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Increasing freeway merge capacity through on-ramp metering

by

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B. Eng. (Chulalongkorn University) 1999
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of the

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Spring 2005

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University of California, Berkeley

Spring 2005

Increasing freeway merge capacity through on-ramp metering

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by

Jittichai Rudjanakanoknad

Abstract

Increasing freeway merge capacity through on-ramp metering

by

Jittichai Rudjanakanoknad

Doctor of Philosophy in Engineering – Civil and Environmental Engineering

University of California at Berkeley

Professor Michael J. Cassidy, Chair

This research describes field studies of how on-ramp metering can increase the capacity of freeway merges. Some effects of on-ramp metering have been known for a long time. We have known that on-ramp metering can 1) increase freeway flow and speed upstream of a merge; and 2) reduce system-wide delay by alleviating gridlock-causing queues that have blocked off-ramps. However, past studies have not conclusively shown that on-ramp metering can increase the maximum outflow (capacity) of freeway merges.

The experiments conducted in the present study verify that on-ramp metering can increase freeway merge capacities. Detailed traffic data collected from videos for more than 30 rush periods at two merge bottlenecks unveil six major research findings: 1) merge capacity diminishes after merges became active bottlenecks; 2) the mechanism of "capacity drop" has been identified and was found to be reproducible across all days and at both sites. By metering the on-ramp in certain strategic ways, the capacity drop mechanism can be 3) reversed; and 4) even averted; 5) such metering strategies can be

fully automated using loop detector measurements; and 6) control strategies other than ramp metering also hold promise for increasing merge capacities.

These findings provide much-needed information concerning how to control freeway traffic. They also offer basis for more realistic theories of merging traffic flow.

_____

Professor Michael J. Cassidy,

Committee Chair

DEDICATION

This work is dedicated to my parents, who supported and encouraged me through years with love and understanding. I also dedicate this work to my home country, Thailand, where I was born and had lived for more than twenty years of my life.

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1. INTRODUCTION

This dissertation documents a discovery of a capacity drop mechanism at freeway merge bottlenecks and a role for on-ramp metering to increase capacity at these bottlenecks. To this end, extensive observations were collected and carefully studied to identify the traffic phenomena that arise at two freeway merges, after these became active bottlenecks.[1] This was followed by the development and the experimental testing of improved metering schemes to prove that on-ramp metering can favorably affect merge capacities.

Detailed observations collected using video cameras over 30 days at two merge bottlenecks reveal that capacity drops (a substantial and persistent reduction in unconstrained outflow following the onset of upstream queues) are triggered by a queue that forms near the merges in the freeway's shoulder lane. Once the vehicle accumulation in this queue reaches a critical value, shoulder-lane vehicles slow down and lane-changing maneuvers increase sharply as drivers attempt to avoid slow traffic in and near the shoulder lane. This maneuvering spread the queue laterally across the freeway. The capacity drop ensued and generally persisted through the entire rush.

Controlling the shoulder-lane vehicle accumulation and lane-changing maneuvers are thus the key to postponing and/or reversing capacity drop. Field experiments at one site show that by metering the on-ramp in certain ways, metering can favorably affect this capacity drop mechanism by reversing and/or postponing the mechanism. Reversing

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[1] The term "active" is used to characterize a bottleneck with a queue discharge rate that is not affected by downstream traffic conditions (Daganzo, 1997). Traffic measurement from an active bottleneck is essential for studying capacity.

capacity drop can be done first by using restrictive metering until vehicle accumulations on the shoulder lane diminished below the critical value. Then, high outflows can be fully recovered by relaxing the metering rate to bring the freeway queue to the brink of re-forming at the merge. Drivers in this traffic state apparently become sufficiently motivated, such that the merge can pump-out higher outflow. The observations also infer that the capacity drop mechanism can be averted entirely by metering in a proactive fashion, i.e., if metering is implemented in such ways as to always keep vehicle accumulations on the shoulder lane below the critical value, the capacity drop can be avoided entirely at the merge.

The study also found the relationship between occupancies detected from the loop detectors just upstream of the merge and vehicle accumulations in the shoulder lane. It follows that measured occupancies can be the basis for implementing the traffic-responsive metering schemes described above in a fully automated fashion. Such metering logic was tested and found to produce a longer period of high outflows.

The evidence from a second freeway merge site implies that a high capacity can be gained even when the on-ramp inflow is high. This happens when inflows to the merge from the freeway shoulder lane are low.

In summary, this dissertation is the first study to identify a capacity drop mechanism in detail and to demonstrate that on-ramp metering can be used to increase merge capacities.

Given these findings, the dissertation provides important information concerning how to control freeway traffic at merge bottlenecks and can also advance the present knowledge in traffic flow theory.

The remainder of the dissertation is organized as follows. Section 2 summarizes related research. The freeway sites used for this study and the data collected there are described in Section 3. Section 4 presents the capacity drop mechanism at two merge sites. Section 5 shows the results of metering experiments that were tested at one site. Section 6 describes proposed traffic control strategies based on the findings. Areas of further research are discussed in the seventh and final section.

2. RELATED RESEARCH

This section summarizes two distinct research areas related to the dissertation: traffic phenomena at freeway merge bottlenecks and on-ramp metering experiments. Section 2.1 presents earlier works relating to traffic phenomena at merge bottlenecks. This section explains why the merging mechanism had not been understood in a thorough way. Section 2.2 presents previous on-ramp metering experiments. This discussion clarifies why earlier metering experiments had not explicitly addressed issues of merge capacity.

2.1 TRAFFIC PHENOMENA AT MERGE BOTTLENECKS

Many earlier works have reported that outflow from a freeway merge diminished following the queue formation immediately upstream (e.g., Banks, 1990; Hall and Agyemang-Duah, 1991). As explained below, some of these works were inconclusive because of the methods used to collect and process the measured data. Still other (later) studies that did confirm the existence of capacity drops by collecting and processing the data more carefully did not provide explanations as to why these capacity drops actually occur (Cassidy and Bertini, 1999).

Banks (1990) studied four merge bottlenecks on San Diego freeways using data collected by freeway loop detectors and from videos. He reported that flow across all freeway lanes decreased by about 3 percent when queues formed upstream. Later, Hall and Agyemang-Duah (1991) studied a freeway merge west of Toronto, Canada. They reported that a bottleneck there caused capacity to drop by about 6 percent.

However, both the above studies are questionable, in part because the researchers failed to verify that measurements were taken downstream of active bottlenecks. Consequently, the flows measured in these studies were not necessarily merge capacities, but could have been instead queued flows affected by downstream bottlenecks. Furthermore, the researchers did not process the measured data in high resolution ways. Their studies used coarse time-series plots of flow and of occupancy. Such data treatment methods can obscure important details of freeway traffic flow: i.e., fluctuations in traffic flows over time make difficult to determine the precise times when flows change.

Cassidy and Bertini (1999) conducted an empirical study at two merge bottlenecks on freeways in and near Toronto, Canada. (One of their sites was the same site used by Hall and Agyemang-Duah.) Cassidy and Bertini processed the measured data using oblique plots of cumulative counts and occupancies. This data treatment can greatly aid in the interpretation of some important traffic features (See Cassidy and Windover, 1995; Muñoz and Daganzo, 2002a). Consequently, they verified that capacity drops occur at active merge bottlenecks, and they successfully partitioned the periods before and after these capacity drops. They reported an average daily capacity drop of 10 percent. This reduction is notably higher than what had been reported previously. Still, they did not provide any explanations as to why this phenomenon occurred.

More recently, Chung (2004) studied bottleneck capacities and how to increase them. Although his research shares some similar objectives with this dissertation, there are important differences. The major differences lie in the types of bottlenecks that were

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analyzed by Chung and in the degree of detail that these were studied. Chung's work is directed at bottlenecks formed by a horizontal curve and by a lane-reduction, and not by on-ramp merges. He found that the capacity drop happened when the vehicle accumulations (in all lanes) near the bottlenecks reached some critical values. In contrast, the present dissertation unveils a more detailed capacity drop mechanism.

From the literature, it is clear that the capacity drop at freeway merge bottleneck had not yet been studied in a thorough way. In the present work, detailed data were extracted from videos and analyzed in detailed, high resolution ways.

2.2 ON-RAMP METERING EXPERIMENTS

On-ramp metering is the use of semifores to restrict inflows from the on-ramp to the freeway. Any number of objectives might be used in deploying ramp metering, including the maximization of freeway flows (not necessary capacities) and improved traffic safety. This dissertation, however, demonstrates with how on-ramp metering can be used to increase the outflows, i.e., capacities, of a merge, and thereby save commuter delay. Although on-ramp metering has been use in the U.S. for more than 50 years (see Newman, et al, 1969), the feasibility of using meters to increase merge capacities had until now been an open question.

To address the issues of relevance here, consider first a freeway queue that forms within a system with on- and off-ramps, as demonstrated with the shading in Fig. 1(a). If this queue propagates beyond off-ramps, it will impede exit flows and reduce system

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capacity. Daganzo (1996) describes this as "gridlock mechanism" because on closed-loop systems, this mechanism can drive system capacity to zero. This fact underscores the benefit of on-ramp metering on closed-loop systems and points to one way that metering can reduce driver trip times and system-wide delay.

Metering can also improve freeway flow without increasing system capacity by moving delay on the freeway to on-ramps. Fig. 1(b) shows that metering can promote higher flows and speeds on an "internal" freeway link by moving the queue to one or more on-ramps. Notably, higher flows and speeds on an internal link do not necessarily mean higher system capacity. If the metering is too restrictive and starves the downstream merge of flow, system capacity will actually be lowered. The discussion on this "starvation mechanism" is available in Cassidy (2003).

It is well understood how systems like those in Figs. 1(a) and (b) can be affected by metering. The present dissertation, however, studies the effect of metering on the capacities of active merge bottlenecks, like the one in Fig. 1(c).

Some of the literature (e.g., Papageorgiou and Kotsialos (2002); Persaud, et al. (1998), etc) has *assumed* that ramp metering can maintain the higher outflows at a merge bottleneck and thus increase merge capacity. This assumption was premature. However, since previous field studies show no evidence of this. Review of these previous studies is provided below.
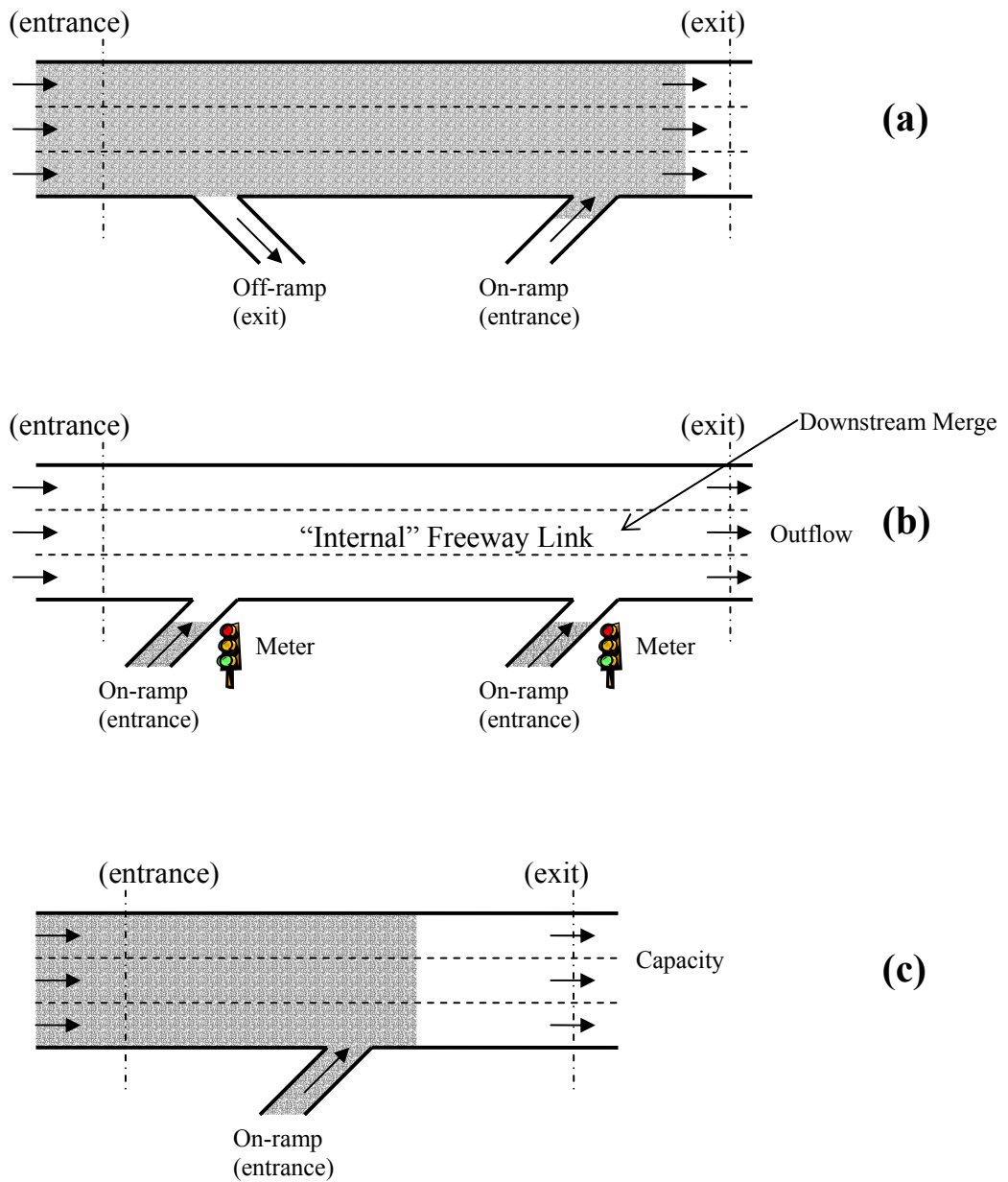
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Figure 1

Hypothetical Freeway Systems

(a) Gridlock Mechanism

(b) Starvation Mechanism

(c) Active Merge Bottleneck

Haj-Salem and Papageorgiou (1995) reports that metering (three) on-ramps reduced overall driver trip times on a 12-km stretch of the Boulevard Peripherique, a closed –loop freeway in Paris. Given the freeway's geometry, this finding merely confirms that metering can decrease system driver trip times by mitigating the gridlock mechanism, as discussed earlier with the aid of Fig. 1(a). Trip time reductions were also reported from metering on-ramps on the A6 Motorway, also in Paris (Haj-Salem, et al (2001)). Both studies involved systems with many on- and off-ramps and do not focus on freeway merge capacities.

More closely to the issue, some studies (e.g., Diakaki, et al (2000), and Papageorgiou, et al (1998)) show that metering increases flow downstream of a merge. Unfortunately, the benchmarked downstream flows they used were the queued flows instead of unrestricted outflows. Since the queued flows were influenced by exogenous downstream restrictions, they can not be used as benchmarks to compare the effect of on-ramp metering on merge capacity. Diakaki, et al (2000) shows that outflow from a merge on the M8 Freeway in Glasgow, Scotland increased by about 5 percent after metering an on-ramp. But the data (joint measurements of flow and speed from loop detectors) in Fig. 5 of Diakaki showed that the benchmark traffic conditions downstream of the merge were not free-flowing; speeds, for example, were below 65 km/hr. Similarly, Papageorgiou, et al (1998) reported that metering several on-ramps along a 7-km stretch of a closed-loop freeway (the A10 West Motorway in Amsterdam) increased flows downstream of the metered ramps to capacity levels. However, the downstream flows they used were the queued flows restricted by a downstream bottleneck (a tunnel).

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A report by the FHWA (1996) states that on-ramp metering can increase freeway flows and speeds. Extensive metering experiments performed in Twin Cities, MN confirmed this (MnDOT, 2001). Regrettably, these studies have not evaluated the effect of on-ramp metering on merge capacities. Instead, they merely reconfirmed that metering can improve the condition on internal freeway links by moving queues from a freeway to one or more on-ramps, as previously described using Fig. 1(b).

More recent studies (Papageorgiou and Kotsialos, 2002; Smaragdis, et al, 2004) explicitly focused on the merge capacity from active bottlenecks. Notably, however, these studies were based on computer simulations that assumed driver behaviors at merges and used other mathematical approximations that may or may not be realistic. Only observation of nature can furnish unequivocal answers to the question of merge capacity.

In conclusion, previous on-ramp metering experiments have not actually addressed the issue of merge bottleneck capacities. The experiments in this dissertation (as documented in Section 5) are the first to study this issue correctly.

3. STUDY SITES AND DATA DESCRIPTION

As described in Section 2, the sites used for studying the capacity drop at merge

bottlenecks must be an active bottleneck. In addition, to collect high-resolution traffic

data via videotape, vantage points (e.g., over-crossings) should be available near the

merge

The data used in this study were collected by video cameras from two freeway merges in

Southern California; (i) northbound Freeway 805 in San Diego County (Section 3.1); and

(ii) eastbound State Route 22 in Orange County (Section 3.2).

3.1 NORTHBOUND FREEWAY 805 IN SAN DIEGO COUNTY

Fig. 2 is a sketch of the first study site, a stretch of northbound Freeway 805 and its

junctions with several on-ramps and off-ramps in San Diego County, California. There

are two metered on-ramps in this area. The 43rd St on-ramp forms an additional lane on

the freeway. The 47th St/Palm Ave does not, however. The figure also shows that there

are loop detectors in each lane upstream of the 47th St/Palm Ave on-ramp merge. These

detectors record vehicle counts and occupancies over 30-sec sampling intervals. The

detectors proved to be useful in the metering experiments described in Section 5.

From the Logan Ave over-crossing, multiple video cameras were positioned to view the

47th St/Palm Ave on-ramp merge to the freeway. The high-resolution data extracted from

this site and analyzed are described next.

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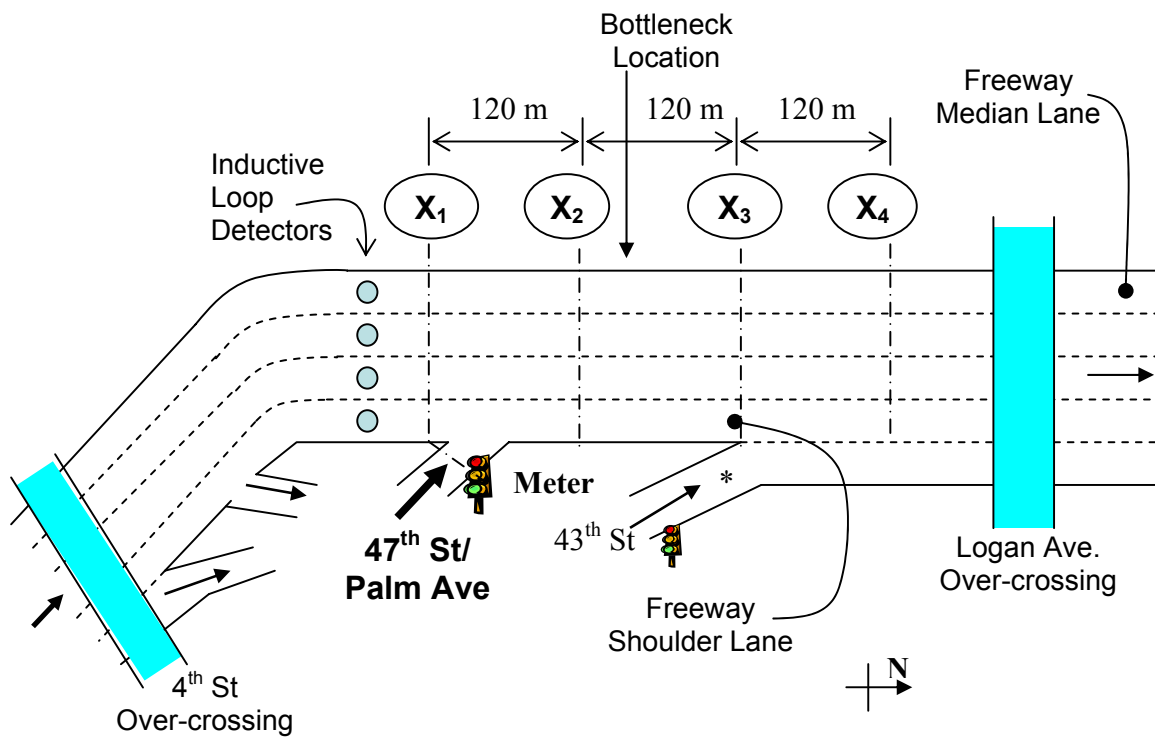
Figure 2

Study Site, Northbound Freeway 805, San Diego, California

From the Logan Ave over-crossing, individual vehicle arrival times at four fixed locations (labeled X_1 through X_4 in Fig. 2) along the freeway stretch were measured. The vehicle accumulations (number of vehicles residing in a section) were measured over time. Lane-changing maneuvers between measurement locations were counted as well.

All of these data were collected during morning rush hours for 24 days, beginning fall 2002 to summer 2004. Data from 7 of these 24 days were unusable. On 4 of these 7 days, the merge was not an active bottleneck because an exogenous freeway queue propagated from downstream to restrict the merge capacity. On three other days, bad weather made data collection unusable for analysis.

Data from the 17 usable days were analyzed. Section 4.1 presents data collected on a single (example) day at this site without having altered the 47th St/Palm Ave on-ramp meter's existing logic. It will be shown that an active bottleneck is located between X_2 and X_3 and is caused by merging traffic from the 47th St/Palm Ave on-ramp. The verification of this bottleneck, as well as its capacity drop mechanism is described in Section 4.1

Data from 9 experimental days are shown in Section 5. Presented there are details of the experiments whereby the metering rates for the 47th St/Palm Ave on-ramp were altered in certain strategic ways.

3.2 EASTBOUND STATE ROUTE 22 IN ORANGE COUNTY

Fig. 3 is a sketch of the second study site, a stretch of eastbound State Route 22 and its junction with the Fairview Avenue on-ramp in Orange County, California. Loop detectors are located in each lane at X_0.

Similar to those from the previous study site, the data consisted of the individual vehicle arrival times at X_0 through X_4 (as labeled in Fig. 3). Vehicle accumulations on a shoulder lane between X_0 and X_2 were sampled over time. Lane-changing maneuvers between measurement locations were counted as well. These high-resolution data were manually extracted from videotapes that were recorded by cameras placed on the Lewis St over-crossing just downstream of the merge (as shown in Fig. 3).

These data were taken during afternoon rush hours for ten days from winter 2000 to summer 2004. Data from two of these ten days were not used because the bottleneck did not activate on these days.

At this second site, an active bottleneck is formed by the on-ramp from Fairview Ave and is located between X_2 and X_3, just under the over-crossing. Unfortunately, this prevented the full views of the capacity drop mechanism. Nevertheless, the findings from this site also support the capacity drop mechanism that happened at the first site since both share important features. Data from the second site are described in Section 4.2.
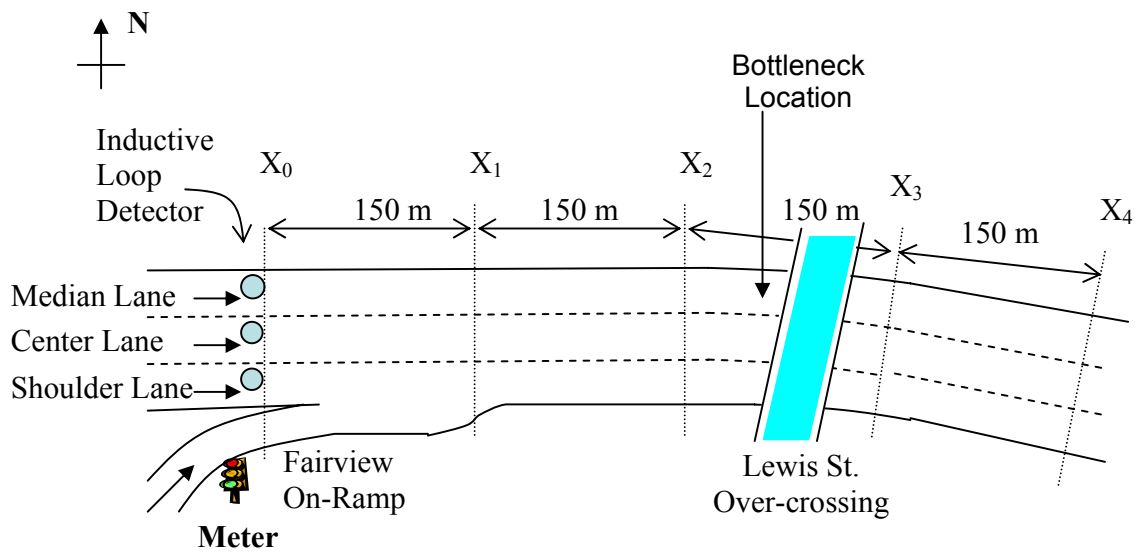
Figure 3

Eastbound State Route 22, Orange County, California

From the site's geometry, Caltrans did not allow metering experiments. This site is close to a major street and there is insufficient queue storage space at the Fairview on-ramp to accommodate the more restrictive metering that would have been tested.

Data from an observation day (June 8, 2004) at this site provide particular valuable findings. They suggest that controlling shoulder-lane inflow upstream of the merge can lead to higher merge capacity without restricting on-ramp flows. The details of this argument are described in Section 6.3

4 CAPACITY DROP MECHANISM

This section describes the details of the capacity drop mechanism at both merge study sites. The presentations provided below verify that (i) both sites have an active merge bottleneck; (ii) the bottleneck's activation eventually causes a capacity drop; and (iii) the capacity drop at both locations is triggered by a queue that initially forms in the shoulder lane near the merge and then spreads laterally, as drivers change lanes to the left to avoid slowing down.

This section is divided into two subsections, one for each study site. Section 4.1 presents the findings at northbound Freeway 805. It also includes the explanation of an analysis method, i.e., plotting cumulative vehicle count curves in an oblique coordinate system. The findings at the other site, eastbound State Route 22, are described in Section 4.2.

4.1 CAPACITY DROP AT I-805 AND ITS MECHANISM

This first study site (see Fig. 2) contained an active bottleneck between X_2 and X_3 on all observation days. The following traffic data presented below were collected on one such day (September 18, 2000). Data on this day are typical of other "observation" days, i.e., days when metering logic was not altered.

Fig. 4 (a) displays curves of cumulative vehicle count versus time, t, measured from video at the locations labeled X_1 through X_4 (in Fig. 2). The curves were constructed such that the vertical displacements between any two of them are the excess vehicle accumulations between their respective measurement locations due to vehicular delays.

These vertical displacements were amplified and made visible to the naked eye by plotting the curves on an oblique coordinate system. The plots presented here are in oblique coordinates, the curves display the quantity $O(t) = V(t) - q_0 \times (t-t_0)$ versus t; i.e., the cumulative virtual vehicle count to time t, $V(t)$, minus a background reduction, $q_0 \times (t-t_0)$; q_0 is a background flow.

The oblique coordinate system also amplifies changes in slopes. Since the slopes of the O-curves are proportional to the flows at each measurement location, these plots facilitated visual identification of the times when these flows actually changed. Further discussion on the construction and interpretation of O-curves are available in a number of references (e.g., Cassidy and Windover (1995); Muñoz and Daganzo (2002)).

From the O-curves in Fig. 4(a), it is clear that traffic was nearly freely flowing during the early minutes of the period shown; i.e., these curves remained nearly superimposed before time t = 6:13. This includes the period from t = 6:07 to 6:11 marked by a high average flow of 10,480 vph, as shown by a dashed trend line.

But by t = 6:13, the upstream-most curves at X_1 and X_2 diverged from their downstream counterparts while the downstream curves at X_3 and X_4 are always superimposed. This indicates that the excess vehicle accumulations and delay arose just upstream of X_3. These verify that the segment between X_2 and X_3 is the location of an active bottleneck.
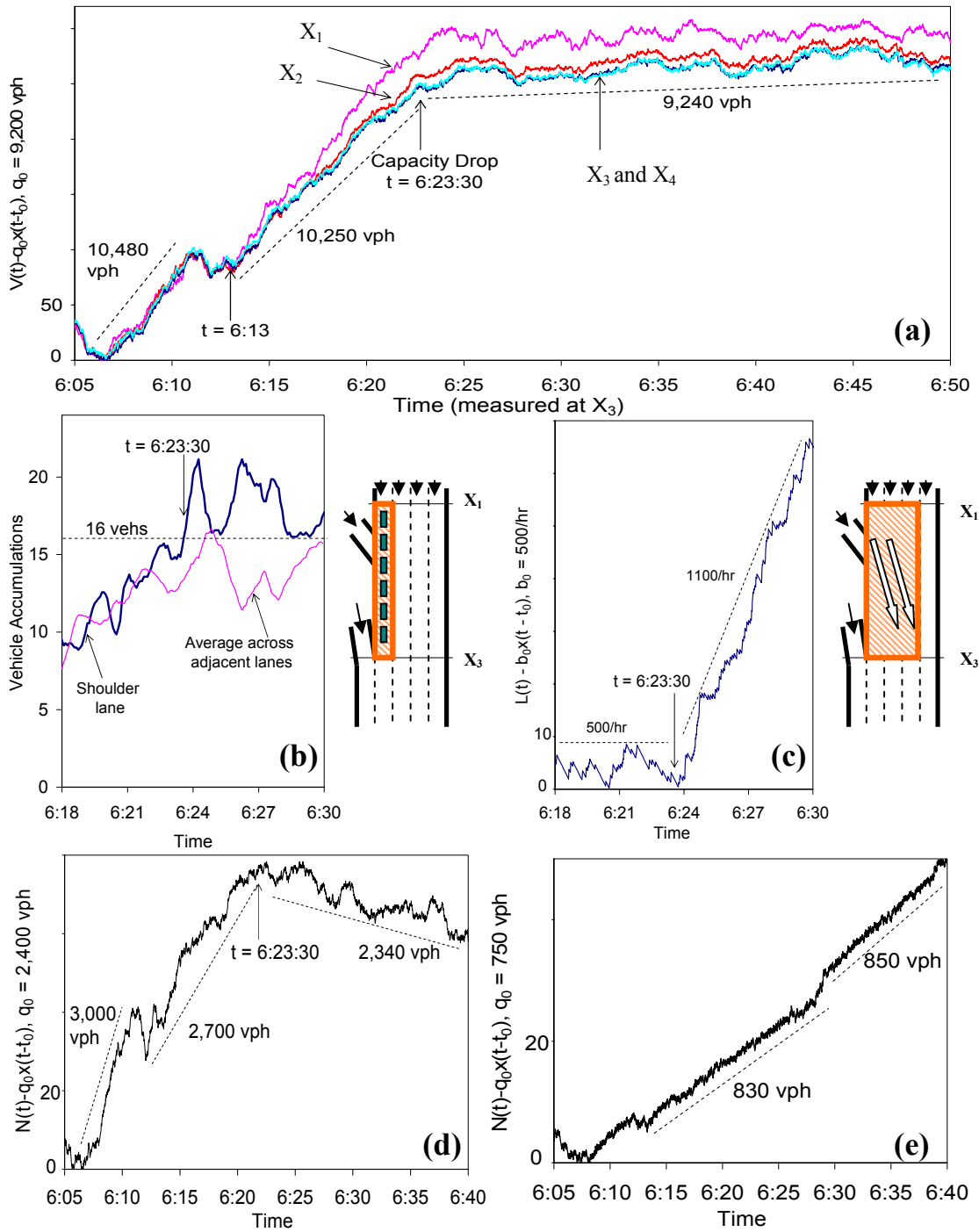
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Figure 4 (September 18, 2002 at I-805N)

(a) O-curves at X_1 through X_4 (b) Vehicles accumulations
(c) Oblique cumulative curve of lane-changing counts
(d) Oblique cumulative curve of median-lane outflow at X_3
(e) Oblique cumulative curve of counts from 47th St/Palm Ave on-ramp

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Since X_3 is the location downstream of the bottleneck, the slopes of the curve in the

figure plus the background flow (represented by the dashed trend lines) are thus the

bottleneck capacities. Fig. 4(a) shows that after the bottleneck's activation, its capacity

remains at the high rate of 10,250 vph until t = 6:23:30, the time when the capacity drop

occurred.

Being an active bottleneck, it affirms that the drop in capacity at t = 6:23:30 was neither

the result of a reduction in traffic demand (because queues persisted upstream), nor the

result of an exogenous downstream restriction (because traffic was freely flowing

downstream of the merge formed by the 47th St/Palm Ave on-ramp). Thus, the outflow

reduction shown in Fig. 4(a) was the result of the traffic phenomena referred to here as

the "capacity drop". The figure shows that with this capacity drop, outflow fell to an

average of 9,240 vph, a reduction of 10 percent from the outflow that immediately

preceded it. The lower rate persisted for the remainder of the rush.

The capacity drop was triggered by a queue that formed in the freeway shoulder lane near

the merge. The dark line in Fig. 4(b) is a time series of vehicle accumulations counted in

the shoulder lane between locations X_1 and X_3, as shown in the diagram next to Fig. 4(b).

These vehicle accumulations were sampled every 5 seconds and the curve presents the 1-

min moving averages of these counts. At t = 6:23:30, the curve first exceeded an

accumulation of 16 vehicles; i.e., the capacity drop coincided with the curve's first

passage at 16. The time series then remained above 16 vehicles for the remainder of the

rush.

The first occurrence of 16 vehicles within a specific segment in the shoulder lane triggered the capacity drop each day with uncanny reproducibility. The number of 16 vehicles is thus called "critical accumulation" at this merge site. Table 1 shows the average outflows measured for extended periods of 5 minutes or more before shoulder lane accumulations (between locations X_1 and X_3) first reach 16 vehicles (column 2) and after the capacity drop occurred (column 3). The data indicate that the critical accumulation partitions the high and low outflows measured before and after capacity drop. These data also reveal that both outflows (both before and after the capacity drop) varied from day to day. Further evidence of the causal relation between critical accumulation and capacity drop is provided next. (Yet more evidence will be shown in Section 5).

Notably, it was accumulation in the shoulder lane, and not in other freeway lanes, that triggered the capacity drop. The light curve in Fig. 4(b) displays the average accumulation between X_1 and X_3 measured across other three lanes next to the shoulder lane. The capacity drop coincided with a sharp rise in the shoulder lane accumulation (the dark line in Fig. 4(b)). The average accumulation in other lanes rose more gradually; however, and reached its peak some time later than the one in the shoulder lane.

Table 1

Outflows before and after critical accumulation in the shoulder lane on I-805N

| | (1) | (2) | (3) | (4) | (5) |
	Date	Outflows prior to critical accumulation (vph)	Outflows after critical accumulation (vph)	Change (%)	Duration of high outflows (min)
	Sep 17, 2002	9740	8930	8.3	8
	Sep 18, 2002	10230	9220	9.9	11
	Jan 8, 2003	8540	7800	8.7	5
	Jan 9, 2003	9780	8820	9.8	12
	Jan 10, 2003	9680	8650	10.6	8
	Mar 4, 2003	10520	8700	17.3	7
	Mar 5, 2003	10190	8690	14.7	13
	Mar 6, 2003	10730	9280	13.5	6
	Average	**9926**	**8761**	11.7	8.6

That accumulations peaked in this sequence is evidence that the queue formed first in the shoulder lane and then spread laterally to the left as drivers maneuvered from the (slow-moving) shoulder lane into other freeway lanes. This maneuvering marked the final stage of the capacity drop mechanism and was confirmed by the observed increase in lane-changing activities described below.

Shortly after the capacity drop, driver lane-changing maneuvers increased noticeably in the two right-most freeway lanes. Fig. 4(c) is a plot of cumulative lane-changing counts over a fixed distance $L(t)$ vs time. This was plotted in the oblique coordinate system, i.e., the curve in Fig. 4(c) displays $L(t) - b_0 \times (t-t_0)$, where b_0 is a background lane-changing rate reduction. The counts for this curve were taken between X_1 and X_3 and are the sum of lane changes to the left from the two right most lanes; see the schematic illustration on the right of Fig. 4(c). The curve shows that there was a sharp increase in lane-changing activity (from 500/hr to 1,100/hr) after the capacity drop at $t = 6{:}23{:}30$. This lane-changing spread the queue to adjacent freeway lanes and disrupted flows in these lanes.

The capacity drop might not be explained by lane-changing alone. Fig. 4(d) is an oblique plot of cumulative vehicle counts, N, in the median lane at X_3. The outflow rates (labeled by the dashed line) show that the capacity was denoted by a substantial loss in median lane outflow of 360 vph. This drop is more than one-third of the total outflow loss (1010 vph).

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However, on this day, as on other observation days, the capacity drop occurred even when lane-changing maneuvers into (and out of) the median lane increased relatively little after the capacity drop. On all observation days, lane-changing rates into the median lane increased less than 100/hr after the capacity drop. These were small comparing with those in adjacent lanes. But capacity drops on the median lane were always greatest among all lanes.

In addition, by sampling vehicle trip times in the median lane between X_1 and X_3, the data show that vehicle speeds in the median lane slowed down significantly during the capacity drop. Once this slow-down occurred, discharge from the merge was roughly equal in all freeway lanes. From Fig. 4(a), the average outflow after capacity drop was 2,310 vph, which is very close the median's lane outflow following the capacity drop as shown in Fig. 4(d).

The traffic phenomenon in the median lane might be explained by a cautionary driver behavior, i.e., drivers in the median lane may have decelerated in response to slowing traffic in the freeway shoulder lane and other adjacent lanes. This driver behavior was previously observed at freeway diverge bottlenecks (Cassidy, et al (2002), Muñoz and Daganzo (2002b)).

In summary, data from the "observation" days show that the capacity drops caused substantial losses in merge capacities. The mechanism of these drops was initiated when vehicle accumulations near the merge become too high (above the critical value). This

high accumulation was accompanied by disruptive lane-changing that occurred as drivers maneuvered around this shoulder lane queue and by cautionary responses from drivers in the median lane.

Finally, the oblique cumulative count curve in Fig. 4(e) displays the inflows from the on-ramp (at 47th St/Palm Ave) generated by the metering logic that existed there at that time. In later experiments, this metering logic was altered for metering experiments that will be explained in Section 5.

4.2 CAPACITY DROP AT SR-22 AND ITS MECHANISM

This section documents a capacity drop mechanism that occurred at Eastbound State Route 22 (see Fig. 3). The mechanism is qualitatively consistent with that at the Northbound I-805 above. This second site, however, has only three freeway lanes (as compared with the four lanes on I-805). This simpler geometry at this site provides even greater insights into the capacity drop mechanism, as shown below.

Fig. 5(a) displays an oblique plot of cumulative vehicle counts, measured from video at the locations labeled X_1 through X_4 (in Fig. 3) on Mar 28, 2002, a typical observation day. These curves remained nearly superimposed before time t = 12:54:30. The average outflow in this period (from t = 12:47 to 12:54:30)was 6,850 vph, and was as high as 7,350 vph for 4 minutes during this time.

At about t = 12:54:30, the bottleneck activated between X_2 and X_3, i.e., freeway queue arose upstream of X_3 while downstream traffic were freely flowing. After this activation, outflows dropped to an average of 6,600 vph. The outflow loss from this drop was only about 4% (compared to the average of 6,850 vph during the earlier period). This outflow level persisted for six minutes. Subsequently, at time t = 13:00:30, the capacity dropped further by 5 percent to 6,250 vph. The lowest capacity sustained through the rush on this day. The total losses were about 8 percent from the free-flow period.

Two capacity drops were related to shoulder lane vehicle accumulations. Fig. 5(b) shows the 1-min moving average vehicle accumulations in the shoulder lane between X_0 and X_2, as per the illustration to the right of the figure. The time-series curve shows that from t = 12:54:30 to 13:00:30, the accumulations were between 13 and 16 vehicles. After that, the accumulations rose and stayed above 16 vehicles through the rush period.

The small capacity drop occurred due to a drop in the center lane outflow. The large capacity drop occurred because both center- and median- lane outflows dropped. Fig. 5(d) shows oblique cumulative curves of center- and median-lane outflows measured at X_3. At t =12:54:30, the outflow in the center lane dropped from 2,400 vph to 2,150 vph (a 10 percent reduction), while outflows in the median lane had not dropped. The outflow on the median lane dropped later at t = 13:00:30, the time that the shoulder lane accumulation rose above 16 vehicles.
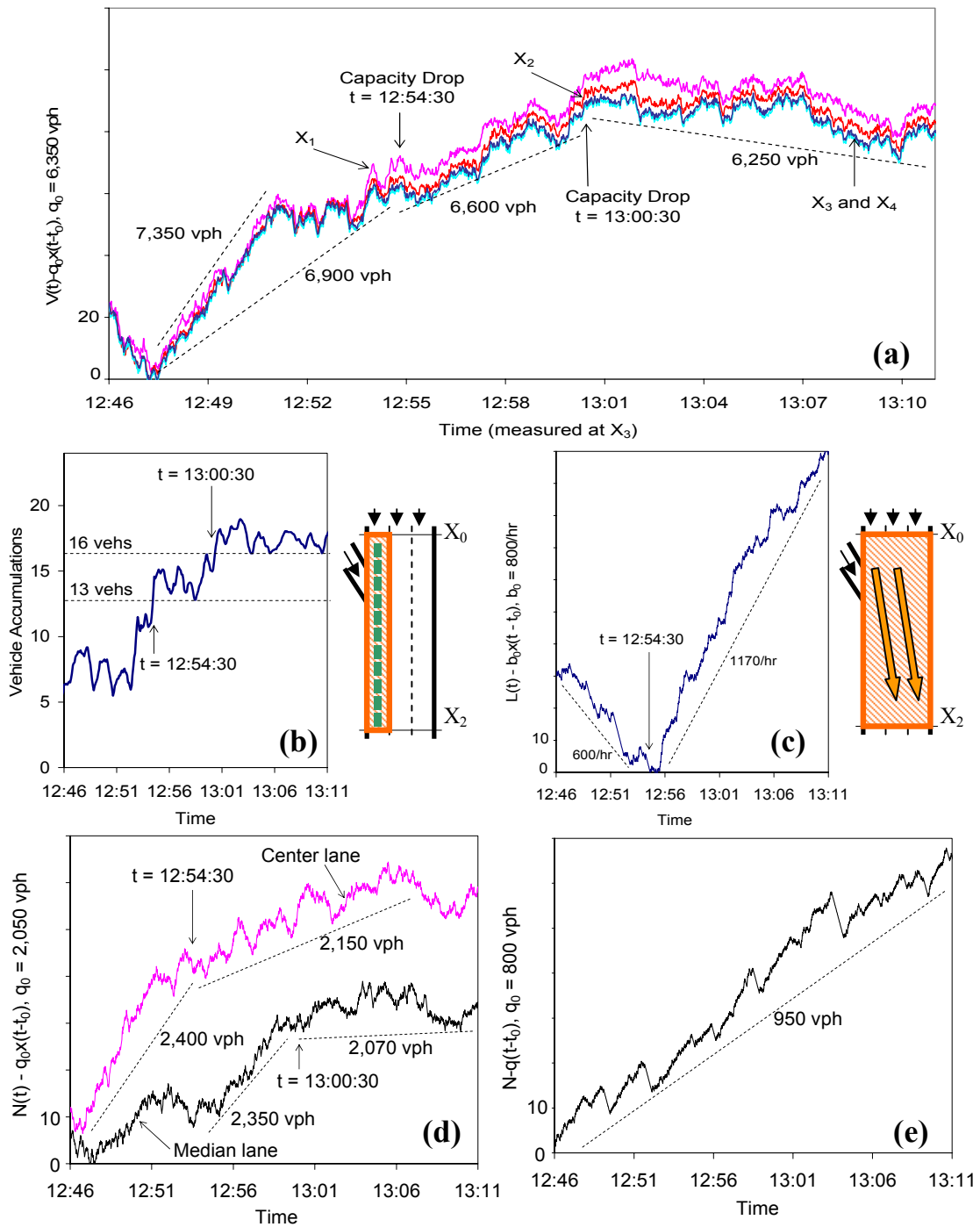
Figure 5 (March 28, 2002 at SR-22)

(a) Oblique N-curves at X_1 through X_4 (b) Shoulder-lane accumulations
(c) Oblique cumulative curve of lane-changing counts
(d) Oblique cumulative curves of center- and median-lane outflow at X_3
(e) Oblique cumulative curve of counts from Fairview St on-ramp

On this day, as well as on other days, the two-level capacity drops were observed to be reproducible and consistent with the accumulations; i.e., the small capacity drop occurred when the accumulations rose above 13 vehicles, and the large one occurred when accumulations rose above 16 vehicles. The 13- and 16- vehicle accumulations are thus called "critical accumulations" at this site. Table 2 shows the average outflows measured for 5-min period before shoulder lane accumulations first reach 13 vehicles (column 2), average outflow when accumulations were between 13 to16 vehicles (column 3), and average outflow when accumulations rose above 16 vehicles (column 4).

Data from Table 2 indicate that the critical accumulations of 13- and 16- vehicles partition the levels of outflows. When outflows in the median lane drop (as the accumulations rose above 13 vehicles), the capacity losses were about 7 percent (by averaging the outflows over 7 days). Later each day, when the critical accumulation rose above 16 vehicles, the merge capacities dropped by an additional 6 percent (marking an overall reduction of 13 percent).

On some observation days, the accumulations rose from below 13 vehicles to above 16 vehicles immediately and dropped down in the range of 13-16 vehicles; (an example of such a day will be presented in Section 6.3).

Table 2

Outflows before and after each level of critical accumulations in the shoulder lane

	(1)	(2)	(3)	(4)

Date	Average outflow (vph) when vehicle accumulations were		
	< 13 vehicles	13-16 vehicles	>16 vehicles
Nov 8, 2000	6,520	6,140	5,650
Feb 20, 2001	7,300	6,400	5,950
Feb 21, 2001	6,800	6,600	5,920
Mar 15, 2001	6,800	6,350	6,200
Mar 26, 2002	6,820	6,130	5,690
Mar 28, 2002	6,900	6,600	6,250
Jun 8, 2004	6,760	6,050	5,760
Jun 9, 2004	6,500	6,150	5,800
Average	**6,800**	**6,300**	**5,900**

Like the previous study site, the accumulations that initially rose in the shoulder lane

caused outflow losses in other adjacent lanes due to lane-changing maneuvers. Fig. 5(c)

is an oblique plot of cumulative lane-changing maneuvers to the left that happened

between X_0 and X_2. The figure shows that lane-changing activities increased from 600/hr

to 1,170/hr once the capacity first dropped at t = 12:54:30. This increase of lane-changing

activity was almost double its original rate, which is consistent with the previous study

site (see Fig. 4(c)). Interestingly, this lane-changing activity was nearly constant after the

first capacity drop and did not change when the greater drop eventually occurred at t =

13:00:30. The lane-changing maneuvers spread the queue to other lanes, and disrupted

flows in these lanes.

Fig. 5(e) displays the inflows from the on-ramp (at Fairview Ave) generated by the

metering logic that existed there. It appears that the average on-ramp inflows at this 3-

lane freeway were very high (950 vph, as compared to only about 800 vph for 4-lane

freeway at the first study site. The high on-ramp inflows, combined with a relatively

small number of freeway lanes, might be the cause of the multi-level of capacity drop

mechanisms that were not discernible at the pervious site.

In summary, observations at both merge sites reveal similar traffic details at freeway

merges. The capacity drop occurred when vehicle accumulations on the shoulder lane

rose above a critical accumulation and triggered disruptive lane-changing activities that

caused lower capacity to persist. This mechanism caused sizable losses in merge

capacities. It follows that controlling shoulder-lane accumulations and lane-changing are

the key to postponing capacity drops and/or reversing the effects once the drops happen. Data from metering experiments that prove these arguments are explained in the following section. These data show that the capacity drop mechanism can be postponed, and even completely avoided by appropriate metering strategies.

5. ON-RAMP METERING EXPERIMENTS

This section describes the results of metering experiments at the I-805 merge site (see

Fig. 2). There are three major findings from these experiments:

1. on-ramp metering can restore higher outflows after capacity drop occurs;

2. capacity drop mechanism can be averted by metering in a proactive fashion;
   and

3. real-time automatic metering strategies can be implemented by using
   information formed by loop detectors.

The metering strategy used in the experiments was a bang-bang strategy. When a

capacity drop occurred, the metering rate was changed to a low rate (400 vph). This

restrictive control eventually reduced shoulder lane vehicle accumulations below the

critical value and the freeway queue was cleared in the vicinity of the merge. At this

point, high metering rates in the range between 600 to 900 vph (depending on each

experiment) were then restored to the on-ramp. By restoring high metering rates, drivers

evidently became "motivated" so that the merge pumped out higher capacity.

The above traffic phenomenon is further explained with the aid of Fig. 6. Fig. 6(a) shows

the traffic state once the low metering rate cleared the freeway queue in the vicinity of the

merge. In this state, drivers apparently lose motivation to discharge from the merge at

short headways. The observations show that merge outflows could not return to the high

flow in the earlier period.

Freeway Queue

On-ramp

Low outflow

Restrictive Metering

(a)

Freeway Queue

On-ramp

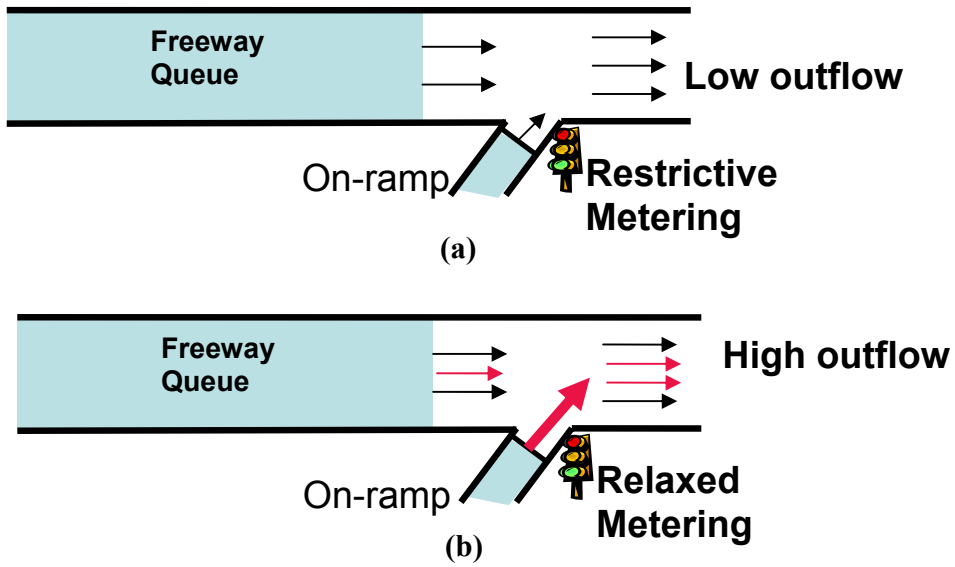**High outflow**

Relaxed Metering

(b)

Figure 6

How metering reverses capacity drop mechanism

(a) Restrictive metering   (b) Relaxed metering

Fig. 6(b) shows the state when the higher metering rate was restored. The observations suggest that the relaxed metering rate motivated drivers in the freeway queue to discharge at smaller headways, resulting in higher outflows from the merge. This phenomenon is described in a theory of driver behavior proposed by Daganzo (2002). At this point, the outflows remained high as long as the shoulder lane accumulations stayed below the critical value. When the shoulder lane queue reappeared, however, the capacity drop re-occurred.

Metering experiments were conducted during thirteen morning rush periods from summer 2003 to fall 2004 at the first study site (Northbound I-805). On four of these days, the merge bottleneck was inactive due to exogenous downstream queues. Samples from five of the remaining nine days are presented in this section. They illustrate the range of outcomes observed over those nine days.

Section 5.1 shows the results from initial metering experiments. These experiments were done by restricting (and then eventually relaxing) the metering rate at 47th St/Palm Ave on-ramp only once a day.

Section 5.2 describes relationships among capacity drop, vehicle accumulations, and occupancies from the loop detectors at the merge. These relationships make it possible to deploy traffic-responsive metering strategies at this merge. Then, the traffic-responsive metering scheme was tested and the results are shown in Section 5.3

5.1 RESULTS OF INITIAL METERING EXPERIMENTS

This section shows the results from initial metering experiments that were done by restricting the metering rates only once a day when an observer on the Logan Ave over-crossing (see figure 2) observed a dense shoulder lane queue at the merge. The restricted metering rate at 400 vph was prolonged for approximately 10 minutes each day and was then returned to the original rates (700-800 vph).

Figure 7(a) presents O-curves measured at location X_1 through X_4 on October 23, 2003. Prior to t = 6:14:30, outflows reached an average of 9,250 vph. Freeway queueing arose upstream of X_3 and starting at around t = 6:14:30, unconstrained outflows dropped to an average of 8,800 vph. This day was unusual in that the average outflow that preceded capacity drop (9,250 vph) was low relative to most other days, and that the outflow loss from the capacity drop was only about 5 percent. (Losses of at least 8 percent were more the norm.)

Fig. 7(b) shows that the capacity drop at t = 6:14:30 coincided with a shoulder-lane accumulation between locations X_1 and X_3 of 16 vehicles. Fig. 7(c) displays the increased lane-changing activity that arose at the capacity drop as well; the oblique cumulative curve of lane-changing counts over a fixed distance exhibited a sharp rise and persisted at a rate of 800/hr from t = 6:14:30 to t = 6:23:30.
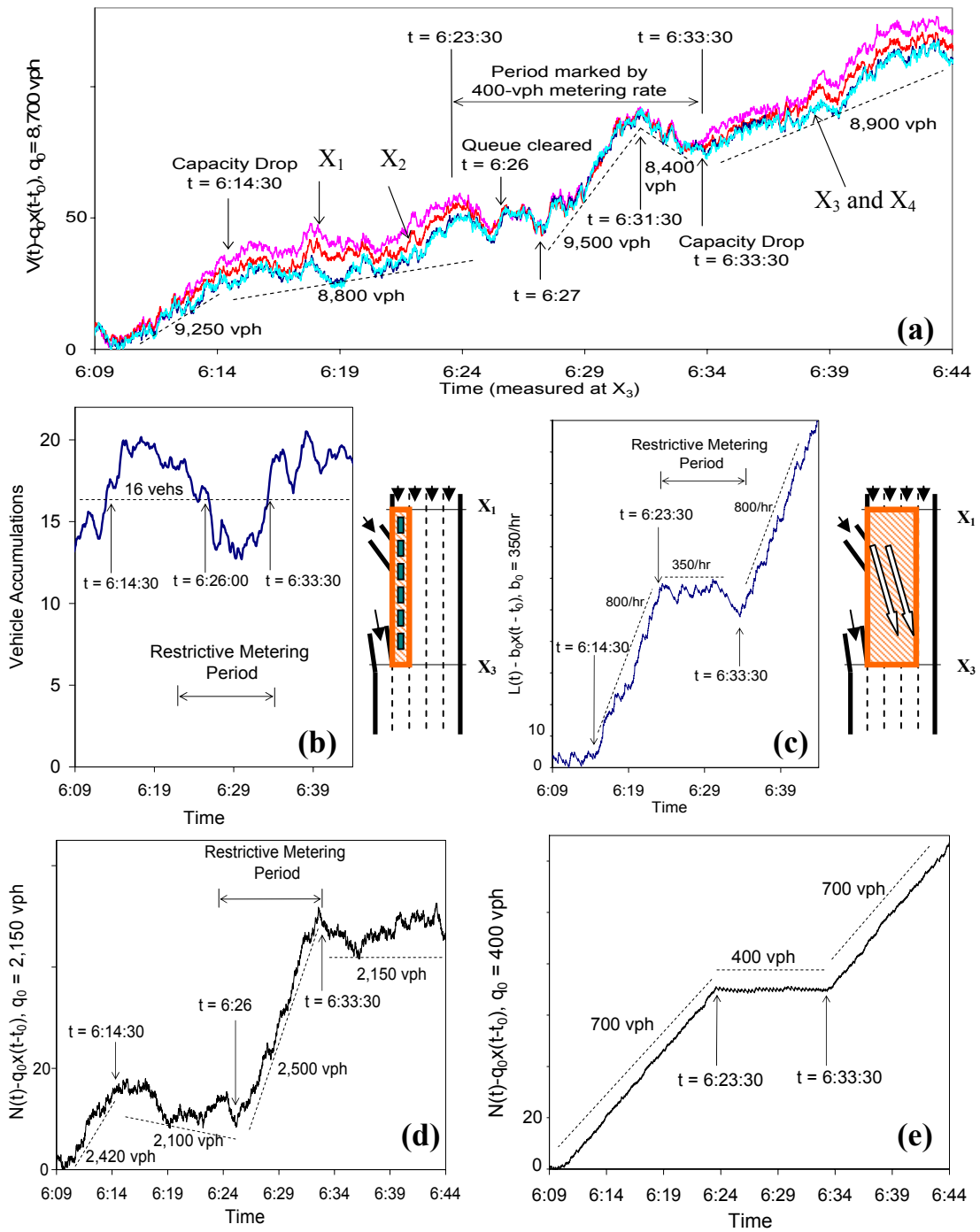
Figure 7 (October 23, 2003 at I-805N)

(a) O-curves at X_1 through X_4 (b) Shoulder-lane accumulations
(c) Oblique cumulative curve of lane-changing counts
(d) Oblique cumulative curve of median-lane outflow at X_3
(e) Oblique cumulative curve of counts from 47th St/Palm Ave on-ramp

At t = 6:23:30, the restrictive metering rate of 400 vph was implemented for 10 mins (see Fig. 7(e)). This restrictive metering rate immediately damped the lane-changing activity from 800/hr to 350/hr (see Fig. 7(c)). Moreover, this control action eventually reduced shoulder lane accumulation below the critical value (Fig. 7(b)) and cleared the freeway queue from the merge (Fig. 7(a)); the latter two events both occurred at t = 6:26.

Remarkably, Fig. 7(d) shows that when shoulder lane accumulation dropped below the critical value (at t = 6:26), median lane outflow recovered; it rose to an average of 2,500 vph, a rate that slightly exceeded the highest outflow (2,420 vph) measured prior to the capacity drop. However, the increased flow in the median lane did not generate higher (total) merge outflows for a prolonged period. Fig. 7(a) shows that total outflow rose to 9,500 vph, but that this high outflow persisted for only 4.5 mins.

The freeway arrival rates to the merge were not sufficient to sustain an outflow recovery for a long time. Outflow even diminished (to 8,400 vph) beginning at t = 6:31:30. Arrival rates in the freeway's center and shoulder lanes diminished at this time. These arrival reductions may have been due to some short-lived flow-restricting event upstream. In any case, the outflow reduction underscores how easy it is to (inadvertently) over-control a bottleneck and starve it of flow.

The reduction in outflow continued until t = 6:33:30, at which time the on-ramp's metering rate was restored to 700 vph (Fig. 7(e)) and freeway arrival rates to the merge increased. The outflows rose, but the ensuing freeway queue that formed near the merge brought with it an unconstrained discharge of only 8,900 vph, a rate comparable to what

had followed from the first capacity drop that occurred earlier in the day (Fig. 7(a)).

These details indicate that a capacity drop re-occurred at t = 6:33:30. This re-occurrence

coincided with the return of a "critical accumulation" in the shoulder lane (Fig. 7(b)),

resurgence in lane-changing maneuvers (Fig. 7(c)), and reduction in median lane outflow

(Fig. 7(d)).

Happily, returning to a relaxed metering rate did not always retrigger a capacity drop

immediately. On other days, restoring the metering rate to 700 vph generated full outflow

recoveries that persisted for some minutes. Evidence of this desirable outcome is

illustrated by the data from other days, shown next.

Figure 8(a) presents O-curves measured at location X_1 through X_4 for part of the morning

rush on October 15, 2003. The initial portions of the O-curves in this figure were

measured during a capacity drop: the four curves verify that the merge was an active

bottleneck to t = 6:40 with an average discharge of 8,640 vph. (Although not shown in

Fig. 8(a), the average outflow that preceded this capacity drop was 9,820 and this high

rate persisted for 8 mins.)

A restrictive metering rate of 400 vph was deployed at t = 6:29 (Fig. 8(e)). It had the

immediate effect of curbing lane-change activity (Fig. 8(c)). By t = 6:40, the restrictive

metering had diminished shoulder lane accumulation below the critical value (Fig. 8(b))

and cleared the head of the freeway queue in the vicinity of the merge (Fig. 8(a)).

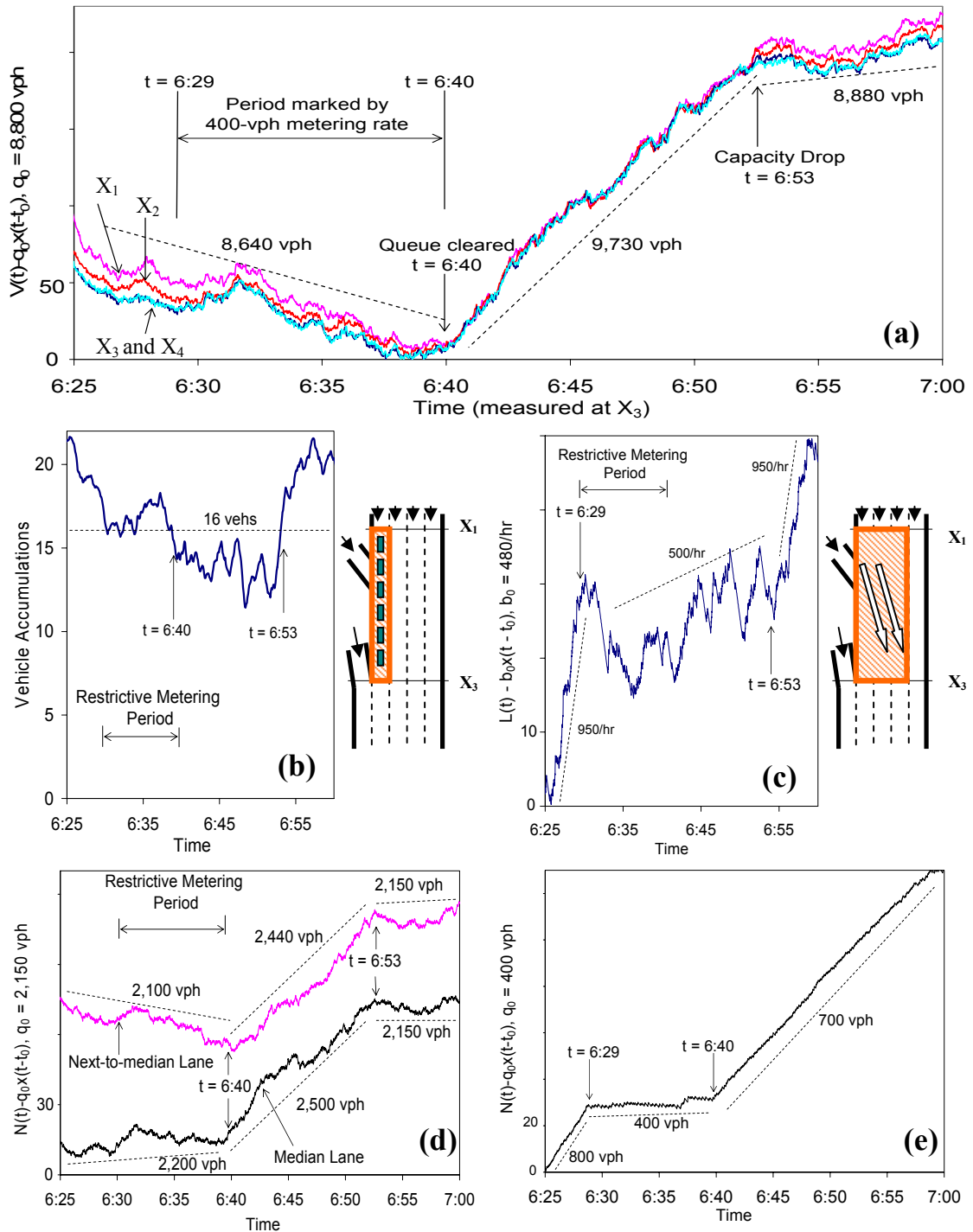Metering was restored to 700 vph at this same time (Fig. 8(e)).

Figure 8 (October 15, 2003 at I-805N)

(a) O-curves at X_1 through X_4 (b) Shoulder-lane accumulations

(c) Oblique cumulative curve of lane-changing counts

(d) Oblique cumulative curves of median and next-to-median lane outflows at X_3

(e) Oblique cumulative curve of counts from 47th St/Palm Ave on-ramp

On this day, relaxing the ramp control did not immediately produce a "critical" accumulation in the freeway shoulder lane; the accumulation fluctuated but did not exceed 16 vehicles until t = 6:53 (Fig. 8(b)). Lane-changing activity fluctuated in similar fashion, but did not exhibit a persistent increase until this same time (Fig. 8(c)).

The favorable outcome is evident in Fig. 8(a): outflow recovered to 9,730 vph. This high outflow is close to the outflow of 9,820 vph before the first capacity drop. With the relaxed metering rate, the merge pumped-out an average flow that was about 13 percent greater than that of the capacity drop and this higher outflow persisted for 13 mins before shoulder lane accumulation again exceeded the critical value. Outflows during this 13-min period increased in all freeway lanes, as exemplified in Fig. 8(d), showing oblique cumulative count curves for the median lane and the lane immediately adjacent. (Curves for additional lanes are omitted from the figure to avoid clutter.)

Outflows were recovered in this way on other days as well (although for different periods of time) and an example is illustrated in Fig. 9. The O-curves in Fig. 9(a) reveal the occurrence of the capacity drop at t = 6:16. It coincided with the first instance of critical accumulation in the shoulder lane (Fig. 9(b)) and greater lane changing (Fig. 9(c)). Lane changing then diminished at t = 6:21 and shoulder lane accumulation eventually dropped below the critical value at t = 6:33. These reductions occurred due to the intermittent restrictive metering that was initiated at t = 6:21. (Restrictive metering occurred intermittently on this day due to a malfunction. The experiment still showed that metering can recover capacity losses at the isolated merge.)
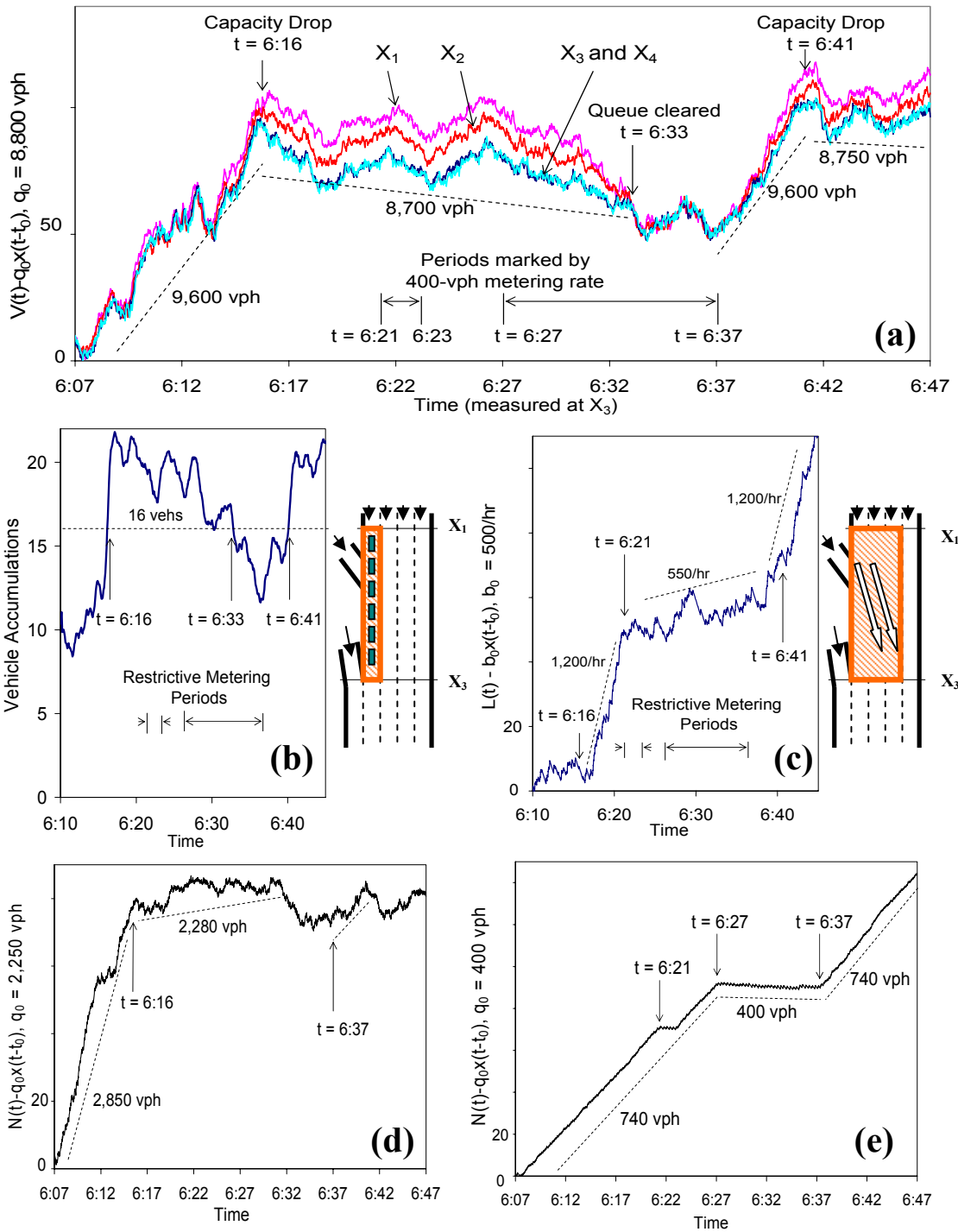
Figure 9 (October 21, 2003 at I-805N)

(a) O-curves at X_1 through X_4 (b) Shoulder-lane accumulations
(c) Oblique cumulative curve of lane-changing counts
(d) Oblique cumulative curves of median lane outflows at X_3
(e) Oblique cumulative curve of counts from 47th St/Palm Ave on-ramp

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Importantly, Fig. 9(a) shows that outflow increased to 9,600 vph, a gain of over 10 percent from the unconstrained queue discharge rate that preceded it. In this instance, the outflow gain persisted for 4 mins. It began precisely when a relaxed metering rate of 700 vph was restored to the on-ramp. It ended when shoulder lane accumulation returned to the critical value (Fig. 9(b)) and high lane-changing rates resumed (Fig. 9(c)).

The experiments in the latter two days (Figs. 8 and 9) reveal a noteworthy detail: restoration (i.e., the relaxation) of the metering rate increased on-ramp inflow to the merge by only about 300 vph and yet the gains in merge outflows were much greater than this; in one case, outflow rose by nearly 1,100 vph (Fig. 8(a)). This finding indicates that, despite the restrictive metering, the freeway queue on these days evidently persisted upstream of the merge. (as illustrated in Fig. 6) It thus suggests that the relaxed metering rate motivated drivers in the upstream freeway queue to discharge at smaller headways, resulting in higher outflows from the merge.

The findings from these experiments verify that ramp metering can reverse the capacity drop mechanism. Furthermore, the findings point to control strategies that may sustain higher merge capacities over an entire rush, and not just the relatively short periods observed here. Such strategies are discussed in Section 6.

5.2 RELATIONSHIP BETWEEN OCCUPANCIES AND ACCUMULATIONS

The findings show that controlling vehicle accumulations on the shoulder lane is the key to reverse the capacity drop mechanism. The data further show that the measured occupancies from the site's detector station (with loops in all lanes as shown in Fig. 2) serve as reasonable proxies for shoulder lane vehicle accumulations between X_1 and X_3. Figs 10(a) – (c) display occupancies measured by the detectors for each experiment day previously presented in section 5.1. The 30-sec sample points shown are 1-min moving averages across all lanes. The times that capacity drops occurred are annotated in the figures, as are the times shoulder lane accumulation were brought below the critical value of 16 vehicles.

The figures reveal two important features that were used in a traffic-responsive metering logic in the next set of experiments:

    1. the capacity drops always occurred at or shortly before the times that occupancies rose to 27 percent; and

    2. the high shoulder lane vehicle accumulations were always reduced below 16 vehicles at or before the times that occupancies dropped below 22 percent.

It follows that for this merge, average occupancies of 27- and 22- percent can be thresholds for initiating restrictive and relaxed metering, respectively.
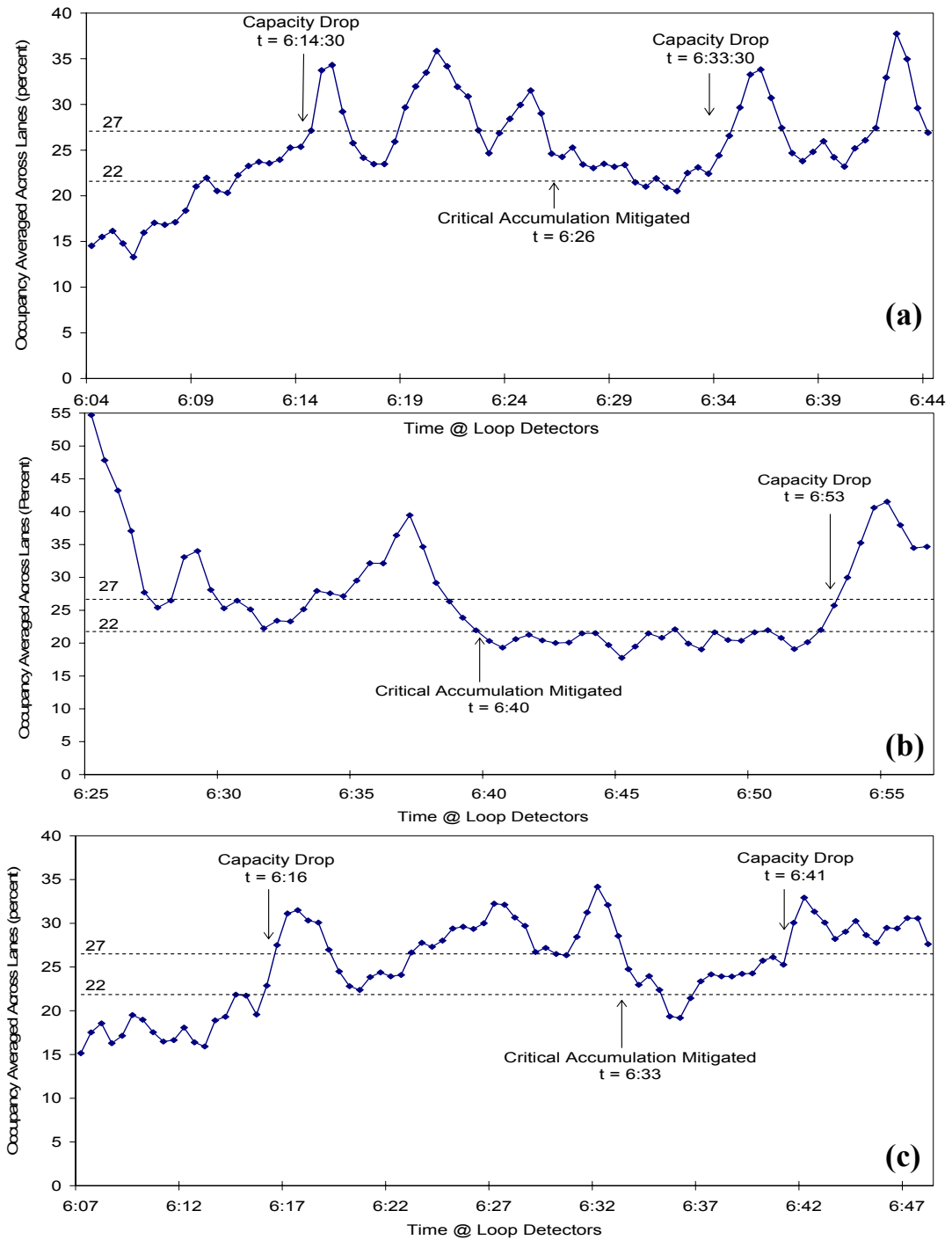
Figure 10

Time series of detector occupancies

(a) Oct 23, 2003   (b) Oct 15, 2003   (c) Oct 21, 2003

Note that the choices of occupancies are site-specific and choosing too low or too high a number could result in over-controlling the merge or wasting more time to recover capacity losses. The thresholds of 27- and 22- percent at this site were found to be the best proxies and they were reproducible across all others observation days.

An automated bang-bang metering strategy based on these above thresholds was tested and the results are shown in the next section.

5.3 RESULTS OF REFINED METERING EXPERIMENTS

This section presents results of metering experiments using the occupancy thresholds discussed in the previous section. In these experiments, relaxed metering rates were varied (from 600 to 900 vph) each time to determine the extent to which these metering rates can generate high merge outflows. The major finding of the experiments is that after the freeway queue at the merge is cleared, the judicious choice of a relaxed metering rate can postpone the re-occurrence of a capacity drop and can thus generate high merge outflows for a longer period of time. Evidence of this finding is described next.

The experiments were performed for three morning rush periods. However, on one day, the bottleneck was not active due to a freeway queue that spilled-over from downstream. The data shown here are from the two remaining days.

The metering experiments were done by monitoring real-time occupancy data from the loop detectors. The metering rates were changed according to the changes in average

occupancies (as per the occupancy thresholds established in the previous section). There were time lags of a few minutes between receiving occupancy data and changing metering rates. In addition, due to a long queue upstream of the on-ramp, metering rates had to return to relaxed rates even before the freeway queue was cleared. The data from these two days reveal important findings.

Fig. 11(a) presents O-curves measured at locations X_1 through X_4 on Aug 11, 2004. Before time $t = 6:18:30$, outflows reached an average of 9,650 vph. But, the vehicle accumulations on the shoulder lane rose above the critical value of 16 vehicles at $t = 6:18:30$ (Fig. 11(b)) and caused outflows to drop by 11 percent to 8,600 vph (Fig. 11(a)). At $t = 6:21$, on-ramp flow was restricted to 400 vph (Fig. 11(c)) and the accumulations began to drop gradually (Fig. 11(b)).

Later at $t = 6:29$, the freeway queue was cleared when the shoulder lane vehicle accumulations reduced below the critical value (Figs 11(a) and (b)). The outflows briefly recovered to 9,250 vph (Fig. 11(a)). At $t = 6:31$, the on-ramp meter was relaxed to 900 vph (Fig. 11(c)). This caused accumulations to rise immediately (Fig. 11(b)); the capacity drop re-occurred; and outflows dropped to 8,400 vph (Fig. 11(a)). Notably, the outflow of 8,400 vph was close to the previous outflows (8,600 vph) that prevailed after the first capacity drop (see Fig. 11(a)).

(a)

V(t)-q₀x(t-t₀), q₀ = 8,700 vph

Capacity Drop
t = 6:18:30

X₁

Capacity Drop
t = 6:31

X₂

8,400 vph

t = 7:03

8,600 vph

9,250 vph

Queue cleared
t =6:53:30

Capacity Drop
t = 6:44

8,600 vph

50

9,650 vph

Queue cleared
t = 6:29

X₃ and X₄

9,250 vph

8,950 vph

Queue cleared
t = 6:43

0

6:12 6:17 6:22 6:27 6:32 6:37 6:42 6:47 6:52 6:57 7:02 7:07 7:12

Time (measured at X₃)

(b)

25

Vehicle Accumulations

t = 6:21

t = 6:36

t = 6:48:30

20

t = 6:31

t = 6:44

15 16 vehs

t = 6:18:30

t = 6:29

t = 6:43

t = 6:53:30

10

5

0

6:12 6:22 6:32 6:42 6:52 7:02 7:12

Time

X₁

X₃

(c)

N(t)-q₀x(t-t₀), q₀ = 400 vph

620 vph

t = 6:48:30

t = 6:36

900 vph

400 vph

900 vph

400 vph

400 vph

t = 6:55

700 vph

400 vph

40

t = 6:44

t = 6:21
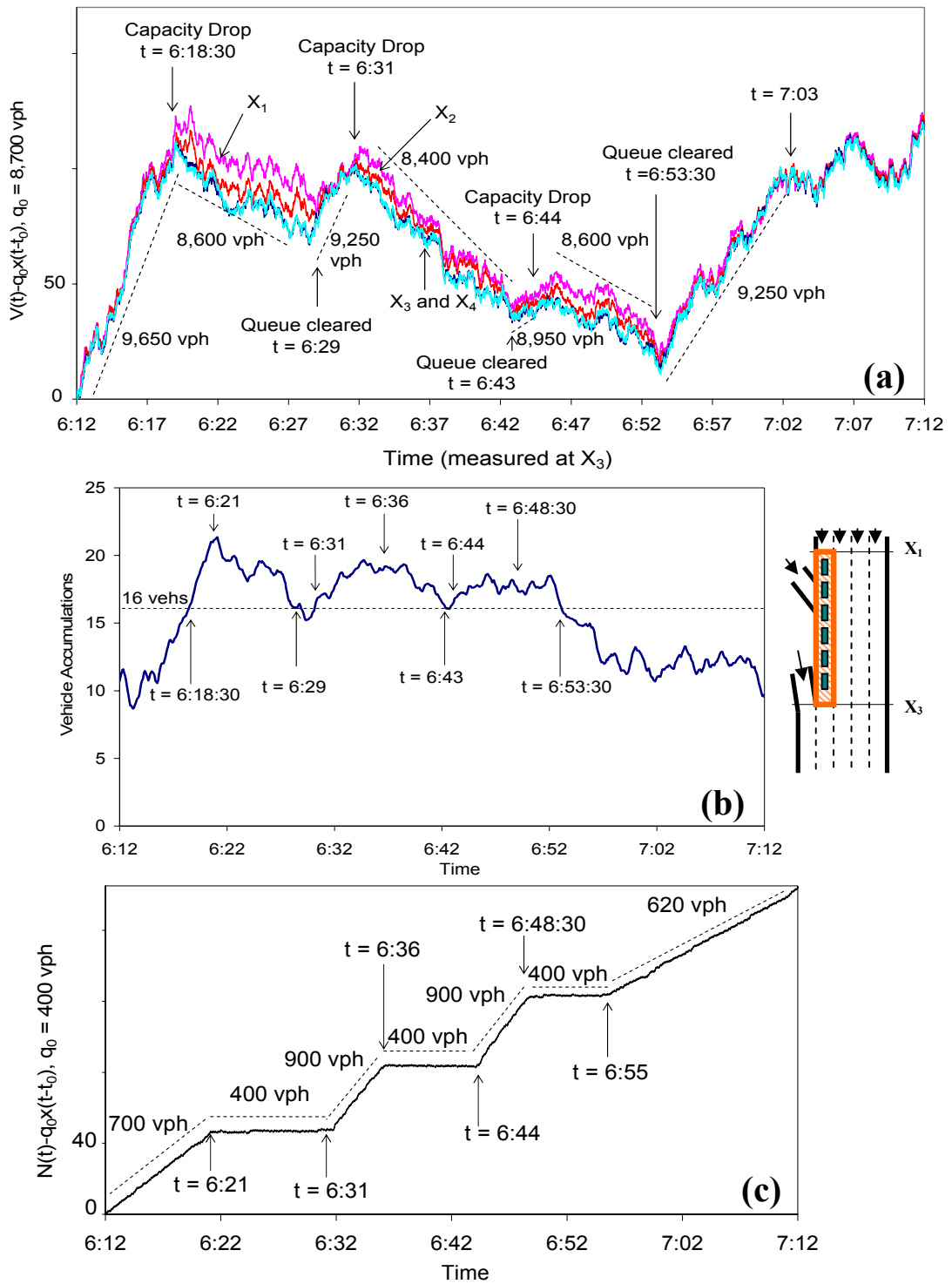
t = 6:31

0

6:12 6:22 6:32 6:42 6:52 7:02 7:12

Time

Figure 11 (Aug 11, 2004 at I-805N)

(a) Oblique N-curves at X₁ through X₄ (b) Shoulder-lane accumulations
(c) Oblique cumulative curve of counts from 47th St/Palm Ave on-ramp

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The metering rate was then restricted to 400 vph at t = 6:36 (Fig. 11(c)). At t = 6:43, the shoulder lane vehicle accumulations dropped below the critical value and the freeway queue was cleared (Figs. 11(a) and (b)). The on-ramp meter was relaxed to 900 vph at t = 6:44 and this again caused the capacity to drop to 8,600 vph (Figs. 11(a) and (c)). The finding indicates that the 900-vph metering rate could not sustain high outflow at this merge and instead caused the capacity to drop immediately.

In contrast, a lower relaxed metering rate implemented after the freeway queue was cleared was found to sustain outflow recovery for an extended period of time. At t = 6:55, the meter was relaxed from 400 vph to only 620 vph (Fig. 11(c)). The outflow then recovered to 9,250 vph (Fig. 11(a)). This high outflow was sustained until the freeway demand evidently dropped at t = 7:03 (Fig. 11(a)).

A similar metering experiment was performed on Aug 12, 2004 as shown in Figs. 12(a)-(c). On this day, the first capacity drop occurred at t = 6:43 (Fig. 12(a)) when the on-ramp meter changed from 400 vph to 900 vph (Fig. 12(c)) and brought the vehicle accumulations on the shoulder above the critical value (Fig. 12(b)). Then, the metering rate was restricted to 400 vph at t = 6:48 (Fig. 12(c)) and the freeway queue was cleared at t = 6:51 (Fig. 12(a)). The outflow was recovered to 9,250 vph. Again, at t = 6:55, the metering rate was relaxed to 900 vph and a capacity drop re-occurred immediately (Figs. 12(a) and (c)).
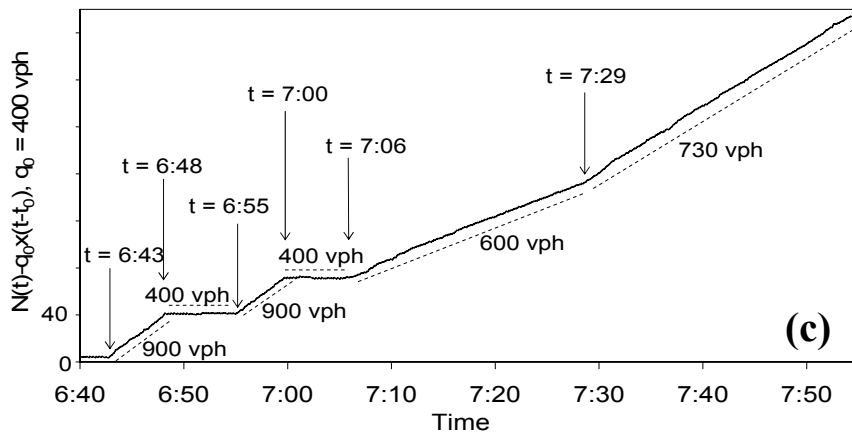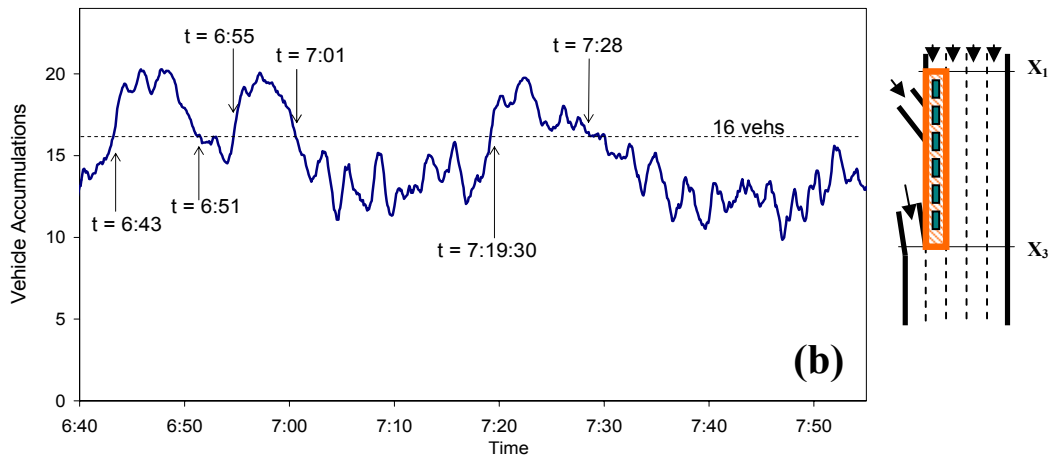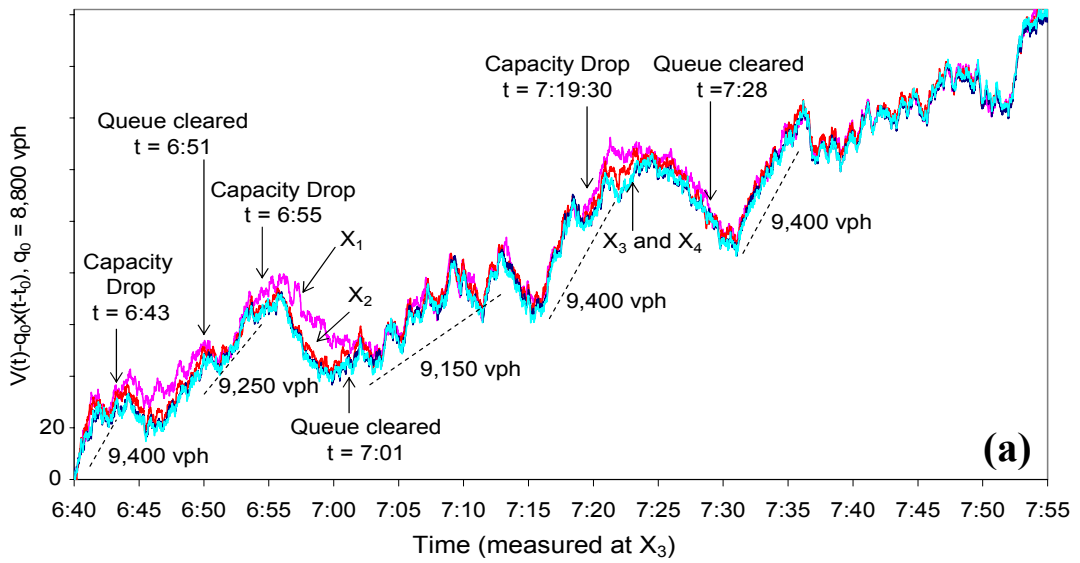
Figure 12 (Aug 12, 2004 at I-805N)

(a) Oblique N-curves at X_1 through X_4 (b) Shoulder-lane accumulations
(c) Oblique cumulative curve of counts from 47th St/Palm Ave on-ramp

At t = 7:06, the metering rate was relaxed to 600 vph (Fig. 12(c)) and high outflows were sustained until t = 7:19:30, the time when another capacity drop occurred (Fig. 12(a)). The average recovered outflow during t = 7:06 to t = 7:19:30 was about 9,250 vph. Notably, this day's average recovered outflow was the same as the previous day's one while being metered at the same 620-vph rate. This outflow was as high as 9,400 vph during t = 7:16 to t = 7:19:30 (Fig. 12(a)). This reconfirms that the 600-vph metering rate can sustain high outflows for an extended period of time (more than 13 minutes, the longest sustainable period observed with 700-vph relaxing metering rate, see Fig.8(a)).

At t = 7:28, the drop in freeway traffic demand brought the vehicle accumulations below the critical value and the queue was cleared (Figs. 12(a) and (b)). This occurred naturally without changing the metering rates since it was near the end of the rush.

One minute later, the metering rate was relaxed to 720 vph (Fig. 12(c)) due to the long queue at the on-ramp. Notice that this higher metering rate did not activate the capacity drop and the outflows from the merge remained high with the average of 9,150 vph for 25 minutes or more. (The observations on this day was ended at t = 7:55).

The data from these experiments yield an important finding regarding relaxed metering rates and duration of outflow recovery. The summary of outflow recoveries on all experimental days is shown in Table 3. The days shown in this section and their corresponding figures are in Column 1. Column 2 presents the relaxed metering rates implemented after the freeway queue was cleared on each day. Column 3 shows the

Table 3

Relaxed metering rates and durations of outflow recovery

(1)	(2)	(3)	(4)
Date	Relaxed Metering rates (vph)	Average outflows recovered (vph)	Duration of outflow recovery (min)
Oct 23, 2003 (Fig. 7)	700	-	0
Oct 15, 2003 (Fig. 8)	700	9,730	13
Oct 21, 2003 (Fig. 9)	740	9,600	4
Aug 11, 2004 (Fig. 10)	900	-	0
Aug 11, 2004 (Fig. 10)	620	9,100	17+*
Aug 12, 2004 (Fig. 11)	900	-	0
Aug 12, 2004 (Fig. 11)	600	9,200	13.5

*An incident caused a downstream freeway queue spillover to the merge after the 17-minute period. If there was no incident, the outflow recovery would have persisted longer than 17 minutes.

average outflows measured from the time when a metering rate was relaxed to the time when a capacity drop reoccurred. The last column (column 4) shows the durations over which capacity recoveries persisted.

The table shows that using a high relaxed metering rate (e.g., 900 vph), the capacity drop re-occurred nearly immediately. In contrast, high outflows can be sustained with a low relaxed metering rate (e.g., 600-620 vph) for 13 minutes or more. These data confirm that after the freeway queue is cleared, low metering rates can postpone the subsequent capacity drop and generate high merge outflows for a longer period of time.

These data also infer that if a proactive on-ramp metering strategy was carefully implemented in such a way as to keep vehicle accumulations on the shoulder lane below the critical value at all times, the capacity drop might be avoided entirely at this merge.

The proposed traffic control strategies based on these findings to increase freeway merge capacities are described in the following section (Section 6).

6. PROPOSED TRAFFIC CONTROL STRATEGIES

This section contains two proposed traffic control strategies: on-ramp metering (Section 6.1) and freeway speed advisories for controlling shoulder lane inflows (Section 6.2). These strategies share a similar idea, i.e., to increase the merge capacities by controlling shoulder-lane vehicle accumulations in the vicinity of a merge.

6.1 ON-RAMP METERING

From Section 4, the findings prove that on-ramp metering can be used both to reverse and to postpone a capacity drop at merge bottlenecks. The metering strategy suggested here is developed from these findings.

First, a strategy is needed to detect immediately the time when shoulder lane vehicle accumulations rise above and drop below the critical value. Restricting an on-ramp before a capacity drop occurs in an attempt to avert it leads to over-controlling and under-utilizing a merge. Instead, restricting an on-ramp meter immediately once a capacity drop occurred will restore the high capacity within a short period of time. Similarly, once the accumulations drop below the critical value, the meter now would be relaxed immediately to pump out higher outflows. Pulsing the metering rates over an entire rush can produce a long-run average merge outflow that is higher than what the merge would otherwise sustain.

Luckily, in the first study site (see Fig. 2), loop detectors are in a strategic location and the detectors' data yield good correlations with shoulder lane vehicle accumulations.

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Consequently, the occupancy data can be used as the basis for traffic responsive metering (as explained in Section 5.2).

However, if loop detectors are not in a desirable location, excess vehicle accumulations (vertical separations of two curves in O-curves) might be used as thresholds instead. In this regard, Chung, et al (2005) shows that the excess vehicle accumulations from two sets of loop detectors (upstream and downstream of a bottleneck) can be served as real-time proxies to determine when shoulder lane vehicle accumulations exceed the thresholds.

Choices of restrictive and relaxed metering rates depend on many criteria. Theoretically, the restrictive metering rate is the minimum rate allowable at each site. McDermott, et al (1979) reported that driver compliance with meters decreases significantly when drivers must wait at the meter for longer than fifteen seconds (this is equivalent to a 240-vph metering rate). In this experimental study, the restrictive rate used was 400 vph. With this rate, Caltrans reported that meter violations during the restrictive metering period almost doubled as compared with the regular metering rates (650-900 vph).

A suitable relaxed metering rate should be determined by field tests. The rate should be high enough to motivate drivers in the upstream freeway queue so as to pump out higher merge outflows. It must not be too high, however, to disrupt traffic streams and promptly bring about another capacity drop.

Data from these metering experiments can form the discussion concerning two existing popular metering strategies, i.e., demand-capacity schemes (Wattleworth (1964)), and ALINEA schemes (Papageorgiou, et al (1991)) as follows:

Demand-capacity metering schemes is a metering strategy that adjusts an on-ramp metering rate according to upstream traffic demand to maintain a "target flow", i.e., an assumed fixed merge capacity (Wattleworth (1964)). Nonetheless, the data (including those presented in Tables 1 and 2 show that merge outflows varied greatly from day to day and the "target flow" can exhibit a range as large as 2,000 vph for a four-lane freeway (see Table 1) and 800 vph for a three-lane freeway (see Table 2). Thus, fixed capacity assumed in this strategy is questionable. This strategy thus seems inadvisable in practice. Ideally, metering rates would instead be altered in response to vehicle accumulations near the merge.

ALINEA (Asservissement LINeaire d'Entree Autroutiere) is a metering scheme based on occupancies detected from loop detectors downstream of the merge (Papageorgiou, et al (1991)). Although ALINEA's main concept is similar to this study's bang-bang metering experiments (i.e., it uses loop detector occupancies in a vicinity of the merge as the basis for changing metering rates), there is an important difference. The ALINEA scheme changes metering rates gradually depending on the difference between the current and critical occupancies. However, ALINEA metering scheme has not been appropriately tested and has not been shown to increase merge capacities. The data from this study's experiments suggest that abrupt changes in metering rates can bring favorable outcomes.

This study did not test, however, whether gradual changes (ALINEA schemes) in metering rates are more or less favorable. A number of metering experiments at various bottleneck locations are needed to compare both metering strategies.

Although the present experiments show that on-ramp metering can be effective in increasing freeway merge capacities, long on-ramp queues can become a problem, particularly if the on-ramp queue propagates upstream and blocks local streets or intersections nearby. The policy is inequitable, moreover, because the system-wide delay reduction that it produces occurs by imparting added delays to the on-ramp traffic. A control strategy to resolve this issue is discussed in the following section.

6.2 CONTROLLING SHOULDER-LANE INFLOW

The data indicate that the mitigation of the deleterious shoulder lane queues that diminish merge capacity can be achieved by means other than metering on-ramps. The data from one day at the second study site in Orange County (Fig. 3) show that shoulder lane queues are held below the critical value (and high merge capacities are consequently sustained) when the shoulder lane's vehicle arrival rates in advance of the merge are sufficiently low.

Fig. 13(a) presents O-curves on June 8, 2004, the only day that this phenomenon was observed. It shows that the capacity dropped at time t = 14:27 to 5,760 vph, a reduction of nearly 15 percent from the high average outflow (of 6,760 vph) that arose earlier.

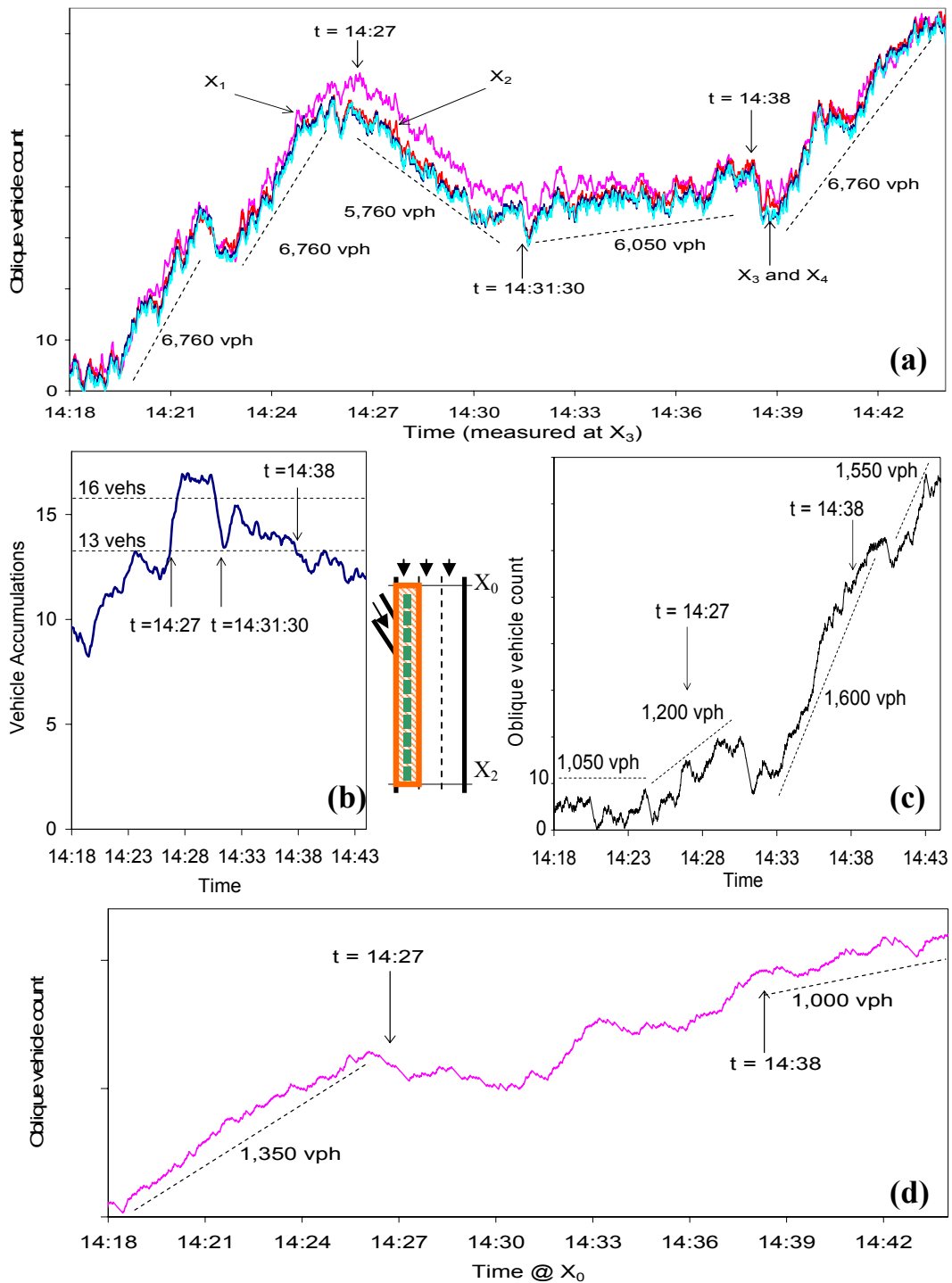Figure 13 (June 8, 2004 at SR-22E)

(a) Oblique count curves at X_1 through X_4
(b) Shoulder-lane accumulations
(c) Oblique cumulative curve of counts from Fairview St on-ramp
(d) Oblique cumulative curve of shoulder lane inflow at X_0

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Outflow increased (to 6,050 vph) later at t = 14:41:30 and then again (to the original high rate of 6,760 vph) at t = 14:38. This final increase came after the upstream queue had dissipated (i.e., the curves at X_1 and X_2 became superimposed), such that the merge was no longer an active bottleneck. The changes in merge capacities were linked to critical accumulations (or 13- and 16- vehicles) as shown in Fig. 13(b).

Fig. 13(c) presents an oblique curve of on-ramp vehicle counts. Inspection of the curve shows that the initial capacity drop at t = 14:27 occurred minutes after the on-ramp's meter began admitting vehicles at a higher average rate of 1,200 vph. Remarkably, however, the full capacity recovery that began just after t = 14:38 was maintained even though on-ramp inflows by this time had further risen to rates as high as 1,600 vph; i.e., higher capacity was sustained even in the presence of very high on-ramp inflows.

The above observations thus reveal that in one instance, a lower on-ramp flow (of 1,200 vph) accompanied a capacity drop, while later that rush a higher capacity persisted with a high on-ramp flow (of 1,600 vph). The explanation for this seems to be the variations that occurred in shoulder lane inflows to the merge. Fig. 13(d) presents an oblique curve of shoulder lane counts (only) measured at location X_0 upstream of the merge (see again Fig. 3). Fig. 13(d) reveals that the initial capacity drop at t = 14:27 occurred when the shoulder lane demand reached an average of 1,350 vph. By the time capacity fully recovered at t = 14:38, average demand was only 1,000 vph. (Shoulder lane flows measured between these two times were constrained due to the bottleneck's queue and therefore cannot be interpreted as demands.)

The above findings suggest that controlling shoulder lane inflow can be an effective means of generating high merge capacity, even while permitting high inflows from the on-ramp. More research is needed to obtain further observations of this kind and to generalize the findings.

It follows that an effective and equitable policy for increasing merge capacity would be to exogenously affect inflows to the merge from the freeway shoulder lane. This may be achieved by issuing speed advisories to shoulder lane drivers (e.g. via portable changeable message signs) upstream of active merge bottlenecks. The advisories might suggest that these shoulder lane drivers reduce their speeds slightly. Messages of this kind can favorably influence shoulder lane flows since vehicle's deceleration causes drivers upstream to respond, either by decelerating or by changing lanes. Either response would be desirable in that both would diminish shoulder lane inflow to the merge. This strategy can be operated alone or jointly with on-ramp metering, such that ramp delays and queue lengths could be kept to manageable levels.

7. CONCLUSIONS

This final section contains a summary of the study (Section 7.1) and an outline of further research areas (Section 7.2).

7.1 SUMMARY OF THE STUDY'S FINDINGS

This dissertation has unveiled a capacity drop mechanism at freeway merge bottlenecks and has demonstrated a role for traffic control strategies to increase capacity at these merges. This research is the first to deliver the following findings:

1) The capacity drop mechanism has been identified. Capacity drop is initiated by a queue that forms near the merge in the freeway shoulder lane. Once the vehicle accumulation in this queue reaches a critical value, shoulder-lane vehicles slow down and lane-changing maneuvers increase sharply as drivers attempt to avoid slow traffic in and near the shoulder lane. This maneuvering spread the queue laterally across the freeway. The capacity drop generally persisted through the entire rush.

2) Field experiments show that metering can favorably affect this capacity drop mechanism by reversing and/or postponing the mechanism. Reversing capacity drop can be done by using restrictive metering until vehicle accumulations on the shoulder lane diminished below the critical value. Then, high outflows can be fully recovered by relaxing the metering rate so that drivers in the upstream freeway queue become motivated and the merge can pump-out higher outflow. The observations also infer that the capacity drop mechanism can be averted by metering in a proactive fashion.

3) Controlling shoulder-lane inflow may be an effective mean of generating high merge capacity, even while permitting high inflows from the on-ramp.

Given these findings, this dissertation can help traffic researchers to understand the traffic phenomena at merge bottlenecks and help traffic engineers to operate on-ramp metering and freeway traffic properly.

In summary, this dissertation provides important information concerning how to control freeway traffic at merge bottlenecks and can also advance the present knowledge in traffic flow theory. The areas of further research are described next.

7.2 AREAS OF FURTHER RESEARCH

This research has sought a greater understanding of the capacity drop mechanism at two merge bottlenecks and has done experimental tests of on-ramp metering at one site. Further analyses of traffic data and on-ramp metering experiments at other merge sites are required to compare findings and confirm the reproducibility of the observed traffic features described herein. Some additional areas of further research are suggested below.

This study did not provide evidence of what happened upstream of the merge when capacity drops were recovered (see Section 5). There might be significant changes in lane-changing activities upstream that were not observed in this study due to limited vision. Further research on this matter is ongoing.

It appears that real-time detections of shoulder-lane vehicle accumulations are critical for implementing traffic control strategies at a merge. More research is needed to find the best detecting strategies. These include, but are not limited to, using real-time occupancy data from loop detectors as described in Section 5.2, and using excess vehicle accumulations that were briefly mentioned in Section 6.1.

Also, several metering strategies should be tested at more merge bottlenecks. The results of metering experiments would bring more understanding of benefits and disbenefits of each metering strategy. Specifically, ALINEA and bang-bang metering schemes would be tested as described in Section 6.1.

Other kinds of traffic control strategies in addition to on-ramp metering should be tested. Section 6.2 described possible benefits of controlling shoulder-lane inflows by using a changeable message sign. In fact, other control strategies that result in reducing upstream freeway flows might be also effective. One example is metering several upstream on-ramps. These ideas are described in Daganzo et al (2002) but have not been tested in the field.

Lastly, a merge is not the only form of freeway bottlenecks. More observations and experimental works are needed at other types of bottlenecks such as diverges, weaves, etc. The study of these bottlenecks like those described in this dissertation would bring a greater understanding of the capacity drop mechanisms and how to manage traffic there.

These kinds of research would contribute more realistic traffic flow theories and to guidelines for traffic engineers.

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