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Fingerprinting traffic from static freeway sensors

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Ask most commuters and they will agree that congestion has reached an intolerable level. To reduce this congestion, engineers need detailed traffic information. Highly detailed information is also prized by traffic scientists, as a prerequisite to improve current traffic theories. Ideally, engineers and scientists would like to obtain from field data the position of each vehicle on a particular facility at every moment in time. The technology to record space-time vehicle trajectories on a massive scale is in its infancy; therefore, analysts must work with much less data. Many freeways are equipped with primitive sensors that can record only anonymous vehicle passages at specific locations with a time series of 0's and 1's. Typically, these detectors are installed on all lanes at sites, called stations, which are spaced about 1 km apart. This article will show that, despite this anonymity and the spatial discreteness of the measurements, a treasure trove of detailed information can be recovered from 0-1 detector data, if one analyzes the data with the right tools. Field data from a 5-lane freeway in Oakland, California (se Figure 1) is used to demonstrate the ideas.

Figure 2a shows the time series of vehicle counts from the left lane at station 0, discretized in 2-second intervals, for a 6-hour period, covering the afternoon rush. Clearly, very little information can be obtained from this graph because the data include the effects of lane changes, driver differences, etc. If one adds all the time-series of a station, as if a single detector were recording vehicle passages over all lanes (see Figure 2b), lane-changing noise is eliminated. Although some patterns emerge, it is still impossible to detect the behavior of individual vehicles. The difficulty remains if the data are aggregated over longer time periods, as in Figure 2c. Fortunately, more patterns emerge if the data are compared across stations as is shown below.

Synchronized cumulative counts (known as N-curves) are the most informative way for engineers and scientists to visualize and compare data from multiple stations. N-curve diagrams display the cumulative number of vehicles that have passed over a series of stations over time, using one curve per station. The counts are initialized at each station with the passage of a reference vehicle. Figure 3a is an example. By synchronizing the counts across stations new information is obtained. Vehicle trip times are given by the horizontal separation between curves, and vehicular accumulation by the vertical separation. Other traffic features, such as the average flow at a station in any interval of time, given by the slope of the N-curve, can also be visualized easily.

However, when faced with real traffic information encompassing many vehicles for long periods of time, subtle but important features, such as slight changes in accumulation, are

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obscured by the large scale required to display the data. This is illustrated by Figure 4a where data for the three stations of our freeway have been displayed. For our purposes, this diagram is useless because the total number of vehicles passing through each station in the 6-hour period is two orders of magnitude larger than the typical vehicle accumulation between stations.

This scaling problem can be overcome by plotting the N-curves on an oblique coordinate system, defined by two non-orthogonal families of individually labeled parallel lines. In our examples, these lines will be either vertical or slanted, as shown in Figure 3b, which displays the two idealized curves of Figure 3a. In Figure 3b and elsewhere in this article coordinate labels are shown in boldface for vertical (time) lines and unbolded for slanted (number) lines. The reader is invited to verify that the pairs of N-curves in Figures 3a and 3b are graphs of the same data. Note that vehicle accumulation is still given by vertical separation between curves, and that trip times are now given by curve separations in the direction parallel to the oblique axis. Note as well that the separation between curves can now be amplified by reducing the vertical scale.

Figure 4b displays the curves of Figure 4a on an (amplified) oblique system. Notice the appearance of previously hidden information. For example, one can now clearly see (and quantify) a drop in flow at all stations between 15:00 and 15:30 hrs. The drop was first felt at downstream station (0), and later at the upstream stations. It is also easy to see how vehicle accumulation and trip times increased immediately after that flow reduction. The diagram shows that a queue grew from station 0 to station 15 and beyond, and that this queue began to dissipate around 17:30 hrs starting at station 15.

As occurs with many fluids, information in traffic moves as waves. For instance, a freeway accident that causes a bottleneck will be felt later further upstream; this information travels as a wave against the traffic stream. Upstream-moving waves such as that observed at the test facility between 15:00 and 15:30 hrs, reflect the presence of congested conditions. Uncongested conditions, on the other hand, are characterized by forward-moving waves that propagate with the traffic speed. They can be clearly identified in Figure 5, which displays data at stations 0 and 15, from 14:15 to 14:45 hrs. It can be clearly seen that (except for a discrepancy around 14:28 hrs) traffic conditions at station 15 defined conditions at 1.5 kms downstream with less than a minute of delay very accurately, and that trip times remained quite constant despite the fluctuations in count.

The discrepancy at 14:28 hrs presents a new opportunity to show the potential of oblique plots. At first sight, it appears that station 0 stopped recording vehicles for a short period. To look into this further let us re-scale the oblique plot to achieve a desired magnification level (as with a microscope) and also add the curve for the intermediate station; see Figure 6a. It now becomes apparent that the detectors were not malfunctioning because the interruption in flow is also present at station 10. Because the interruption grew while moving downstream, other explanations such as a traffic accident or a sudden drop and recovery in travel demand must also be ruled out. Such events would have left different signatures. The only plausible explanation for the observation is that the bottom of the

"V" was caused by an obstruction moving forward with traffic. Inspection of the figure shows that said obstruction traveled slightly below the speed limit (88 km/hr). Note as well that an observer at station 0 would have observed normal flow conditions, followed by a 30-second period of extremely low flow and then two minutes of flow at nearly the maximum rate on a 5-lane freeway. The most likely explanation for these patterns (high speed for the moving obstruction with negligible downstream flows) is that a police car traveling close to the speed limit entered the road somewhere upstream of station 15; when the vehicle count was N≈3400. A police car may have induced drivers to pass hesitantly, even on the wide freeway, thus causing a moving queue.

By looking at Figure 6a in more detail one can identify the flow downstream and upstream of the slow vehicle, as well as the speed of the transition zone between the upstream free-flowing traffic and the back of the moving queue. Furthermore, by comparing the flow in the queue after the slow vehicle passed through stations 10 and 0 (regions D and C of Figure 6a), the reader may be able to see that the flow was significantly higher at station 10 that at station 0. This suggests that the first hundred drivers packed themselves closely upon joining the queue and later relaxed. The data also show that drivers who arrived later did not act in this way, since drivers labeled with higher numbers (up to N= 3750) never experienced the high flows. This change in behavior maybe explained by proximity to the bottleneck when vehicles joined the queue. We speculate that the first drivers may have adopted very short spacings in the hope of getting through the bottleneck quickly, and that their motivation disappeared upon realizing that the queue would last for a while. Drivers who arrived later may not have seen the bottleneck and thus had no reason to follow aggressively.

All this information has been condensed in Figure 6b, which also includes the "best-fit" space-time trajectories of the moving bottleneck and the affected vehicles. Labels A-D link traffic patterns found in Figure 6a with their respective space-time regions in Figure 6b. Note that the oblique plot technique reveals from noisy 0-1 data the precise time and place of the police car's appearance (point E in the figure). Interestingly, and quite reassuringly, it turns out that there is an on-ramp without detectors at the point of appearance.

This illustration shows how much information can be obtained from seemingly poor data with a simple visualization tool. The detection of our "moving bottleneck", and the quantification of its interesting regularities (including changes in driver behavior) was made possible only by the oblique plot technique. As a result of this new technique, scientists have gained new insights into the following: wave propagation in traffic, bottlenecks caused by freeway merges, bottlenecks caused by off-ramps, and transition zones at the back of freeway queues. Perhaps, this technique can also be useful in other fields where the unidimensional movement of objects is of interest.

Further Readings in oblique plots and related techniques:

Cassidy, M.J. and Bertini, R.L. "Observations at a Freeway Bottleneck." Proceedings of the Fourteenth International Symposium on Transportation and Traffic Theory (ISTTT), Jerusalem, Israel, Elsevier, July 1999.

Cassidy, M. and Windover, J. (1995), "Methodology for assessing dynamics of freeway traffic flow", Trans. Res. Rec. **1484**, 73-79.

Daganzo, C. F. (1997) *Fundamentals of Transportation and Traffic Operations,* Pergamon-Elsevier, Oxford, U.K.

Muñoz, J.C. and Daganzo, C.F. (2000) "Experimental characterization of multi-lane freeway traffic upstream of an off-ramp bottleneck" PATH Working Paper 2000-13, Institute of Transportation Studies, Univ. of California, Berkeley, CA.
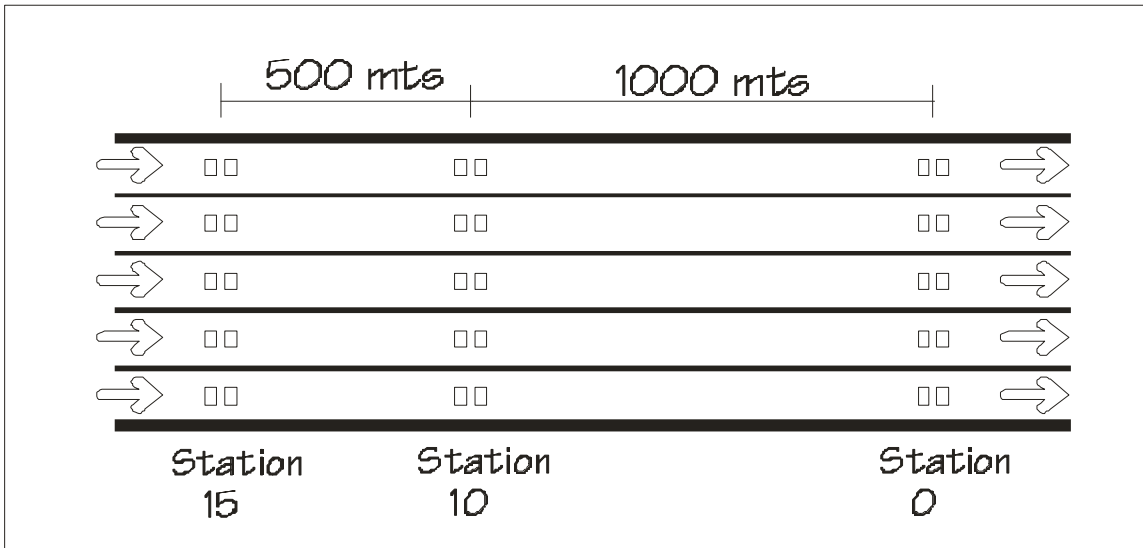
Figure 1: Site description and stations locations.
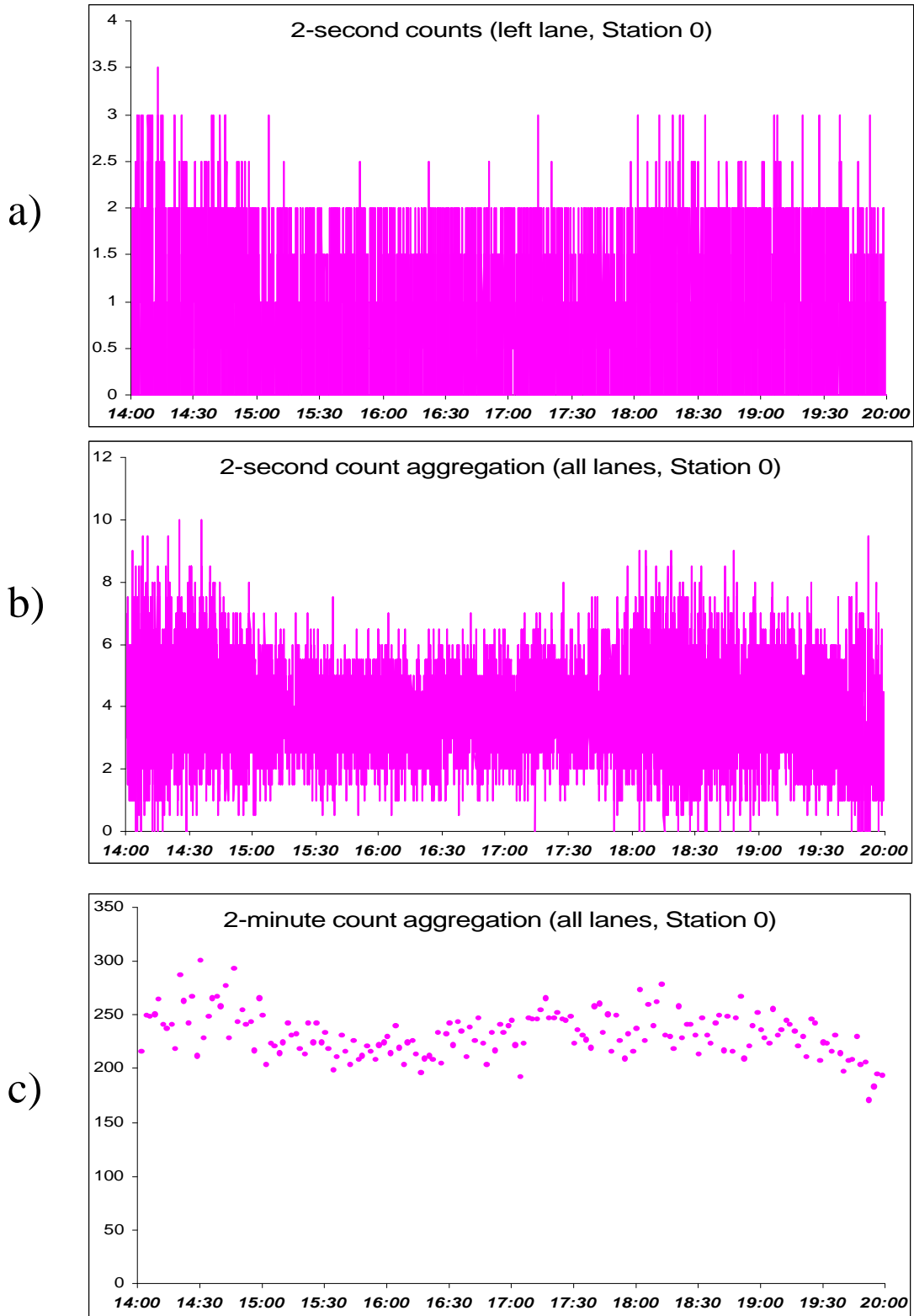
Figure 2: Counts at station 0 vs. time of day (a) 2-second counts at a single detector; (b) 2-second counts at all detectors; (c) 2-minute counts at all detectors.
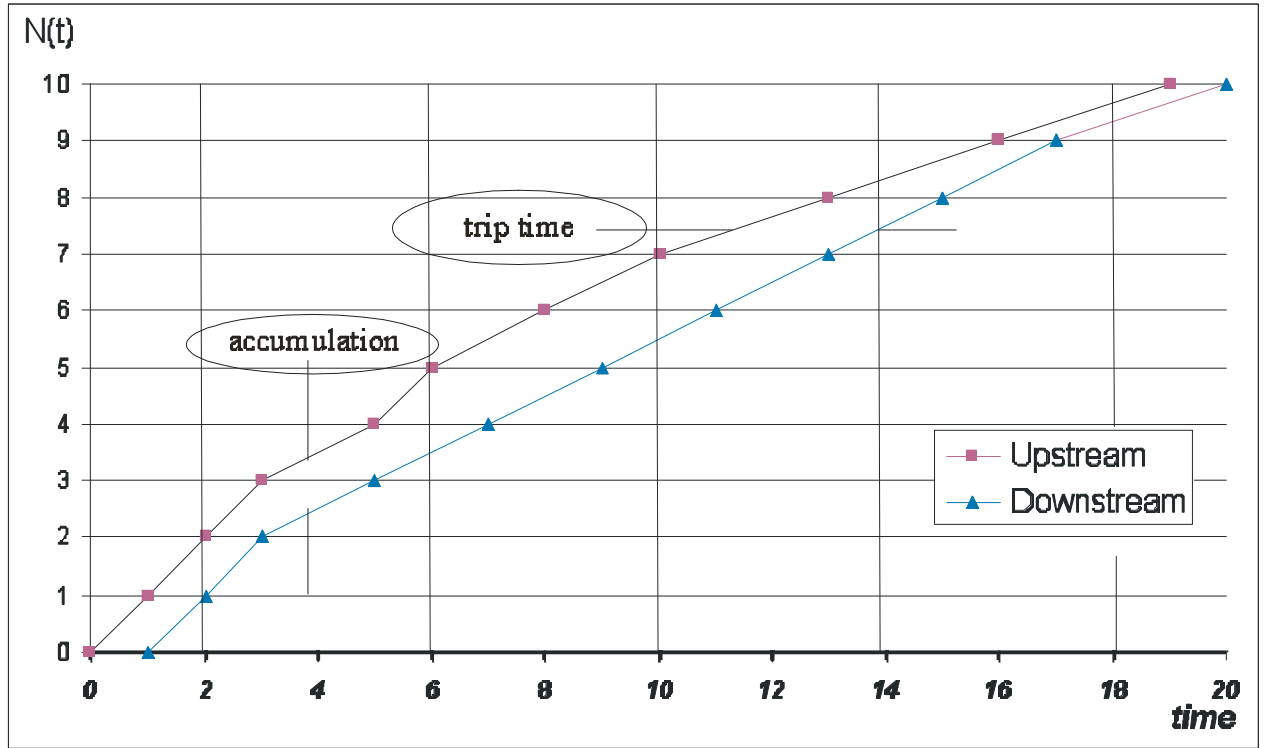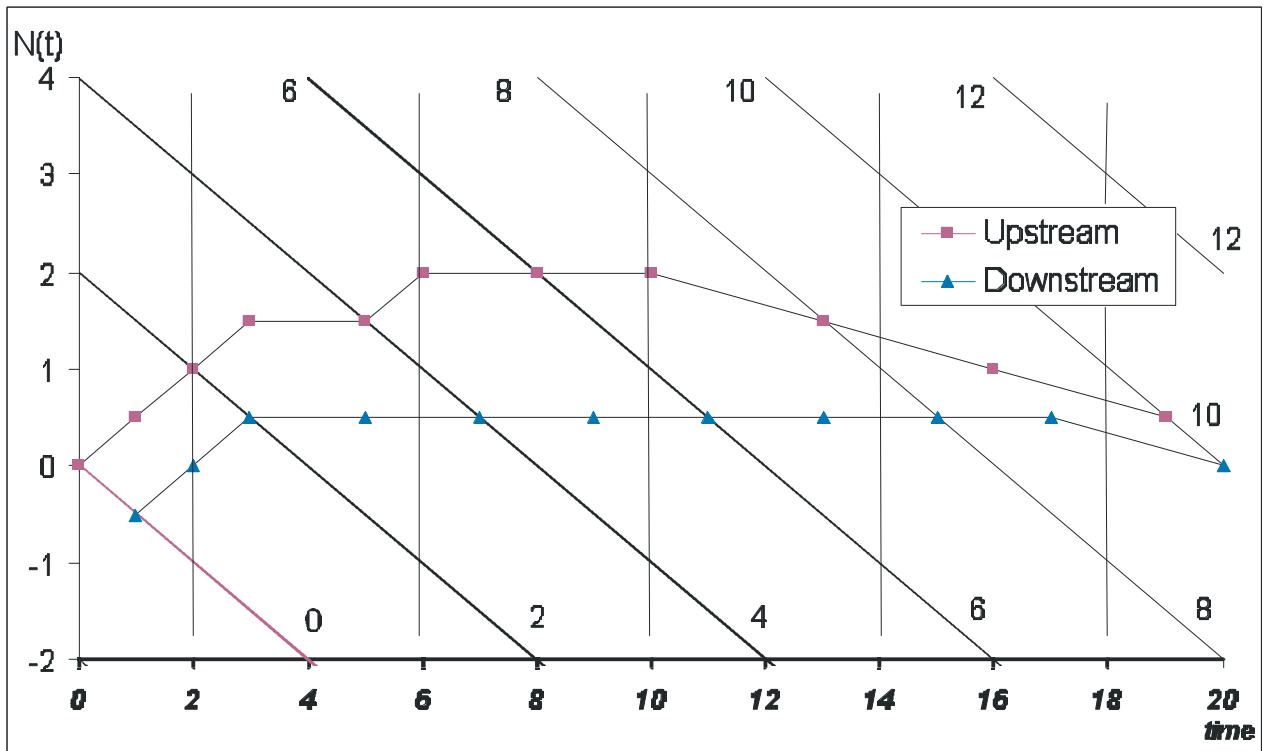
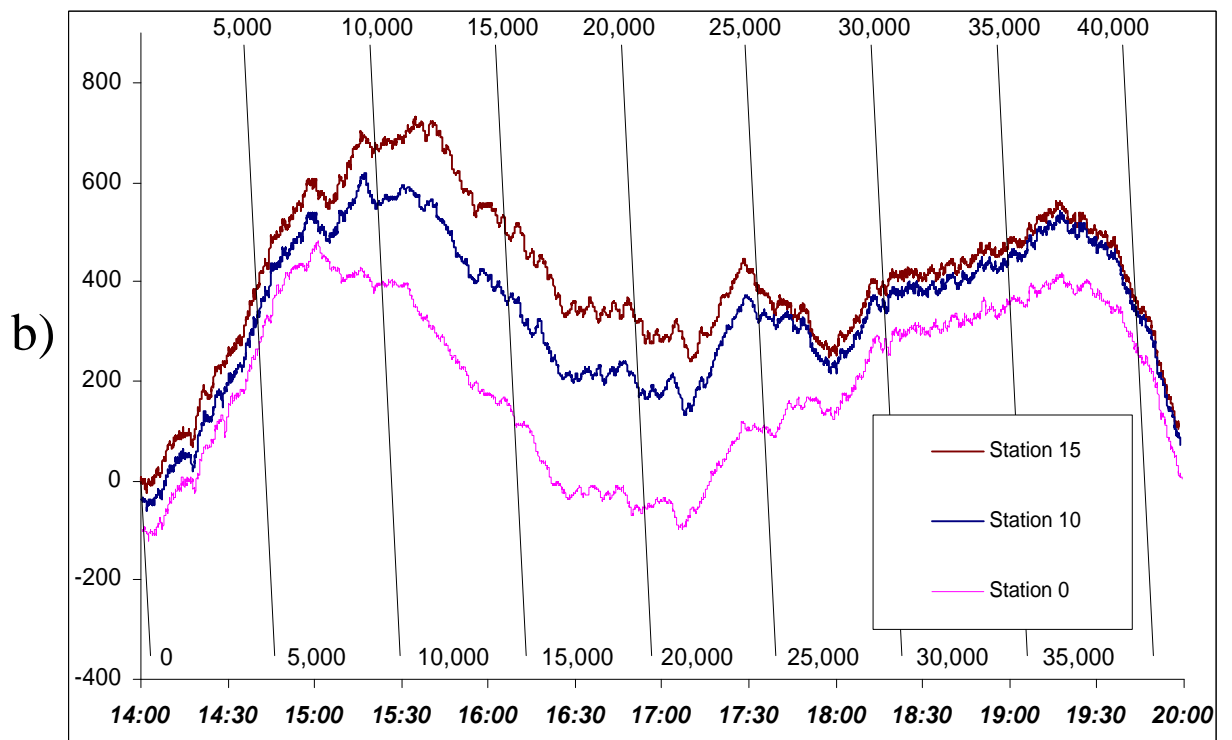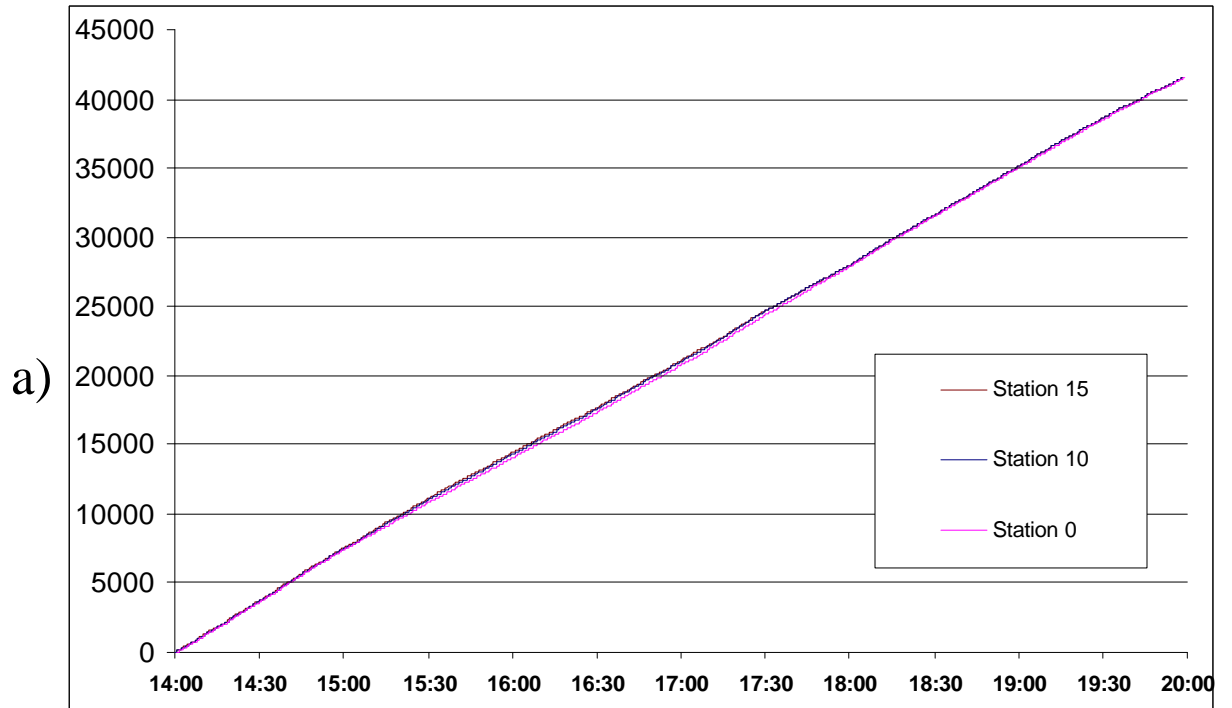Figure 3. Hypothetical N-curves at two locations: (a) orthogonal coordinate system; (b) oblique system

Figure 4. N-curves for all lanes at stations 0, 10 and 15 between 14:00 and 20:00 hrs:
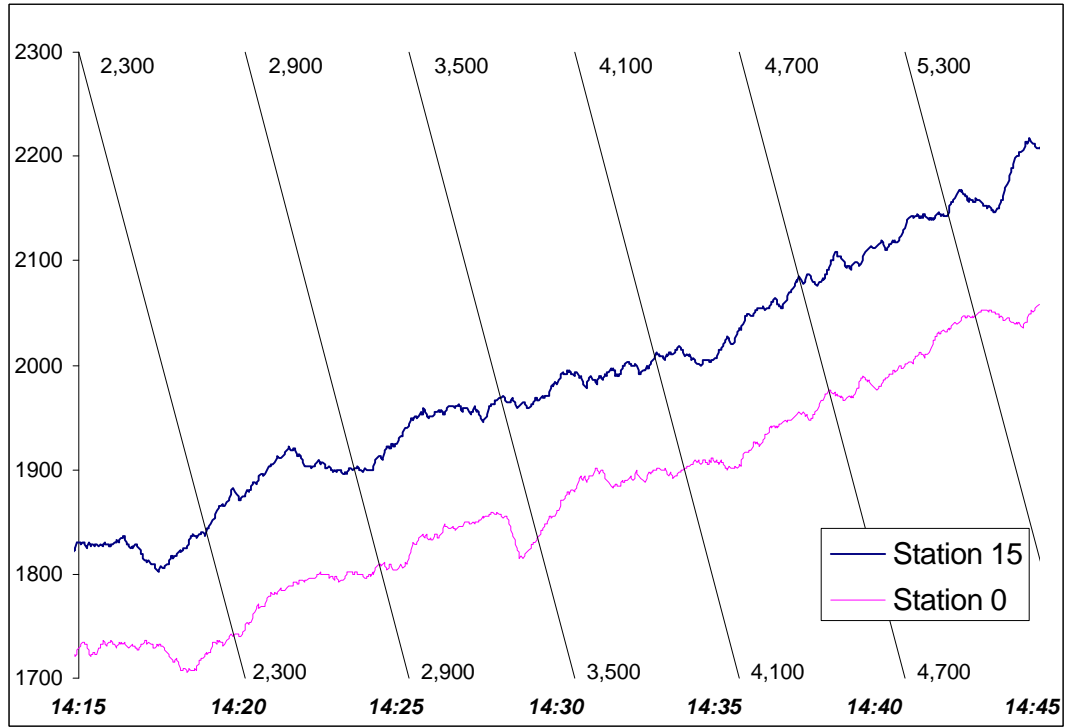(a) orthogonal plot; (b) oblique plot.

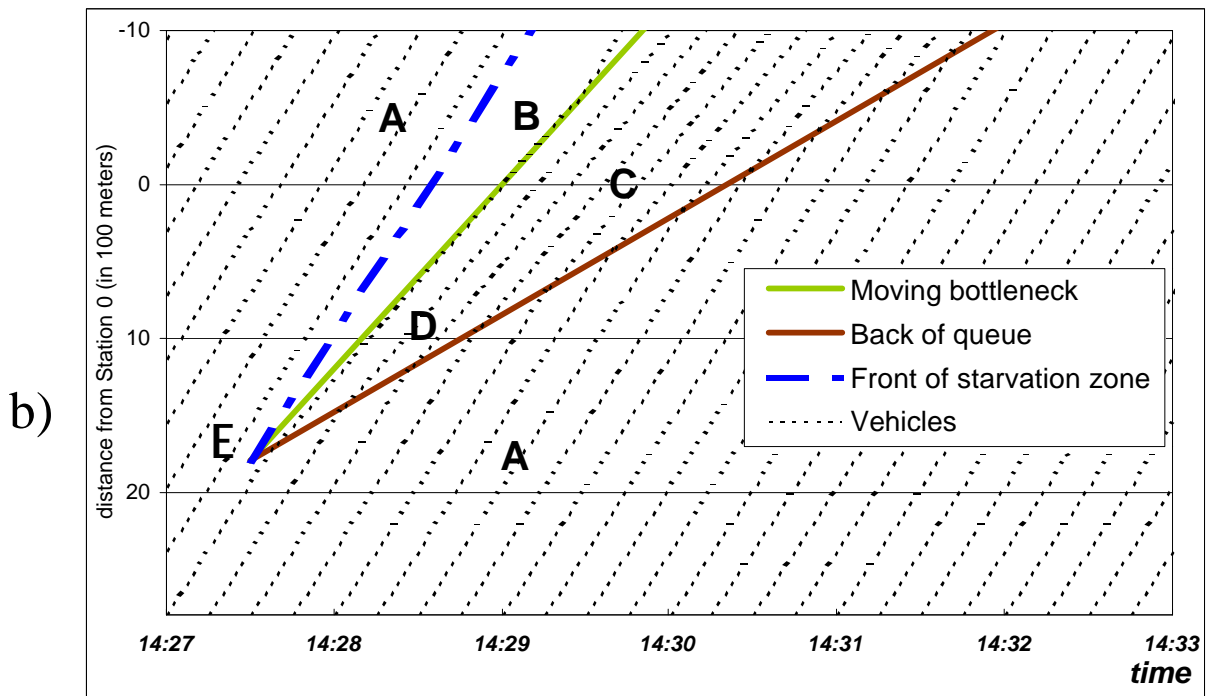Figure 5. Traffic conditions at stations 0 and 15 between 14:15 and 14:45 hrs.
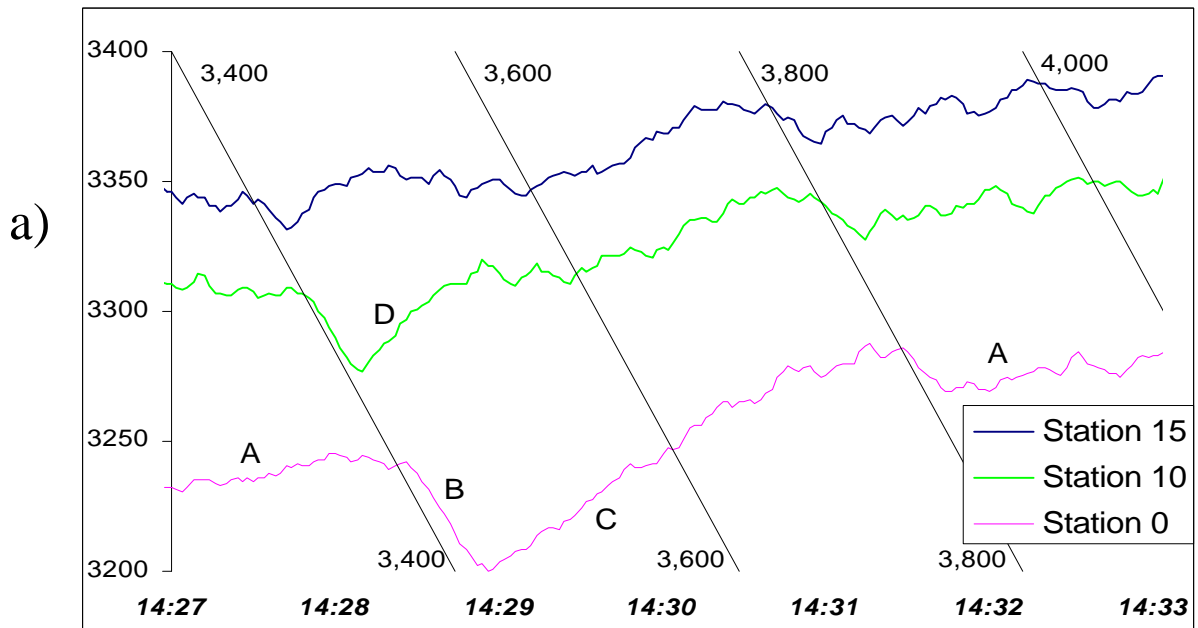
Figure 6. Traffic patterns around a moving bottleneck: (a) N-curve signature detected at stations 27, 22 and 12; (b) evolution in time and space.