Lane Change Maneuvers Consuming Freeway Capacity

Coifman, B.[1,2], Krishnamurthy, S.[1,3], Wang, X.[1,4]

[1] The Ohio State University
Columbus, OH, 43210, USA

[2] Assistant Professor, Coifman.1@OSU.edu, http://www.ceegs.ohio-state.edu/~coifman
-Department of Civil and Environmental Engineering and Geodetic Science
-Department of Electrical Engineering

[3] Graduate Research Assistant, krishnamurthy.26@osu.edu, Department of Civil and Environmental Engineering and Geodetic Science

[4] Graduate Research Assistant, wang.833@osu.edu, Department of Civil and Environmental Engineering and Geodetic Science

Abstract: Conventional traffic flow theory dictates that flow on a freeway is usually constrained only by a small number of critical locations or bottlenecks. When active, these bottlenecks cause queues that can stretch for several miles and reduce flow on other parts of the network. Bottlenecks are often thought to arise over short distances and are usually modeled as if they occur at discrete points since the resulting queues are thought to be much longer then the bottleneck region. This paper presents evidence that the delay causing phenomena may actually occur over extended distances. Some of which may occur downstream of the apparent bottleneck where drivers are accelerating away from the queue, while related phenomena are observed in the queue, over a mile upstream of the apparent bottleneck. It is shown that lane change maneuvers are responsible for some of the losses, reducing travel speed and consuming capacity when vehicles enter a given lane. These losses in one lane are not fully balanced by gains in other lanes.

Keywords: freeway traffic, traffic flow theory, bottlenecks, congestion

1 INTRODUCTION

Conventional traffic flow theory dictates that flow on a freeway is usually constrained only by a small number of critical locations or bottlenecks. When active, these bottlenecks cause queues that can stretch for several miles and reduce flow on other parts of the network. Bottlenecks are often thought to arise over short distances and are usually modeled as if they occur at discrete points since the resulting queues are thought to be much longer then the bottleneck region.

This conventional model of bottleneck operation proved to be insufficient when attempting to localize precisely the source of delay through a major freeway interchange on Interstate 71 (I71) in Columbus, Ohio, USA. Using probe vehicle data, the apparent bottleneck location drifted from day to day, falling in a range of almost a half mile without any clear geometric explanation such as an on-ramp or lane drop. Further investigation of vehicle detector data upstream of the bottleneck revealed that velocity increased as traffic approached the bottleneck, which is consistent with earlier findings. Using loop detector data, both Hall et al (1992) and Cassidy and Mauch (2001) observed average velocity dropping, flow dropping, and occupancy increasing in the queue as one moved further upstream of a bottleneck. The worsening conditions were attributed to vehicles entering on the ramps and consuming some of the capacity of the bottleneck that would otherwise be available for the mainline traffic upstream of the ramp.

Unlike the earlier research, however, the dropping velocity as one moves upstream of the bottleneck on I71 cannot be explained by ramp flows alone, e.g., the phenomena was observed between two consecutive stations that have conservation of flow. As will be shown in this paper, by measuring vehicle inflow, i.e., the difference between the number of vehicles that enter a lane and those that leave the lane between two locations (Coifman, 2003), closer investigation reveals that lane change maneuvers reduced the effective capacity in adjacent lanes. Of course the total number of lane change maneuvers may be greater than the inflow, since one exiting vehicle could be replaced by another entering, but the results do not depend on the exact number of lane change maneuvers. In any event, the phenomena was observed both within the half mile first identified from the probe vehicle data as containing the bottleneck location, and a mile upstream of the apparent bottleneck. This latter point indicates that the bottleneck mechanisms result in complicated events that can trigger a drop in capacity far upstream of the initial source of delay.

The remainder of this paper begins by examining the probe vehicle data and providing a detailed overview of the freeway corridor to localize the bottleneck. It then uses loop detector data to study the evolution of the queue and examine features that may impact vehicle throughput. Finally, it closes with a brief summary and conclusions.

2 ANALYSIS

We examined northbound I71 in Columbus, Ohio first by collecting Global Positioning Satellite (GPS) data from over 70 probe vehicle runs passing through the corridor. The GPS data used in this study were collected on pre-selected Tuesdays, Wednesdays, and Thursdays over a period of approximately one year. From these GPS data, we were able to localize the apparent location of a major bottleneck. However, as noted earlier, the precise location appeared to drift from one run to the next, falling in a range of almost a half mile. Then to gain a more complete temporal picture, we examined the corresponding loop detector data.

2.1 *BOTTLENECK LOCALIZATION*

The probe vehicle runs were sorted based on traffic conditions. A few of the runs indicated the presence of queued conditions at the downstream end of the corridor and they were omitted from further study since the subject bottleneck was not the source of the queue. Of the 66 remaining runs, 29 did not exhibit any queuing and 37 showed some degree of queuing arising from a bottleneck within the study corridor. Taking the average within each of these sets, Figure 1A shows the spatial evolution of the two averages. Note that to the eye the active bottleneck average ("congested") becomes indistinguishable from the inactive bottleneck average ("free flow") at approximately mile 5.3. When the bottleneck is active, the average velocity decreases as one moves upstream of this location, with a significant drop at mile 4.5.

For this study we examined five days in detail that were selected because the queue was particularly long, extending upstream of mile 4, namely December 5, 2001; February 28, 2002; April 23, 2002; May 7, 2002; and July 23, 2002. For four of these days the long queue is evident in the probe vehicle data, as shown in Figure 1B. All four of these runs were also included in the congested average curve. From these individual runs the reader can see that the exact location of the bottleneck changes from run to run, with the given congested run becoming indistinguishable from the free flow average at different locations between mile 5 and 5.5.

To place the data in context, Figure 1C shows a straight line schematic of the corridor at the same scale as the previous plots. The central business district (CBD) ends around mile 5.2 and I670 eastbound leads to the suburbs. Following the Ohio Department of Transportation (ODOT) convention, lanes are numbered consecutively starting with one in the median lane and increasing to the outside shoulder. The probe vehicle drivers were instructed to drive in lane 2, i.e., second from top in this diagram. Several loop detector stations are in the corridor, as indicated on the schematic. The averages in Figure 1A suggest that the bottleneck is somewhere between mile 4.5 where a significant increase in average congested run velocity corresponds to the addition of two lanes from I70 westbound and mile 5.3 where the two curves become indistinguishable from one another just downstream of a diverge to I670 eastbound. Using the detector on the ramp from the I670 westbound connector, no velocity drops were evident on the subject days, verifying that queues did not back up on to the ramp and providing further evidence that this ramp was downstream of the bottleneck(s). For completeness, Figures 1D-E show the elevation and geometry, respectively, for this corridor. Note that the latter is shown at a different scale than the other plots in this figure.

2.2 *QUEUE EVOLUTION*

Detector stations 109 and 110 are within the region identified as containing the bottleneck in section 2.1. Figure 2 shows plots of time series velocity and flow sampled every five minutes for the entire day in lane 2 at these stations on May 7. The general trends are similar on the four other days in the study. In Figure 2B we see low flows before 5:00 and then a sharp increase in demand during the morning peak, rising to 2500 vehicles per hour (veh/hr), which many practitioners believe is the maximum capacity of a freeway lane. As will be discussed shortly, it is believed that this peak represents capacity conditions and the true bottleneck is very close to station 110 in the morning. Figure 2A shows that velocity starts dropping to 40 mph just before this peak flow is reached. Although not explicitly shown in this paper, these morning peak data fall in the upper portion of the velocity versus flow curve. Thus, the data from this period do not correspond to the congested regime, rather, the drop in velocity is likely due to conditions approaching theoretical capacity within the uncongested regime. Velocity was measured directly from the dual loops at station 109 while it was estimated from the single loops at station 110 (as well as the other stations) using the methodology presented in Coifman et al (2003). As was shown in the earlier paper, this estimation technique yields good results except during low flow, and is evident by the noise in the velocity time series from station 110 during the low flow period prior to 5:00.

In theory the Long St. on-ramp, which enters just downstream of station 110, should have sufficient capacity for all entering vehicles since the additional lane continues for over 10 miles. However, drivers from I71 wishing to reach I670 eastbound must cross this lane in under 0.2 miles. In the morning peak both the Long St. on-ramp and I670 eastbound off-ramp should see lower demand than the evening peak since the flow is away from the CBD. We do not have detector data from either of the two ramps, but except for a brief disturbance during the morning peak on this day, the high velocity data at stations 109 and 110 support this supposition. As already noted, these data fall within the uncongested regime of the velocity versus flow plane. It is further reinforced by the fact that changes in the time series flow and occupancy are positively correlated during this period, further indicating non-queued conditions.[1] In the evening peak, flow begins to climb and then flow and velocity usually drop into a queued state, around 15:00 and shortly after 16:00, respectively, in the sample time series. A return to free flow velocities around 17:00 indicates that the queue has receded past these stations. The flow typically increases concurrent with this velocity recovery, suggesting that a downstream restriction is alleviated rather than upstream demand dropping. We believe that either the I670 eastbound off-ramp is backing up, or more likely, a high demand from Long St. prevents I71 drivers from finding gaps to merge into the outside lane and reach I670 during the evening peak. The exact source of the evening bottleneck is the subject of on-going research and for this paper the analysis in this link is restricted to the morning peak.

Extending our analysis beyond lane 2 and examining another morning peak, absent the brief disturbance seen at 8:00 in Figure 2A, Figure 3A and B show the time series velocity during the morning peak in lane 1 and 2, respectively. Each plot includes data from the two stations, 109 and 110, for the given lane to facilitate comparison. One can observe the velocity dropping slightly in both lanes at both stations shortly before 6:30. These plots also show that in each lane the drop is on the order of 4mph greater at station 109 than at 110. Figures 3C-D show that in each lane the drop in velocity occurs just before flow reaches the maximum rate in lane 2, and this rate is sustained for over 30 minutes. At both stations the peak flow in lane 2 is roughly 500 veh/hr greater than that of lane 1.

Conventional traffic flow theory would tell us that the increase in velocity from station 109 to 110 indicates that these two stations are downstream of the bottleneck and that the plots show traffic accelerating away from the queue.[2] Yet the flow in lane 2 at station 109 is near the

---

[1] During non-queued conditions, all commonly accepted flow-occupancy relationships indicate that increasing occupancy corresponds to increasing flow, while during queued conditions increasing occupancy corresponds to decreasing flow.

[2] Again, although not shown in a figure, these morning peak data fall in the upper portion of the velocity versus flow curve.

theoretical capacity of a freeway lane and as shown in Figure 4A, measuring vehicle inflow to this lane (Coifman, 2003), between 6:00 and 9:00 approximately 190 additional vehicles pass station 110 than 109 in lane 2 (although not shown, an equivalent reduction is seen in lane 1). Using the straight-line approximations superimposed on Figure 4A, the percentage of flow that is attributable to the inflow was calculated and is shown in Figure 4B. The merging vehicles represent just over three percent of the flow in lane 2 at station 110 between 6:00 and 9:00. The rising flow in lane 2 as one travels downstream of the apparent bottleneck and the proximity to lane capacity represents another mechanism that can limit flow and potentially give rise to the disturbances that evolve into stop and go traffic. Either there is a sequence of short bottlenecks that trade dominance in restricting flow over a short distance, or the actual bottleneck spans a non-negligible distance. If the former, lane 1 drivers take advantage of an upstream restriction to merge into lane 2, if the latter, these lane changing drivers are causing delay to lane 2 drivers and stretch the bottleneck over an extended distance.

In either case, this long bottleneck theory implies that all traffic states below pure free flow may limit upstream throughput. In the subject link, vehicles entering lane 2 would delay drivers upstream because each entering driver consumes a minimum of one unit headway of time at station 110, analogous to the impact of on-ramp inflow degrading upstream conditions in a queue, as discussed in Hall et al (1992) and Cassidy and Mauch (2001). There are no ramps in this link, rather, the entering traffic comes from the adjacent lane. It is hypothesized that drivers in lane 1 assume lower velocity than dictated by conditions in the lane, presumably because they are matching velocity with lane 2 either to merge or because the drivers do not like to pass traffic in adjacent lanes with a significant difference in relative velocity. This coupling hypothesis will be the subject of future research, for this paper, it is sufficient to note that the delays to lane 2 drivers are not balanced by improvements to lane 1 drivers.

Returning the focus to lane 2, the accelerating drivers experience a delay compared to traversing the entire link at the velocity observed at station 110. Assuming they accelerate at a constant rate, each driver would experience the following delay,

$$\Delta t = \frac{2x}{v_{109} + v_{110}} - \frac{x}{v_{110}} \tag{1}$$

where,

x = the distance between the two stations, and
v_i = velocity at station i.

During very high flow and queued conditions, each entering vehicle would delay the following driver and these delays would propagate upstream. If each entering vehicle resulted in exactly one unit headway delay, the location of lane changes were uniformly distributed between the two stations, and the signals travel at empirically established velocities of well formed signals (on the order of 14 mph, Mauch and Cassidy, 2002), one would expect the delay arising from a single vehicle entrance to impact drivers in the link for just over 40 sec. The exact location of the lane change maneuvers are unknown and it is conceivable that more occur closer to station 110, thus potentially increasing the expected dwell time of the disturbance in the link. Meanwhile, the average time between lane change maneuvers is on the order of 55 sec on this day. So the expected number of such unit headway delays a driver must pass through is just below one. If the unit headway was simply the inverse of the maximum observed flow, 1.5 sec, the expected delay is on the order of $\Delta t \approx 1.3\text{sec}$ in this case. These findings do not refute the long bottleneck theory that vehicles entering lane 2 between stations 109 and 110 during uncongested, high flow periods restrict flow upstream of 109. If conditions downstream of the apparent bottleneck impact the flow of traffic through the constriction, then that could help explain the formation and behavior of bottlenecks, but further research is needed to eliminate alternative explanations.

Moving further upstream and returning to May 7, 2002, Figure 5 shows the time series velocity and flow in lanes 1 and 2 at stations 106 and 107 (lanes 3 and 4 at station 107 are omitted for clarity). On this morning, the two lanes at station 107 exhibit a slow drop in velocity starting shortly after 7:00. At 7:30 velocity drops much more suddenly at station 106 as the queue passes over. Unlike station 107 in which velocity dropped by roughly the same amount in both lanes, at station 106 the velocity drop in lane 2 is roughly twice that of lane 1. Also at station 106, the flow drops in lane 2 shortly after the velocity does. This drop is consistent with what one would expect since a queue grows only as long as demand exceeds capacity. Thus, the demand flow upstream of the queue should be larger than the flow within the queue after it grows past the station. But the two following features are unexpected. First, Figure 5D compares the lane 2 flow at both stations, while the station 107 flow remains relatively constant, station 106 flow actually drops below the downstream flow, which is also in the queue. Secondly, as shown in Figure 5C, the flow in lane 1 at station 106 actually increases after the velocity drop.

Two lanes enter the link just upstream of station 107 from eastbound I70, precluding conservation of flow for lane-to-lane comparisons. However, one can still measure the net lane inflow, as shown in Figure 6A-B. Between 7:30 and 8:00, lanes 1 and 2 exhibit an inflow of -130 and 200 vehicles, respectively. Figure 6C shows that the inflow to lane 2 accounts for approximately 20 percent of the lane flow at station 107. Meanwhile, Figure 5A shows that velocity in lane 1 at station 106 drops down to that of station 107 after the queue passes over the upstream station, while Figure 5B shows that at the same time the velocity in lane 2 at station 106 drops more than 10 mph below that of station 107. In other words, vehicles departing lane 1 do not appear to benefit upstream drivers while vehicles entering lane 2 appear to delay upstream drivers.

3 CONCLUSIONS

This paper used probe vehicle and loop detector data to examine more closely some of the mechanisms that occur in bottlenecks and consume freeway capacity. Section 2 used one case study to examine the small delay occurring between stations 109 and 110, though the results were typical of the morning peak on all five days that were studied. Evidence was presented to suggest that although velocity was near free flow and conditions may indicate vehicle discharge downstream of a queue, lane change maneuvers within this link may actually be restricting flow through the apparent bottleneck upstream, i.e., the long bottleneck theory. If the theory proves robust, it may help explain the formation backwards propagating *stop and go* waves and other bottleneck phenomena. Future research will test further this hypothesis.

A second case study found that vehicle maneuvers within a queue can also impact the throughput, as observed between stations 106 and 107. Each of the five days examined was selected because a queue reached station 106 and the case study presented above was representative of the behavior whenever a queue reached station 106 on the subject days. This point indicates that the bottleneck mechanisms result in complicated events that can trigger a drop in capacity far upstream of the initial source of delay. Understanding these capacity drops upstream of the primary bottleneck will help explain how disturbances arise in traffic queues. Eliminating these capacity drops <u>might</u> help drivers who exit the queue at a ramp or diverge upstream of the bottleneck. But this solution alone is not expected to increase the number of vehicles that can pass the primary bottleneck since it continues to restrict capacity even though the upstream capacity drops reduce the demand on the primary bottleneck. Furthermore, after concentrating the capacity drop to a single location, the queue will still spread upstream and could continue to impact those drivers that exit before the primary bottleneck.

In the freeway interchange we studied, we believe the queue arises due to vehicles changing lanes to reach an off-ramp. By channelizing the queue, i.e., restricting lane change maneuvers that enter the lane adjacent to the off-ramp, it may be possible to reduce queue spillover to the other lanes and thus, increase the effective capacity of those remaining lanes. However, drivers are unlikely to accept such a complicated control scheme and the speed differential between adjacent lanes may cause new problems. A more feasible solution is to control the percentage of flow that reaches the bottleneck location from each origin and increase the net percentage of vehicles that are <u>not</u> destined for the off-ramp.

As one should expect, the case studies found that drivers entering a lane consume capacity and delay upstream drivers. But both case studies revealed the unexpected result that the degraded conditions due to vehicles entering a lane are not balanced by improvements to the lane from which the vehicles departed.

4 ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the Ohio Department of Transportation in this research. This material is based upon work supported in part by the National Science Foundation under Grant No. 0133278.

5 REFERENCES

Cassidy, M.J., Mauch, M. (2001). An observed traffic pattern in long freeway queues, *Transportation Research: Part A*, 35(2), pp 143-156.

Coifman, B. (2003). Estimating Density and Lane Inflow on a Freeway Segment, *Transportation Research: Part A*, 37(8), pp 689-701.

Coifman, B., Dhoorjaty, S., and Lee, Z. (2003). Estimating Median Velocity Instead of Mean Velocity at Single Loop Detectors, *Transportation Research: Part C*, 11(3-4), pp 211-222.

Hall, F.L., Hurdle, V., Banks, J. (1992). Synthesis of recent work on the nature of speed-flow and flow-occupancy (or density) relationships on freeways, *Transportation Research Record 1365*, pp 12-17.

Mauch, M., Cassidy, M.J. (2002). Freeway traffic oscillations: observations and predictions, *International Symposium of Traffic and Transportation Theory*, (M.A.P. Taylor, Ed.) Elsevier, Amsterdam, pp 653-674.

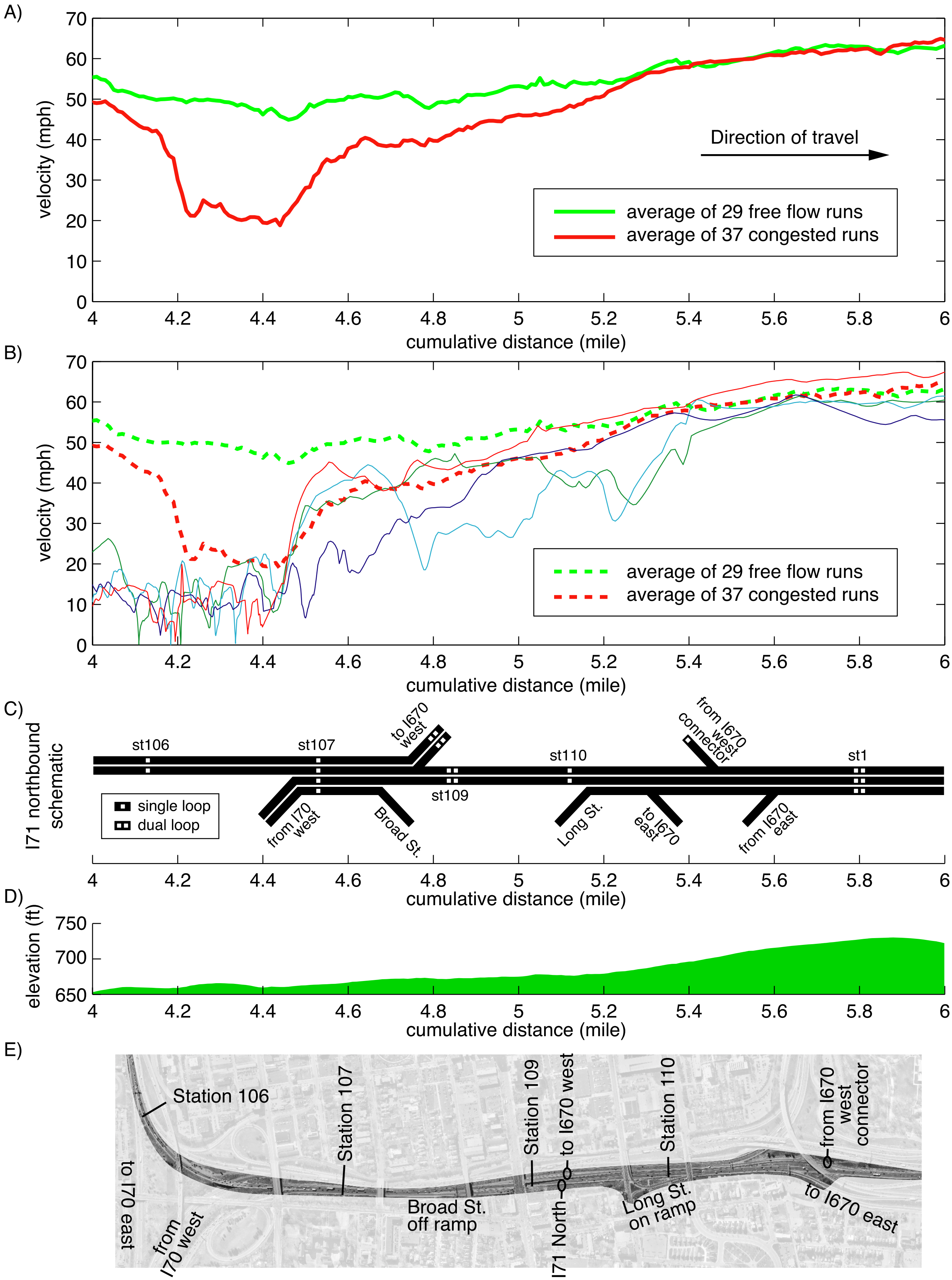

Figure 1, (A) Average velocity versus time for 66 probe vehicle runs through a bottleneck on northbound I71, (B) superimposing four individual runs on part A, (C) the corresponding schematic and (D) elevation diagram of the freeway segment. Finally, (E), an aerial photo showing the geometry of the freeway segment.

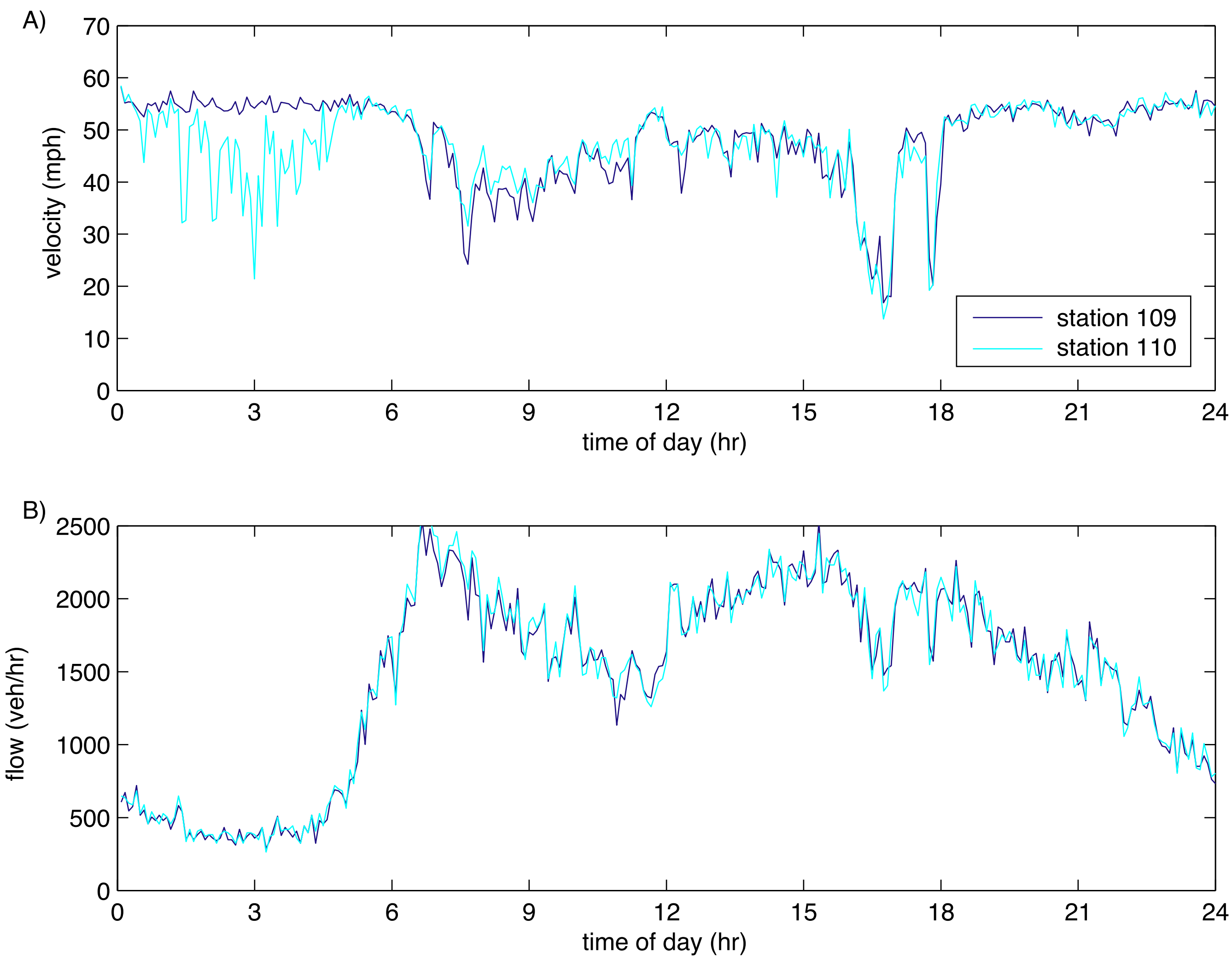

Figure 2, Five minute average (A) velocity and (B) flow for lane 2 at stations 109 and 110, all day, on May 7, 2002.

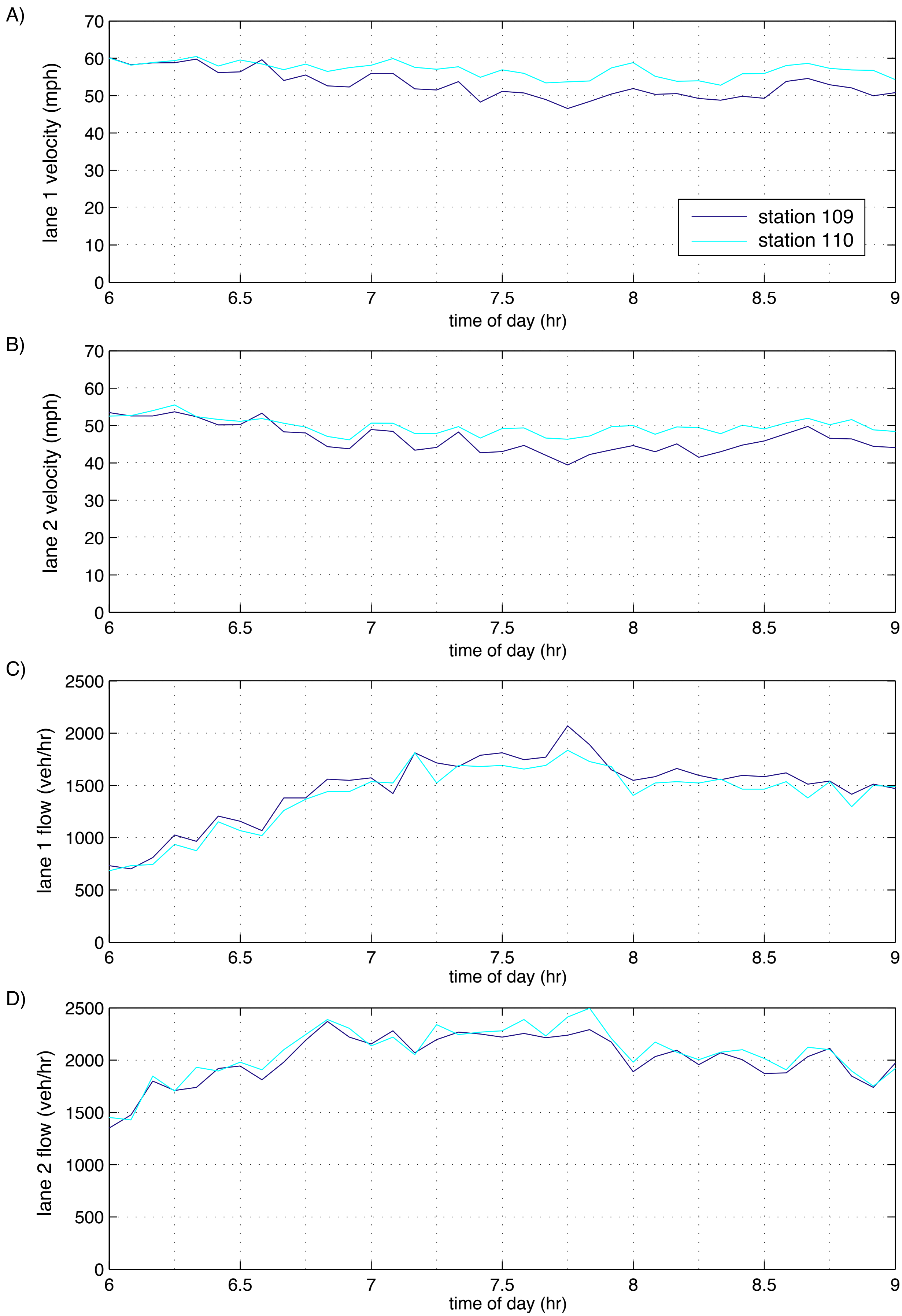

Figure 3, Station 109 and 110 five minute average velocity in (A) lane 1, (B) lane 2, and flow in (C) lane 1, (D) lane 2, during the morning peak on February 28, 2002.

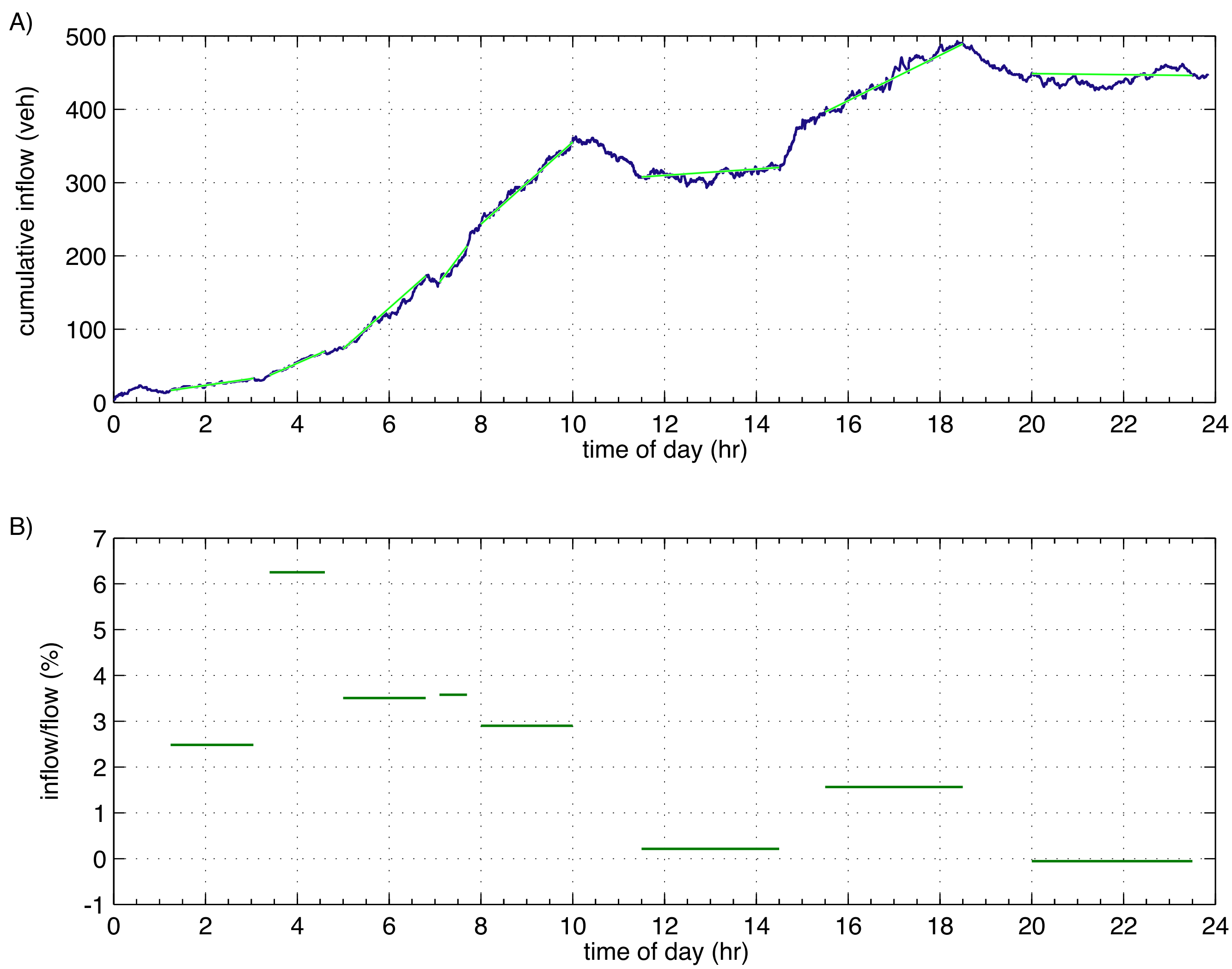

Figure 4, (A) cumulative inflow to lane 2 between stations 109 and 110 and (B) the corresponding inflow as a percentage of flow, all day on February 28, 2002.

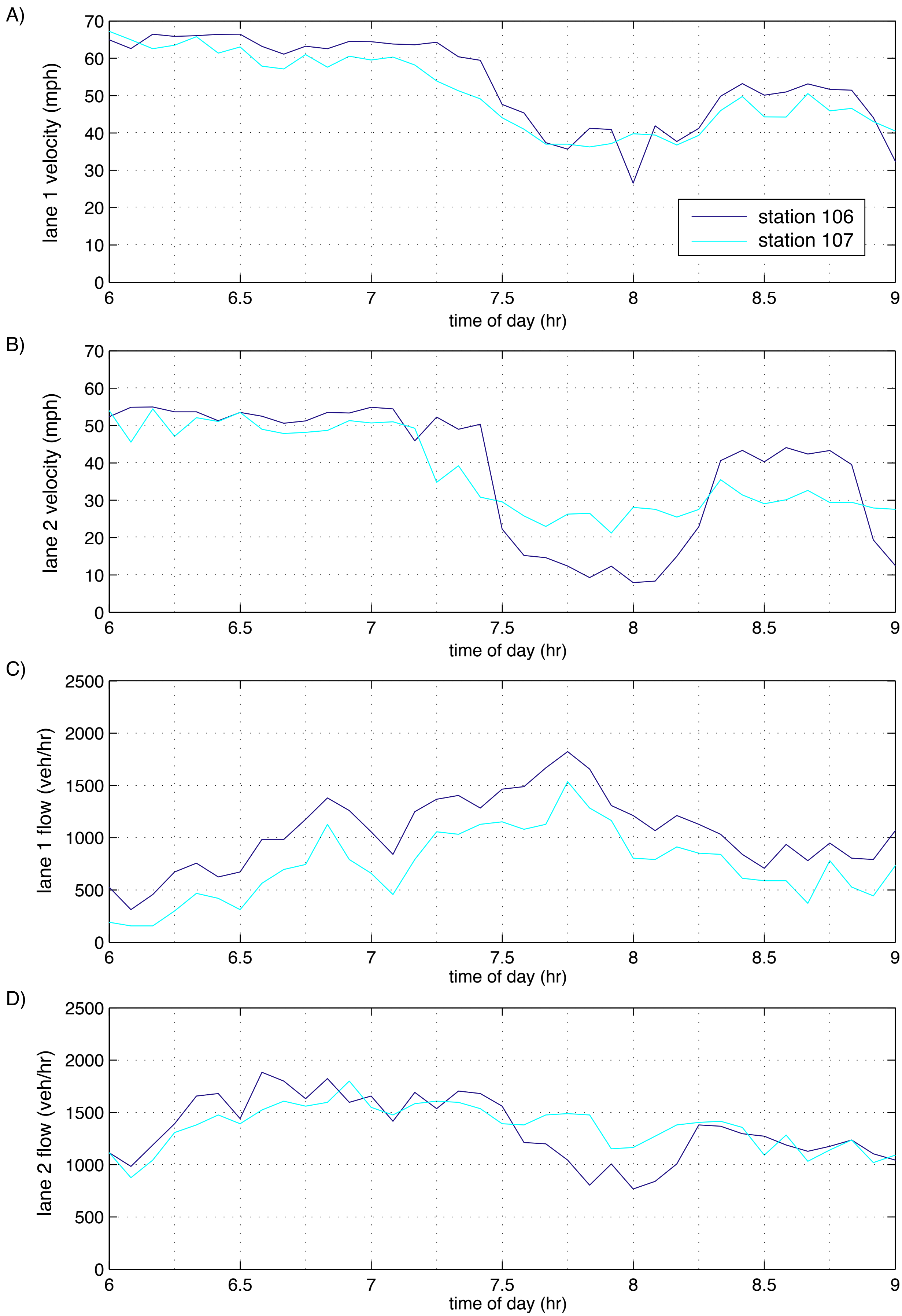

Figure 5, Station 106 and 107 five minute average velocity in (A) lane 1, (B) lane 2, and flow in (C) lane 1, (D) lane 2, during the morning peak on May 7, 2002.

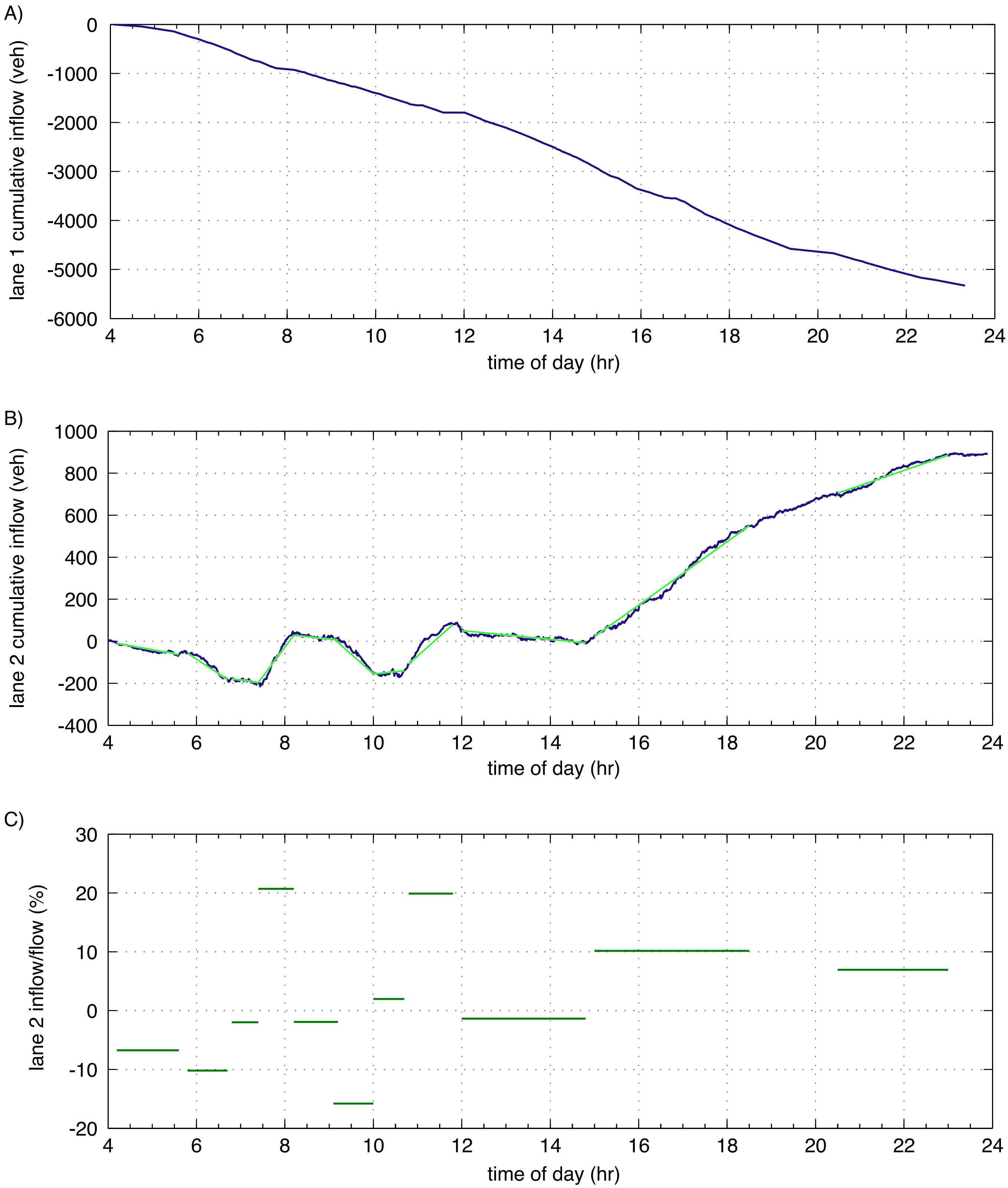

Figure 6, (A) cumulative inflow to lane 1 between stations 106 and 107, (B) cumulative inflow to lane 2 between stations 106 and 107 and (B) the corresponding inflow as a percentage of flow for lane 2, all day on May 7, 2002.