On-Ramp Metering Experiments to Increase Freeway Merge Capacity

Authors

Cassidy, Michael J.
Rudjanakanoknad, Jittichai

Publication Date

2005-09-01

CALIFORNIA PATH PROGRAM
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

On-Ramp Metering Experiments to Increase Freeway Merge Capacity

Michael J. Cassidy,
Jittichai Rudjanakanoknad

California PATH Research Report
UCB-ITS-PRR-2005-28

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation, and the United States Department of Transportation, Federal Highway Administration.

Final Report for Task Order 5312

September 2005

ISSN 1055-1425

FINAL REPORT FOR PATH
Task Order 5312

On-Ramp Metering Experiments to Increase Freeway Merge Capacity

By

Michael J. Cassidy and Jittichai Rudjanakanoknad
University of California
Department of Civil and Environmental Engineering
And the Institute of Transportation Studies
109 McLaughlin Hall
Berkeley, California 94720
(510) 642-7702
Cassidy@ce.berkeley.edu

July 1005

ABSTRACT
Observations of two freeway/on-ramp merges unveil the mechanism that causes their capacities to diminish when queues form just upstream. Field experiments at one of the sites demonstrate that by responding to occupancies measured near the merge, ramp metering can reverse this mechanism, or postpone its occurrence, and thereby generate higher merge capacities. Detailed observations at the second site imply that higher merge capacities can also be achieved using traffic control schemes that regulate inflows to the merge from the freeway shoulder lane. Collectively, the findings point to further experiments needed to refine capacity-enhancing control schemes so that such schemes might enjoy wide spread deployment.

EXECUTIVE SUMMARY

This report confirms the capacity drop mechanism at freeway merge bottlenecks and further demonstrates a role for on-ramp metering to increase capacity at these bottlenecks. To these ends, extensive observations were collected and carefully studied to verify the traffic phenomena that arise at two freeway merges, after these became active bottlenecks.[1] This was followed by experimental tests of an on-ramp metering scheme. The tests show that a fully automated, traffic-responsive metering logic can favorably affect merge capacities.

Detailed observations collected at a merge bottleneck using video cameras have previously shown that “capacity drops” (substantial and persistent reductions in unconstrained outflow following the onset of upstream queues) are triggered by a queue that forms near the merge 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 spreads the queue laterally across the freeway. The capacity drop invariably ensues and persists 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.

The previous study also found the relationship between (i) occupancies measured by the loop detectors located just upstream of the merge and (ii) vehicle accumulations in the freeway shoulder lane. Measured occupancies thus became the basis for a fully automated, traffic-responsive metering logic. The logic was tested in the present research project and, when properly calibrated, was found to produce high merge outflows for prolonged periods.

As part of this new research, field experiments performed at a merge site in San Diego show that automated, traffic-responsive metering can postpone and/or reverse the capacity drop mechanism. Reversing capacity drop can be done first by using restrictive metering until detector occupancies indicate that vehicle accumulation in the freeway shoulder lane has diminished below the critical value. High outflows can then be fully

[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.

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 postponed and even avoided 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 averted at the merge.

Further, the data now collected from a second freeway merge (in Orange County) imply that a high capacity can be gained even when the on-ramp inflow is high. This can be achieved when inflows to the merge from the freeway shoulder lane are sufficiently low.

The findings verify that automated, traffic-responsive metering can generate higher capacities at an active merge bottleneck. The findings further suggest that less conventional control schemes can also be an effective means of increasing merge bottleneck capacity. (Such schemes might include freeway traffic speed advisories, as described in the report itself.) The findings are important, since after all, higher bottleneck capacities mean commuter delays are reduced system-wide.

But the observations and experiments to date are limited. The metering experiments at the San Diego site were conducted for only three days. Beneficial refinements to the metering logic used there would likely be unveiled through further experiments. More importantly, it remains to be seen if the favorable outcomes obtained at the site can be reproduced at other merge bottleneck locations. And finally, the interesting observations taken at the Orange County site are quite preliminary at this stage.

The findings indicate that a suitable *implementation strategy* for Caltrans would be to support further experiments of the kind presented here. These additional experiments could help to refine a capacity-enhancing metering logic; they could verify the effectiveness of this logic at other merge locations; and they could assess the value of less conventional control schemes, such as freeway speed advisories. It is hoped that the favorable findings reported here will help advance the cause of further experimentation.

TABLE OF CONTENTS

1. INTRODUCTION

This report unveils a queue formation mechanism at two active merge bottlenecks in Southern California. Capacity drops were a reproducible feature at both these merges. Each capacity drop was triggered by a queue that formed near the merge in the freeway shoulder lane. Once the vehicle accumulation in this shoulder lane queue reached a critical value, lane change maneuvers increased sharply in number as drivers sought to avoid slow traffic in and near the shoulder lane. This maneuvering spread the queue laterally across the freeway and the capacity drop ensued.

By restrictively metering the on-ramp to diminish shoulder lane accumulation below the critical value (and simultaneously clear the freeway queue from the merge), high outflows often returned to the median lane. Outflow could then be fully recovered by relaxing the metering rate and allowing greater inflows from the on-ramp to return.

Relaxing the metering rate served to bring the freeway queue at the merge to the brink of re-forming. Drivers in this traffic state evidently became sufficiently motivated, such that the merge could pump-out higher flow.

Section 2 summarizes previous metering experiments at the first of the two bottlenecks studied here, a merge in San Diego (*Cassidy and Rudjanakanoknad, 2005*). This earlier work showed that ramp metering can reverse the capacity drop at the merge. The earlier findings also pointed to control strategies that can sustain the outflow recovery by using real-time information provided by loop detectors.

The results of these earlier experiments led to an automatic control strategy that was tested as part of the present research. The findings from these new experiments are presented in Section 3. The major findings are that (i) 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; and (ii) this kind of control can be deployed in a fully automated fashion.

Section 4 presents data from a second freeway merge, this one located in Orange County. The data from this second site reveal a capacity drop mechanism that is qualitatively consistent with the mechanism unveiled at the first site (in San Diego). The data from this second site further show that the mitigation of the deleterious shoulder lane queues that diminish merge capacity can be achieved by means other than metering on-ramps. These data show that shoulder lane queues are held below the critical value (and high merge capacities are consequently sustained) when the freeway shoulder lane's vehicle arrival rates in advance of the merge are sufficiently low.

A summary of this new study is provided in the fifth and final section.

2. BACKGROUND

In this section, we summarize the earlier metering experiments at a merge bottleneck in San Diego (*Cassidy and Rudjanakanoknad, 2005*) showing that ramp metering can reverse the capacity drop there. We further provide here the observations that real-time occupancies obtained from a nearby set of loop detectors can be a reliable proxy to detect the bottleneck's vehicle accumulations that trigger capacity drops. This latter presentation led to the traffic-responsive metering logic that was tested in the present research and was found to generate higher merge capacities.

The earlier experiments showed that the capacity loss that occurs whenever the San Diego freeway merge became an active bottleneck can be recovered by metering its on-ramp. Detailed observations collected from video revealed a reproducible "trigger" of capacity loss at this bottleneck: a queue that forms near the merge in the freeway shoulder lane. A capacity drop ensued each time vehicle accumulations in this queue reached a critical value. Outflow recovery could only be realized once ramp metering diminished the queue's accumulations below the critical value.

By metering restrictively to mitigate this deleterious shoulder lane accumulation (and simultaneously clear the freeway queue at the merge), appreciably higher outflows sometimes returned to the median lane. And once the freeway queue was cleared, substantially higher outflows could be generated in all freeway lanes by then relaxing the metering rate and allowing higher inflows from the on-ramp to return.

The metering logic used in these earlier experiments was rather coarse, and perhaps this is why the outflow recoveries never persisted for more than 13 minutes. Yet this initial verification that merge capacity can be recovered is important. It proves ramp metering can favorably affect merge capacity. Verification of these findings for a single study day is provided below.

Fig. 1 displays the San Diego study site. Video cameras were set up on the downstream over-crossings shown in the figure. Data from morning rush periods on 20 days were manually extracted from the videos. These data are unprecedented in their detail, as illustrated in the following examples.

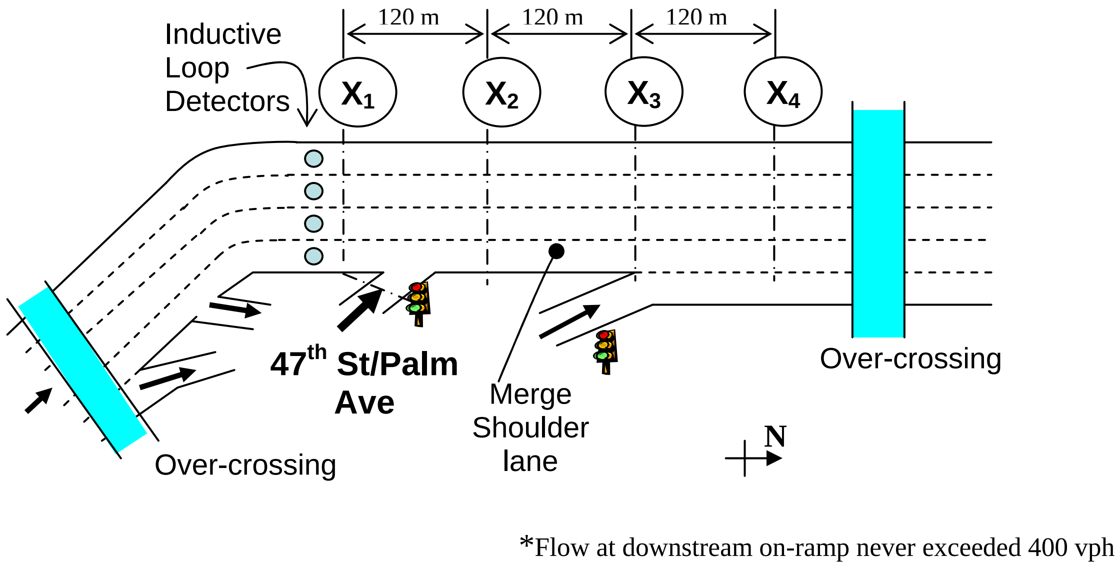

Figure 1

Study Site, Northbound Freeway 805, San Diego, California

Fig. 2(a) displays curves of cumulative vehicle count versus time, t, measured from video at the locations labeled X_1 through X_4 (in Fig. 1) on one of the study days (Oct. 21, 2003). 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 plot displays the quantity $O(t) = V(t) – q_0×(t-t_0)$ versus t; i.e., the cumulative virtual vehicle count to time t, V(t), minus a background reduction, $q_0×(t-t_0)$; q_0 is a background flow. The curves thus reveal that unqueued conditions persisted between X_3 and X_4 (the curves at these locations were always superimposed) while queueing (curve displacements) arose upstream. These features verify that a bottleneck activated between X_2 and X_3.

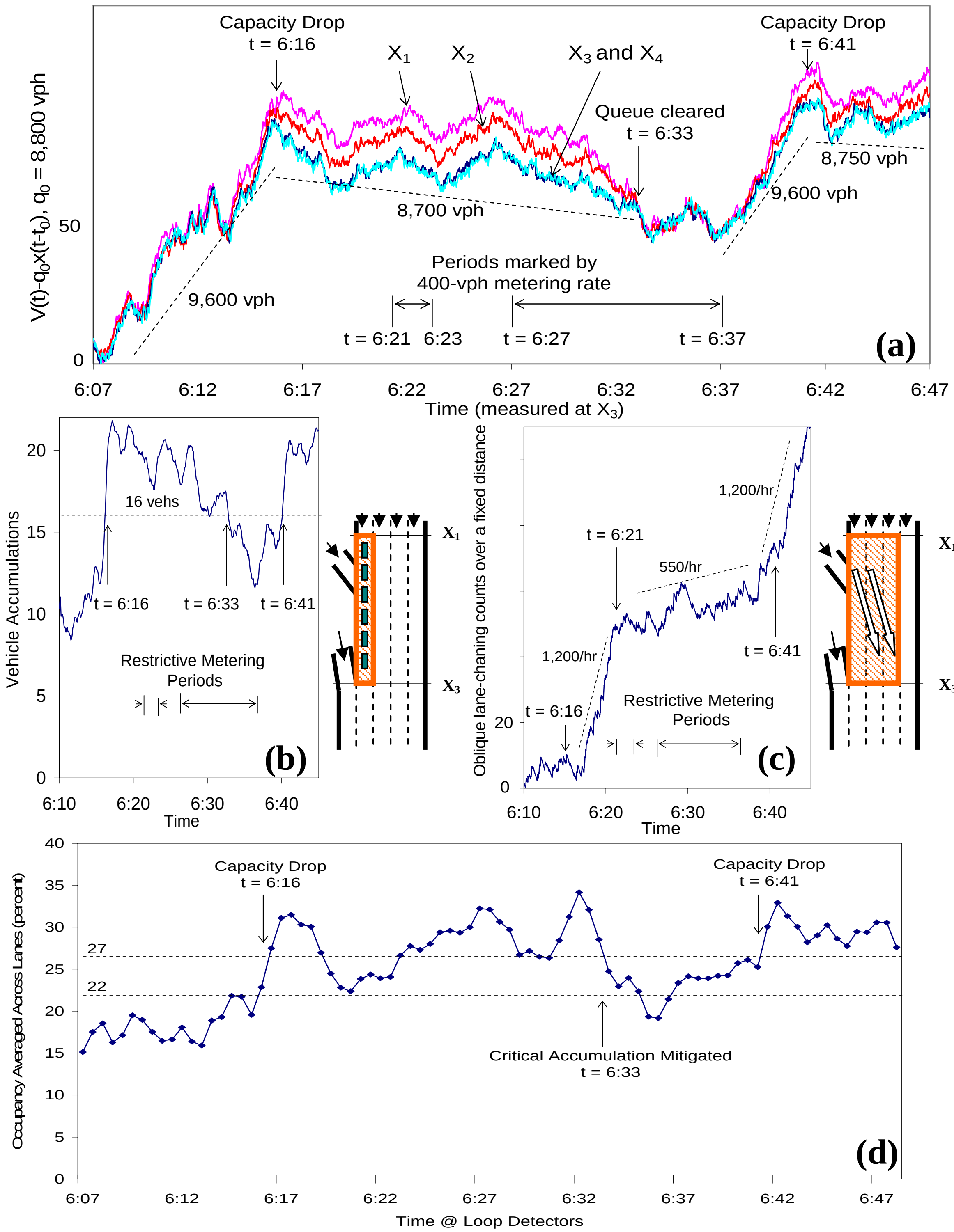

Figure 2 (October 21, 2003)

(a) Oblique N-curves at X_1 through X_4
(b) Shoulder-lane accumulations
(c) Oblique curve of cumulative lane-changing counts over a fixed distance
(d) Time series of detector occupancies

O-curves collected on the other study days verified that the merge site consistently became an active bottleneck. This verification was essential to show that metering can favorably affect the unconstrained outflow (capacity) of an active merge bottleneck. Such verification has been absent in previous studies on the subject of metering and merge capacity.

Fig. 2(a) includes dashed lines showing flow trends (flows are proportional to the slopes of the O-curves). These indicate that a capacity drop occurred at t = 6:16; at this time, longer-run average outflow from the merge dropped from 9,600 vph to 8,700, a reduction of nearly 10 percent.

Figs. 2(b) and (c) reveal apparent causes of the capacity drop. The first of these figures is a time series of vehicle accumulations counted in the freeway shoulder lane (only) between locations X_1 and X_3, as shown in the illustration directly to the right of Fig. 2(b). These accumulations were sampled (from video) every 5 secs and counts averaged over 1-min intervals are shown. Notably, the capacity drop coincided with the first passage of this time series at 16 (and we showed in our previous report that an accumulation of 16 vehicles triggered capacity drop with uncanny reproducibility).

This high shoulder lane accumulation (queue) induced drivers to maneuver around the slow traffic it created. The sharp increase in disruptive vehicle lane-change maneuvers is shown in Fig. 2(c), an oblique curve of cumulative lane-change counts in the two right-most lanes measured between locations X_1 and X_3; these counts were taken as illustrated to the right of the figure. The sudden increase in the curve's slope at t = 6:16 denotes the rise in lane-change activity.

Our experiment on this day began at t = 6:21. For brief periods starting at this time, the on-ramp's metering rate was diminished from 740 vph to a rate of 400 vph; these periods of restrictive metering are annotated in Figs. 2(a) – (c) and the latter of these figures shows how restrictive metering immediately curbed lane changes. Fig. 2(a) shows this metering cleared the freeway queue at the merge at t = 6:33, as indicted by the re-superimposition of the O-curves. At this same time, shoulder lane accumulation dropped below 16 vehicles (Fig. 2(b)).

After the freeway queue was cleared, the metering rate was restored to 740 vph at t = 6:37. Merge outflow immediately recovered to 9,600 vph (Fig. 2(a)). The recovery on this day persisted for only 4 mins.[2] At t = 6:41, capacity drop reoccurred at the merge. Shoulder lane accumulations at this time rose again above 16 vehicles (Fig. 2(b)), high lane changing reappeared (Fig. 2(c)) and, very importantly, average outflow diminished to 8,750 vph (Fig. 2(a)).

Fig. 2(d) displays occupancies measured by the detectors just upstream of the merge (see Fig. 1). The 30-sec sample points shown in Fig. 2(d) are 1-min moving averages across all lanes. The times that capacity drops occurred are annotated in the figures, as is the time that restrictive metering brought shoulder lane accumulation below the critical value of 16 vehicles.

Figures of this kind constructed from the data on the other study days (and shown in our previous report) revealed two important features that we have since used in a traffic-responsive metering logic:

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. 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 (San Diego) site were found to be the best proxies since, as noted above, their relation to capacity drops and shoulder lane queue mitigation were reproducible across the others study days.

The present study is the logical extension of the previous findings described above. In this new work, an automated “bang-bang” metering strategy based on the above findings was tested. The results of these new experiments are presented in the following section.

---

[2] Our previous report demonstrated that on other study days, metering could sustain higher merge capacities for more prolonged periods.

3 RESULTS OF AUTOMATED METERING EXPERIMENTS

This section presents results of metering experiments using the occupancy thresholds discussed in the previous section. In these experiments, the relaxed metering rates initiated in response to reduced shoulder lane accumulations were varied (from 600 to 900 vph) to determine the extents to which these metering rates can generate high merge outflows. The major findings of this new set of experiments are 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 that this can be achieved in an automated fashion. Evidence of these findings is provided below.

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 involved monitoring, and responding to, real-time occupancy data from the site's upstream 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 long queues at the on-ramp, metering rates were returned to relaxed rates even before the freeway queue was cleared from the merge. The data from these two days reveal important findings nonetheless.

Fig. 3(a) presents O-curves measured at the San Diego merge 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 at t = 6:18:30 (Fig. 3(b)) and caused outflows to drop by 11 percent to 8,600 vph (Fig. 3(a)). At t = 6:21, on-ramp flow was restricted to 400 vph, as shown in Fig. 3(c), an oblique curve of cumulative on-ramp vehicle counts. Consequently, the shoulder lane accumulations began to drop gradually (Fig. 3(b)).

Later at t = 6:29, the freeway queue was cleared and the shoulder lane vehicle accumulations dropped below the critical value (Figs 3(a) and (b)). The outflows very briefly recovered to 9,250 vph (Fig. 3(a)). At t = 6:31, the on-ramp meter was relaxed to 900 vph (Fig. 3(c)). This caused accumulations to rise immediately (Fig. 3(b)); the capacity

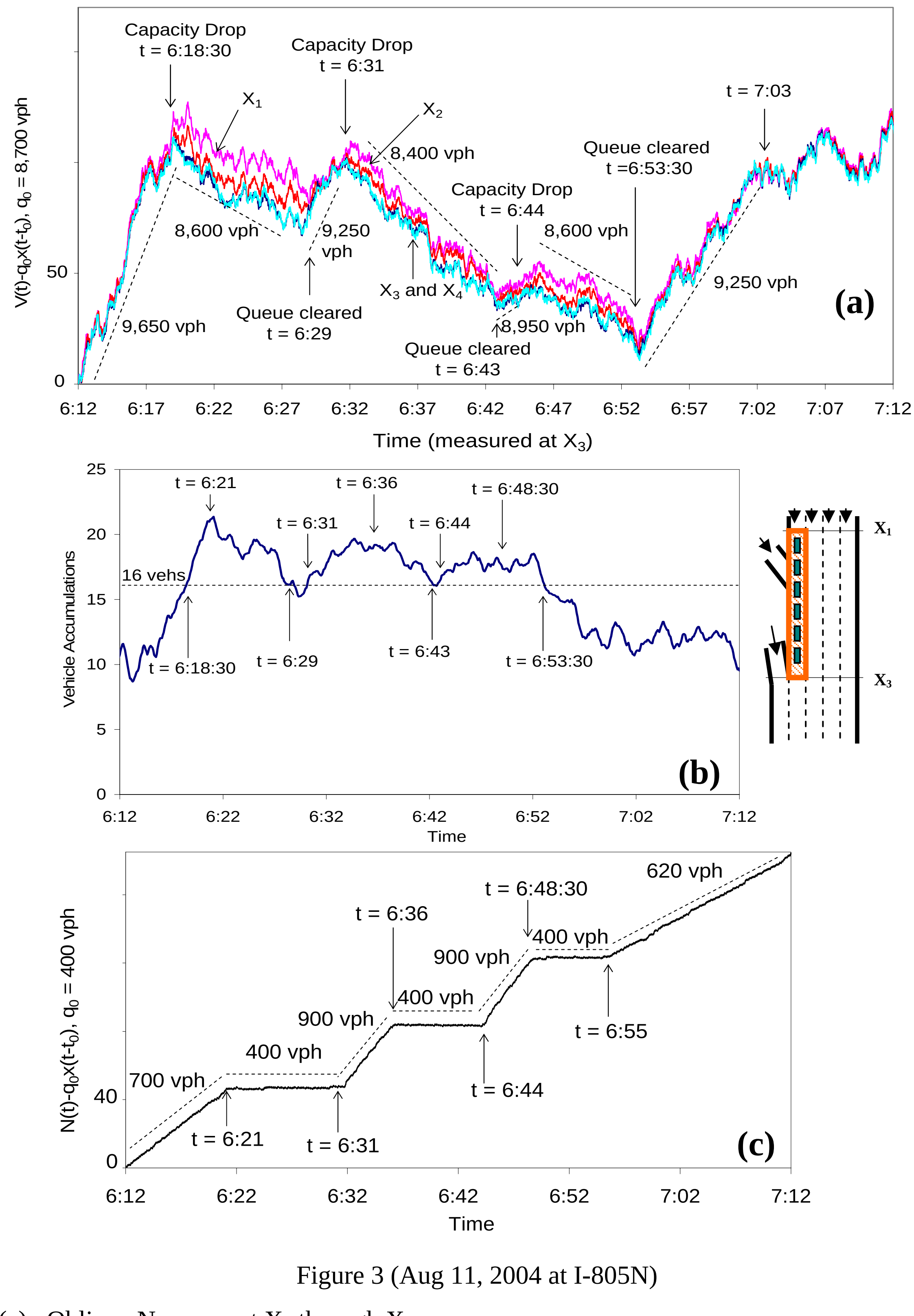

Figure 3 (Aug 11, 2004 at I-805N)

(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

drop re-occurred and outflows dropped to 8,400 vph (Fig. 3(a)). Notably, the outflow of 8,400 vph was close to the previous outflow (8,600 vph) that prevailed after the first capacity drop (see Fig. 3(a)).

The metering rate was then restricted to 400 vph at t = 6:36 (Fig. 3(c)). At t = 6:43, the shoulder lane vehicle accumulations dropped below the critical value and the freeway queue was cleared (Figs. 3(a) and (b)). The on-ramp meter was relaxed to 900 vph at t = 6:44 (Fig. 3(c)) and this again caused the capacity to drop to 8,600 vph (Fig. 3(a)). The finding indicates that the 900-vph metering rate could not sustain high outflow at this merge and instead caused the capacity drop to re-occur immediately.

In contrast, a lower relaxed metering rate implemented after the freeway queue was again cleared later that morning 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. 3(c)). The merge outflow then recovered to 9,250 vph (Fig. 3(a)). This high outflow was sustained until the freeway demand dropped at t = 7:03 (Fig. 3(a)).

A similar metering experiment was performed on Aug 12, 2004 as shown in Figs. 4(a) – (c). On this day, the first capacity drop occurred at t = 6:43 (Fig. 4(a)) precisely when the on-ramp metering rate changed from 400 vph to 900 vph (Fig. 4(c)) and brought the vehicle accumulations on the freeway shoulder lane above the critical value of 16 (Fig. 4(b)). The metering rate was then restricted to 400 vph at t = 6:48 (Fig. 4(c)) and as a consequence, the freeway queue was cleared and the shoulder lane accumulation was mitigated at t = 6:51 (Figs. 4(a) and (b)). The merge outflow recovered to 9,250 vph. At t = 6:55, the metering rate was again relaxed to 900 vph and a capacity drop re-occurred immediately (Figs. 4(a) – (c)).

At t = 7:06, the metering rate was relaxed to only 600 vph (Fig. 4(c)) and high outflows were sustained until t = 7:19:30, at about which time another capacity drop occurred (Figs. 4(a) and (b)). The average outflow recovered from t = 7:06 to t = 7:19:30 was about 9,250 vph.[3] This outflow rose as high as 9,400 vph from t = 7:16 to t = 7:19:30 (Fig. 4(a)). This reconfirms that a metering rate of about 600 vph can sustain high outflows for an extended period of time.

[3] This day's average recovery outflow was the same as on the previous day when the relaxed metering rate was 620 vph.

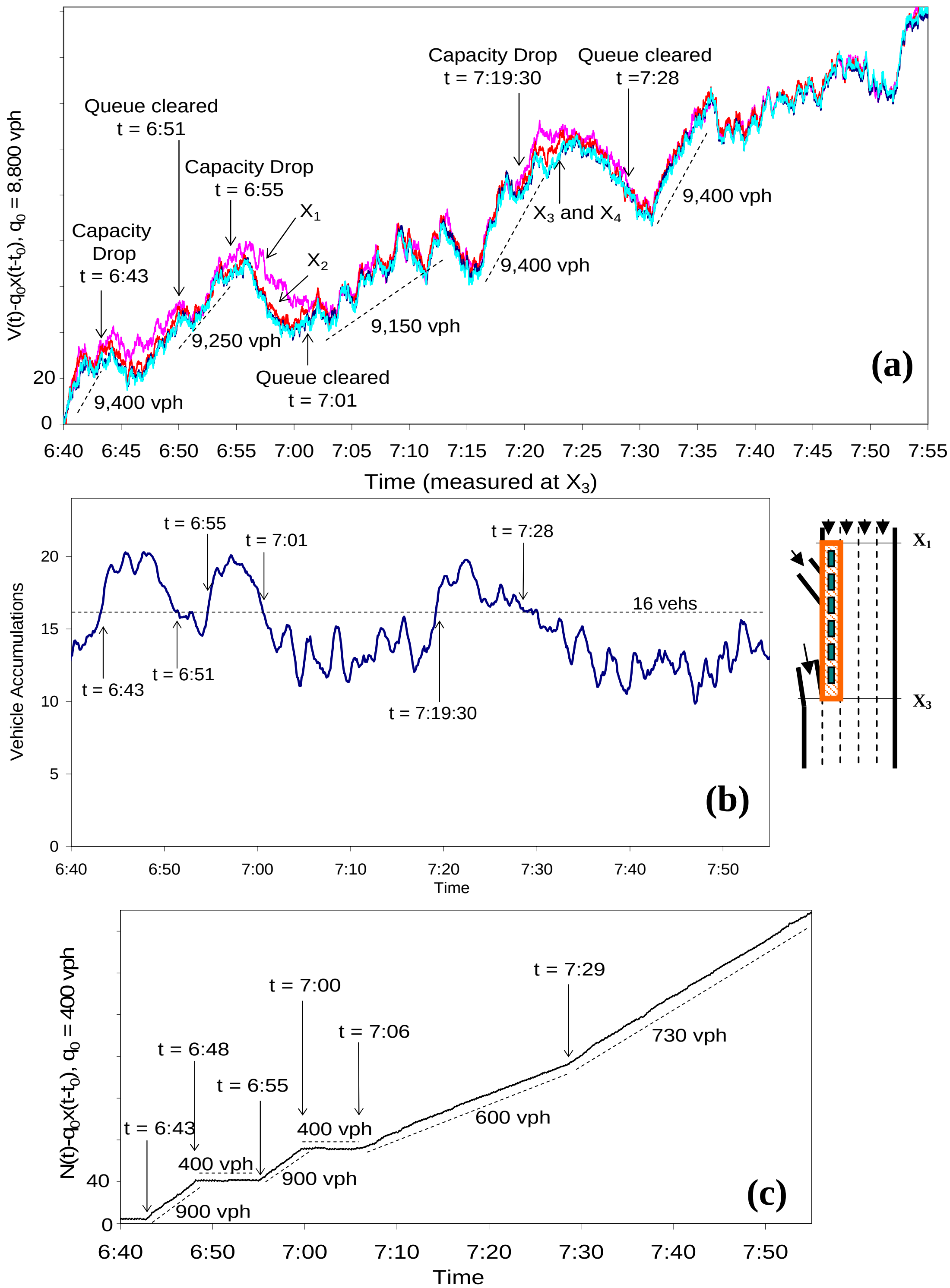

Figure 4 (Aug 12, 2004 at I-805N)

(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 = 7:28, the drop in freeway traffic demand brought the shoulder lane vehicle accumulations below the critical value of 16 and the freeway queue was cleared at the merge (Figs. 4(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 730 vph (Fig. 4(c)) due to the long queue at the on-ramp. This higher metering rate did not trigger a capacity drop and the outflows from the merge temporarily rose to 9,400 vph. An ensuing average outflow of 9,150 vph persisted for more than 25 minutes. (Observations on this day were ended at t = 7:55).

These experiments yield an important finding regarding relaxed metering rates and outflow recovery. A summary of outflow recoveries on all experimental days is shown in Table 1. Column 2 of this table lists the relaxed metering rates implemented each time the shoulder lane accumulation was mitigated and the freeway queue was cleared. Column 3 shows the average outflows measured from the time when a metering rate was relaxed to the time when a capacity drop re-occurred. The last column (column 4) shows the durations over which these capacity recoveries persisted.

Table 1

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	700	-	0
Oct 15, 2003	700	9,730	13
Oct 21, 2003	740	9,600	4
Aug 11, 2004	900	-	0
Aug 11, 2004	620	9,100	17+*
Aug 12, 2004	900	-	0
Aug 12, 2004	600	9,200	13.5

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

The table shows that when using a high relaxed metering rate (e.g., 900 vph), the capacity drop re-occurred immediately. In contrast, high outflows can be sustained for longer periods with a lower relaxed metering rate of 600-620 vph. These findings confirm that after the freeway shoulder lane accumulation is mitigated, low metering rates can postpone the subsequent capacity drop and thus produce higher merge outflows.

These findings also infer that if a proactive on-ramp metering strategy is 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.

Although the present experiments show that on-ramp metering can be effective in increasing freeway merge capacities, the longer on-ramp queues that result 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 these shortcomings is discussed in the following section.

4. THE SIGNIFICANCE OF FREEWAY 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 (shown in Fig. 5) reveal that shoulder lane queues are held below the critical value (and high merge capacities are consequently sustained) when the freeway shoulder lane's vehicle arrival rates in advance of the merge are sufficiently low.

Fig. 6(a) presents O-curves measured at the locations X_1 through X_4 shown in Fig. 5. These data were collected on June 8, 2004. The curves show that the merge became an active bottleneck prior to t = 14:27. These curves also show 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.

Outflow increased (to 6,050 vph) later at about 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 freeway queue near the merge had dissipated (i.e., the curves at X_1 and X_2 became superimposed), such that the merge was no longer an active bottleneck. Note that the changes in merge

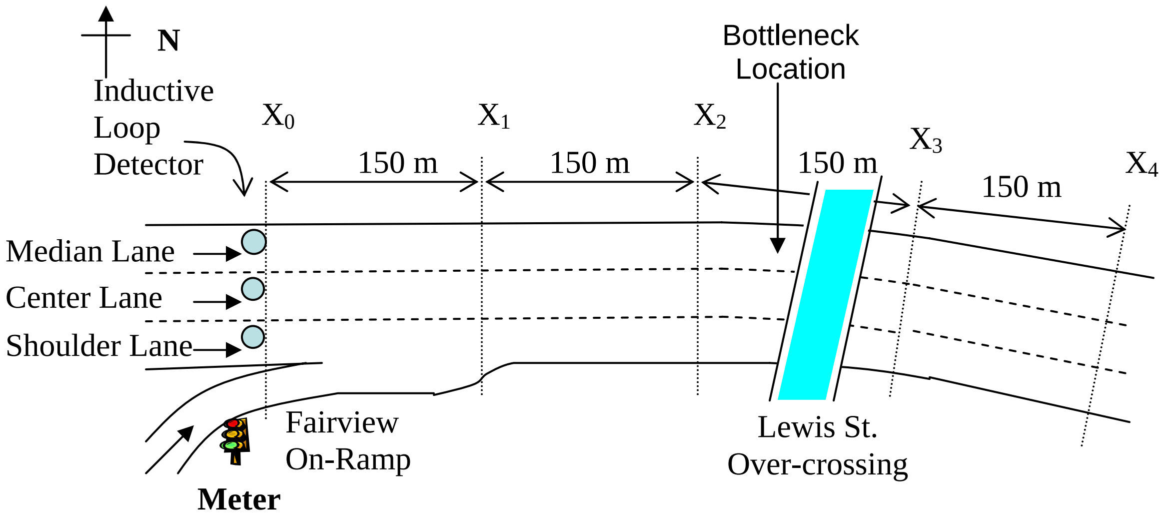

Figure 5

Eastbound State Route 22, Orange County, California

capacities were linked to shoulder-lane vehicle accumulations (of 13- and 16- vehicles) as shown in Fig. 6(b). As a notable aside, shoulder lane accumulations of 13 and 16 vehicles were found to correspond to capacity drops at this site on all days from which observations were collected. The capacity drop mechanism at this second site is thus qualitatively consistent with the mechanism unveiled at the San Diego site.

Fig. 6(c) presents an oblique curve of on-ramp vehicle counts measured at the Orange County site during the June 8 study day. Inspection of this curve shows that the initial capacity drop at t = 14:27 occurred minutes after the on-ramp's meter began admitting vehicles at a high 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. 6(d) presents an oblique curve of freeway shoulder lane counts (only) measured at location X_0 upstream of

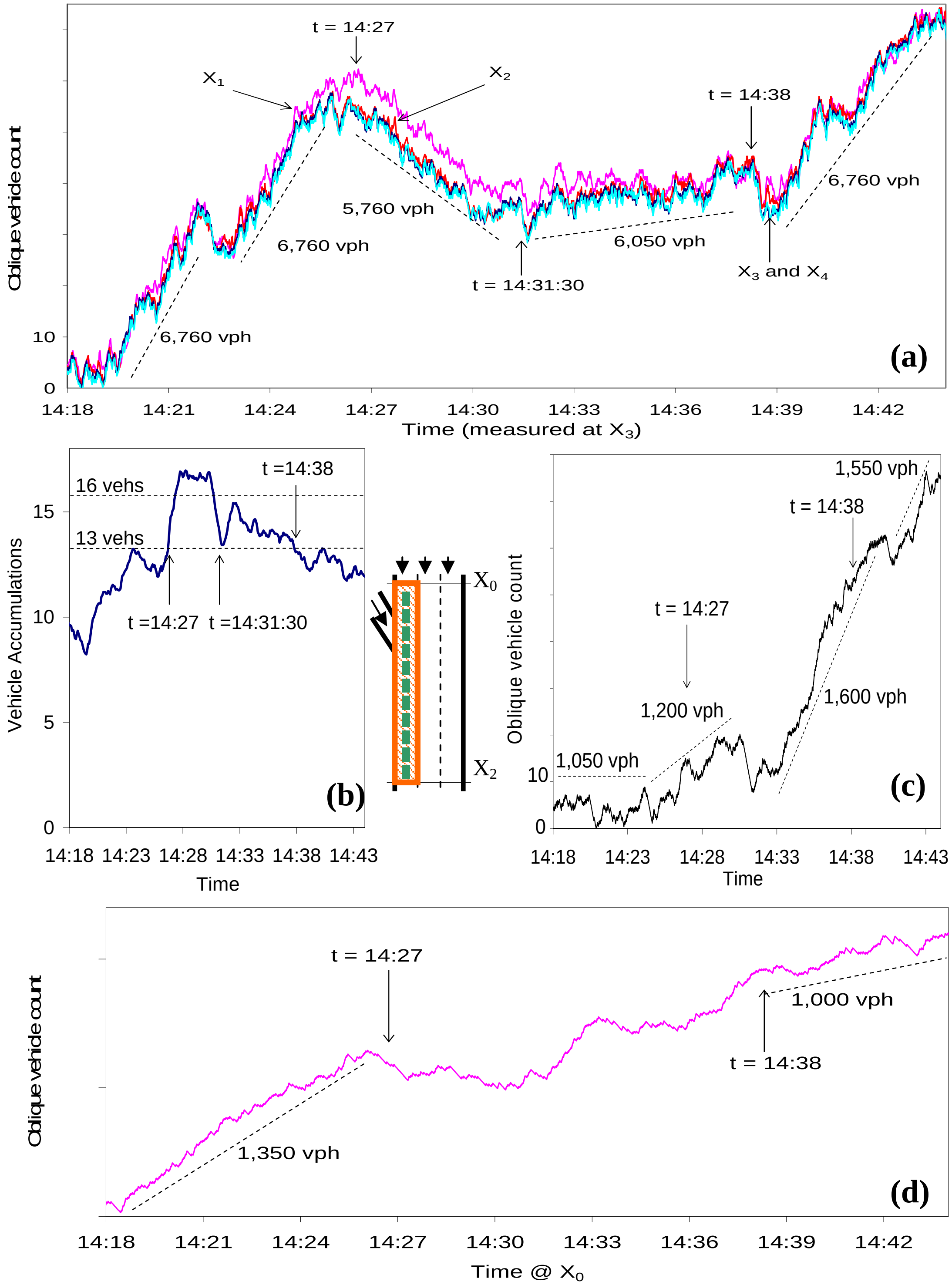

Figure 6 (June 8, 2004 at SR-22E)

(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

the merge (see again Fig. 5). Fig. 6(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 t = 14:27 and t = 14:34 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 might 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 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 in dense traffic, a 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.

5. SUMMARY OF THE STUDY FINDINGS

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

1) Field experiments show that metering can favorably affect this capacity drop by responding to loop detector occupancies. The capacity drop can be reversed using restrictive metering until the measured occupancies indicate that vehicle accumulations in the freeway shoulder lane have 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.

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

ACKNOWLEDGEMENT

The authors gratefully acknowledge Caltrans, particularly personnel in San Diego, for facilitating the field experiments described herein.

REFERENCES

1. Cassidy, M. J., and Rudjanakanoknad, J. (2005), *Increasing Capacity of an Isolated Merge by Metering its On-Ramp,* in press in Transportation Research Journal (Part B).

2. Daganzo, C. F. (1997), *Fundamentals of transportation and traffic operations,* Elsevier, New York.