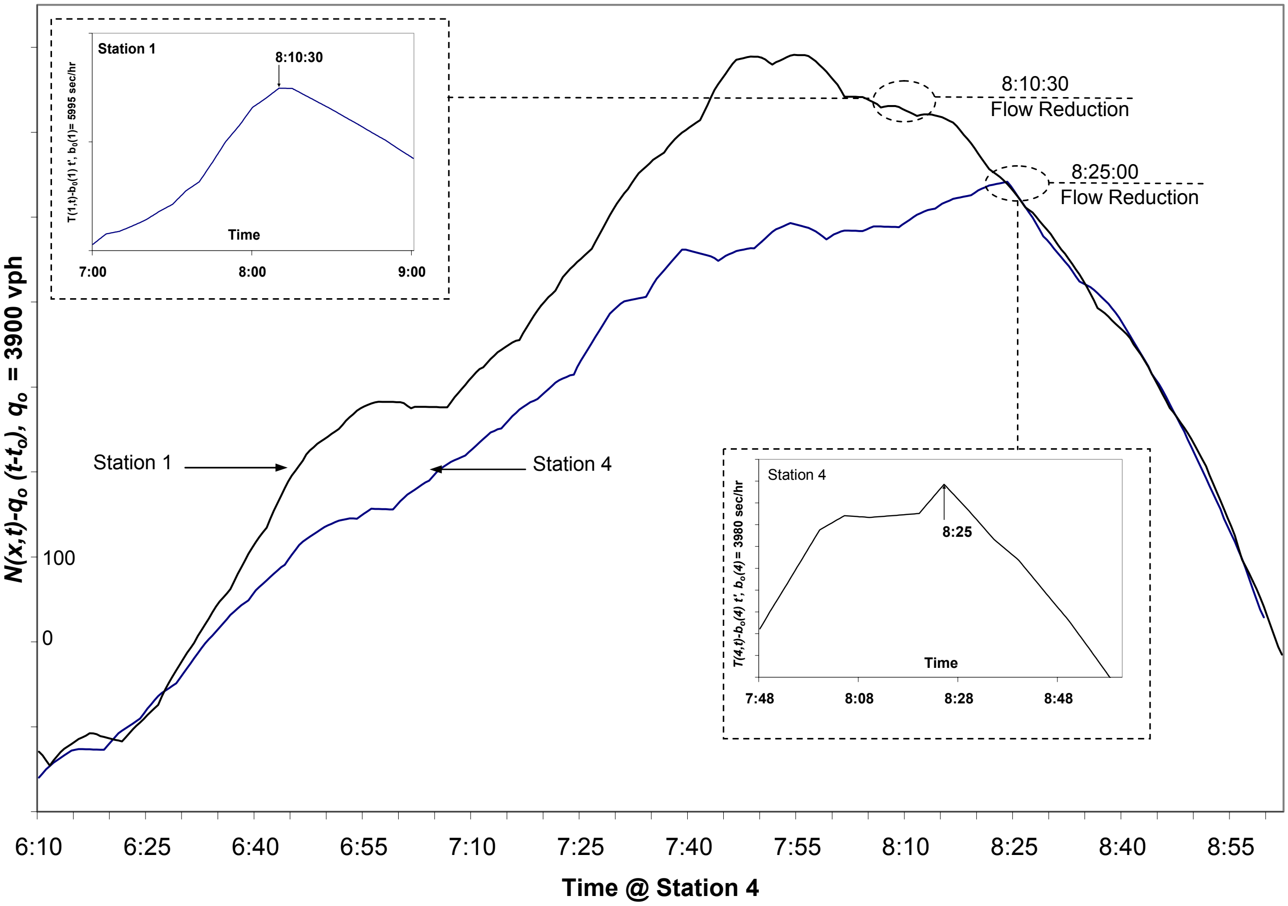


Figure 9: Oblique $N(x,t)$ and $V(x,t)$ at detector 4 on I-494

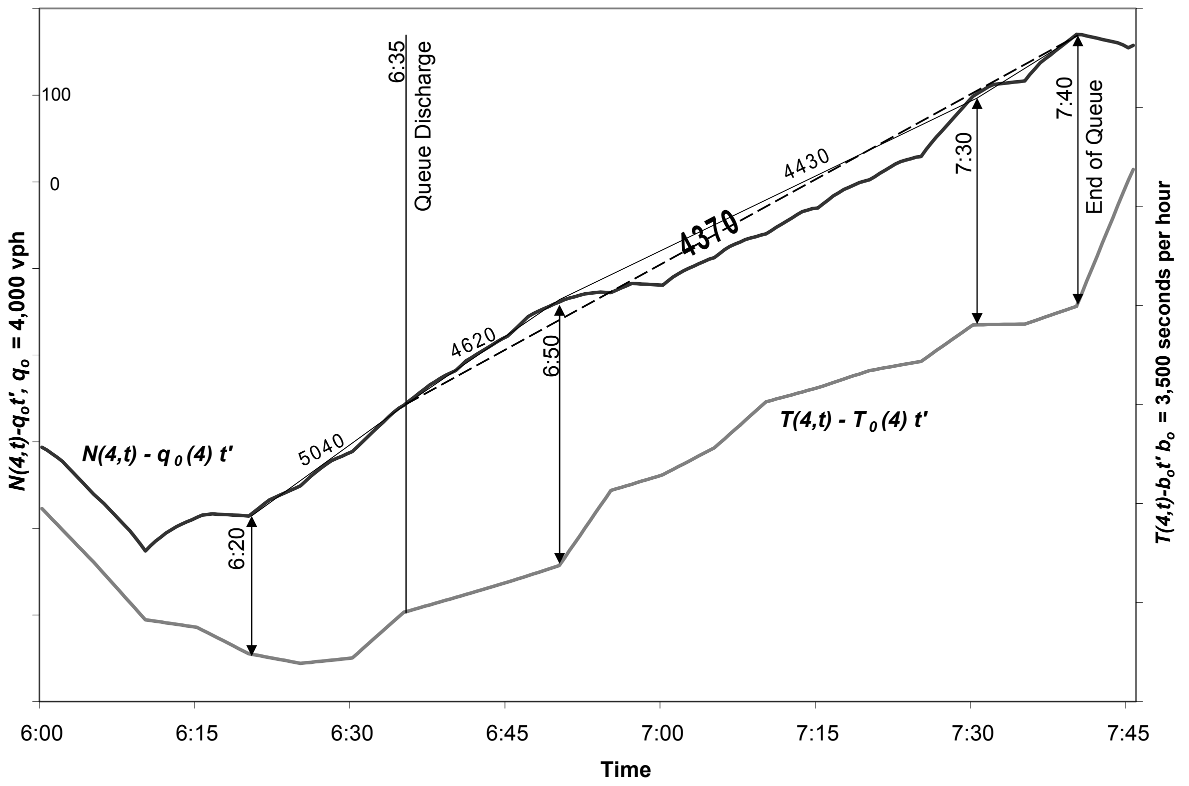


Figure 10: Oblique *V(x,t)* at detectors 2 and 9 on the M4