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CALIFORNIA PARTNERS FOR ADVANCED TRANSIT AND HIGHWAYS

Testing Daganzo's Behavioral Theory

For Multi-lane Freeway Traffic

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1. Introduction

This report describes the detailed, albeit still preliminary study of traffic on stretches of two different freeways. Both were plagued by merge bottlenecks. The first of these sites is the Gardiner Expressway, a 3.3 km long freeway stretch in Toronto, Canada. The site was selected because of its suitable geometry (i.e. its merge bottleneck) and its well-tuned loop detectors located upstream and downstream of the bottleneck. The site thus provided for an exceptionally good "laboratory" for testing Daganzo's behavior theory of drivers (*Daganzo, 1999*). It turns out that the observations from this stretch qualitatively match the theory in a number of important ways, as will be described in this report.

The second site is a 1.8 km stretch of westbound Interstate 24 just upstream of the Caldecott Tunnel in Berkeley, California. This site provided a means for verifying Daganzo's theory for "California conditions." It is especially suitable for this study thanks to its very disruptive bottleneck and to its numerous vantage points (i.e., adjacent hillsides) from which to videotape traffic. Four cameras were strategically deployed along this freeway stretch. The detailed traffic data (manually) extracted from these videos were, like the Toronto data, found to be qualitatively consistent with much of Daganzo's theory.

Moreover, the very detailed data from California have been affording us greater opportunity to identify and study some noteworthy aspects of traffic flow. Namely, discharge flows increased when changes in traffic conditions caused the bottleneck to move upstream of the merge. These aspects of traffic flow lie beyond the scope of Daganzo's theory, but they may have important implications for freeway traffic control.

Prior to demonstrating this feature, the findings of the work to date are summarized in the following section. The detailed presentation of these findings for the Toronto and California sites then come in sections 3 and 4, respectively. (Section 4 includes the demonstration of the increased discharge that coincided with the bottleneck's change in location). Notably, the presentations in sections 3 and 4 are, for the time being, limited to observations from a single day at each of our two sites. These observations exemplify the findings from all days studied to date. (Naturally, a summary of findings from multiple observation days will be included in a final report for this work). Future research plans are included in the fifth and final section of this progress report.

2. Summary of Findings

Much as in Daganzo's theory, the data from our Toronto and California sites indicate traffic can be described by a family of stationary density-flow models like those illustrated in Fig. 2.1. The discontinuous relation shown with bold lines describes traffic in the freeway's passing lane(s). These drivers prefer traveling fast. Thus, Daganzo refers to these drivers as "rabbits." The thin curve in Fig. 2.1 describes the macroscopic behavior of a traffic stream composed of drivers to whom Daganzo refers to as "slugs." These are slower-moving drivers who occupy the freeway's shoulder lane(s).

The only notable difference between the relations shown in Fig. 2.1 and those offered by Daganzo is that the relation for slugs shown in the former has a non-linear

form. This non-linearity merely indicates that, near capacity, slug speed is sensitive to flows.[1]

The following features have been observed in the data. As these features are in general agreement with Daganzo's theory, they can be explained with reference to Fig-2.1. Indeed, each phenomenon described below is labeled on this figure.

In unqueued or freely flowing traffic, rabbits and slugs travel at different speeds; i.e., speed differences are observed between the passing and shoulder lanes. As flows increase during the rush, traffic can enter a so-called semi-congested state marked by reductions in speed among rabbits. Traffic eventually evolves to a fully congested state that is accompanied by reduced outflows from the bottleneck. These flow reductions are said to occur because rabbits become "unmotivated;" i.e. rabbits are no longer willing to drive at small headways.

The queue signaling the fully congested state propagates backward in the passing lane(s) as a fast-moving shock. The speed of this shock is given by the slope of the dashed line in Fig. 2.1. The queue eventually spreads to the freeway's shoulder lane(s) as rabbits, who no longer enjoy higher speeds, re-distribute themselves across all available lanes. After discharging from this queue, rabbits return to the passing lane(s) to satisfy their tastes for driving fast.

The following two sections of this report provide carefully constructed plots of measured data to verify the above features. These features point to the existence of density-flow curves of the forms shown in Fig. 2.1. It is in this manner that we have been verifying Daganzo's theory.

Additional Findings
Further study of these data, particularly the very detailed California data (from westbound I-24), seem to point to some features of queued traffic that are not part of Daganzo's theory but are important nonetheless. As noted earlier, we have observed that when bottleneck's moved upstream of the merge areas, higher discharge flows resulted. We continue to study this phenomenon and discussion of our ongoing work in this area is provided later in this report.

3. Findings from the Gardiner Expressway (in Toronto)
Data from the first site were measured from the paired loop detectors on the segment of the westbound Gardiner Expressway shown in Fig. 3.1. These detectors are labeled as per the numbering scheme adopted by the regional transportation authority. They record vehicle counts, occupancies and average speeds over 20-sec intervals. Traffic entering the freeway from the Spadina on-ramp is not metered and the Jameson on-ramp is closed each weekday from 15:00 to 18:00.

Fig. 3.2 is the first of a number of data plots we use to verify Daganzo's behavioral theory. It displays cumulative curves of vehicle count, N, vs. time, t, measured across all travel lanes at detectors 50-80. Each curve was measured relative to an imaginary reference vehicle that passed its detector at time t_o; i.e., t_o is the starting time for each curve. Further, each curve was shifted forward by an average free flow

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vehicle trip time from its respective detector to downstream-most detector 80. The vertical separations between any two curves are thus the excess vehicle accumulations between the respective detectors due to vehicular delays.

An oblique coordinate system was used to plot $N(t) - q_{o*}(t-t_o)$ for some choice of background flow, q_o; the value of q_o was selected so that the range of $N(t) - q_{o*}(t-t_o)$ was small as compared with the N itself. This coordinate system reduced the vehicle count actually displayed on the ordinate of Fig. 3.2. This, in turn, amplified the curves' vertical separations, rendering them more visible to the naked eye. The oblique coordinate system also made more visible the slope changes in the curves; these changes in slopes denote flow changes at the detector stations.

The N-curves in Fig. 3.2 are superimposed until t = 15:18, indicating that freely flowing traffic initially prevailed on the freeway stretch. The displacements between curves that came later reveal the gradual vehicle slowing as traffic transitioned to the semi-congested state. The N-curves separate more dramatically at t = 15:51:20, marking the start of the fully congested state.

Fig. 3.2 also verifies the presence of the *active* bottleneck[2] between detectors 60 and 70. The displacements between the curves indicate that queuing arose upstream of detector 70. That the curves at 70 and 80 are superimposed indicates that traffic was freely flowing at, and downstream of, detector 70.

The figure also shows that reductions in outflows from the bottleneck accompanied the fully congested state. This finding is consistent with the theory that rabbits eventually loose their motivation for traveling at small headways. Further verification of this loss in motivation comes later.

Further details of traffic evolution are revealed by the occupancy-flow scatter plots shown in Figs. 3.3 (a)-(d).[3] These display measurements from detector 40. Data from the median or left-hand lane are shown with the shaded circles. Data from the shoulder lane are represented by the unshaded ones.

Each of the scatter-plots displays data from a distinct traffic state. (These states were partitioned using the oblique N-curves previously shown in Fig. 3.2.).

Fig. 3.3(a) provides observations collected over 100-sec sampling intervals in freely flowing traffic (at detector 40) from t = 14:33 to 15:18. As per Daganzo's theory, the speeds of rabbits (in the median lane) were higher than those of the slugs (in the shoulder lane). Lines have been fit to each set of data in Fig. 3.3(a) to emphasize this point.

Fig. 3.3(b) displays data from 100-sec sampling intervals taken during a portion of the semi-congested state from t = 15:18 to t = 15:31. As per the theory, the speeds of rabbits in this state were lower than rabbits' free flow speed. This is highlighted in the figure using lines with slopes labeled "A" and "B." The scatter in the shaded data points indicates that, in the semi-congested state, the flows of rabbits fluctuated randomly about a nearly constant speed. The average of these shaded data points is shown in Fig. 3.3(b) as a lightly shaded rectangle. One can envision this rectangle lying somewhere on the

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[2] A so-called "active" bottleneck is one characterized by queues immediately upstream and freely flowing traffic conditions downstream (*Daganzo, 1996*)

[3] Occupancy is a dimensionless measure of density. Thus, the scatter-plots in Figs 3.3(a)-(d) can be related directly to the density-flow relations previously exemplified in Fig. 2.1.

portion of an occupancy-flow curve describing rabbits in the semi-congested state; the reader can refer back to the example provided in Fig. 2.1 to help with this visualization.

Fig. 3.3(b) also shows that, while rabbits were in the semi-congested state, the flow of slugs in the shoulder lane sometimes rose a little above the flows observed earlier in freely flowing traffic; the reader can verify this by visually inspecting the unshaded circles in Figs. 3.3(a) and (b). Fig. 3.3(b) indicates that, in this semi-congested state, the speeds of slugs dropped below their free flow speeds. This is evident from the slopes of the lines labeled "C" and "D" (and this is part of what motivated us to illustrate the density-flow relation for slugs in Fig. 2.1 with a non-linear shape near capacity).

Also of note, Fig. 3.3(b) demonstrates that, in semi-congested traffic, the speeds of both rabbits and slugs were quite similar; i.e., these average speeds differed by only 4 mph. Careful inspection of the relations previously presented in Fig. 2.1 will convince the reader that this observation is in keeping with Daganzo's theory.

Fig. 3.3(b) further shows that semi-congested flows in the median lane were greater than those in the shoulder lane; i.e., rabbits adopted smaller headways (and vehicle spacings) than did slugs. But this driver behavior of rabbits was evidently not sustainable. Traffic evolved into a fully congested state, as evident from Figs. 3.3(c) and (d). The former of these figures shows that from t = 15:31 to t = 15:53, rabbits transitioned gradually to the congested branch of the occupancy-flow relation. The shaded data points in Fig. 3.4(c) have been sampled over 300-sec intervals (to reduce statistical fluctuations) and these points have been numbered to illustrate the chronological path of this transition. That the transition occurred in a gradual manner (i.e., it involved multiple 300-sec samples) merely indicates that drivers gradually altered their speeds in response to the shock that arrived from the bottleneck downstream; see Munoz and Daganzo (*2001*) for further discussion of this.[4]

Notably, the flows of rabbits in the transition and fully congested states were lower than some of the rabbit flows observed at earlier times. This becomes apparent by visually inspecting the higher flows corresponding to the shaded data points in Figs. 3.3(a) and (b), including the rectangle in Fig. 3.3(b), and then comparing these with the flows evident by the shaded points in Figs. 3.3(c) and (d). Sizable reductions in rabbit flows are especially evident in the fully congested state described by the shaded data points in Fig. 3.3(d).

This observed reduction in rabbit flow points to a loss of motivation among these drivers. Further evidence of this will be provided momentarily.

Fig. 3.3(d) also shows that a gradual transition from freely flowing to queued conditions occurred in the shoulder lane. The unshaded data points were sampled using 300-sec intervals and are again numbered in chronological order of their occurance.[5] Notably, this transition in the shoulder lane occurred after the transition of the rabbits in the median lane. This sequence of events is consistent with Daganzo's theory.

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[4] It is well understood that dramatic changes in a driver's speed do not occur instantaneously and the gradual transition shown in Fig. 3.4(c) is the consequence of this.
[5] These numbers show that traffic in the shoulder lane transitioned somewhat erratically; i.e., the unshaded data points did not transition strictly from left to right. This same phenomenon was observed in the median lane's transition (among the unshaded data points) when sampling intervals smaller than 300 secs were used.

The data also support the notion that the shoulder lane queue formed because some rabbits forced their way into this lane, thereby interrupting the flows there. Visually comparing the unshaded data points in Fig. 3.3(a) with those in Fig. 3.3(d) indicate that shoulder lane flows were slightly lower before the outset of the fully congested state. These flow differences may be the result of rabbits eventually entering the shoulder lane.[6]

The changes in shoulder-lane flows are confirmed in Fig. 3.4. It displays oblique N-curves for the median and shoulder lanes at detectors 40 before and after the outset of the fully congested state. The figure shows that congestion brought lower flows to the median lane, but higher flows to the shoulder lane. Again, this would seem to reflect the tendency of rabbits to distribute themselves across all lanes once the passing lane(s) no longer accommodate higher speeds

Further details of traffic evolution are revealed in Fig. 3.5. It presents oblique N-curves at detectors 50, 60 and 80. The arrows drawn in bold in this figure trace the path of the shock that separated the semi-congested from the fully congested traffic states. These arrows connect the flow reductions that accompanied the fully congested state. The slope of a bold arrow itself is the speed of the shock. Fig. 3.4 indicates that this shock traveled between detectors 60 and 50 at an approximate speed of 46 km/hr.[7]

This is a very high speed and it is consistent with the assumption of a discontinuous density-flow relation for rabbits. (The slope of the dashed line previously shown in Fig. 2.1 is the shock speed).

Fig. 2.1 also indicates that the (backward-moving) waves that arise in queued traffic presumably propagate at a (nearly) constant speed slower than that of the shock. This feature is also revealed by the oblique N-curves in Fig. 3.5. The thinly drawn arrows in this figure trace some of these waves; these arrows connect changes in slopes on curve 60 with similar changes on curve 50. The slopes of these arrows indicate that average wave speed was about 23 km/hr. (This estimated wave speed is approximate for the reason given in footnote 7)

Finally, Daganzo's behavior theory predicts that, upon discharging from the bottleneck's queue, rabbits again assign themselves to the freeway's passing lanes in order to satisfy their preferences for driving fast. (Traffic is thus said to transition from a fully queued, 1-pipe state to an unqueued, 2-pipe state downstream). This feature was evident in the data.

Fig. 3.6(a) presents oblique N-curves measured in the median lane (only) at detectors 60-80. The figure shows that at detector 60 (residing upstream of the bottleneck), median lane flow diminished to about 2,080 vph at the outset of the fully congested state. But as vehicles discharged from the queue and approached detector 70, rabbits began assigning themselves to the median lane. Fig. 3.6(a) indicates that the average discharge flow measured at detector 70 was 2,225 vph, an increase from the rate measured upstream at detector 60. The figure shows that this re-distribution of rabbits

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[6] Also of note, Fig. 3.4(c) shows that slug speed during this period dropped below free-flow speed, indicating the existence of a non-linear or piece-wise occupancy-flow relation.

[7] This estimated shock speed is approximate because the detectors' 20-sec sampling intervals precluded the precise determinations of when the shock arrived to each detector. Eliminating this measurement error was a motivation for our ongoing efforts to extract individual vehicle arrival times at fixed freeway locations from video. These ongoing studies are described later in the report.

into the median lane continued as vehicles moved further from the queue. The average median lane discharge rate at detector 80 rose to 2,360 vph.

This (spatial) trend in median lane flow was accompanied by an opposite trend in the shoulder lane (as rabbits steadily exited this lane as they moved away from the head of the queue). Fig. 3.6(b) shows this exodus of rabbits. The shoulder lane flows gradually diminished from an average rate of about 1,995 vph at detector 60; to a rate of approximately 1,840 vph at detector 70; and finally to a rate of about 1,705 vph at detector 80.

Moreover, Fig. 3.6(b) indicates that the reduction in bottleneck outflow brought by the fully congested state (and previously displayed in Fig. 3.2) did not occur in the shoulder lane. Shoulder lane flows at detectors 60 and 70 remained more or less the same following the outset of fully congested traffic. This suggests that the outflow reductions (shown in Fig. 3.2) were caused by a loss of motivation among rabbits but not among slugs. This finding is consistent with Daganzo's theory; it points to the existence of a density-flow relation for slugs that is continuous in form and a relation for rabbits that is discontinuous. These are the forms previously presented in Fig. 2.1.

4. Findings from Interstate 24 (in Berkeley, California)

The stretch of I-24 used as our second test site is illustrated in Fig. 4.1. Individual vehicle arrival times at fixed freeway locations were manually extracted from videotape. As shown in the figure, four cameras were used to collect arrival times at four locations.

Figs. 4.2(a)-(c) present oblique N-curves to verify that an active bottleneck arose on the California site. Fig. 4.2(a) displays N-curves measured at upstream-most locations 1 and 2. The displacement between these two curves beginning at about t = 14:35:40 marks the outset of the semi-congested state. The sudden and pronounced reduction in flow at approximately t = 15:16:00 marks the beginning of the fully congested state. Fig. 4.2(a) thus verifies that queueing arose at (the upstream end of) the test site.

Fig. 4.2(b), on the other hand, demonstrates that the downstream end of this freeway stretch remained freely flowing over the entire rush. It presents oblique N-curves at locations 3 and 4. The two curves are consistently superimposed, indicating that free flow conditions persisted on the intervening link. Vehicle counts at location 3 can therefore be used for estimating bottleneck capacites.

Fig. 4.2(c) provides transformed N-curves at location 2 and 3; these curves exclude counts from the on- and off-ramps at Fish Ranch Road. The displacements in these curves verify that, during a portion of the rush, the head of the bottleneck's queue resided somewhere between locations 2 and 3. Specifically, the figure shows that excess vehicle accumulation began to occur between these locations at about t = 14:43:10

The pattern of discharge flows exhibited by this (California) bottleneck is qualitatively like the pattern observed on the Gardiner Expressway in Toronto. High flows departed from both sites for sustained periods prior to the outset of the fully congested states. These fully congested states were accompanied by severe flow reductions that persisted for about 10 mins before discharge rates recovered somewhat (but these rates did not return to those very high flows observed at earlier times).

Tables 4.1(a) and (b) summarize outflow measurements from the California and Toronto sites, respectively. The reader can compare these two tables to verify the clear

similarities between the two sites. These observations, moreover, are consistent with Daganzo's theory.

Our data reveal some additional features of bottleneck discharge. A particularly interesting event at our California site is described below.

At t = 15:52:25, a passenger car made an emergency stop; it parked in the left-hand shoulder a short distance upstream of location 2 [8] and remained there until 16:51:00 (refer again the Fig. 4.1). Although the vehicle did not block a travel lane, it apparently did induce some initial "rubber-necking effects." By t = 15:53, the average flow past location 3 dropped from 1,990 vph per lane to 1,805 vph per lane (see Fig 4.2(b)).

Table 4.1(a) Observation from California site

Observation	Start	End	Flow (vph/lane)	% difference[9]
High flow prior to queue formation	15:03:00	15:16:05	2040	
Severe flow reduction	15:16:05	15:27:08	1915	6.1
Recovery flow[10]	15:27:08	15:55:00	1990	2.5

Table 4.1 (b) Observation from Canadian site

Observation	Start	End	Flow (vph/lane)	% difference
High flow prior to queue formation	15:30:43	15:51:03	2190	
Severe flow reduction	15:51:03	16:02:03	1925	11
Recovery Flow	16:02:03	16:31:43	2050	5.3

Since the stalled vehicle restricted flow from proceeding downstream, the vehicle accumulations between locations 2 and 3 returned to those of freely flowing conditions. This is evident in Fig. 4.2(c); the vertical displacements between the N-curves completely disappeared by t = 16:05:35. Excess vehicle accumulations did, however, remain between locations 1 and 2. Thus, the stalled vehicle moved the bottleneck to a location somewhere upstream of location 3 by t = 16:05:35.

Remarkably, it was at this same time that discharge from the bottleneck rose substantially. Fig. 4.2(b) shows that, at t = 16:05:35, the outflow measured at location 3 increased from an average rate of 1,805 vph per lane to 2065 vph per lane.[11] This higher rate persisted for an extended time, as is evident in Fig. 4.2(b).

At present, the explanation for this observed rise in bottleneck capacity remains elusive. The cause may be linked to the on-ramp at Fish Ranch Road; refer again to Fig.

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[8] This event is documented on videotape.

[9] This is with respect to the high flow observed prior to the bottleneck activation at each site.

[10] After the drop in discharge rate, the flow departing the bottleneck increased again at both sites

[11] Similar (although less dramatic) events were observed for our Canadian test site. On multiple occasions, surges from the Spadina on-ramp caused the bottleneck temporarily to move upstream of its original location between detectos 60 and 70; refer again to Fig. 3.1. These events were accompanied by higher outflows measured at detectors 70 and 80.

4.1. It may be that moving the bottleneck upstream of location 3 provided for smoother, less disruptive merging maneuvers at the Fish Ranch interchange and that this contributed to the higher outflow. There may even be some commonality between our present observations and those reported much earlier by Edie and Foote (*1967*). This earlier study found that by restricting vehicles to reduce densities near a bottleneck in a New York tunnel, outflows increased by about 6 percent.

Understanding the details that triggered the higher outflows observed in our present work can have important implications for freeway traffic management. Thus, an understanding of this phenomenon will be an objective in our ongoing efforts. Other areas to be studied as part of this research project are described in the following section.

5. Future Research Plans

Confirming the existence of fast-moving shocks is one of the more pressing issues that remains to be addressed in this work. Observed shock speeds on the Gardiner Expressway in Toronto are consistent with Daganzo's theory. These estimated speeds are approximate, however, because the loop detectors for collecting measurements there used 20-sec sampling intervals. The coarseness of these data render our estimated shock speeds subject to error. Shock speeds could not be studied on our California site (I-24) because the freeway segment upstream of the bottleneck is not homogeneous.

Our future research plans include measuring shock speeds on homogeneous segments of the interstate 80 test bed in Berkeley; i.e., the so-called *Berkeley Highway Laboratory*. The video cameras deployed there should provide high resolution data to estimate shock speeds precisely.

Remaining efforts will also include summarizing observations from additional days. As noted earlier, the final report for this work will document findings from multiple observation days.

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Edie, L.C., and Foote, R.S.(1958) Traffic flow in tunnels. *Highway Res. Board Proc.*, 37, pp 334-344.

Muñoz, J. C. and Daganzo C. F. (2001). 'Structure of the Transition Zone Behind Freeway Queues', forthcoming in Transportation Science (can be found as PATH working paper UCB-ITS-PWP-2000-24)
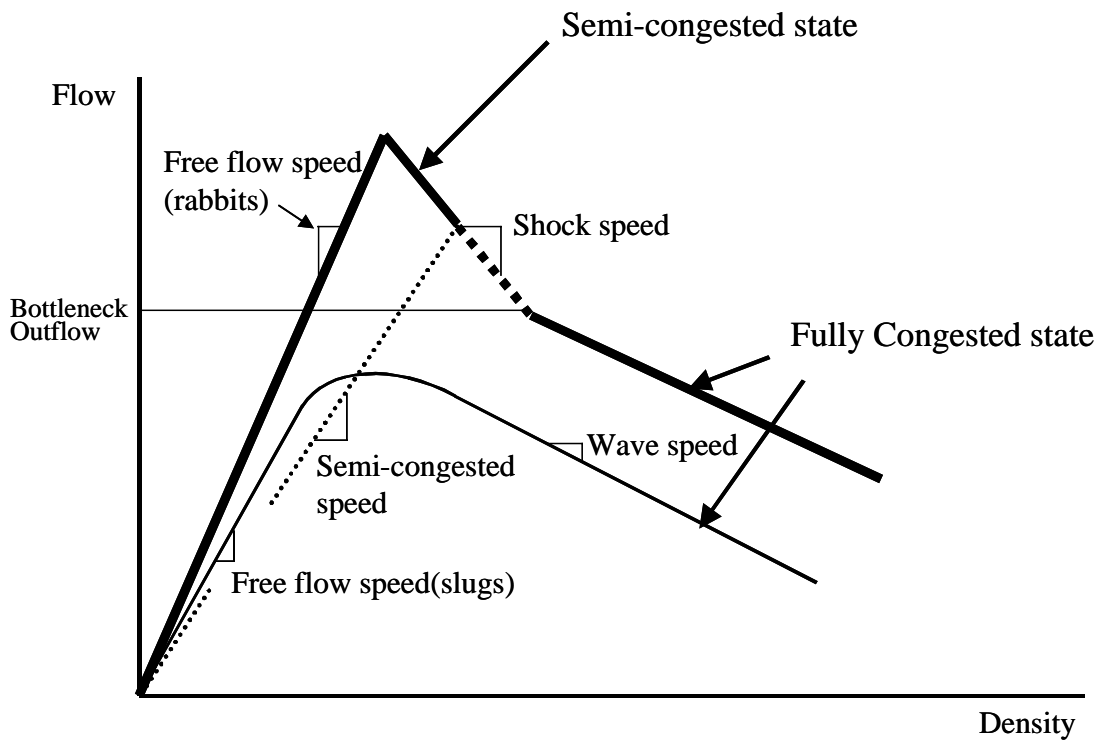
Figure 2.1 Density-Flow Relations Implied from Observation

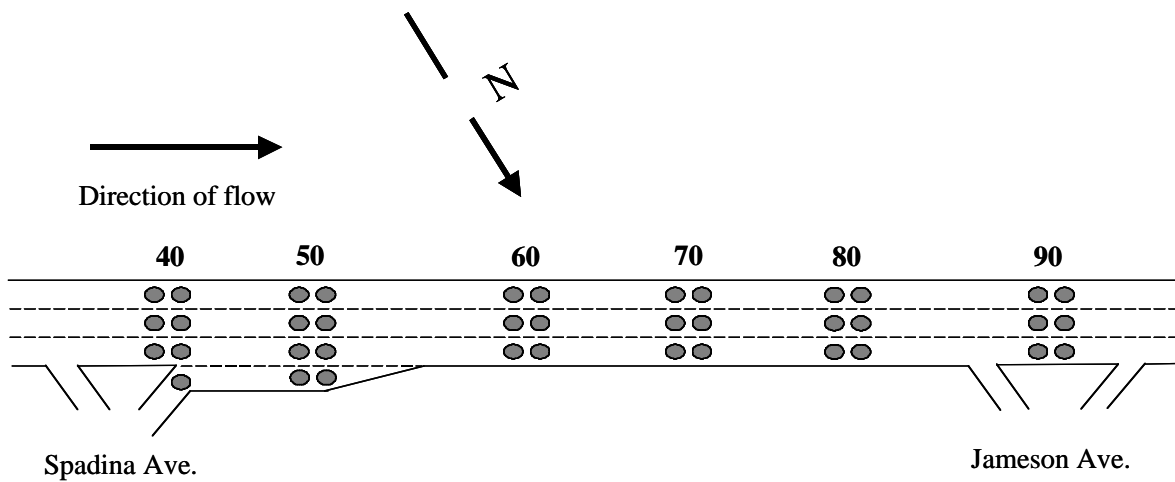Figure 3.1 Gardiner Expressway, Toronto, Canada
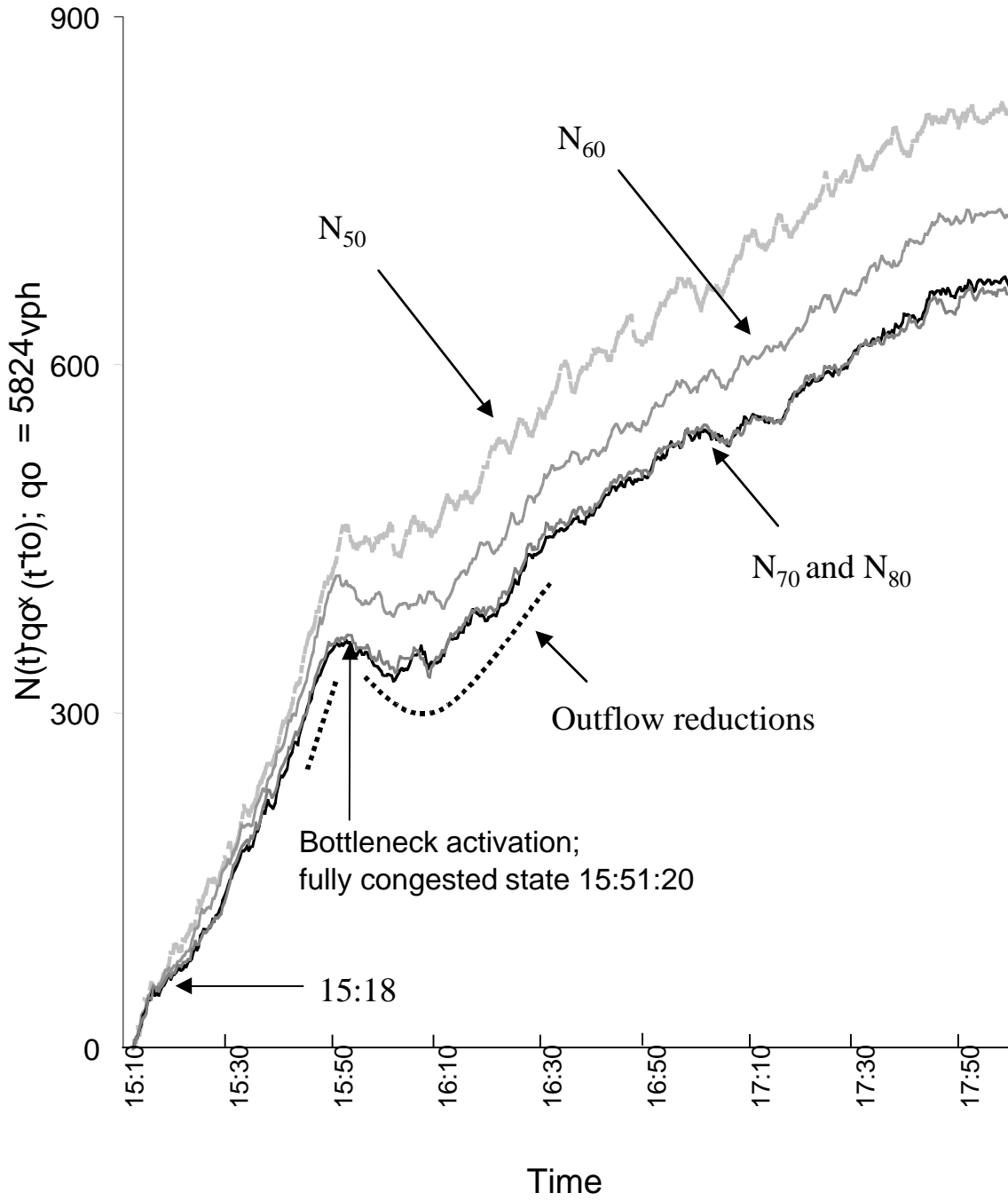
Figure 3.2 Oblique N-curves, Detectors 50-80

$N(t) \cdot q_o \cdot (t \cdot t_o)$; $q_o = 5824$vph

N_{60}

N_{50}

N_{70} and N_{80}

Outflow reductions

Bottleneck activation;
fully congested state 15:51:20

15:18

Time

Figure 3.3(a) Occupancy-Flow Data from Free Flow State at Detector 40 (from 14:33 to 15:18)

Rabbit speed: 95 km/hour

Slug speed: 86 km/hour
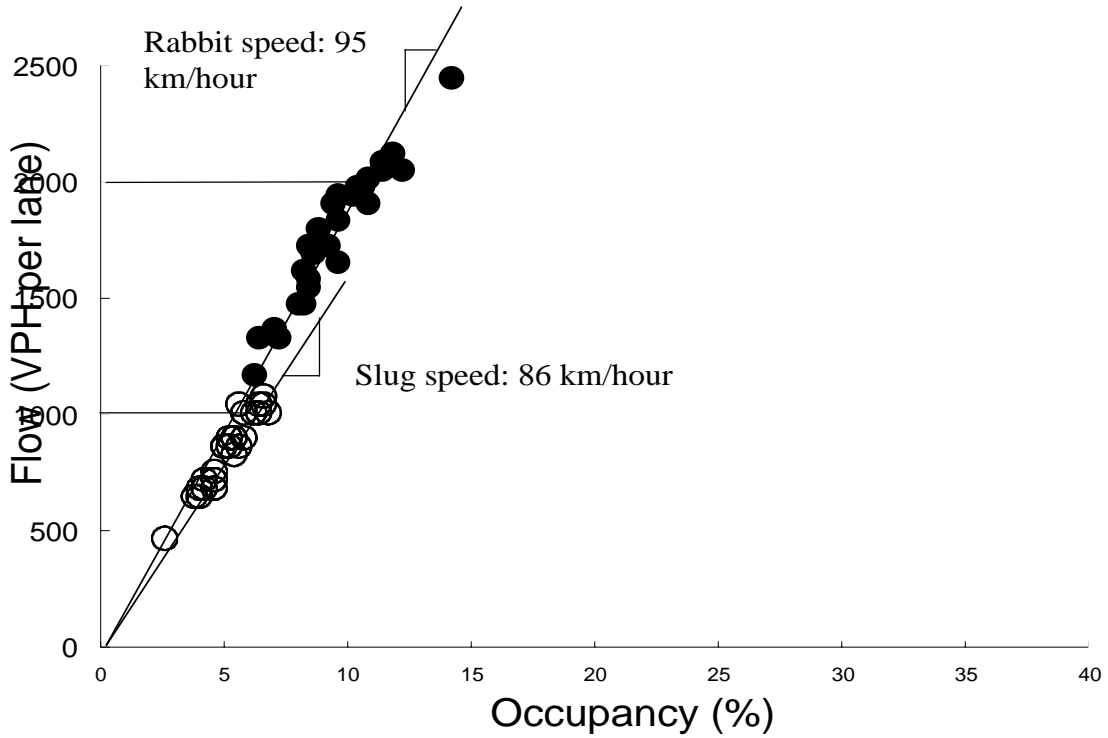
Figure 3.3(b) Occupancy-Flow Data from Semi-Congested State at Detector 40 (from 15:18 to 15:31)

A: Rabbit semi-congested speed: 72 km/hour

B: Rabbit free flow speed: 95 km/hour

C: Slug speed: 76 km/hour

D: Slug free flow speed: 86 km/hour
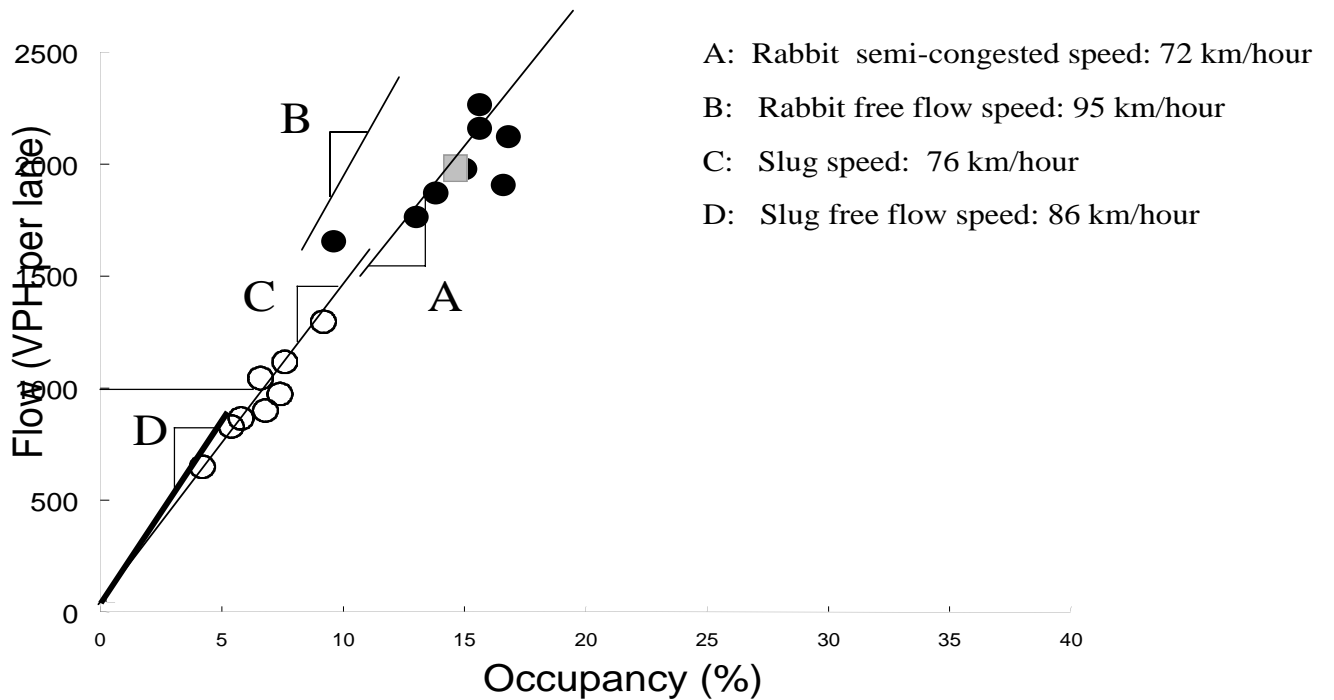
Figure 3.3(c) Occupancy-Flow Data at
Detector 40 From 15:31to 15:53

300-sec Sampling intervals (rabbits)

100-sec Sampling intervals (slugs)

Free flow speed (slugs)
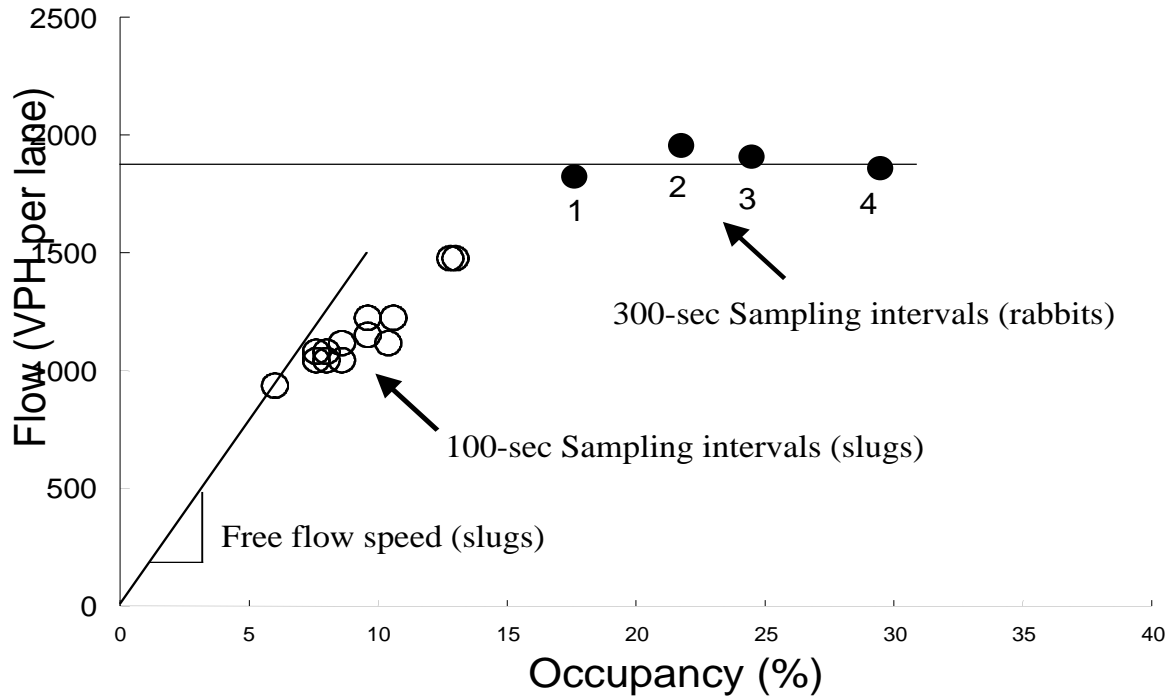
Figure 3.3(d) Occupancy-Flow Data at
Detector 40 From 15:54 to 16:16

100-sec Sampling intervals (rabbits)

300-sec Sampling intervals (slugs)
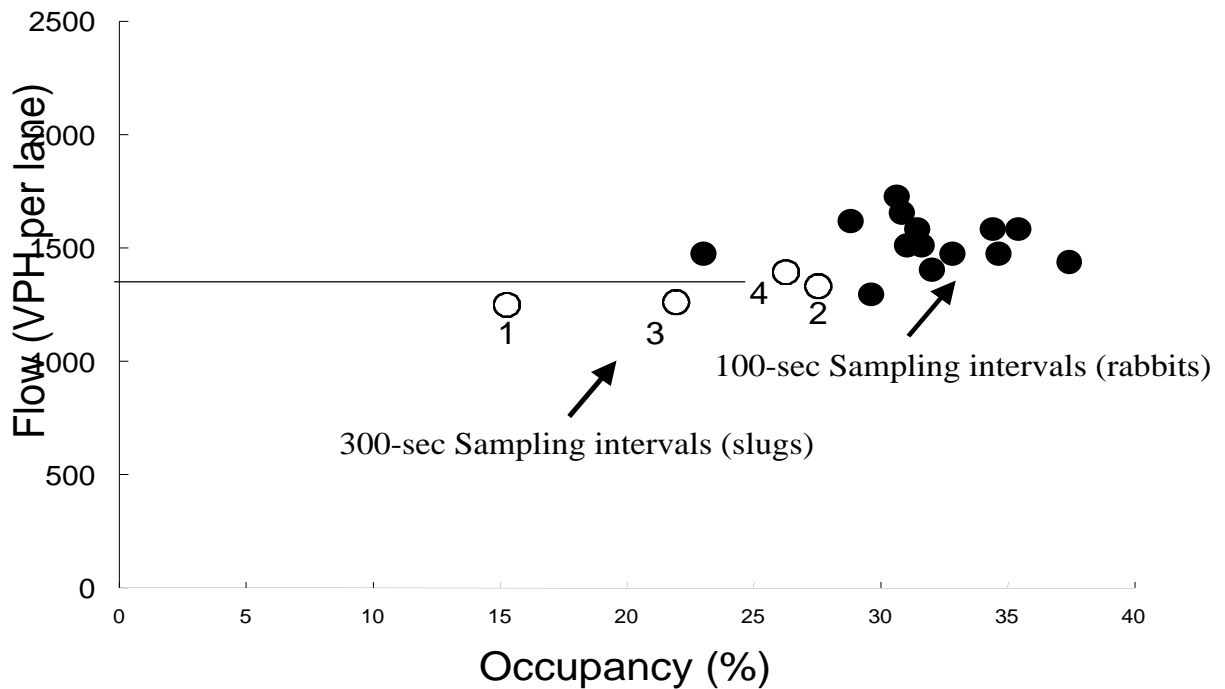
Figure 3.4 Oblique N-Curves at Detectors 40

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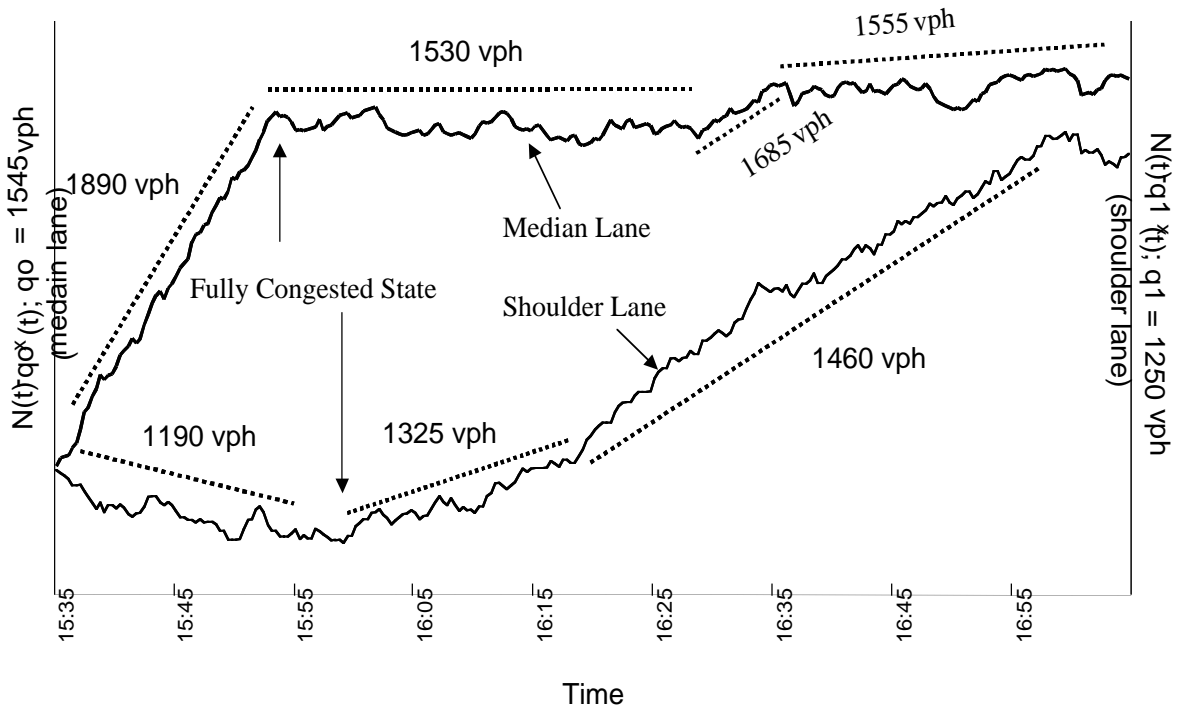
Figure 3.5 Oblique N-Curves at Detectors 50,60 and 80

46km/hour

N_{50}

35 km/hour

28 km/hour

15 km/hour

15 km/hour

N_{60}

N_{80}

N(t)¬qo¥(t); qo = 6000vph

15:40   15:55   16:10   16:25

Time
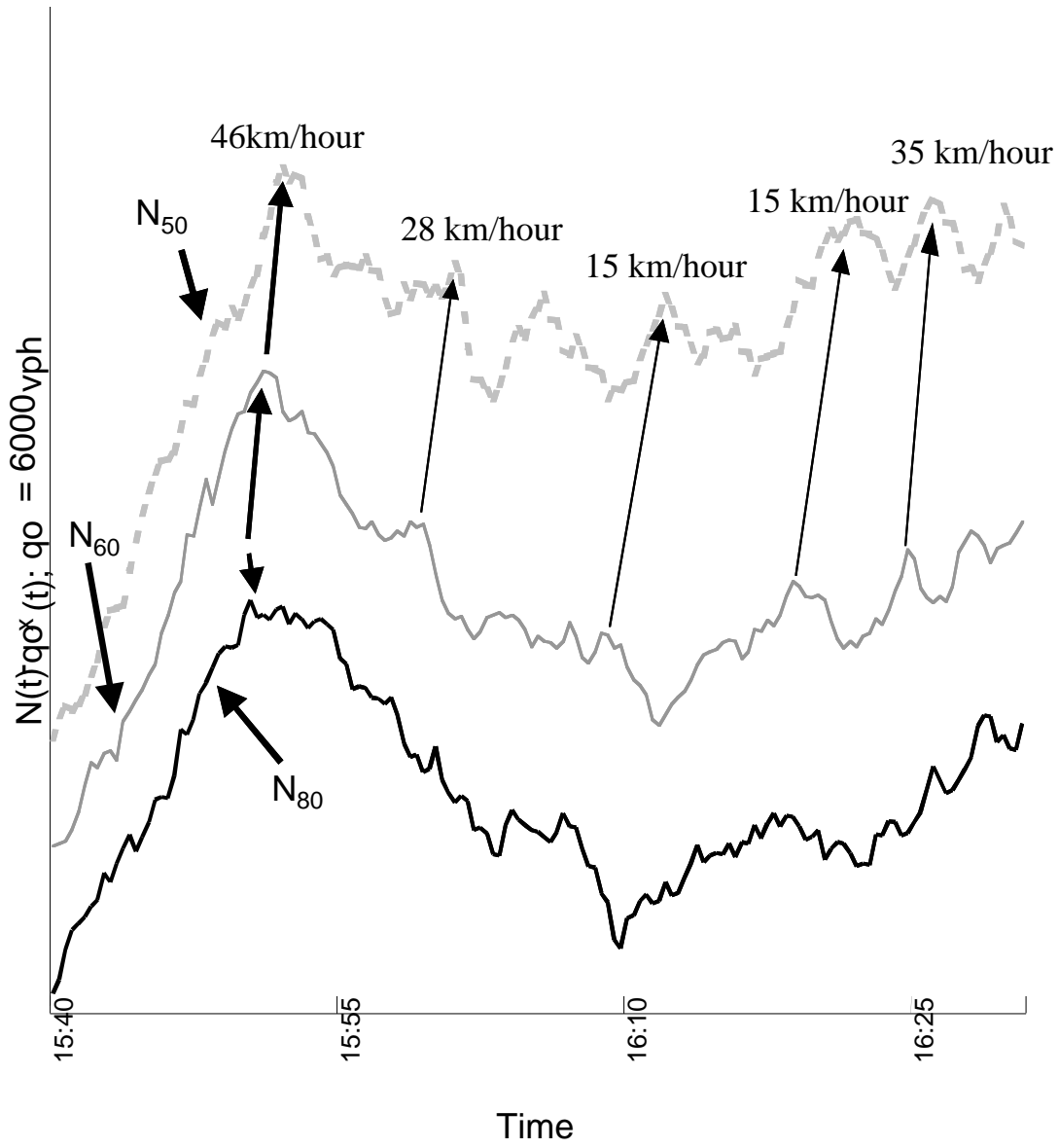
Figure 3.6(a) Oblique N-Curves at Detectors 60-80, Median Lane

2360 vph

N_{80}

2225 vph

2620 vph

N_{70}

2525 vph

2080 vph

2380 vph

Fully Congested State

N_{60}

$N(t)-qo^x(t)$; $qo = 2250$ vph

15:00   15:15   15:30   15:45   16:00   16:15   16:30   16:45

Time
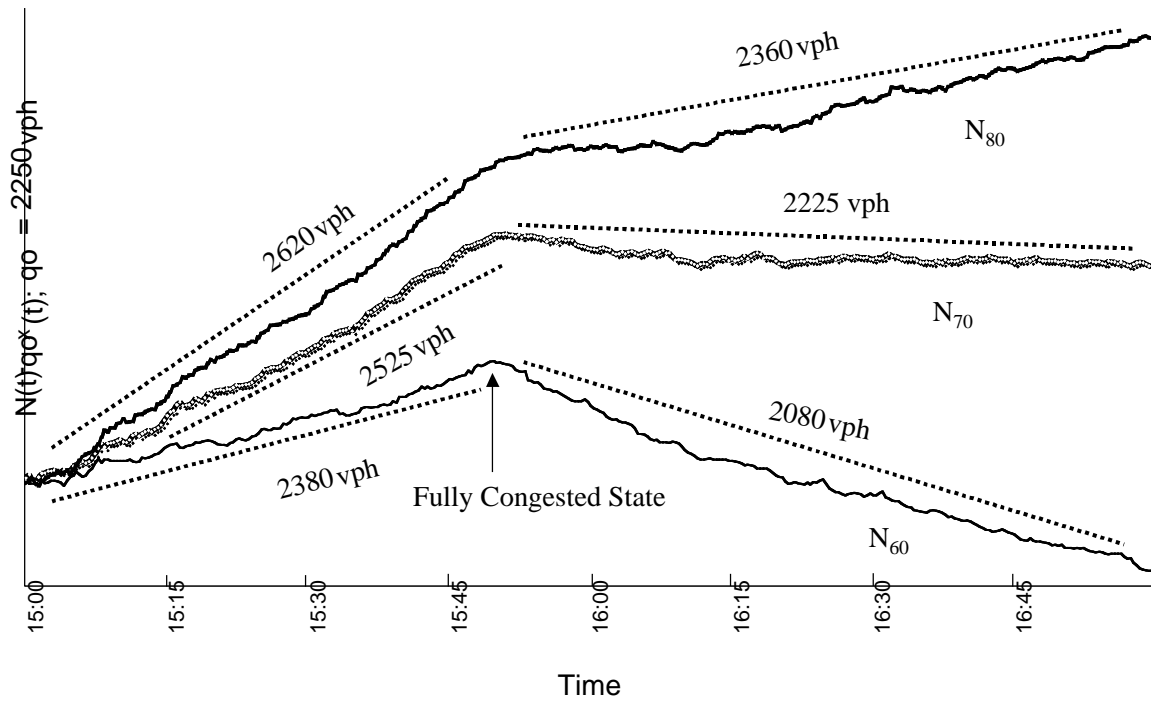
Figure 3.6(b) Oblique N-Curves at Detectors 60-80, Shoulder Lane

1995 vph

N_{60}

Fully Congested State

1840 vph

N_{70}

1705 vph

N_{80}

$N(t)-qo^x(t)$; $qo = 1750$ vph

15:00   15:15   15:30   15:45   16:00   16:15   16:30   16:45

Time

15
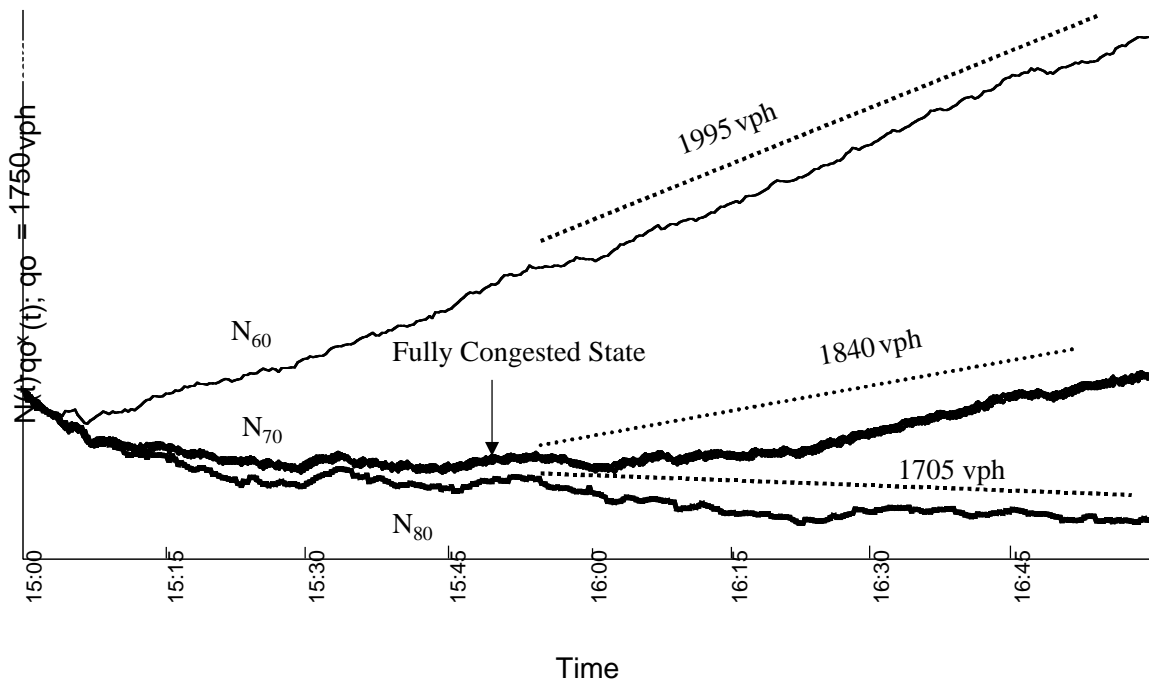
Figure 4.1 Interstate 24, Berkeley, California

Direction of flow

Location 2   Location 3

Caldecott tunnel

Gateway

Fish Ranch road

Location 1

Location 4

Legend

: Camera
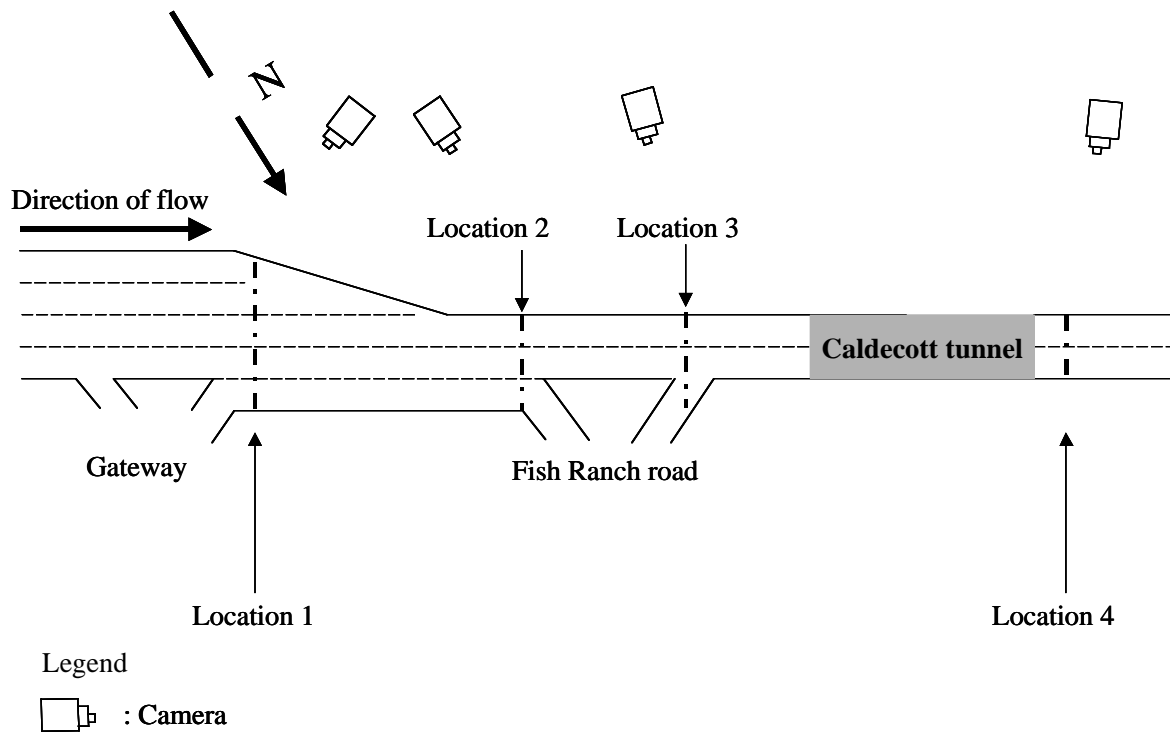
Figure 4.2(a) Oblique N-curves, Locations 1 and 2

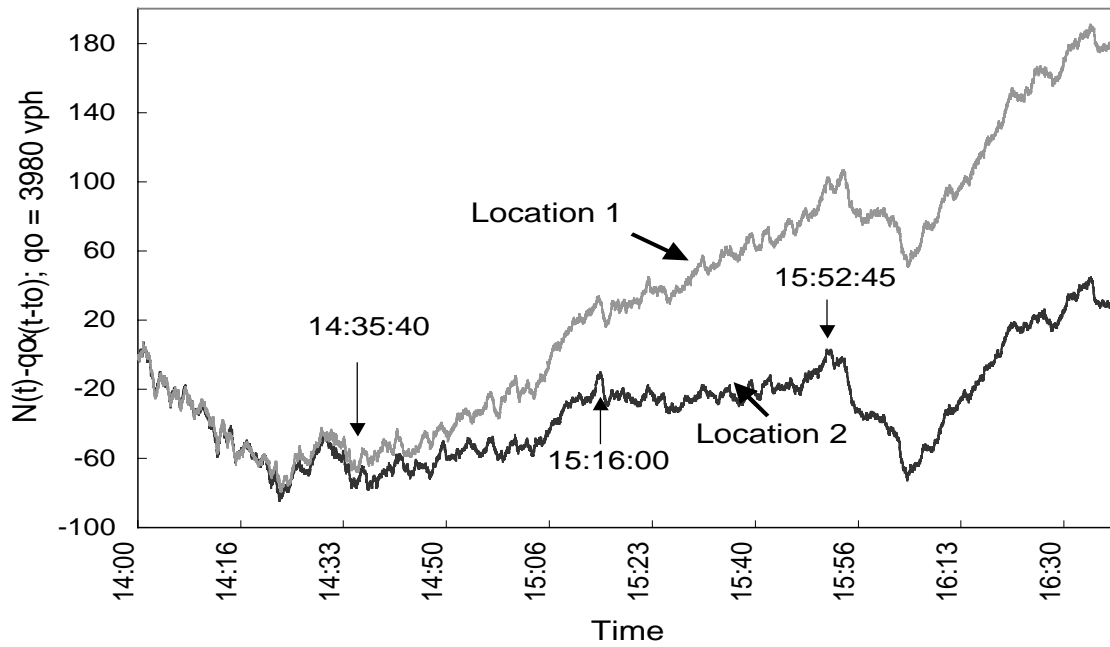Location 1

14:35:40

15:52:45

15:16:00

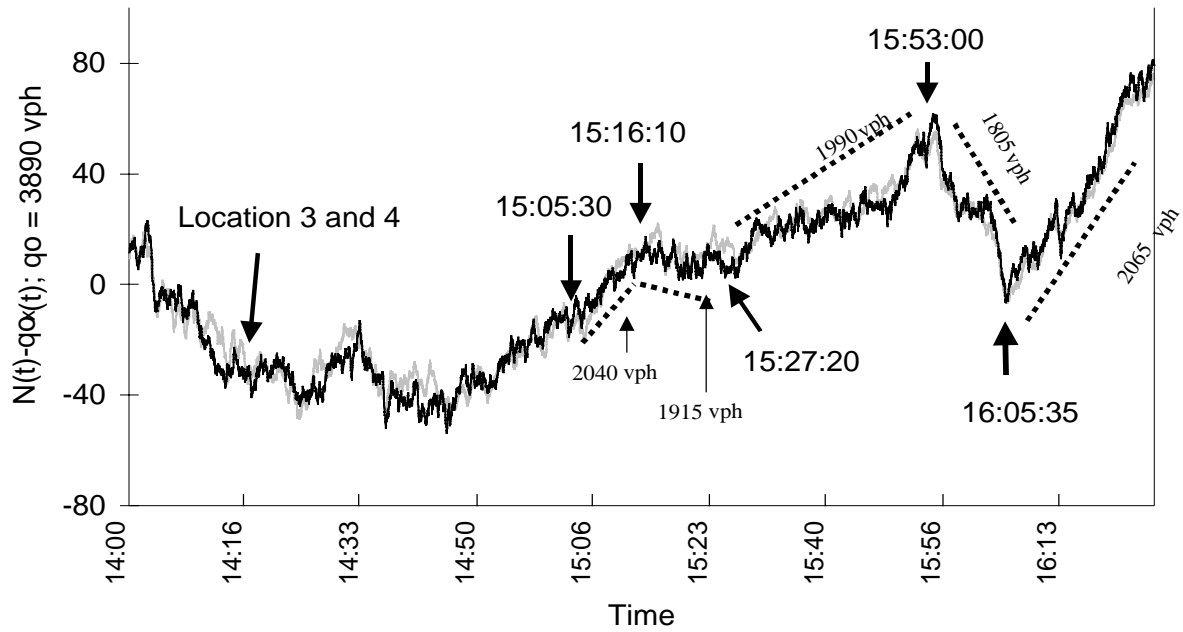Location 2

Time

Figure 4.2(b) Oblique N-curves, Locations 3 and 4

Figure 4.2(c) Olique N-curves, Locations 2 and 3 (excluding ramp counts)

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