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CALIFORNIA PARTNERS FOR ADVANCED TRANSIT AND HIGHWAYS

Study of Freeway Traffic Near an Off-Ramp

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ABSTRACT

A bottleneck with a diminished capacity is shown to have arisen on a freeway segment whenever queues from the segment's off-ramp spilled-over and occupied its mandatory exit lane. It is also shown that the lengths of these exit queues were negatively correlated with the discharge flows in the freeway segment's adjacent lanes; i.e., longer exit queues from the over-saturated off-ramp were accompanied by lower discharge rates for the non-exiting vehicles. In these instances, the explanation appears to be "rubber-necking" on the **part** of the non-exiting drivers. Whenever the off-ramp queues were prevented from spilling-over to the exit lane (by changing the logic of a nearby traffic signal), much higher flows were sustained on the freeway segment and a bottleneck did not arise there. These observations underscore the value of control strategies that enable diverging vehicles to exit a freeway unimpeded.

KEY WORDS: Freeway Traffic Control, Off-Ramps, Bottlenecks

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1. INTRODUCTION

It is shown that a very disruptive freeway bottleneck was averted merely by keeping an off-ramp from becoming over-saturated. This demonstration relies upon traffic data visually extracted from videotapes combined with observations taken in a floating car and, very importantly, visual analyses of cumulative curves of vehicle counts and occupancies that were plotted in special ways. The latter were measured by inductive loop detectors and obtaining these data proved a challenge because some detectors were not always functioning. Certain details concerning these detectors are thus relegated to footnotes so that they do not detract from what is otherwise a simple narrative.

In the following section, the freeway site used for the study is described. Observations of traffic flowing through the bottleneck (i.e., in the presence of the over-saturated off-ramp) are presented in Section 3. Section **4** serves to document the improved freeway conditions that resulted from keeping this ramp under-saturated.' Some implications of these findings are provided in the manuscript's fifth and final section.

2. *STUDY* SITE

Figure 1 is a sketch of the study site, a segment of southbound Interstate 5 in Orange County, California. The loop detectors, shown along with their respective mile post (MP) locations, measured the vehicle counts and occupancies in each lane over 30-second intervals. Also as annotated in the figure, the (regular-use) travel lanes are numbered here from left to right so that lane 1 always refers to the lane immediately adjacent to the high-occupancy vehicle (HOV) lane. Analyses of traffic in the latter are not described here, since HOV operation seemed to have little impact on the regular-use lanes. All on-ramps were metered and their inflows were nearly the same each observation day.

The following section provides observations taken when the La Paz Road off-ramp

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[1] The strategy promoting under-saturated ramp operation was not deployed at the behest of the research team. Rather, one of the ramp's loop detectors, which was used to activate a traffic signal immediately downstream, functioned intermittently. It **was** only during the detector's functioning periods that the traffic signal served the entire ramp queues. The research team merely collected observations both when the detector **was** functioning and when it was not. Both cases were easily distinguished by examining said detector's data (and by measuring exit flows from videos).

became over-saturated, creating a bottleneck between MPs 16.6 and 17.3. The section immediately thereafter describes the much improved freeway conditions that prevailed when the traffic signal (at the downstream end of this off-ramp) allocated sufficient capacity to the ramp to keep it under-saturated.

3. THE BOTTLENECK AND ITS CAUSE

This section begins with a description of the cumulative curves of vehicle count, N, and occupancy, T, used for locating the freeway bottleneck. To this end, Figure 2a presents curves measured by the detectors at MP 17.3 on May 30, 2000. The N-curve, shown in this figure as the thick line, came from the counts summed across all five lanes at this MP. It was constructed by taking linear interpolations through these 30-second counts so that its slopes are the flows past the MP in each (30-second) measurement interval.

But instead of plotting N versus time t, an oblique coordinate system was used to plot $N - q_o \cdot (t - t_o)$ versus t for the curve's starting time, t_o, and some choice of q_o. The latter was chosen so that the range of $N - q_o \cdot (t - t_o)$ over the observation period was small compared with the N itself. In this way, the vertical scale **was** magnified along with the curve's features, such as sustained changes in its slopes and its wiggles. This method of plotting the curves is identical to what was described in Cassidy and Windover (*1995*), but it was Muñoz and Daganzo (2000) who first recognized that this is an oblique plot.

In similar fashion, the thin line in Figure 2a is the T-curve at *MP* 17.3, where cumulative occupancy, T, is measured in units of total time spent by vehicles atop the detectors to time t (*Lin and Daganzo, 1997).* **As** before, the curve describes the measurements (in this case, the occupancies) across all five travel lanes; it was drawn using piece-wise linear interpolations so that its slopes are the occupancy rates; and it is shown using oblique coordinates so that its changing patterns (i.e., its changing occupancy rates) are visible to the naked eye.

The curves in Figure 2a reveal that backward-moving congestion (that emanated from somewhere downstream) arrived at MP 17.3 by time 17:10. At earlier times, changes in the N and T occurred in the "same directions;" i.e., an increase (decrease) in the flow was accompanied by an increase (decrease) in the occupancy rate and the reader can confirm this using a straightedge. This pattern reveals that, before time 17:10, changes in traffic conditions measured

at MP 17.3 emanated from upstream *(Cassidy, 1998)*. At time 17:10, however, a visible reduction in N **was** accompanied by a sharp rise in T, marking the arrival of congestion from downstream. Following this time, changes in the N and T occurred in "opposite directions," revealing the passages of backward-moving acceleration and deceleration waves characteristic of congested traffic *(Cassidy and Bertini, 1999)*. Dotted line segments have been added to Figure 2a to highlight these changing patterns in the N and T, i.e., the dots emphasize that a convex (concave) trend in the N-curve was accompanied by a concave (convex) one in the T.

Figure 2b presents oblique N- and T-curves measured in the four regular-use lanes at the detectors downstream of MP 17.3.[2] Each was constructed as previously described. They reveal that changes in the slopes of both curves occurred in the same directions and piece-wise linear approximations are shown **as** dashed lines in Figure 2b to emphasize this. As such, changes in flow and occupancy rate at *MP* 16.6 were forward-moving and emanated from upstream.

Notably, the backward-moving waves (in congestion) at MP 17.3, combined with forward-moving changes in (uncongested) traffic at *MP* 16.6, reveal that a freeway bottleneck activated somewhere between *(Cassidy and Bertini, 1999)*. Closer inspection of the N and T indicates that this activation occurred at about time 17:00.

Specifically, Figure 2b shows that a severe reduction in flow (and occupancy rate) began at about this time. By time 17:08, flow (and occupancy rate) recovered slightly and henceforth maintained nearly stationary rates that changed slowly over time. These are features that have previously been observed **of** freeway traffic discharging from upstream congestion *(Cassidy and Bertini, 1999)* and they point to the bottleneck's activation time (to have been about 17:00). By showing that congestion arrived to MP 17.3 some minutes later, Figure 2a likewise supports this diagnosis.

In light of the above, the deleterious effects of this bottleneck on freeway flow are evident

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[2] Just prior to this day of data collection, the loop detectors in lanes 1 and 2 at MP **16.6,** and in lanes **3** and **4** at **M P 16.4,** were disabled due to some maintenance activity nearby. This activity never occurred during observation days and did not effect driving conditions on these days. It did, however, require that the curves in Figure 2b be constructed using data from the four functioning detectors (collectively measuring conditions in all four travel lanes) at both MPs **16.6** and **16.4** (see Figure 1). Finagling the data in this fashion is regrettable only because it complicates the narrative; it did not affect the findings, especially since video showed very little lane changing between these two closely-spaced MPs. Except where otherwise noted, the data (euphemistically) described **as** having been measured at MP **16.6** (only) were actually agglomerated measurements at both MPs **16.6** and **16.4.**

in the (flow) differences from time 16:30 to 17:00 and from time 17:00 to about 17:50; (shortly after 17:50, conditions at the bottleneck changed dramatically and this is demonstrated later). **As** annotated on Figure 2b, these were 2,085 vehicles per hour per lane (vphpl) and 1,900 vphpl, respectively. Of note, the latter flow describes vehicles departing from an active bottleneck; i.e., one marked by congestion upstream so that vehicles discharged at a maximum rate and there were no downstream conditions that impeded this (*Daganzo, 1997*).[3] The former flow, however, was merely the one that prevailed prior to the bottleneck's activation; it was not necessarily the highest that could have been sustained by the freeway segment (and, as shown later, higher flows were observed on other days). **As** such, the effect of the bottleneck's activation on the freeway segment's capacity was likely greater than what has been measured here.

In any event, the activation on this day reduced flow through the segment by nearly 10 percent. Observations on additional days showed that reductions of this magnitude, and sometimes much greater, were the norm. On one particular day (when video observations were not available), for example, the bottleneck's activation reduced flow on the freeway by 40 percent *(Anani, et.al; 2000)*. Not surprisingly, data from upstream detectors (sometimes accompanied by observations from a floating car) showed that this bottleneck created extensive freeway congestion each day.

Study of videotapes taken from the Alicia Parkway over-crossing revealed that this bottleneck arose whenever long queues from the La Paz Road off-ramp spilled-over and created stop-and-go conditions in the freeway segment's mandatory exit lane (see Figure 1). To demonstrate this, Figure 3 presents the numbers of vehicles to have occupied the exit lane between MPs 17.3 and 16.7 during the rush (on May 30); these were counted directly from video. Their sharp increases beginning at time 17:00 denote the initial appearance of queues in the exit lane and this was the time previously identified **as** marking the bottleneck's activation.[4]

Large numbers occupying the exit lane (and exit queues) persisted until time 17:50 or shortly thereafter. It was at about this same time that flow (and occupancy rate) increased at MP

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[3] This flow is a reasonable estimate of bottleneck discharge despite the complication described in footnote 2.

[4] It was also at this time that the La Paz off-ramp's middle detector began to malfunction and counts (taken from video) indicated that the downstream traffic signal's ability to serve exiting flows dropped from 1,200 vph to only 820 vph.

16.6, as previously shown in Figure 2b. But Figure 3 shows that the numbers in the exit lane oscillated a good deal from time 17:50 until soon after 18:00. **As** an apparent consequence, freeway vehicles did not exhibit a maximum discharge rate until about 18:05, after which time, the discharge flow past MP 16.6 was nearly stationary with a rate of 2,020 vphpl. Thus, the dissipation of the exit queues returned higher flows to the freeway segment. Yet this higher discharge was still lower than the freeway flow (of 2,085 vphpl) measured prior to the bottleneck's activation and more is said about this in the conclusions.

Of note, the observations showed no evidence of diverging vehicles directly entrapping traffic with destinations further downstream; this might have occurred had the former decelerated before forcing themselves into the exit queues. But video showed that these drivers were disciplined (or courteous) in that they tended to move into the mandatory exit lane upstream of its queues. Even when these queues extended as far back as the Alicia Parkway on-ramp at MP 17.3, the observed rates of vehicles squeezing into them never exceeded 1 or 2 per minute and this seldom seemed to affect through-moving traffic.

Evidently, the deleterious effects of the exit queues were the result of driver rubber-necking in the adjacent lanes; i.e., non-exiting drivers were unwilling to adopt high speeds while proximate to stop-and-go traffic in the exit lane. Observations taken in the floating car indicated that in the presence of these exit queues, speeds were slow in all lanes up to the off-ramp gore at *MP* 16.7 (i.e., vehicles destined for locations further downstream did not accelerate until reaching this location), with speeds often **as** low **as** 25 kilometers per hour in right-hand lanes **3** and **4**.

4. ELIMINATING THE FREEWAY BOTTLENECK

During another observation day, May 31, 2000, the La Paz off-ramp remained under-saturated throughout the rush; the traffic signal immediately downstream provided right-of-way so as to prevent the formation of queues in the exit lanes' and this was verified from video. Consequently, the freeway segment sustained very high flows and no bottleneck even arose there.

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[5] **During this day, the off-ramp's middle detector functioned throughout the rush and the traffic signal accommodated exit demands sometimes exceeding 1,250 vph.**

These desirable outcomes are demonstrated in Figures 4a and 4b, oblique N- and T-curves at MPs 17.3 and 16.6, respectively. The coincident changes in the N and T displayed in Figure 4a mean that on this day, changes in traffic conditions measured at MP 17.3 were forward-moving and thus emanated from upstream. In short, the segment was no longer a source of any freeway congestion.

Study of Figure 4b reveals that from time 17:20 to 17:30, a small reduction in N was accompanied by a (nearly undetectable) rise in T. Apparently on this day, congestion from a less restrictive bottleneck downstream temporarily impeded flow past MP 16.6 (without propagating back to MP 17.3). But even with this short-term impedance, the flows at MP 16.6 were relatively high; as annotated on Figure 4b, the average rate from time 16:45 to 17:45 was over 2,100 vphpl and two shorter periods were marked by flows of 2,200 vphpl. These were appreciably higher than the average discharge flow (of 1,900 vphpl) measured in the presence of exit queues on the previous day.

Traffic on an additional observation day (June 1, 2000) likewise did not encounter any exit queues from the La Paz off-ramp. The resulting freeway flows were again very high and no bottleneck arose in the segment.

5. CONCLUSIONS

The site studied here became an active bottleneck whenever its mandatory exit lane was occupied by stop-and-go queues. These queues apparently gave rise to rubber-necking in the adjacent lanes and all this was eventually averted by keeping the off-ramp under-saturated.

The findings are not surprising. To the contrary, footnote 1 indicates the a "queue elimination" strategy was part of the logic deployed for the nearby traffic signal; i.e., when a certain detector functioned, the signal provided enough capacity to keep the off-ramp under-saturated. The use of this control logic demonstrates an appreciation on the part of the California Department of Transportation (Caltrans) for the negative impacts of exit queues; i.e., Caltrans officials, for example, were not particularly surprised by the findings presented here.

Notwithstanding its absence of surprise, this manuscript's contribution is clear: it serves to document some severe traffic problems caused by rubber-necking and the effectiveness of one simple solution to these problems. As such, the findings underscore the value of control

strategies that expedite freeway exiting. In the present case, the exit queues were completely eliminated in a simple way and, in certain instances, suitable signal logic might do this without having much impact on surface street traffic nearby. But where the complete elimination of exit queues may not be feasible, the present observations suggest that at least some improvement in freeway conditions can be realized by keeping these queues as small as possible.

As evidence of this, Figures 5a and 5b present data from an earlier observation day, March 30, 2000. Figure 5a shows some counts of vehicles occupying the segment's mandatory exit lane. These were sampled (from video) at discrete times, as shown by the figure's vertical bars. The figure is provided here merely to demonstrate that, on this day, the numbers in the exit lane were smaller than the largest values measured on May 30 (and previously shown in Figure 3).

The corresponding oblique N-curve measured at MP 16.6 (on March 30) is provided in Figure 5b.[6] Notably, the discharge flows, found to begin at about time 7:04, were typically much higher than the average rate of 1,900 vphpl (that had been measured in the presence of larger numbers occupying the exit lane on May 30).

Also shown in Figure 5b are counts of accumulated vehicles that were actually part of the exit queues on March 30; i.e., these are the counts of vehicles in the exit lane that were either stopped or very slow-moving. To simplify the figure's presentation, these counts were partitioned into categories of zero (or nearly zero) in queue; short queues of 5 to 10 vehicles; moderate and long queues of approximately **15** and 20 vehicles, respectively; and very long queues of about 25 or more. When presented in this way, it is apparent that the lengths of the exit queues affected the freeway discharge rates, with smaller values of the former giving rise to larger values of the latter.

Referring to Figure 5b, the onset of discharge (i.e., the bottleneck's activation) coincided with the initial appearance of exit queues. Soon after the latter's short-term disappearance, the discharge recovered to a rate of 2,090 vphpl; it was temporarily suppressed when exit queues became very long at time 17:22; it increased to a very high rate when queues diminished *5* minutes later; and it was again suppressed at about time 17:42 when queue lengths sharply

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[6] This **curve was actually measured by the four detectors at MP 16.6 and footnote 2 does not apply here.**

increased.

It is puzzling that on this day (March 30), the discharge rates in the presence of some exit queues were about as high, and even higher, than the discharge flow (of 2,020 vphpl) observed after the exit queues had completely disappeared on May 30. At present, we have no explanation for this. And even if this detail is not of great importance, it still points to the need for more traffic experiments.

Indeed, much remains unknown about freeway bottlenecks. The one studied here, for example, might have been even more severe had vehicles with destinations downstream become trapped behind drivers who, in seeking to minimize their own delays, slowed-down and squeezed into the exit queues when nearing the off-ramp gore; (observations of this type have recently been reported by Muñoz and Daganzo [*2000*]). **A** more complete understanding of these and other bottlenecks, and solutions to the problems they create, will only come through further empirical study.

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Figure 1
Southbound Interstate 5, Orange County, California
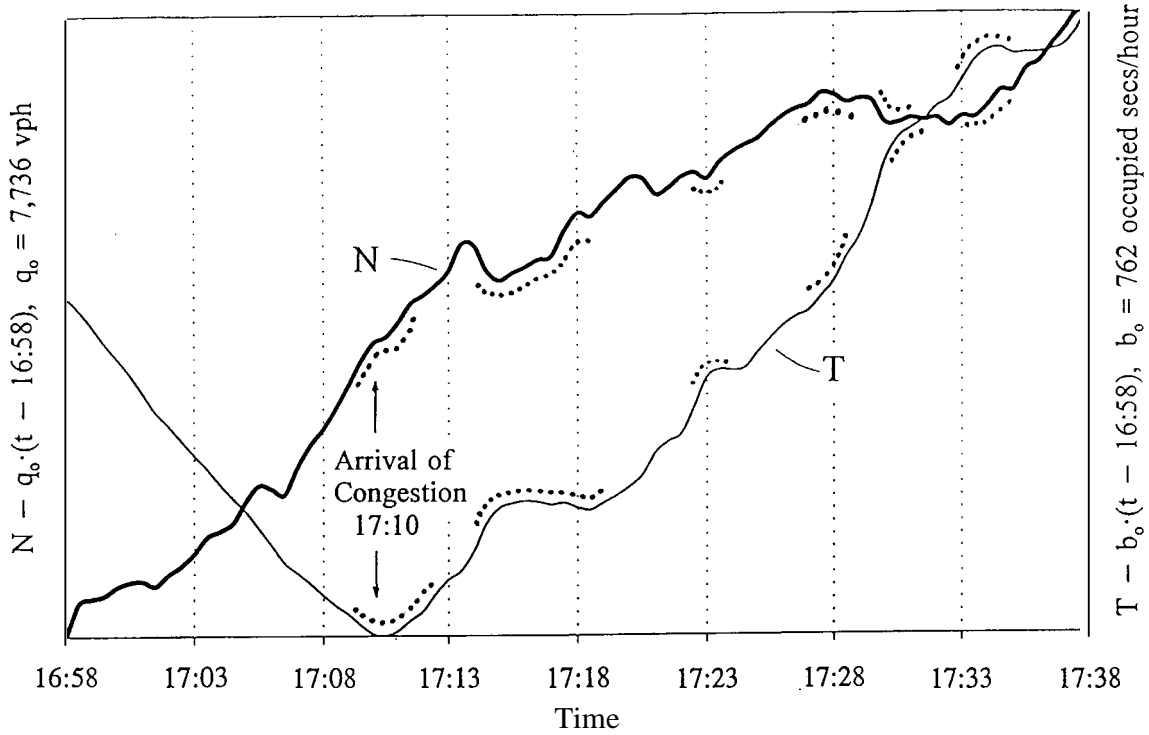(Not to Scale)

Figure 2a
Oblique N- and T-Curves, *MP* 17.3 (May 30, 2000)
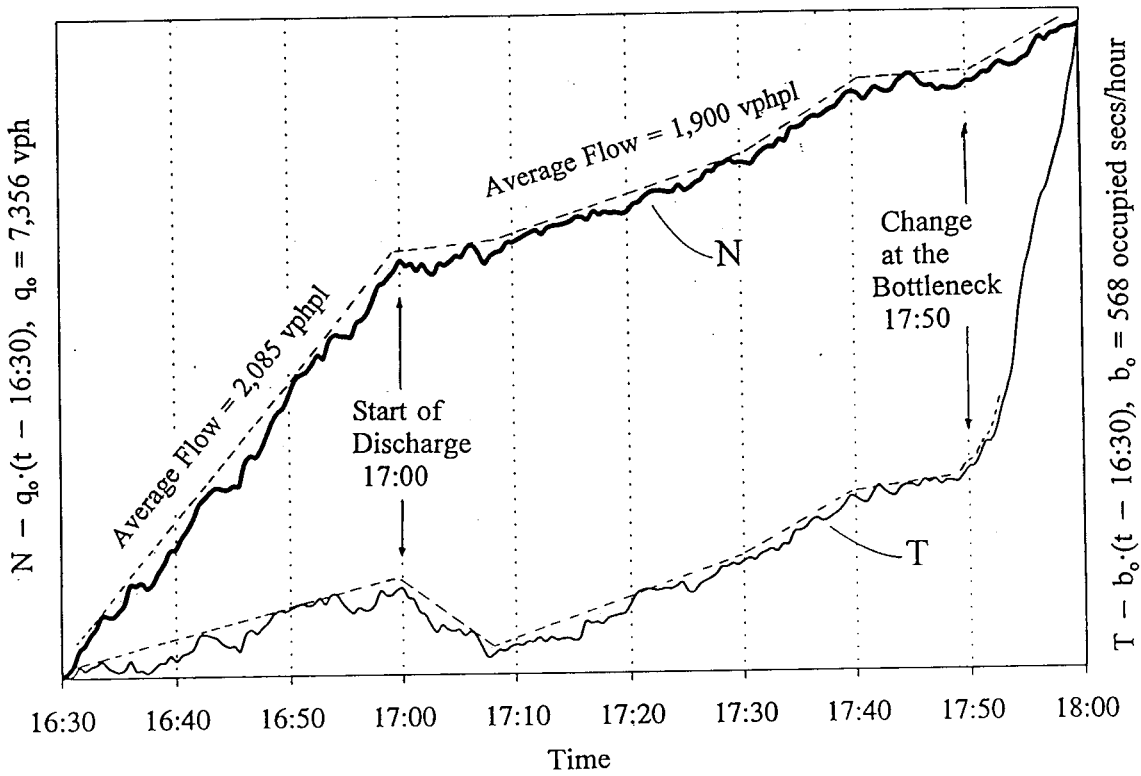Note: b_o is the rate used for displaying T in oblique coordinates

Figure 2b
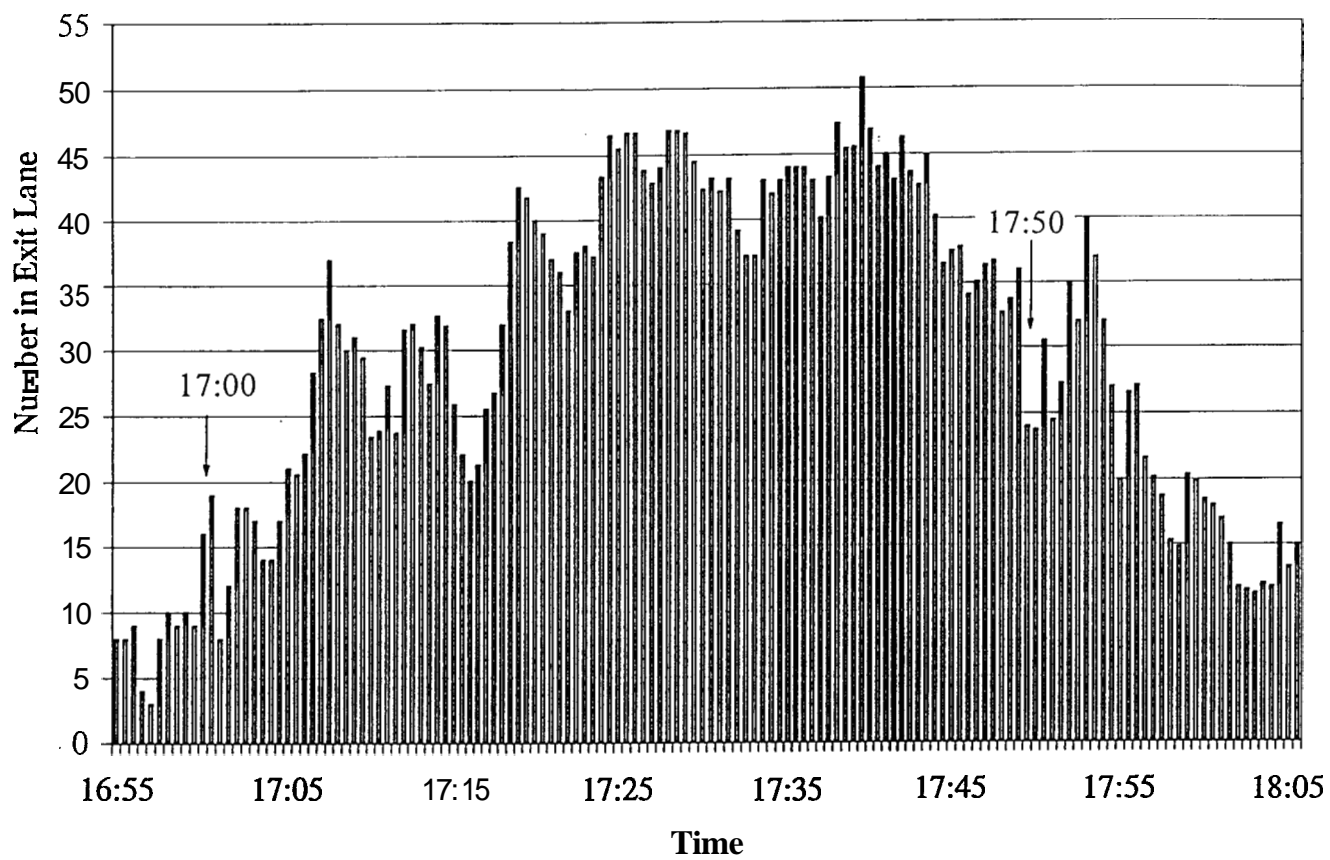Oblique N- and T-Curves, *MP* 16.6 (May 30, 2000)

Figure 3
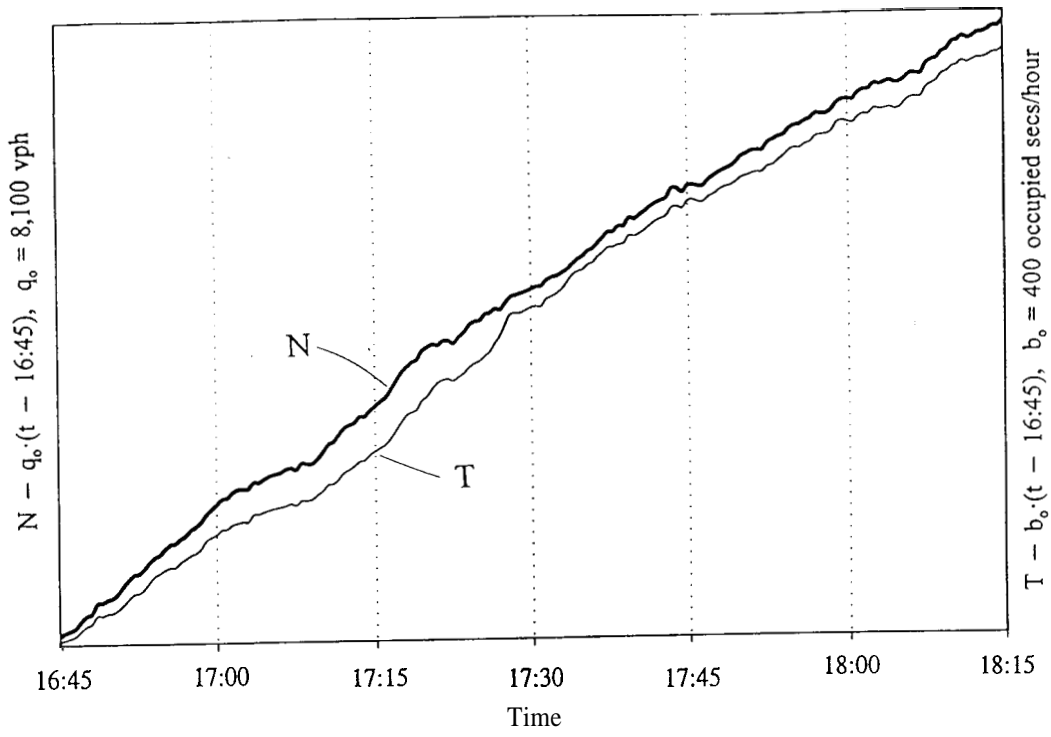Numbers of Vehicles in the Mandatory Exit Lane (May 30, 2000)

Figure 4a
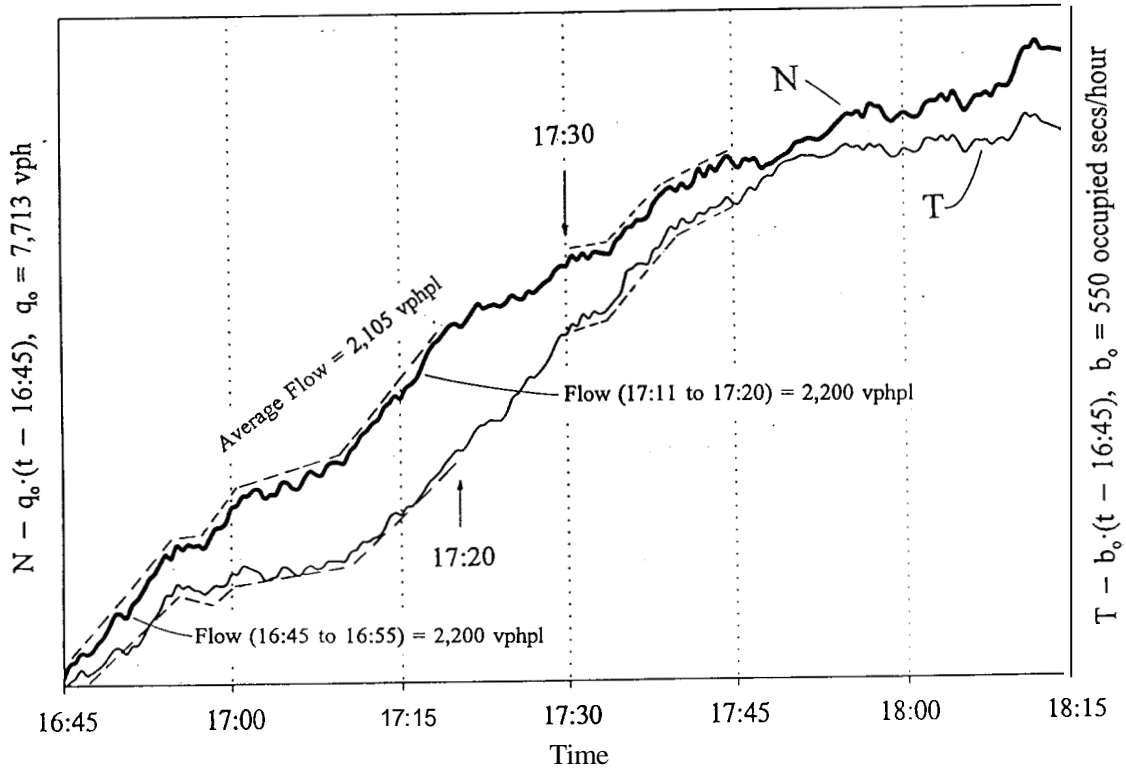Oblique N- and T-Curves, MP 17.3 (May 31, 2000)

Figure 4b
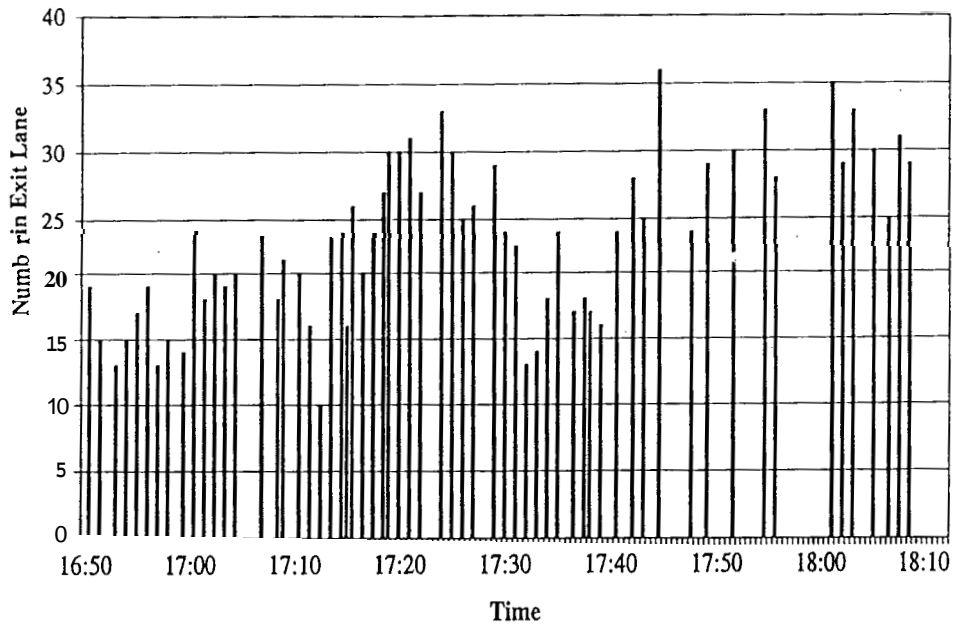Oblique N- and T-Curves, MP 16.6 (May 31, 2000)

Figure 5a

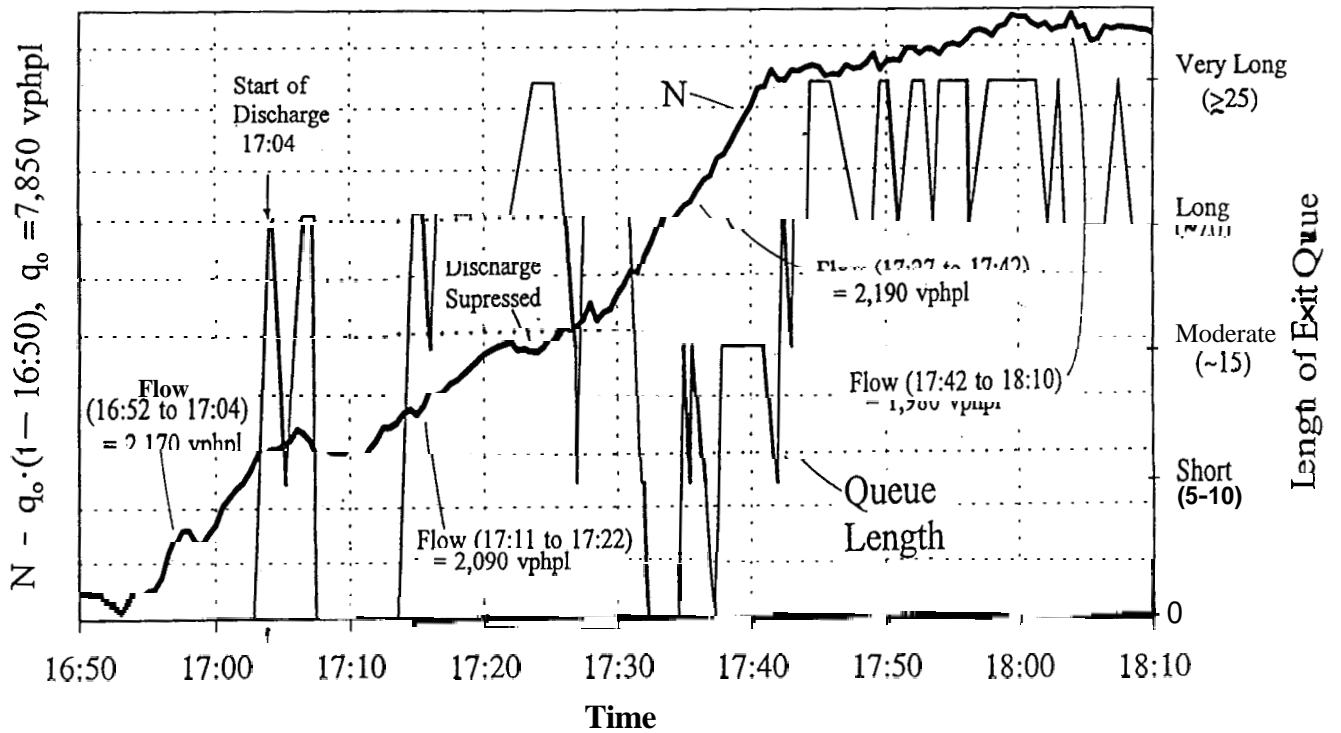Numbers of Vehicles in the Mandatory Exit Lane (March 30, 2000)

Figure 5b

Oblique N-Curve, *MP* 16.6 and Numbers of Vehicles in the Exit Lane (March 30, 2000)