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CALIFORNIA PARTNERS FOR ADVANCED TRANSIT AND HIGHWAYS

STRUCTURE OF THE TRANSITION ZONE BEHIND FREEWAY QUEUES

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Abstract

Observations of freeway traffic flow are usually quite scattered about an underlying curve when plotted versus density or occupancy. Although increasing the sampling intervals can reduce the scatter, whenever an experiment encompasses a rush hour with transitions in and out of congestion, some outlying data stubbornly remain beneath the "equilibrium" curve. The existence of these non-equilibrium points is an ill-understood phenomenon that appears to contradict the simple kinematic wave (KW) model of traffic flow. This paper provides a tentative explanation of the phenomenon, based on experimental evidence.

The evidence was a queue that grew and receded over two detector stations, generating typical flow-density scatter-plots at both locations. The locations were far from other interacting traffic streams. The data revealed that a transition zone where vehicles decelerated gradually existed immediately behind the queue. The transition zone was quite wide (about 1 km at both locations), moved slowly (approximately with the "shock" velocity

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of KW theory) and spent many minutes over each detector station. Disequilibrium flow-density points arose only when the transition zone was over the detectors, suggesting that the transition zone explains their occurrence. The disequilibrium points drifted gradually from one branch of the curve to the other, as KW theory would have predicted if "shocks" had a characteristic width equal to the dimension of the transition zone. Nothing was found in the data to contradict this view. The paper also shows that if one neglects the shocks' physical dimension, the resulting errors are unimportant for practical purposes. Thus, it appears that KW theory can predict traffic behavior at the back of queues when the lanes at the back of the queue are equally attractive to all drivers.

1. INTRODUCTION

This paper is part of a more general study (Muñoz and Daganzo, 2000a) which focused on the generation of freeway congestion by off–ramp bottlenecks. It was found in this reference that a small, oversaturated off-ramp created a first-in-first-out (FIFO) blockage across all freeway lanes, and that the queue generated by this blockage exhibited certain regularities. This paper describes the structure and behavior of the back of such a queue at locations far from the off-ramp that generated it. Interesting details could be obtained because the queue in question grew and then receded over a pair of high-fidelity detector stations. A companion publication (Muñoz and Daganzo, 2000b), based on the same general study with data from detectors close to the off-ramp, focuses on the front of the queue and the bottleneck mechanism that generated it.

The present paper shows that at the back of a freeway queue there is a large transition zone where vehicles reduce their speed. The paper also describes the properties of such a zone. An understanding of transition zones and their effect on scatter-plots of flow vs. density is important because this knowledge sheds light on the adequacy of different traffic theories. The scatter and the direct transitions observed between the two parts of the flow-density diagram are often used as a criticism of the kinematic wave (KW) model of Lighthill and Whitham (1955) and Richards (1956). It turns out, however, that there is some consistency between theory and observation. Windover and Cassidy (2000) have found that small waves propagate regularly through traffic, as in the KW model, although the path of the waves is somewhat random due to driver differences. This causes scatter. Cassidy (1998) has also found excellent grouping of the data along a curve when one only plots the data that correspond to stationary periods. Data for non-stationary

periods tend to fall systematically under the stationary curve. Because this is not yet well understood, this paper takes a close look at these periods.

It is found that the scatter in the flow-density data observed at our site can be explained for the entire observation period by statistical effects (where the scatter declines with increased sampling size) and by the passage of the transition zone. The transition zone was similar in size at the two locations studied, both when the queue was growing and receding. The zone moved with the velocity predicted by KW theory. At least at this site, KW theory explained quite well everything that was observed, despite the scattered flow-density plots. The paper, thus, establishes that scattered flow-density plots and direct transitions between the two branches of the flow-density curves are not justification enough to dismiss the KW model.

This paper is organized as follows: Section 2 describes the site, the data set and the overall conditions that prevailed at the site during the study period. This includes the uncongested regime that prevailed before the onset of queuing and the FIFO queue that ensued. Section 3 examines transition between these two regimes as the queue grew over the observation stations, and Sec. 4 repeats the analysis for the time when the queue receded over the detectors. Sections 3 and 4 also discuss modeling implications. It is shown that if the back of a queue is modeled as a discontinuity, as in the kinematic wave model, the position of vehicles within the transition can be predicted to within just a few vehicular spacings. This suggests that simple models where changes in traffic conditions are approximated by discontinuities may explain phenomena known to be inconsistent with the KW model; e.g., the reverse lambda pattern often observed in flow-density scatter plots upstream of busy merges, and the lane-specific behavior of traffic close to congested off-ramps.

2. THE SITE AND THE DATA SET

Geometry: The study site is a section of northbound U.S. Interstate Freeway I-880, directly upstream of the connecting off-ramp with freeway I-238. A diagram is shown in Figure 1. Lanes are numbered from 1 to 5 starting with the median lane, which is a high occupancy vehicle (HOV) lane. Detector station labels are shown along the bottom of the figure. The labels used in this report express the approximate distance between each station and the I-238 off-ramp in multiples of 100 meters. (For example, the first station from the left which is 2705 meters away from station 0 is labeled "27".) The HOV lane ends between stations 22 and 17. The HOV designation is in force between 15:00 hrs and 19:00 hrs.

The site is interesting because, as noted in Lawson et al. (1999), a troublesome queue starts to backup from the I-238 off-ramp every weekday sometime between 14:30 and 15:00 hrs. The queue eventually grows and fills all the non-HOV lanes, disrupting through flow in a big way. The resulting main-line congestion lasts until 18:00 hrs and beyond.

*Traffic data***:** The *Freeway Service Patrol* data set (Skabardonis et al., 1994) was used for our study because of the high fidelity equipment that was used to collect data, and their fine level of detail. The data set includes 2-second counts and 2-minute occupancies at every station and lane (except for lane 2 of station 17, which had a malfunctioning detector) for a typical day in 1993. The following summarizes what was done to obtain relevant diagrams from the raw data.

Speeds: The flow-occupancy ratio for each detector was multiplied by a constant to convert it into space-mean speed. The constants were chosen so as to force a match

between: (a) the predicted space-mean speed for each detector during the uncongested interval from 14:00 hrs to 14:10 hrs, and (b) the average speed across all lanes observed for the same time-of-day interval during a recent field trip. The time interval (a) was not chosen to be any longer to ensure that it did not include the start of congestion. The speed (b) was found to be 108 km/hr, with only small variations across lanes. The results are not exact, but they are sufficiently accurate for our purposes.

Figure 2a shows the speed time-series obtained from the detector on lane 3 of station 12. Note how the measured speeds drop gradually but substantially after 14:00 hrs and then stabilize at a lower value. This event denotes the onset of congestion. It is estimated to occur at around 15:10 hrs at station 12. A similar pattern, with a gradual drop and subsequent stabilization, was observed at the remaining detectors. Part b of Fig. 2 shows the estimated times when congestion reached individual locations. After 15:38 hrs congestion had spread everywhere and all the speeds remained approximately constant for just over 40 minutes; the traffic stream between stations 27 and 5 was in a steady state until 16:20 hrs. Part c of the figure shows the average speeds observed at each detector during this congested steady state period, and their (small) rate of variation with time. [Since the study period is 2/3 hour long, the maximum deviation in the average speed from the value in the middle of the interval (in km/hr) is only 1/3 of the parenthetical numbers in the figure. The maximum deviation is small at all the locations. The worst case, excluding HOV lane (1), was for station 12, lane 3; i.e., for Fig. 2a, which shows no significant trend in the relevant period (15:40 – 16:20 hrs).]

The data in Fig. 2c show that the variation in speed across the three middle lanes (excluding the HOV lane and the exit lane) was significant downstream of station 12 and quite small for stations 22 (range = 5 km/hr) and 27 (range = 1 km/hr). The data also show

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that the HOV lane remains largely unaffected by the queue. The low speed variation at stations 22 and 27, and the fact that stabilization was quite synchronous across lanes at these locations (see part b of the figure), suggest that the back of a FIFO queue first reached station 22 and then station 27. Since the lane-specific effects of the off-ramp were small beyond station 22, this study focuses on the freeway section between these two stations. (No data were available further upstream.) In this way there is a good chance that the findings of this paper will hold for all FIFO queues, and not just those caused by congested off-ramps. Figures 3 and 4 contain the speed time-series for stations 22 and 27.

N-curves: These curves display cumulative vehicle count versus time at different locations. Counts are started at the different locations with the passage of a reference vehicle, so as to ensure that if vehicles are conserved (no entrances and exits) vertical separations between curves denote vehicle accumulations, and horizontal separations trip times. As usual, to construct these curves, clocks had to be synchronized, and detector counts had to be corrected for drift and bias. The procedures are detailed in appendix A.

Figure 5a summarizes the result. It displays the N-curves for lanes 1-5 (combined) at all the stations upstream of the exits for which complete data were available--stations 12, 22 and 27. Because the range of variation in the count variable is large, a small scale has to be used and not much detail can be discerned.

Detail can be restored if the same data are plotted on an oblique coordinate system in which the coordinate lines for vehicle number (horizontal lines of Fig. 5a) are instead slanted downward, as demonstrated in Fig. 5b. An oblique coordinate system is defined in the standard way, by two families of individually labeled, parallel lines which are either vertical or slanted in this paper. The coordinates of a point are simply the labels of the two lines passing through the point. In Fig. 5b, and elsewhere in this paper, coordinate labels

are shown in boldface for vertical (time) lines and as an ordinary font for slanted (number) lines. The slope of the slanted (number) lines in Fig. 5b is -6930 veh/hr. This means that a horizontal line on that diagram represents a flow of 6930 veh/hr. This flow will be called "the background flow" in agreement with the terminology of Cassidy and Windover (1996) who proposed a precursor of this method for displaying N-curves.

Note that in an oblique plot, positive slopes signify flows higher than the background flow and negative slopes lesser ones. Vehicle trip times can be obtained by noting the times when a (number) coordinate line intersects the various N-curves. They are proportional to the separation between the N-curves along the slanted lines. Vehicle accumulations are proportional to the vertical separation between curves and should be obtained by noting the change in slanted coordinates across the separation. Alternatively, accumulations can also be obtained by projecting the separation in question perpendicularly onto the vertical axis. The total time spent by all the vehicles between two detector stations continues to be given by the area between curves, measured as with orthogonal plots.

Note from Fig. 5b that prior to 14:45 hrs, the N-curves are ostensibly parallel and disturbances in count propagate with the slanted lines; i.e., traffic is in stationary free-flow. However, shortly thereafter the N-curves begin to separate sequentially from station to station as congestion begins to reach all the detectors (when the queue is growing). Eventually, the system reaches another period of stationary *but queued* flow, with parallel N-curves, from a little before 15:40 hrs to 16:20 hrs. This is in agreement with the speed data of Fig. 2c. A quantitative analysis of curves N_{22} and N_{27} reveals (Muñoz and Daganzo, 2000a and 2000b) that this queue exhibits a well-defined kinematic wave with velocity −19.4 km/hr.

Note as well that traffic flow increases considerably around 16:30 hrs although the queues continue, and that the queue dissipation process begins at the upstream detectors (around 17:30 hrs) because the demand subsides; see arrow "f" in Fig. 5b.

Flow-density scatter plots: Flow-density plots for station 27 (lanes 1-5, combined) are presented in Fig.6. Part a of the figure shows that despite the usual scatter, a line with a slope of −19.4 km/hr fits well through the 2-minute, dark triangles that correspond to our steady state queuing period. (The white triangles do not fall on the line; as explained in Muñoz and Daganzo, 2000a and 2000b, they correspond to a non-FIFO "multi-pipe" queuing period when there was little congestion on the two exit lanes because the percentage of exiting vehicles dropped.) Figure 6a also shows that the squares, which correspond to free-flow periods, group themselves along a ray with slope equal to the free-flow speed (about 100 km/hr). Figure 6b shows that the scatter is considerably reduced when the aggregation interval is increased to 8 minutes. Similar reductions in scatter were observed for individual lanes.

3. TRANSITION INTO THE CONGESTED REGIME: (14:45 – 15:40 hrs)

At stations 22 and 27 congestion set in around 15:30 PM, as highlighted for station 27 by points (a)-(e) of Fig. 5b. The regime transition reduced flow by about 1180 veh/hr and propagated from station 22 to 27 in about 8.5 min (+/- 3 min). An explanation of these assertions follows.

The drop in flow was estimated from the change in the average slope of curve N_{27} for the two 15 min time intervals immediately before and immediately after the regime transition was felt at station 27; these intervals are marked by end-points (b, c) and (d, e) in Fig. 5b. The estimated flows were 7550 veh/hr and 6370 veh/hr. Arrows designate the

corresponding two states in Fig. 6b. As expected, they fall near the middle of the last three black squares and the first three black triangles.

The brief drop in flow around points a and a' of Fig. 5b, from about 7300 veh/hr to 6650 veh/hr, and the ensuing recovery at points b and b' look like they may be part of the regime transition. However, the drop and recovery occurred first at station 27 and propagated to station 22 with the traffic speed. Furthermore, no significant changes in average speed were detected either. Therefore, the aforementioned changes in flow were caused by variations in the arrival pattern. (The drop coincided with the time when the HOV designation begins, at 15:00 hrs. It can perhaps be explained by the actions of single occupant vehicles, which may advance their arrivals to benefit from the HOV lane before it is reserved, and by the actions of HOV's, which may postpone their arrivals to make sure that the HOV lane is clear.)

The trip time of the regime transition was estimated to be about 8.5 min from the time series of average speeds on the three middle lanes--lanes 1 and 5 were not used because they are atypical: and HOV lane and an exit lane. The procedure was as follows. First, the time intervals when speeds declined on the three middle lanes were obtained; see Table 1. The centers of these intervals are the most reliable estimates for the time when the apex of the transition passed through each detector. The trip times were found to be similar and fairly synchronous for the three lanes, although not perfectly so by any means. (Imperfect synchronicity suggests that driving may not be very orderly when vehicles slow down in anticipation of the queue; perhaps they change lanes to choose a desirable queuing position.) In any case, the average of the trip times is 8.5 min. The error in this coarse qualitative procedure is estimated to be (+/- 3 min).

Table 1. Intervals of time when speed declined at stations 22 and 27.

	Lane 2	Lane 3	Lane 4
Station 22	(15:16, 15:30)	(15:12, 15:34)	(15:10, 15:18)
Station 27	(15:18, 15:38)	(15:22, 15:38)	(15:16, 15:38)

The trip time estimate indicates that the transition propagated at about -3.5 km/hr (with an error of about +/-1 km/hr). The slowness of the transition should not be surprising in view of the small difference (1180 veh/hr) between the upstream and downstream flows on both sides of the transition (15% difference). The value is consistent with the slope of the dotted line through the tips of the arrows in Fig. 6b.

Table 1 also reveals that the three middle lanes were in transition at station 27 for about 19 minutes. This information is consistent with the two "non-equilibrium" black diamonds in the flow density plot of Fig. 6b, which correspond to the time interval of the transition and confirm that the transition indeed took slightly over 16 min to pass over detector 27. Therefore, the transition zone must have a characteristic length of about 1.13 km, since it travels at 3.5 km/hr. We believe that the error in this estimate (depending on how one defines the transition zone) is about +/-0.3 km.

It is also seen from Fig. 6b that the (flow, density) black diamonds move in an orderly way from the left side of the diagram to the right side approximately along the dotted line. Interestingly, this is precisely what would occur if all vehicles decelerated slowly and in the same way after entering the transition zone; i.e. if their time-space trajectories were transitionally identical, as shown in Fig. 7. To see this, recall that if an observer

moving with velocity v_{obs} is passed by vehicles at a rate q_{rel} (veh/time) when traffic conditions are stationary or changing slowly, then the (q, k)-state satisfies the relation q_{rel} = q - kv_{obs}. In our case all observers moving with the frame of reference (e.g., following the slanted dotted lines of Fig. 7) must record the same passing rate, independent of their position within the transition zone. Thus, the (q, k)-states recorded at different times at a fixed location (e.g., at points P_1 and P_2 of the figure) must satisfy q_{rel} = q - kv_{obs} with q_{rel} and v_{obs} constant. Since this is the equation of a straight line, the assertion follows.

Obviously, Fig. 7 is not what happens in detail, since in reality there is lane changing and less smooth driving, but the data do indicate that the average vehicular speed does vary monotonically through the transition zone as suggested by the black diamonds of Fig. 6b (and Fig. 4). Thus, a simple characterization of the regime transition as a gradual deceleration "shock" may be useful as a macroscopic approximation.

To understand how drivers experience the shock, we should estimate the time a vehicle spends in the transition. This is the ratio of the transition length, 1.13 km, and the average speed of the vehicles in a frame of reference moving with the shock. If we assume that the vehicles decelerate uniformly as they travel through the transition (to the 25 km/hr speed of Fig. 2c or Fig. 6b--from an initial speed of 100 km/hr) then their average speed while crossing the transition must be (100+25)/2 = 62.5 km/hr. Since the velocity of the transition is –3.5 km/hr, the vehicular average speed in the frame of reference of the transition is 66 km/hr. Thus, the time to cross the 1.13 km zone is (1.13/66)(60) = 1.03 min. This implies that the average deceleration rate is quite leisurely, about 0.33 m/s^2 or 0.033 g's. Since these values describe the drivers' perspective, they could be disproved if they were to contradict one's driving experience. The values seem reasonable, though.

The estimated deceleration rate and shock dimensions can be used to obtain an

upper bound on the maximum error in vehicle count that would be committed by a correct but approximate theory of traffic flow that assumes that regime transitions occur instantaneously and vehicle trajectories are piecewise linear, as in Fig. 7. Consideration of the figure, together with our estimates, reveals that the maximum vehicle position error would be about 160 m and the maximum error in vehicle arrival time about 10 s. For 7000 vehicles/hr, the maximum error in count (obtained around the center of the shock) is therefore about 20 vehicles, or 5 vehicles/lane; i.e., the position of a vehicle on the road could be predicted to within 5 vehicular spacings.

We also estimate that the number of vehicles simultaneously present in the transition zone at any given time is about 116 (29 per lane). This can be estimated, using Little's formula of queuing theory, from the number of vehicles crossing the shock in the time it takes for their leader to cross it (1.03 min). Since the HOV lane carried a steady flow of 1000 veh/hr during the transition period, it can be seen from Figs. 5b and 6b that the flow in the non-HOV lanes should have been about 6550 veh/hr prior to the transition. And, since the upstream vehicle speed is 100 km/hr, the relative flow into the transition is about: [6550(103.5/100) = 6779] veh/hr.   Therefore the number of vehicles in the transition at any given time is the product of our two quantities: (6779/60)(1.03) = 116 veh, or about 29 vehicles per lane. Figure 8a is an approximate rendition of the observed vehicular behavior in and around the transition zone; each trajectory represents approximately 20 vehicles.

4. **TRANSITION INTO FREE-FLOW: (17:30 – 17:50 hrs)**

The regime transition on the through lanes was observed again starting at 17:30 hrs, when the queue on lanes 2 and 3 began to recede over detector 27. This event was marked by a drop in the flow of station 27 followed by a drop at detector 22 (see Fig. 5b), with concurrent increases in the recorded speeds for lanes 2 and 3 at both stations (see Figs. 3 and 4).

It should be noted that the queue on exit lanes 4 and 5 started to dissipate earlier and that this exit queue receded ahead of the main-line queue. (This can be seen from the marked jump in the time-series of speed for lane 5 of station 27 at around 16:40hrs--see vertical dotted line on the relevant part of Fig. 4). This state of affairs was attributed in Muñoz and Daganzo (2000b) to a drop in the percentage of arriving exiting vehicles from 29% to 24%, and to the reluctance of through-vehicles to use the exit lanes in sufficient numbers to equalize the speeds across lanes behind the exit queue. Thus, from 16:40 to 17:20, station 27 was in a "multi-pipe" congested regime with different speeds on different sets of lanes. This is the period of time corresponding to the white triangles of Fig. 6, which show (quite logically) that drivers space themselves more widely but still regularly under "multi-pipe" congested conditions.

Since the regime transition observed from 17:30 to 17:50 hrs was more or less confined to two lanes, it may be representative of what may occur on narrower freeways. It is found that in this case too, the back of the queue spans many hectometers.

Figures 5b, 6b and the time-series of speeds, all indicate that the shock took about 15 min to pass over station 27. The speed data further indicate that it passed nearly simultaneously over lanes 2 and 3. Similar effects were observed at station 22, albeit with a delay of about 10 minutes. This implies a shock-velocity of about +3 km/hr. The width

of the transition on lanes 2 and 3 is therefore estimated to be about ¾ km.   Figure 8b is a rendition of the transition zone and the vehicular trajectories crossing it during the recovery period into free-flow.

It is not clear from our data whether the 0.38-km difference in the length of the transition zones when the queue was growing and receding is due to statistical fluctuations or to something systematic. Perhaps, the transition zone is now shorter because, with only two lanes across, lane changes may play a lesser role. If this were true, it would suggest that transition zones should be somewhat smaller in narrow freeways. As in Sec. 3, however, they should still span tens of vehicle spacings and be several hundreds of meters long. The other quantitative features of shock structure derived in Sec.3 should also be approximately true for the recovery shock, and therefore for other freeways too, unless of course drivers disagree about the relative merits of the different lanes and generate multi-pipe queues.

Two final comments will close this paper. First note that an inconsistency seems to exist in our data, since the slope of the transition line from the last white triangle of Fig. 6b to the first white square is significantly greater than 3 km/hr. This is not inconsistent with our findings, however, because the slope of this line represents the shock velocity on lanes 2 and 3 *only if the flow of exiting vehicles on lanes (4 and 5) is constant.* Actually, a steeper line is the expected result if the flow of lanes 4 and 5 declines while the transition zone for lanes 2 and 3 passes over station 27. This is what happened. In retrospect, it should not have been surprising since a drop in the flow of exiting vehicles is what caused the differential behavior of the two queues to begin with.

The second closing comment concerns the queue dissipation transition at station 27. The crosses of Fig. 6 reveal that the transition went directly from the congested to the

uncongested part of the diagram without visiting the "capacity state". This often observed effect has sometimes been used as evidence against KW theory (since in that theory acceleration regime transitions should visit the capacity state). However, this criticism is invalid because a transition from the congested to the uncongested branch of the flow-density diagram with increasing speeds does not necessarily mean that one is observing an acceleration wave. As occurs in our case, when a *deceleration* transition moves forward over a detector, speeds *increase* during the transition. This can be clearly seen by examining the sequence of sample vehicle trajectories of Fig. 8b as they cross the detector line of station 27.

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APPENDIX: SYNCHRONIZATION AND BIAS CORRECTION FOR THE N-CURVES

Station clocks were synchronized in two steps. First, the time lag that maximizes the cross-correlation between the series of cumulative counts from 14:00 hrs to 14:10 hrs was determined without adjusting the clocks. [Simulations show that this is a more powerful estimator of average vehicle trip times than methods based on ordinary counts; see Muñoz and Daganzo, 2000a.] Clocks were then adjusted to force a match between the (adjusted) time lags and the average trip times known to have prevailed during this time; i.e., corresponding to a space-mean speed of 108 km/hr.

Since vehicles are not conserved within lanes but are conserved across stations, corrections for systematic bias and random drift were applied to the *station* counts of stations 22 and 27, using station 12 as the reference. To correct for systematic bias (differentially tuned detectors) the counts for detector stations 22 and 27 were multiplied by a station-specific factor so as to ensure that all three stations counted the same number of vehicles as station 12 during the study period (from 14:00 hrs to 20:00 hrs). The factors were very close to 1 in both cases. To correct for drift, the trip times observed from the curves were checked for consistency with the average speeds that were recorded at 1-hr intervals. Surprisingly, no corrections were necessary, except a very minor one for detector 22, which appeared to have drifted by about 30 vehicles by 18:00 hrs. (This extremely small error, less than 0.1%, is a tribute to the reliability of the special detection equipment that was installed at the site.)
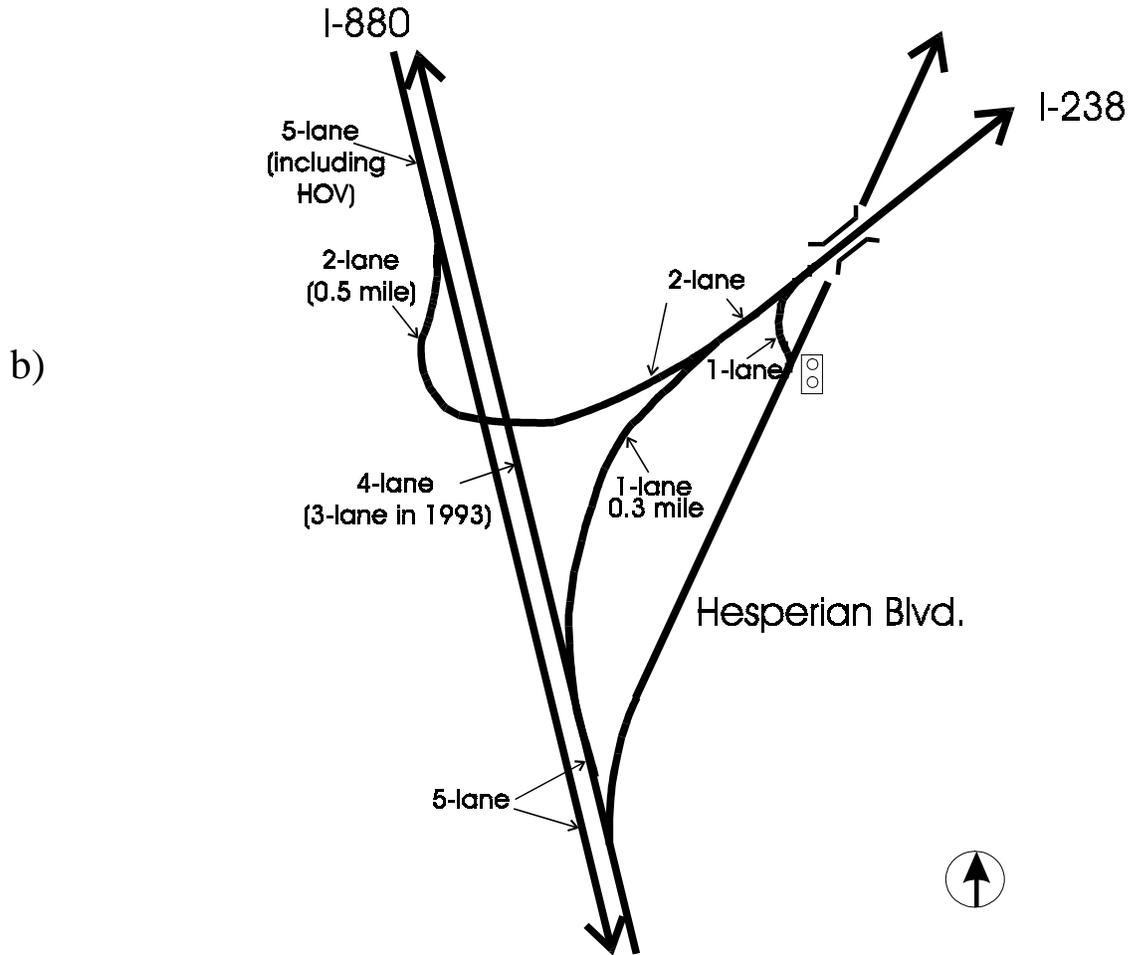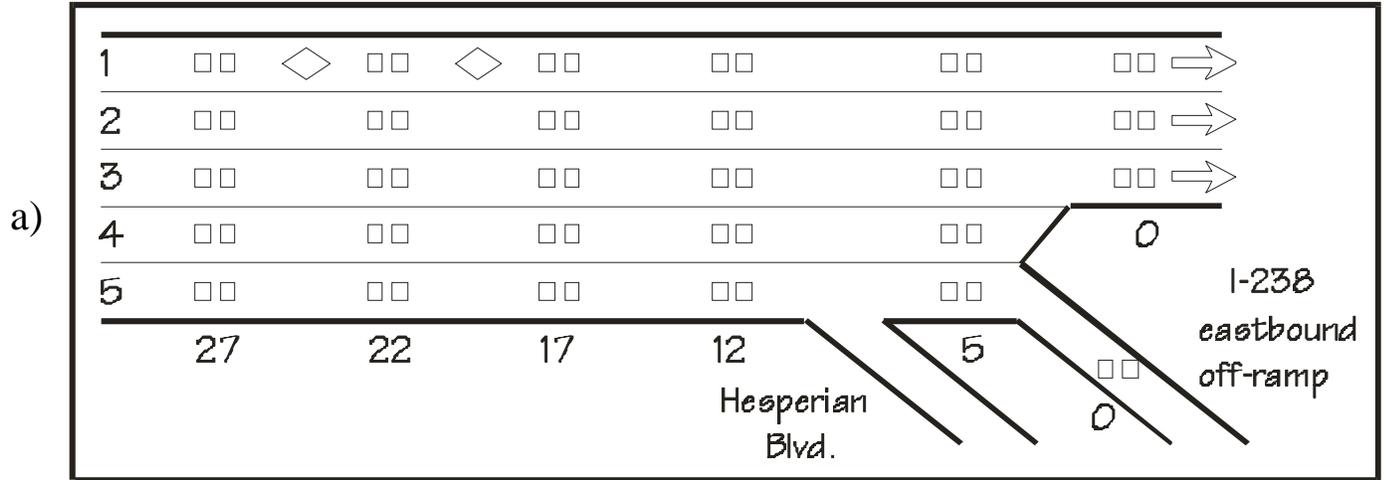
Figure 1. I-880, northbound: (a) site geometry (not to scale); (b) schematic map of the surrounding area.
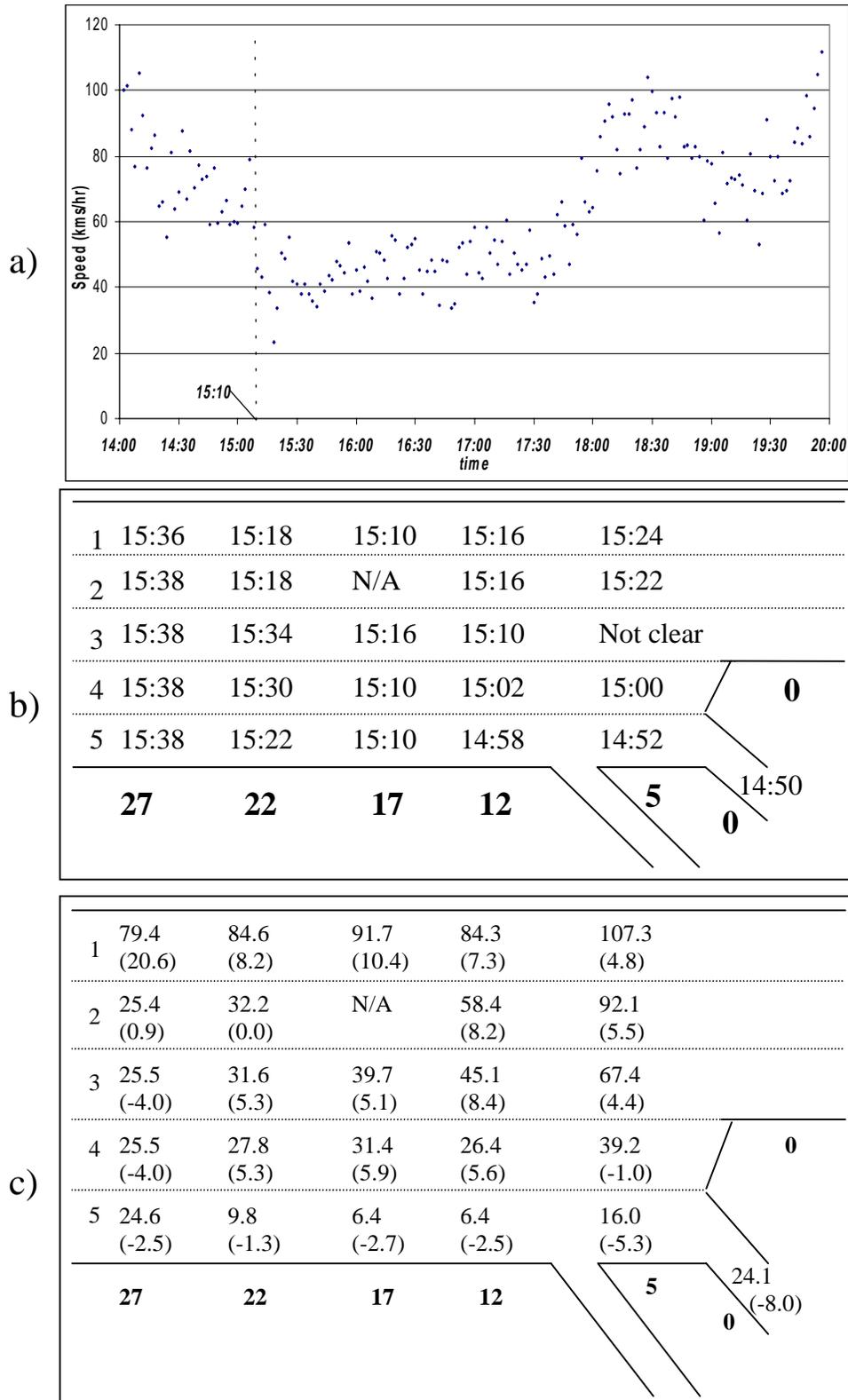
a)

b)

1	15:36	15:18	15:10	15:16	15:24
2	15:38	15:18	N/A	15:16	15:22
3	15:38	15:34	15:16	15:10	Not clear
4	15:38	15:30	15:10	15:02	15:00 · **0**
5	15:38	15:22	15:10	14:58	14:52
	27	**22**	**17**	**12**	**5** · 14:50 · **0**

c)

1	79.4 (20.6)	84.6 (8.2)	91.7 (10.4)	84.3 (7.3)	107.3 (4.8)
2	25.4 (0.9)	32.2 (0.0)	N/A	58.4 (8.2)	92.1 (5.5)
3	25.5 (-4.0)	31.6 (5.3)	39.7 (5.1)	45.1 (8.4)	67.4 (4.4)
4	25.5 (-4.0)	27.8 (5.3)	31.4 (5.9)	26.4 (5.6)	39.2 (-1.0) · **0**
5	24.6 (-2.5)	9.8 (-1.3)	6.4 (-2.7)	6.4 (-2.5)	16.0 (-5.3)
	27	**22**	**17**	**12**	**5** · 24.1 (-8.0) · **0**

Figure 2. Speed conditions on the site: (a) time series of the 2-minute average speeds recorded at station 12, lane 3; (b) times of day (hr: min) when the time-series of speeds at all locations first settled at a lower level; (c) average speed in km/hr (and its rate of change in km/hr^2) at different locations between 15:40 and 16:20 hrs.
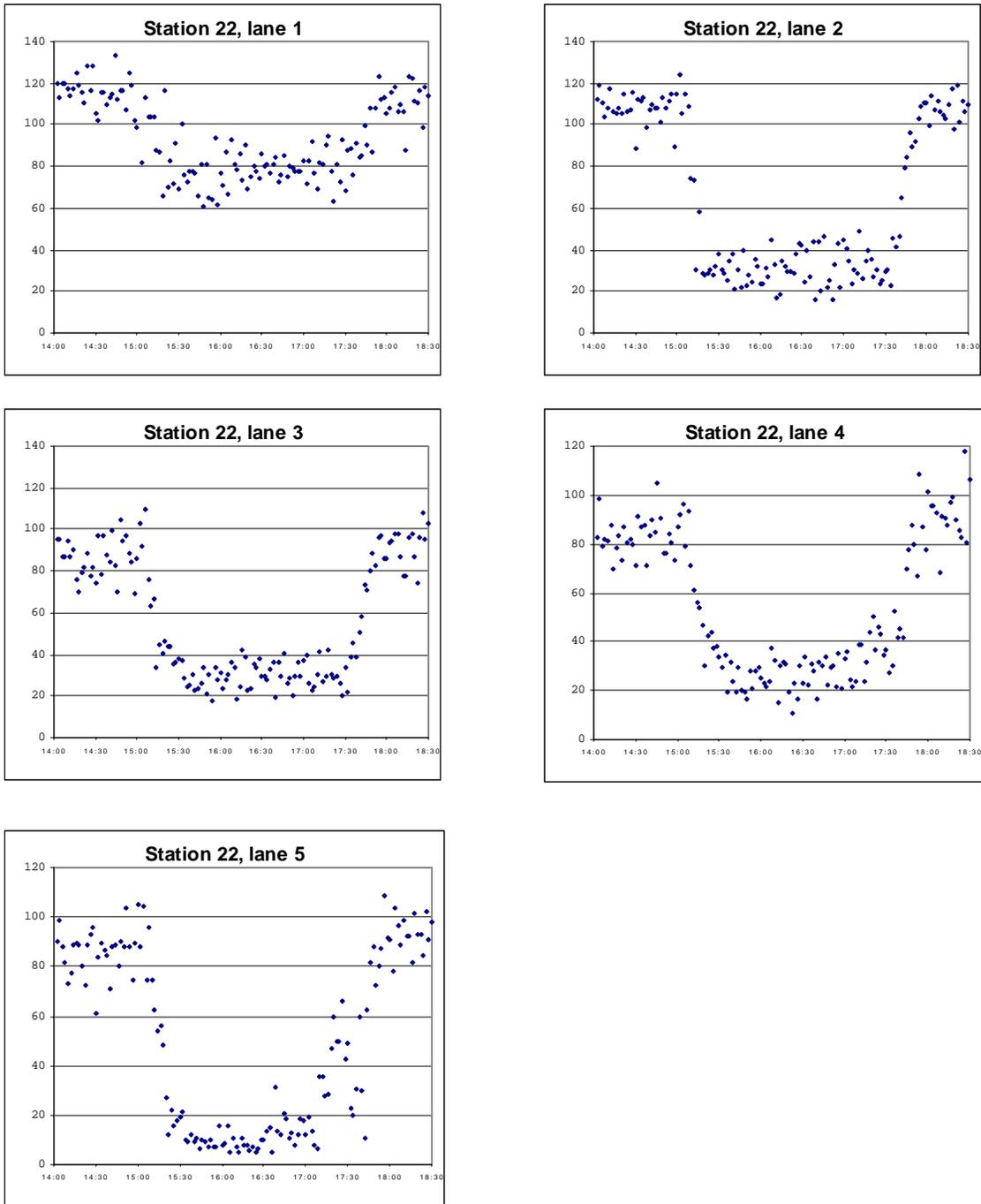
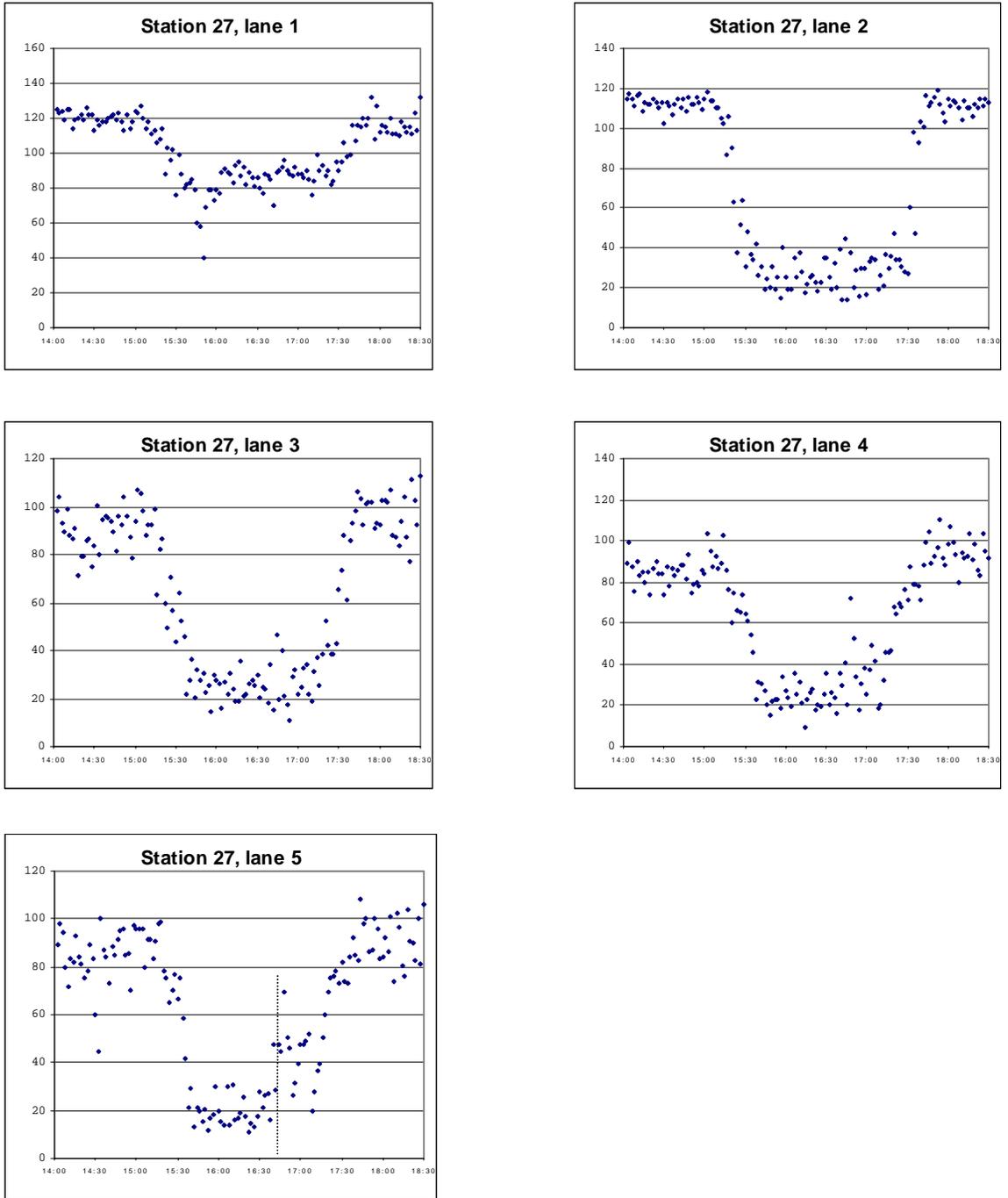Figure 3. Speed estimation at Station 22, all lanes (in km/hr).

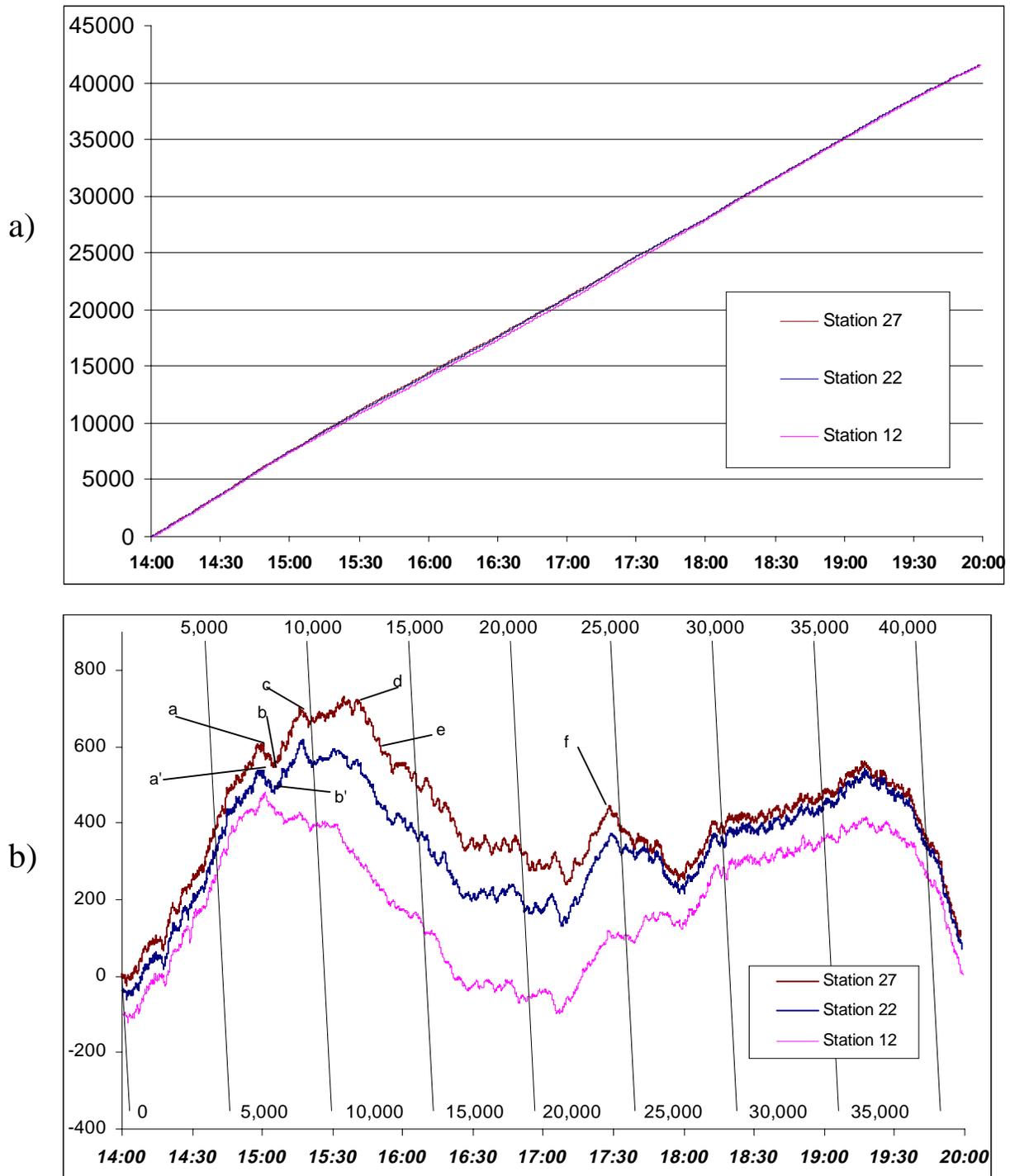Figure 4. Speed estimation at Station 27, all lanes (in km/hr).

Figure 5. N-curves for all lanes at stations 12, 22 and 27 for the whole study period (background flow = 6,930 vph): (a) orthogonal plot; (b) oblique plot.
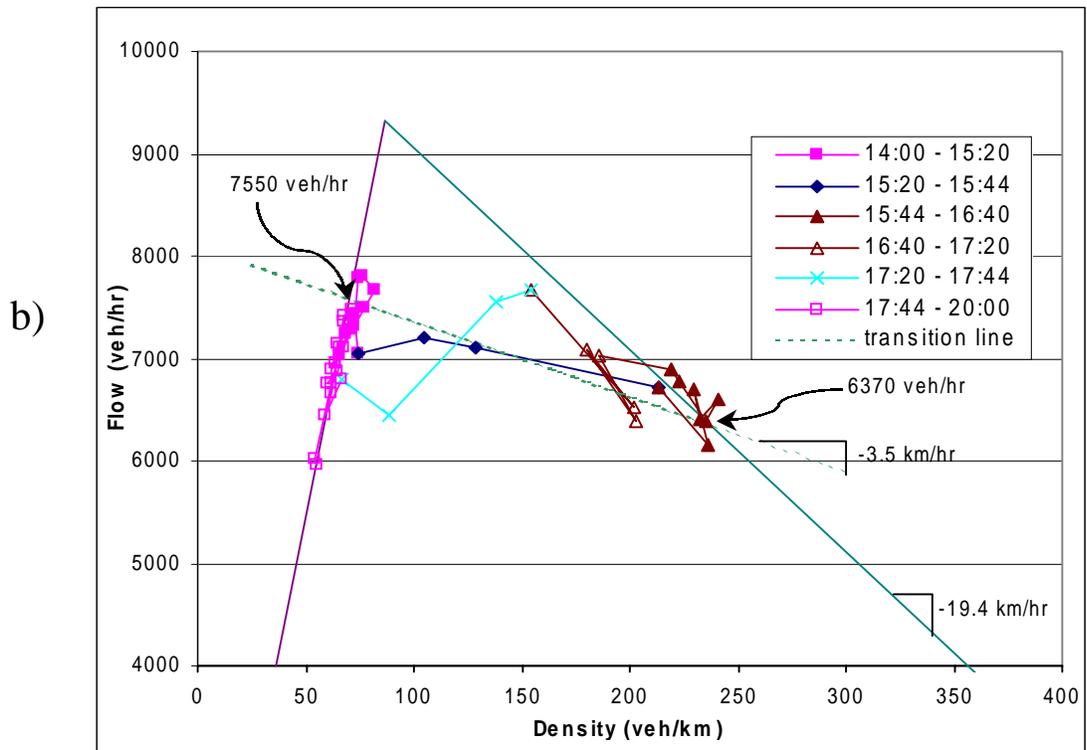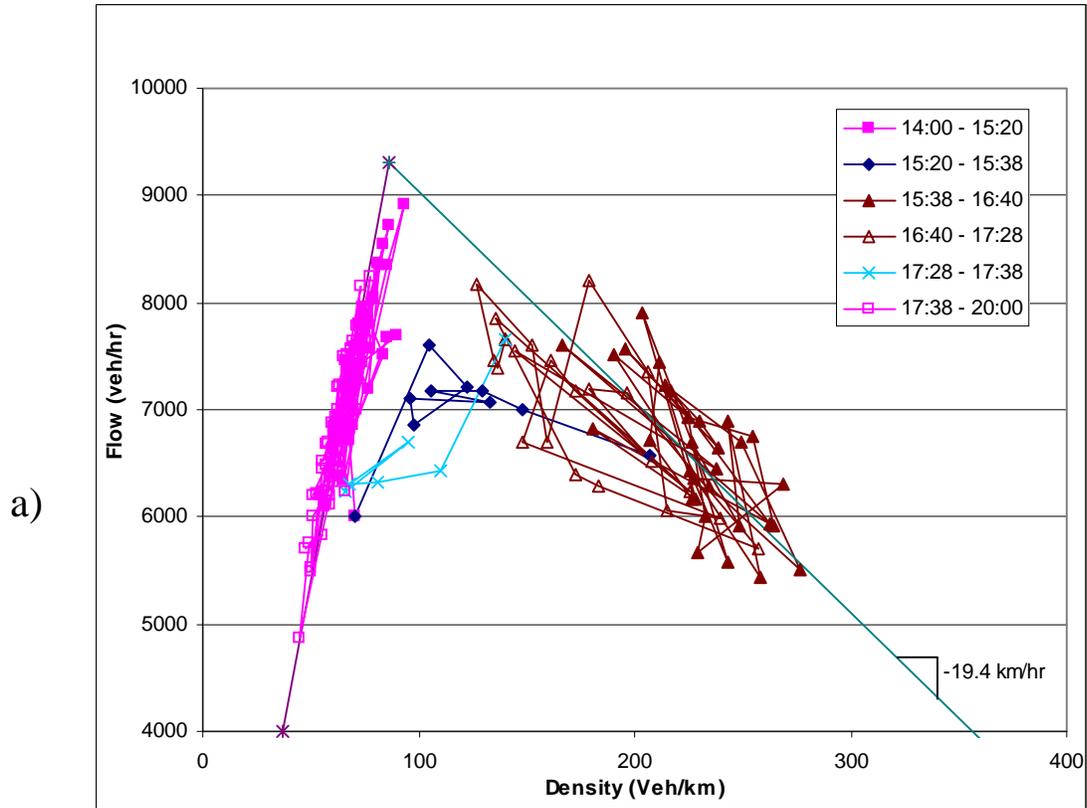
Figure 6. Scatter plots of flow v/s density at station 27 (with HOV lane) from 14:00 – 20:00 hrs: (a) 2-minute aggregation; (b) 8-min aggregation.
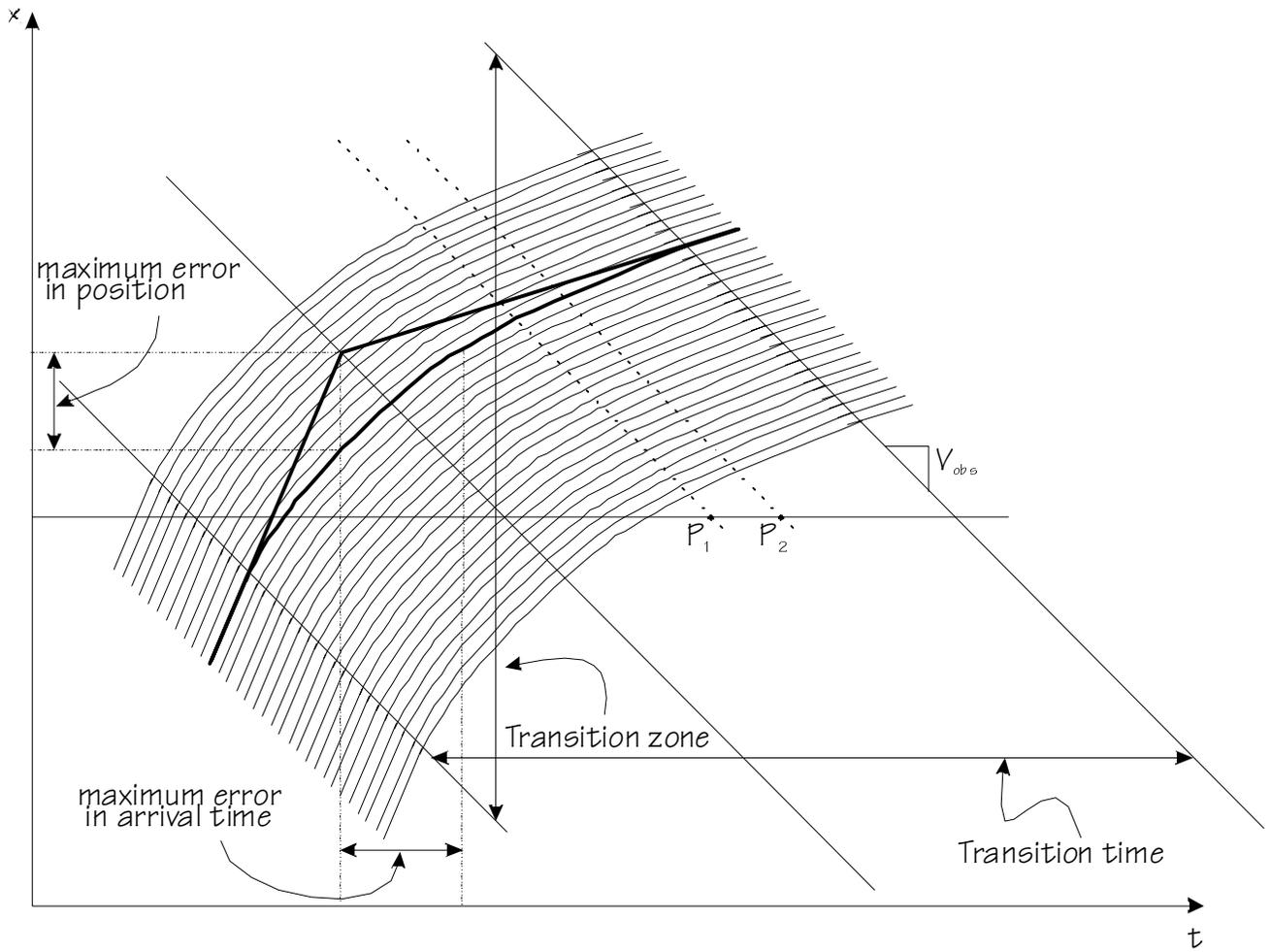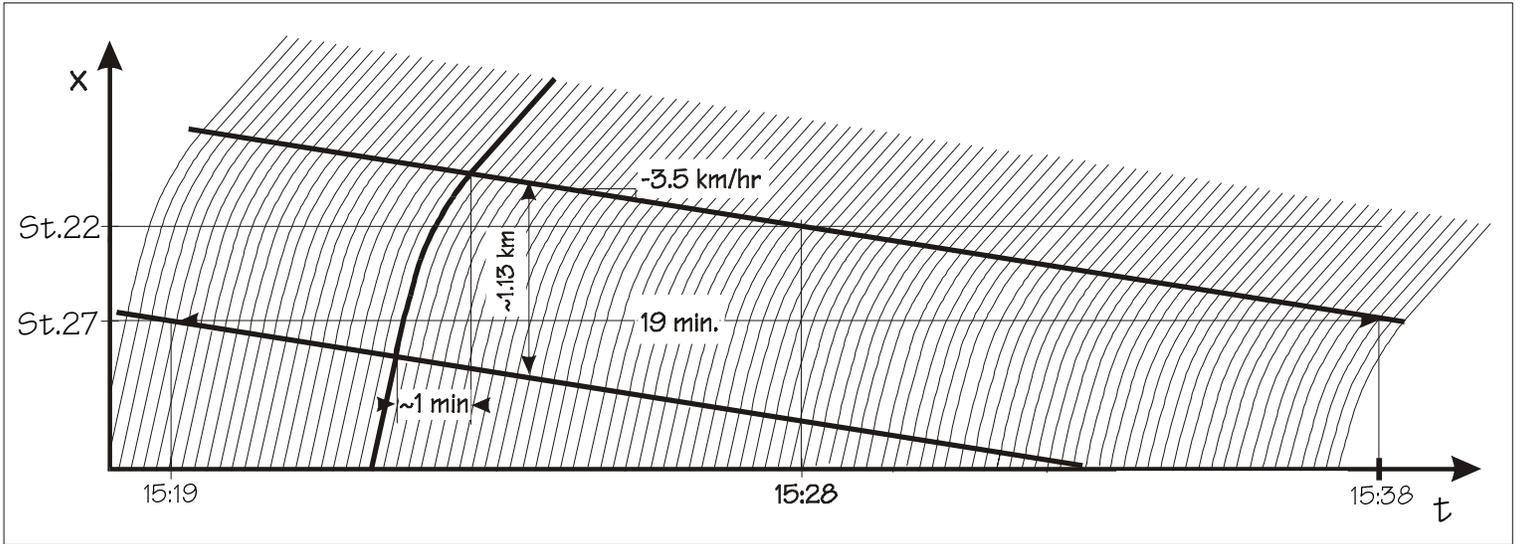
Fig. 7 Time-space diagram where vehicles cross a backward-moving deceleration zone of fixed width while following identical trajectories. A piecewise linear approximation is added.
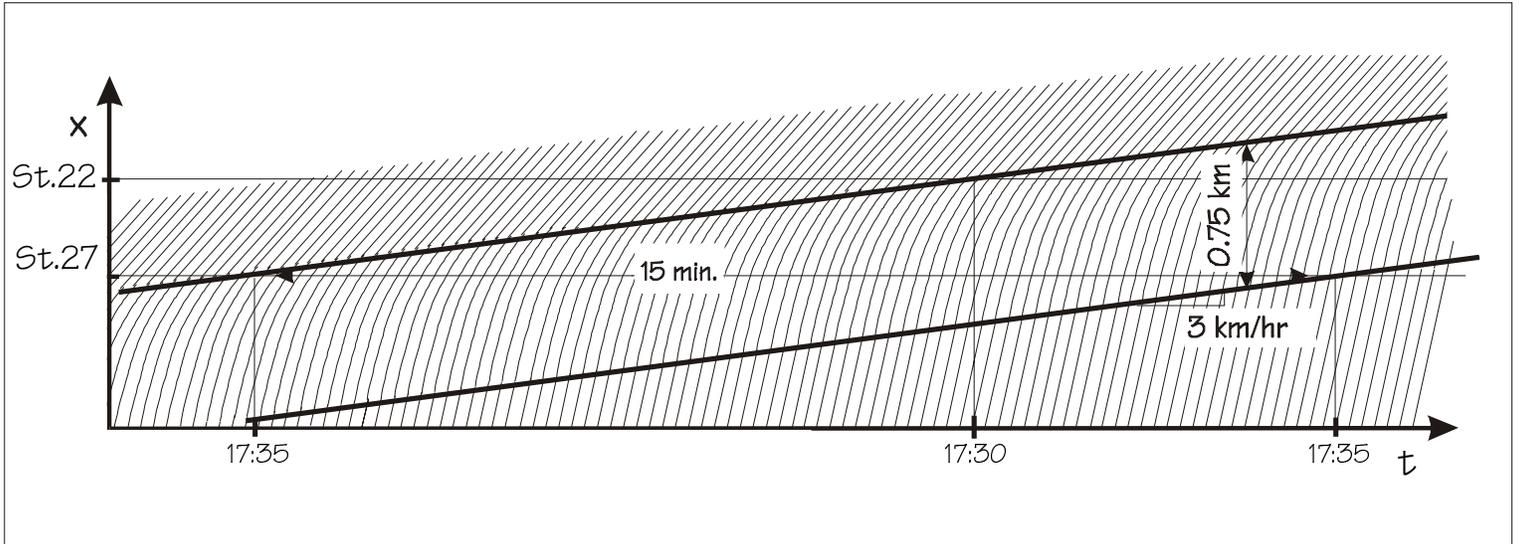
(a)

(b)

Fig. 8 Scale rendition of the transition zone in time-space as it crossed detector stations 22 and 27: (a) when the queue was growing; (b) when the queue was receding.