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Authors
Cassidy, Michael J.
Rudjanakanoknad, Jittichai

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Increasing Capacity of an Isolated Merge
by Metering its On-Ramp

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

ABSTRACT
Measurements taken downstream of freeway/on-ramp merges have verified that discharge flow diminishes when a merge becomes an active bottleneck. We show that metering the on-ramp can recover the higher discharge flow and thereby increase merge capacity. Detailed observations collected using video revealed that the outflow drop following activation was triggered by a queue that formed near the merge in the freeway shoulder lane and then spread laterally, as drivers changed lanes to maneuver around slow traffic. Once restrictive metering mitigated this shoulder lane queue, high outflows often returned to the median lane. Merge outflow could be increased to levels measured prior to the bottleneck activation by then relaxing the metering rate so that inflows from the on-ramp increased. Although outflows recovered in this fashion were unstable and never persisted for periods greater than 13 mins, the findings are the first real evidence that ramp metering can favorably affect the capacity of an isolated merge. The findings point to control strategies that might stabilize outflow and increase merge capacity even more.

1. INTRODUCTION

This paper unveils the queue formation mechanism at an active merge bottleneck in San Diego, California. "Breakdown" (defined here as a substantial and persistent reduction in unconstrained outflow following the onset of upstream queues) was a reproducible feature at the merge. It was triggered each morning rush by a queue that formed there in the freeway shoulder lane. Once the vehicle accumulation in this 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 breakdown 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.

Perhaps the coarseness of this metering logic is why each outflow recovery was unstable and never persisted for more than 13 mins. The findings nonetheless show that temporary outflow gains of 10 percent or more are possible. It follows that alternating the metering rates over the entire rush can produce a higher average discharge in the long run. This implies that merges should not be over-controlled to avoid breakdown.

The findings also point to control strategies that might sustain the outflow recovery by more purposefully mitigating the deleterious shoulder lane queue. Description of one such strategy is provided in the concluding section of the manuscript. Issues regarding implementation of capacity-increasing control strategies are also discussed there.

Section 2 relates the present experiments to the literature and clarifies the unique contribution of our findings. Section 3 includes description of the merge study site and presentation of the traffic details that caused breakdown. The data were collected from video during morning rush periods on ten days and were processed in high-resolution ways. The video collection scheme and data processing methods are further exploited in section 4 to display findings from the metering experiments that took place on ten additional days.

2. BACKGROUND

We define the capacity of a freeway system as the *sustained* flow it discharges (from all its exits) when its entrances are queued (to insure reservoirs of demand) and its exits are unblocked by exogenous restrictions. An exogenous restriction might be a queue that spills-over from further downstream. A system's capacity is not fixed. It can be altered by traffic control measures.

Consider a freeway queue that forms within a system with on- and off-ramps, as exemplified with the shading in Fig. 1(a). If this queue propagates beyond off-ramps, it will affect exit flows and reduce capacity. We call this the "gridlock mechanism" because on closed-loop ("beltway") systems, it can drive system capacity to zero; i.e., total gridlock (*Daganzo, 1996*). By mitigating a gridlock-causing queue, ramp metering can increase system capacity. Mention of this was made as early as in *Newman, et al (1969). Daganzo (1996)* quantified the benefits of ramp metering on closed-loop systems and showed how it diminishes driver trip times.

But metering can also mitigate certain queues and improve freeway flow without increasing system capacity. For the system shown in Fig. 1(b), metering might promote higher flow on the "internal" freeway link by moving the queue to one or both on-ramps. Unfortunately, the higher internal flow can be accompanied by a lower discharge rate (lower system capacity) if metering is overly restrictive and starves the downstream merge of flow. Further discussion on this "starvation mechanism" is provided in *Cassidy (2003)*.

It is well understood how systems like those in Figs. 1(a) and (b) are influenced by metering. The present study, however, addresses an open question: the effects of ramp metering on the capacity of an isolated merge, like the one shown in Fig. 1(c). Outflows higher than the unconstrained queue discharge rate have been measured at merges, sometimes even for periods of 30 mins or more (e.g. *Cassidy and Bertini, 1999*). But these higher rates are never sustained over an entire rush. Something inevitably triggers a queue with a lower discharge rate that then persists for the remainder of the rush.

Although it is often assumed (e.g. in *Papageorgiou and Kotsialos, 2002*) that ramp metering can maintain the higher outflows at an isolated merge and thus increase merge capacity, previous field studies show no evidence of this. Review of these studies is provided below.

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, the closed-loop freeway in Paris. This finding is not surprising given the freeway's geometry; it reconfirms that metering can exploit the gridlock mechanism, as described with Fig. 1(a). Similar trip time reductions were reported from having metered on-ramps on another freeway in Paris (*Haj-Salem, et al, 2001)*. Both studies involved systems with many on- and off-ramps and do not speak to the workings of an isolated merge.

Papageorgiou, et al (1998) comes closer to the issue; it reports 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. But this does not show that metering affected the capacity of these merges because the benchmarks for comparison were queued flows constrained by an exogenous restriction (a downstream tunnel).

Another study (*MnDOT, 2001)* reconfirmed that metering can increase freeway flows. But as described with Fig. 1(b), higher flows within a system are not evidence of increased system or merge capacities.

The only previous studies to explicitly address merge capacity in an isolated setting have relied on computer simulations (*Papageorgiou and Kotsialos, 2002*; *Smaragdis, et al, 2004*). Unfortunately, simulations must rely on assumptions of driver behavior at merges and other mathematical approximations that may or may not be realistic. Only observation of nature can furnish unequivocal answers to the question of merge capacity.

The following section describes our study site and the breakdown mechanism. The section after that demonstrates the capacity improvements achieved by metering.

3. OBSERVATIONS

This section includes description of the site and the data. These data verify that (i) the site has an active merge bottleneck during the morning rush; (ii) the bottleneck's activation eventually produces losses in outflow, particularly in the freeway's median lane; and (iii) this breakdown is triggered by a queue that initially forms in the shoulder lane near the merge and then spreads laterally.

Fig. 2 is an illustration of the site, a stretch of northbound Freeway 805 in San Diego, California. Video cameras were set up each study period on the over-crossings also shown in the figure. Detailed traffic data were manually extracted from videos.

The on-ramp to the merge bottleneck (from 47th St/Palm Ave) is metered. We describe in this section observations collected without having altered the meter's existing logic. Data for this "observational" component of the study were taken from ten morning rush periods extending from fall 2002 to spring 2003.[1] The data presented below were collected on September 18, 2002 and are typical of other observation days.

Fig. 3(a) displays transformed curves of cumulative vehicle count, N, vs time, t; these were measured at the locations labeled X_1 through X_4 (in Fig. 2). The start of each cumulative curve (N = 0) was measured relative to the passage time of a reference vehicle at its measurement location, X. Each N-curve was shifted horizontally to the right by a free flow vehicle trip time from its respective measurement location to X_4. We thereby obtained V-curves that display "virtual" departures past X_4. Vertical displacements between two V-curves are the excess vehicle accumulations on the intervening freeway segment due to vehicular delays.

These displacements were amplified and made visible to the naked eye by plotting the V-curves on an oblique coordinate system. On a rectangular system, the curves display the quantity $O(t) = V(t) - q_0 \times (t - t_0)$; i.e., the cumulative virtual vehicle count to time t, $V(t)$, minus a background reduction; the latter is some specified rate, q_0, multiplied by the interval extending from the curves' start time, t_0, to t. The oblique coordinate system amplifies changes in slopes, making possible the visual identification of flow changes at each measurement location.[2] This data processing method has been used in a number of studies (e.g. *Cassidy and Windover, 1995; Muñoz and Daganzo, 2002a).*

The O-curves in Fig 3(a) reveal key traffic features for the period shown. They indicate traffic was freely flowing or unqueued (i.e., all curves are superimposed) to 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.

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[1] Data from two of these ten days proved unusable. In one instance (Sept. 19, 2002), the merge bottleneck was inactive throughout most of the rush due to an exogenous freeway queue from downstream. On the other day (Jan. 7, 2003), high winds shook the video cameras, such that data could not be extracted.

[2] The flows annotated in figures like Fig. 3(a) were retrieved from the counts actually measured from videos. Oblique cumulative curves facilitated visual identification of time periods marked by changes in flow.

But some of the O-curves diverge from t = 6:13, indicating that excess vehicle accumulations arose near the merge. Outflows remained high during this initial period of queue formation; the average during this time was 10,250 vph.

Further inspection of Fig. 3(a) shows that conditions between X_3 and X_4 remained freely flowing for the entire period shown (the curves at these downstream-most locations are always superimposed) and that all excess accumulation (queueing) arose just upstream of X_3. These features verify that an active bottleneck arose between X_2 and X_3.

The changes in curve slopes thus verify that unconstrained queue discharge from the merge fell to an average of 9,240 vph, beginning at t = 6:23:30. This is a 10 percent reduction from the outflow that immediately preceded it. The lower rate persisted for the remainder of the rush.

This breakdown was evidently triggered by a queue that formed in the freeway shoulder lane. The dark line in Fig. 3(b) is a time series of vehicle accumulations counted in the shoulder lane (only) between locations X_1 and X_3, as per the illustration directly right of the figure. These accumulations were sampled (from video) every 5 secs and the curve presents the averages of these counts over 1-min intervals. The curve first reached an accumulation of 16 vehicles at t = 16:23:30; i.e., the start of breakdown 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 a "critical" accumulation (of 16) in the shoulder lane accompanied breakdown each day with uncanny reproducibility. Table 1 provides for each observation day the average outflows measured some minutes before shoulder lane accumulation first reached 16 vehicles (column 2) and for the entire period of breakdown that followed (column 3). These data indicate that the critical shoulder lane accumulation partitions the high and low outflows measured before and after breakdown. (Still more evidence of the causal relation between shoulder lane accumulation and breakdown is provided in the following section.)

Notably, it was accumulation in the shoulder lane, and not in other lanes, that initiated breakdown. The lightly drawn line in Fig. 3(b) displays the average accumulation per lane between X_1 and X_3, as measured from N-curves and normalized by the number of freeway lanes (four). The onset of breakdown coincided with a sharp rise in the shoulder

lane accumulation (the dark line), while the average in all lanes only rose soon thereafter. Accumulations increased in this sequence because the formation of the shoulder lane queue motivated drivers to maneuver into adjacent freeway lanes. This manuvering marked a final stage of the breakdown mechanism and was confirmed by the observed increase in lane-changing activity described below.

Fig. 3(c) is an oblique plot of cumulative lane changes over a fixed distance vs time, $L(t)$. (In the rectangular coordinate system, the curve of Fig. 3(c) actually displays $L(t) - b_0 \times (t - t_0)$, where b_0 is a background rate reduction.) The counts for this curve were taken between X_1 and X_3 and are the sums of lane changes to the left (only) from the two right-most lanes; how these counts were taken is schematically illustrated to the right of Fig. 3(c). The curve itself shows that a sharp increase in this lane-changing activity (from 500/hr to 1,100/hr) followed breakdown at $t = 6:23:30$. This lane changing spread the queue to adjacent freeway lanes and disrupted flows in these lanes.

But lane changing alone might not explain breakdown. Fig. 3(d) is an oblique plot of cumulative vehicle counts in the median lane at X_3. The discharge rates labeled on the curve show that breakdown was marked by a loss in median lane outflow of 360 vph. (This is more than one-third the total outflow loss at breakdown, as can be determined from the discharge rates labeled in Fig. 3(a).) Yet on this day, as on others, the outflow reduction occurred even though lane-changing maneuvers into (and out of) the median lane increased relatively little after breakdown.[3]

Vehicle speeds in the median lane did drop sharply during breakdown, however, as was determined by sampling median lane trip times (from X_1 to X_3) from video. Drivers in the median lane may have decelerated in response to queueing in adjacent lanes.[4] This cautionary driver behavior was previously observed at freeway diverge bottlenecks (*Cassidy, et al, 2002; Muñoz and Daganzo, 2002b*).

In summary, breakdowns resulted in sizable losses in merge outflows. The breakdown mechanism was initiated by a queue in the freeway shoulder lane. The

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[3] Following breakdown, vehicle entry rates into the stretch of median lane rose from 240/hr to 330/hr. This was the largest increase of its kind observed on any study day. On some days, breakdown brought almost no increased maneuvering into the median lane. Increases that did occur were always small relative to those in adjacent lanes, yet outflow reductions were always greatest in the median lane.

[4] Once traffic slowed in the median lane, discharge from the congested merge was roughly equal in all (four) freeway lanes. The reader can infer from Figs. 2 and 3(a) that after breakdown occurred, the average outflow per lane was 2,310 vph. This average is very close to the median lane's breakdown flow shown in Fig. 3(d).

mechanism was completed by disruptive lane changing that occurred as drivers maneuvered around this queue and by what appears to be cautionary responses from drivers in the median lane.

The findings suggest that breakdown might be combated if the on-ramp is metered to mitigate the deleterious shoulder lane queue. The oblique cumulative count curve in Fig. 3(e) displays the inflows from the on-ramp (at 47th/Palm) generated by the metering logic that existed there at the time. Outcomes from altering this logic are presented next.

4. EXPERIMENTS

Experiments show that once restrictive metering (at 400 vph) reduced shoulder lane accumulation below the critical value, (i) high outflows returned to the median lane; and (ii) merge outflow can be fully recovered, albeit temporarily, if the metering rate is relaxed (to 700 vph). These experiments were conducted during ten morning rush periods in summer and fall 2003. On three of these days, the merge bottleneck was inactive due to exogenous downstream queues. Samples from three of the remaining seven days are presented below. They illustrate the range of outcomes observed over those seven days.

Fig. 4(a) presents O-curves measured at locations 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 t = 16:14:30, unconstrained outflows dropped to an average of 8,800 vph. This day was unusual in that the outflow that preceded breakdown (9,250 vph) was low relative to most other days, and that the outflow loss from breakdown was only about 5 percent. Losses of at least 8 percent were more the norm.

Fig. 4(b) shows that breakdown coincided with a shoulder-lane accumulation (between locations X_1 and X_3) of 16 vehicles. Fig. 4(c) displays the increased lane-changing activity that arose at breakdown as well; the oblique cumulative curve of lane-changing counts over a fixed distance exhibited a sharp rise that persisted to t = 6:23:30.

At this time, the restrictive metering rate of 400 vph was implemented for 10 mins (Fig. 4(e)). In addition to mitigating immediately the lane-changing activity (Fig. 4(c)), this control action reduced shoulder lane accumulation below the critical value at t = 6:26 (Fig. 4(b)) and cleared the freeway queue from the merge (Fig. 4(a)).

Remarkably, Fig. 4(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 breakdown. Unfortunately, the increased flow in the median lane did not generate higher (total) merge outflows for a sustained period. Fig. 4(a) shows that total outflow rose to 9,500 vph, but that this persisted for only 4.5 mins. This indicates that the restrictive metering cleared the freeway queue even upstream of the merge and that freeway arrival rates (demands) were no longer sufficient to produce a persistent outflow recovery. In fact, total outflow markedly diminished (to only 8,400 vph) beginning at t = 6:31:30. This reduction occurred when arrival rates dropped in the freeway's center and shoulder lanes (and these drops could have been caused by some short-lived flow-restricting event upstream). In any case, the reduction illustrates how easily a merge can be starved of flow.

The outflow reduction continued until t = 6:33:30, at which time the on-ramp's metering rate was restored to 700 vph (Fig. 4(e)) and freeway arrival rates increased. The ensuing freeway queue with its unconstrained discharge of 8,900 vph (Fig 4(a)) marks the re-occurrence of breakdown. This re-occurrence coincided with the return of a "critical accumulation" in the shoulder lane (Fig. 4(b)), resurgence in lane-changing maneuvers (Fig. 4(c)), and reduction in median lane outflow (Fig. 4(d)).

The good news here is that returning to a relaxed metering rate did not always re-trigger breakdown 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 (for part of the morning rush on October 15, 2003) in Fig. 5(a). The initial portions of the O-curves in this figure were measured during breakdown conditions: the four curves verify that the merge bottleneck was active to t = 6:40 with an average discharge of 8,640 vph.[5]

A restrictive metering rate of 400 vph was deployed at t = 6:29 (Fig. 5(e)). It had the immediate effect of curbing lane-change activity (Fig. 5(c)). By t = 6:40, the restrictive metering had diminished shoulder lane accumulation below the critical value (Fig. 5(b))

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[5] Although not shown in Fig. 4(a), the average outflow that preceded this breakdown was 9,820 and this high rate persisted for 8 mins.

and cleared the freeway queue from the merge (Fig. 5(a)). Metering was restored to 700 vph at this same time (Fig. 5(e)).

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. 5(b)). Lane-changing activity fluctuated in similar fashion, but did not exhibit a persistent increase until this same time (Fig. 5(c)).

The outcome is evident in Fig. 5(a): outflow recovered to 9,730 vph. With the relaxed metering rate, the merge pumped-out an average flow that was about 13 percent greater than that of breakdown 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. 5(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.)

We observed that outflows were recovered in this way on other days as well (albeit for periods shorter than 13 mins) and a final example is illustrated in Fig. 6. The O-curves in Fig. 6(a) reveal the occurrence of breakdown at t = 6:16. It coincided with the first instance of critical accumulation in the shoulder lane (Fig. 6(b)) and greater lane changing (Fig. 6c)). 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.[6] Very importantly, Fig. 6(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.

The above findings verify that ramp metering can mitigate the breakdown mechanism and temporarily restore higher outflow to the isolated merge. These findings also point to control strategies that may sustain higher merge capacity over an entire rush, and not just for the relatively short periods observed here. Such strategies are discussed next.

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[6] 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.

5. FINAL THOUGHTS

Our findings that merge capacity can be recovered means there is no need to over-control (starve) the merge in an attempt to prevent its breakdown. It follows that pulsing the metering rates over an entire rush can produce a long-run average discharge higher than what the merge would otherwise sustain.

Ideally, the metering rates would be pulsed in response to vehicle accumulations near the merge. Although accumulations in the shoulder lane were found to trigger the breakdown mechanism, the metering logic could respond to accumulations measured across all lanes, since key changes in these lagged very closely behind those in the shoulder lane. A methodology for the real-time estimation of accumulations (in all lanes) between neighboring loop detector stations is a subject of a forthcoming paper.

For now, it is fortunate that our study site's single detector station (with loops in all lanes, as shown in Fig. 2) is located sufficiently close to the merge that measured occupancies serve as reasonable proxies for accumulations there. Figs. 7(a) – (c) display occupancies measured by the detectors each experiment day previously presented. The 30-sec sample points shown are 1-min moving averages across all lanes. The times that breakdowns occurred are annotated in the figures, as are the times shoulder lane accumulations were brought below the critical value of 16 vehicles.

The figures reveal two features that can be used in a traffic-responsive metering logic:

1. breakdowns always occurred at or shortly before the times measured occupancies rose to 27 percent; and

2. the deleterious shoulder lane accumulations were always reduced below 16 vehicles at or shortly before the times occupancies dropped to 22 percent.

It follows that for our merge, average occupancies of 27- and 22 percent can be thresholds for initiating restrictive and relaxed metering, respectively. Ramp control would thus suitably respond to changes in merge conditions soon after these key changes occurred.

And since breakdowns were triggered by queues in the freeway shoulder lane, there may be value in augmenting ramp metering with schemes that regulate the freeway traffic. As an example, speed advisories issued to shoulder lane drivers in advance of the merge

(e.g. using changeable message signs) might mitigate the shoulder lane queue, particularly if these advisories motivate some drivers to exit the shoulder lane while still upstream of the merge (*Daganzo, et al, 2002*). This type of control might stabilize outflow recovery, even when relaxing the metering rate to prevent ramp queues from growing long, and perhaps even when queues at the merge cannot be cleared from the freeway's median and center lanes.

We plan to test the above ideas through experiments. We also plan to explore the extent to which our present findings can be generalized to other isolated merges.

REFERENCES

1. Cassidy, M. J. (2003), *Freeway On-Ramp Metering, Delay Savings, and Diverge Bottleneck*, In Transportation Research Record 1856, TRB, Washington D.C., pp. 1-5.

2. Cassidy, M.J., and R. L. Bertini (1999), *Some Traffic Features at Freeway Bottlenecks,* In Transportation Research, Vol. 33B, 1999, pp. 25-42.

3. Cassidy, M. J., and J. R. Windover (1995), *Methodology for Assessing Dynamics of Freeway Traffic Flow*, In Transportation Research Record 1484, TRB, Washington D.C., pp. 73-79.

4. Cassidy, M.J., Ananai, S.B. and Haigwood, J.M. (2002), *Study of freeway traffic near an off-ramp*, In Transportation Research, Vol 36A (6), pp. 563-572.

5. Daganzo, C. F. (1996), *The nature of freeway gridlock and how to prevent it,* In Transportation and Traffic Theory, Proc. 13th Int. Symp. on Transportation and Traffic Theory (J.B. Lesort, editor) Pergamon-Elsevier, Tarrytown, N.Y., pp. 629-646.

6. Daganzo, C. F., J. Laval, and J. C. Muñoz (2002), *Ten Strategies for Freeway Congestion Mitigation with Advanced Technologies,* California PATH Research Report, UCB-ITS-PRR-2002-3.

7. Haj-Salem, H., and M. Papageorgiou (1995), *Ramp metering impact on urban corridor traffic: field results*, In Transportation Research, Vol. 29A, pp. 303-319.

8. Haj-Salem, H., P. Poirier, J. Heylliard, and J. Peynaud (2001), *ALINEA: a local Traffic Responsive Strategy for Ramp Metering: Field Results on A6 Motorway in Paris*, IEEE Intelligent Transportation Systems Conference Proceedings – Oakland (CA).

9. Minnesota Department of Transportation (2001), Twin cities Ramp Evaluation, Executive Summary, Cambridge Systematics, Inc., Cambridge, Mass., 2001. http://www.dot.state.mn.us/rampmeterstudy

10. Muñoz, J. C. and C. F. Daganzo (2002a), *Fingerprinting Traffic from Static Freeway Sensors*, Cooperative Transportation Dynamics, 1, pp. 1-11.

11. Muñoz, J. C. and C. F. Daganzo (2002b), *The bottleneck mechanism of a freeway diverge*, In Transportation Research, Vol36A, pp. 483-505.

12. Newman, L., A. Dunnett, and G. Meis (1969), *Freeway Ramp Control: What it can and cannot do*, Los Angeles: California Division of Highways, District 7.

13. Papageorgiou, M., and A. Kotsialos (2002), *Freeway Ramp Metering: An Overview*, IEEE Transactions on Intelligent Transportation Systems, Vol. 3, No. 4.

14. Papageorgiou, M., H. Hadj-Salem, and F. Middelham (1998), *ALINEA local ramp metering-summary of field results*, In Transportation Research Record 1603, TRB, Washington D.C., pp.90-98.

15. Smaragdis, E., M. Papageorgiou, and E. Kosmatopoulos (2003), *A flow-maximizing adaptive local ramp metering strategy*, In Transportation Research, Vol. 38B, pp. 251-270.

Table 1

Outflows before and after critical accumulation in the shoulder lane (observation days)

(1)	(2)	(3)	(4)
Date	Outflows before critical accumulation (vph)	Outflows after critical accumulation (vph)	Change (%)
Sep 17, 2002	9740	8930	8.3
Sep 18, 2002	10250	9240	9.9
Sep 19, 2002	Data not used; see Footnote 1		
Jan 7, 2003	Data not used; see Footnote 1		
Jan 8, 2003	8540	7800	8.7
Jan 9, 2003	9780	8820	9.8
Jan 10, 2003	9680	8650	10.6
Mar 4, 2003	10520	8700	17.3
Mar 5, 2003	10190	8690	14.7
Mar 6, 2003	10730	9280	13.5
Average	**9928**	**8763**	**11.7**

(entrance)   (exit)   **(a)**

Off-ramp
(exit)

On-ramp
(entrance)

(entrance)   (exit)   Downstream Merge

"Internal" Freeway Link   Outflow   **(b)**

Meter

On-ramp
(entrance)

On-ramp
(entrance)

Meter

(entrance)   (exit)

Capacity   **(c)**
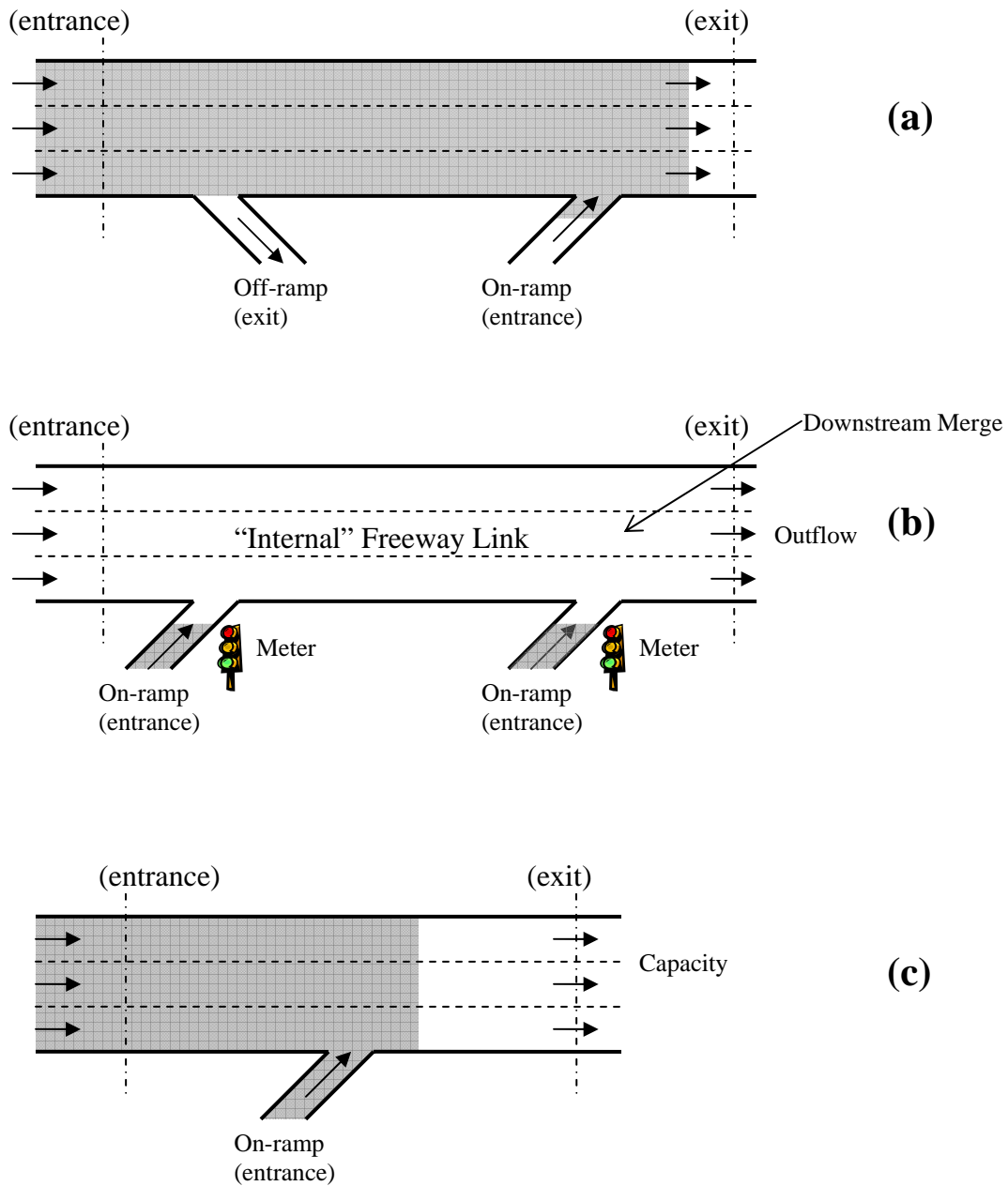
On-ramp
(entrance)

Figure 1

Hypothetical Freeway Systems

(a) Gridlock Mechanism

(b) Starvation Mechanism

(c) Isolated Merge
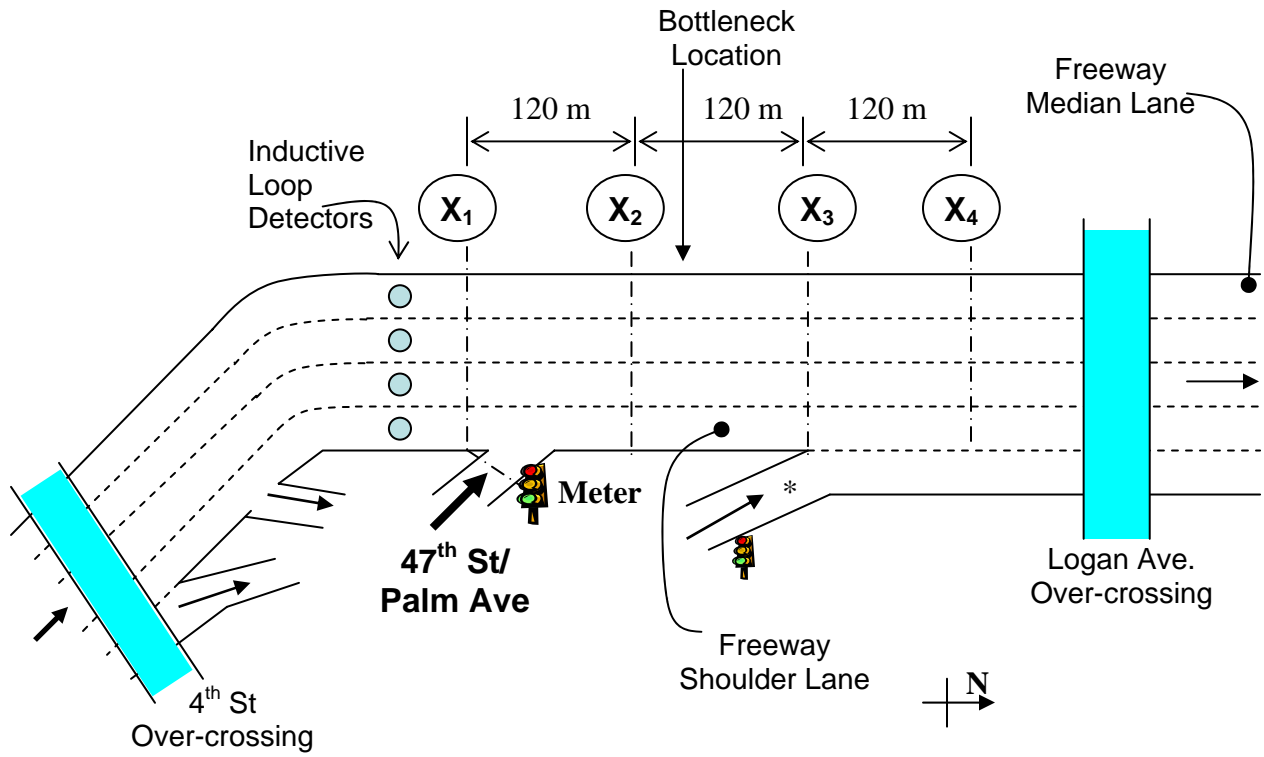
Figure 2

Study Site, Northbound Freeway 805, San Diego, California
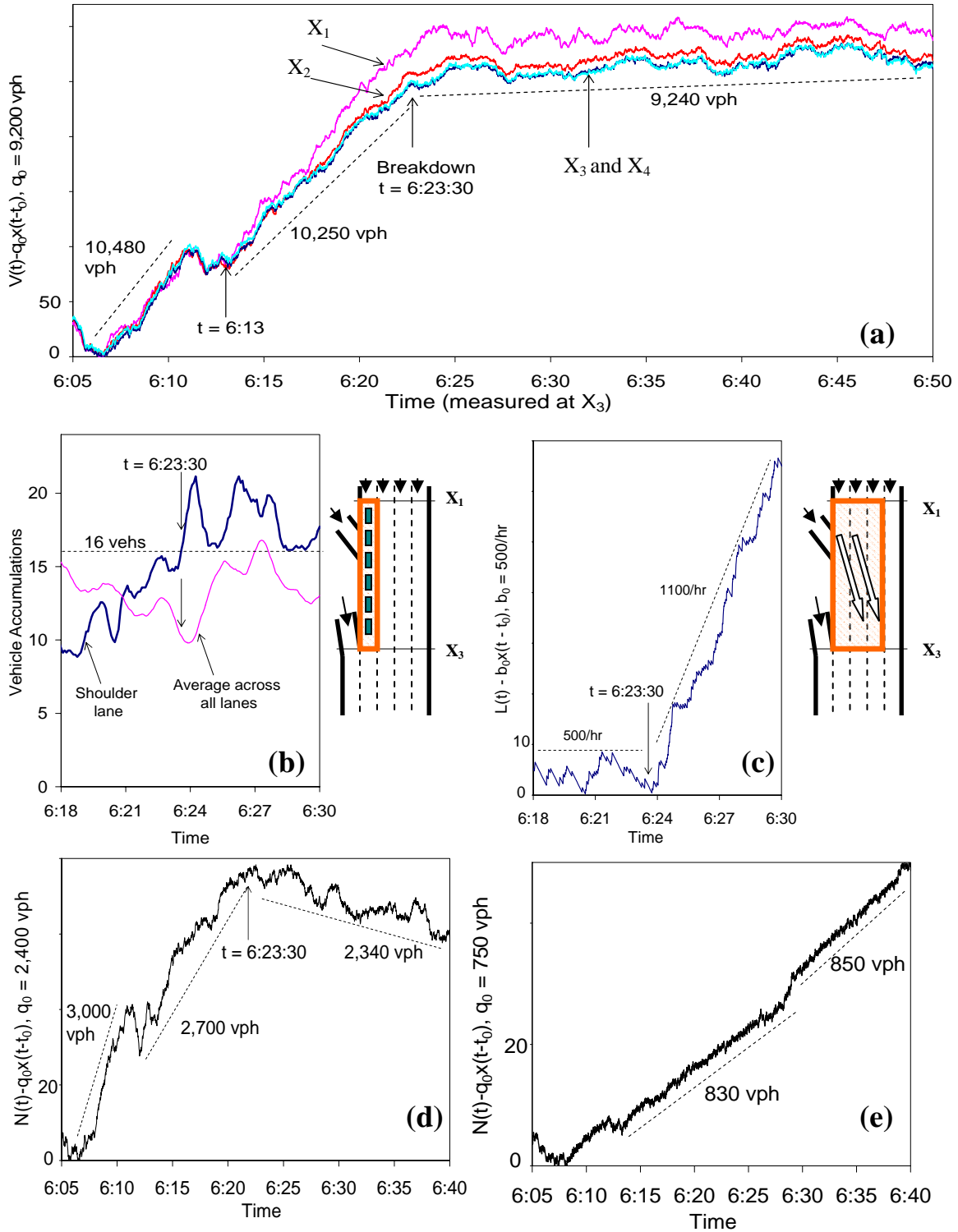
Figure 3 (September 18, 2002)

(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
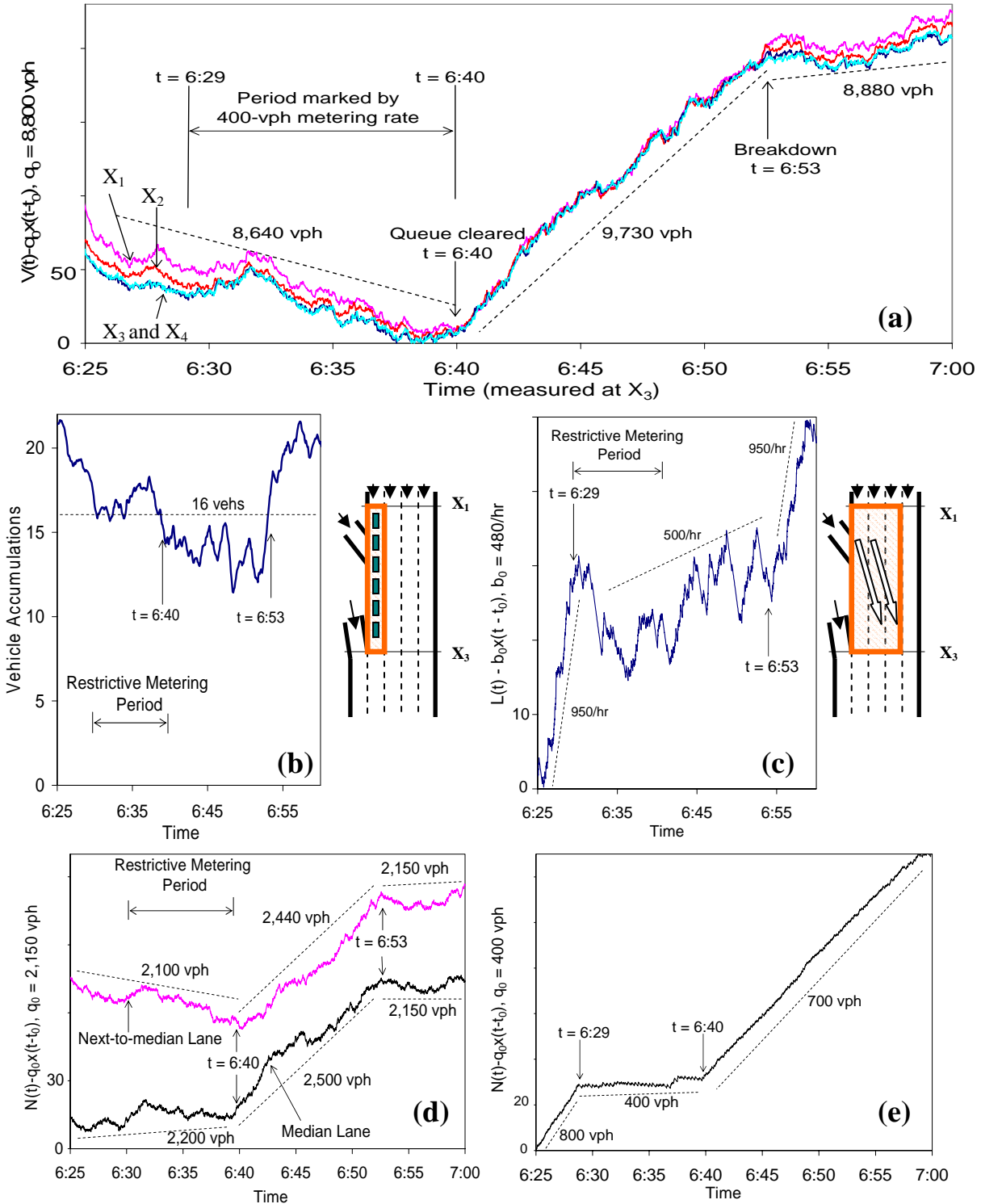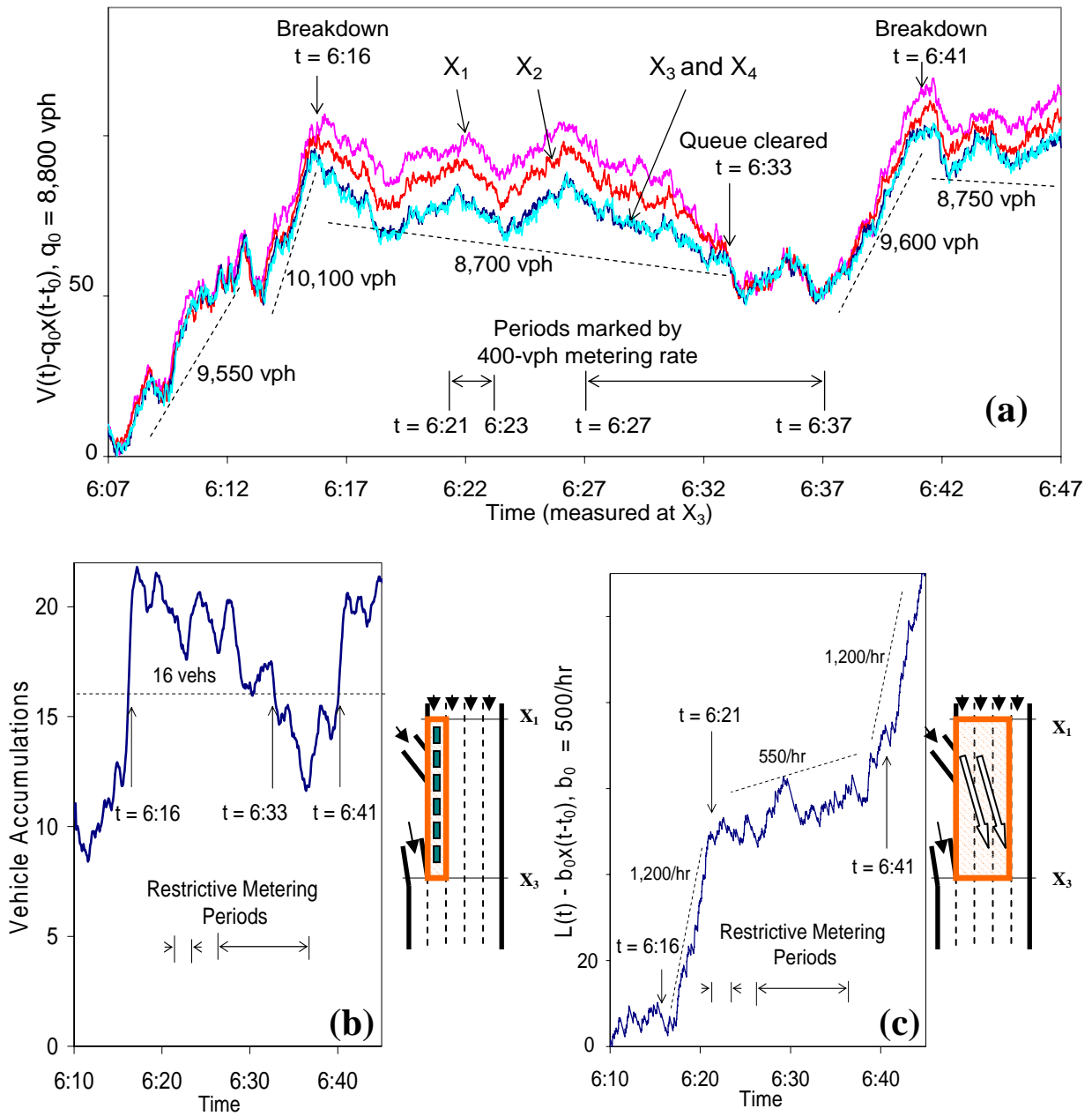(e) Oblique cumulative curve of counts from 47th St/Palm Ave on-ramp
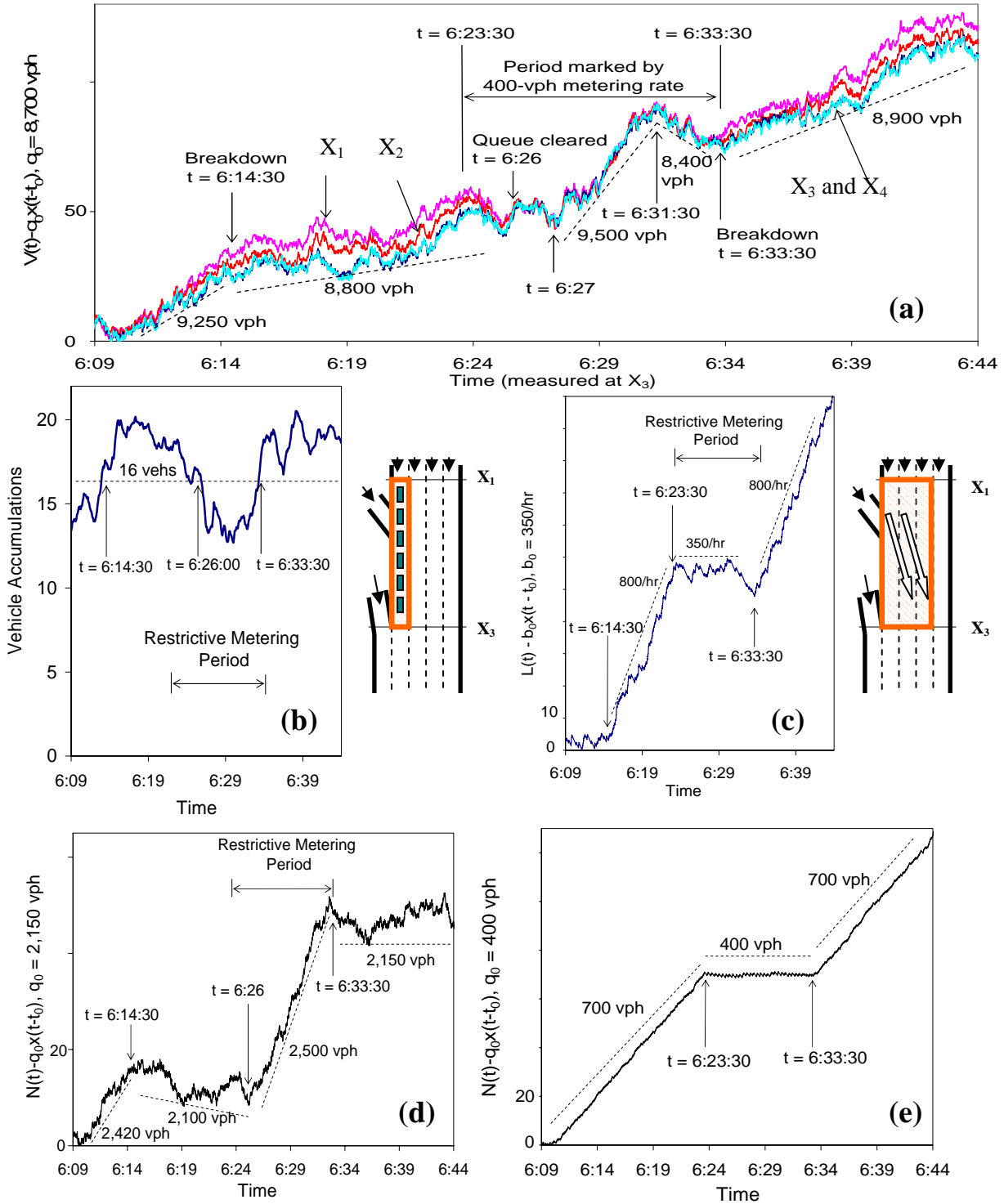
Figure 4 (October 23, 2003)

(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

Figure 5 (October 15, 2003)

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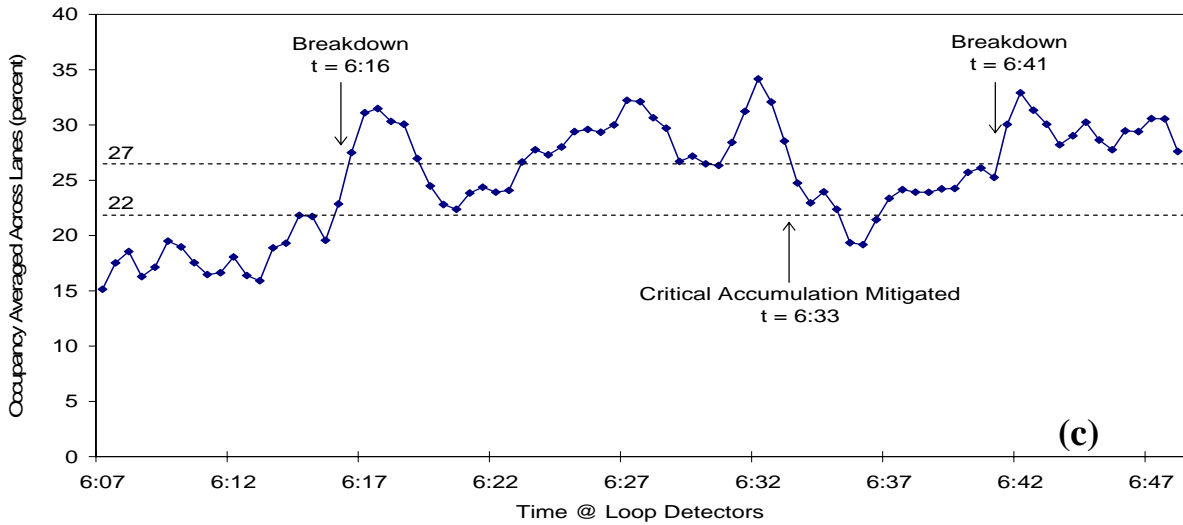(c) Oblique cumulative curve of lane-changing counts
(d) Oblique cumulative curves of median and next-to-median lane outflows at X_3
(e) Oblique cumulative curve of counts from 47th St/Palm Ave on-ramp

Figure 6 (October 21, 2003)

(a)   O-curves at X_1 through X_4
(b)   Shoulder-lane accumulations
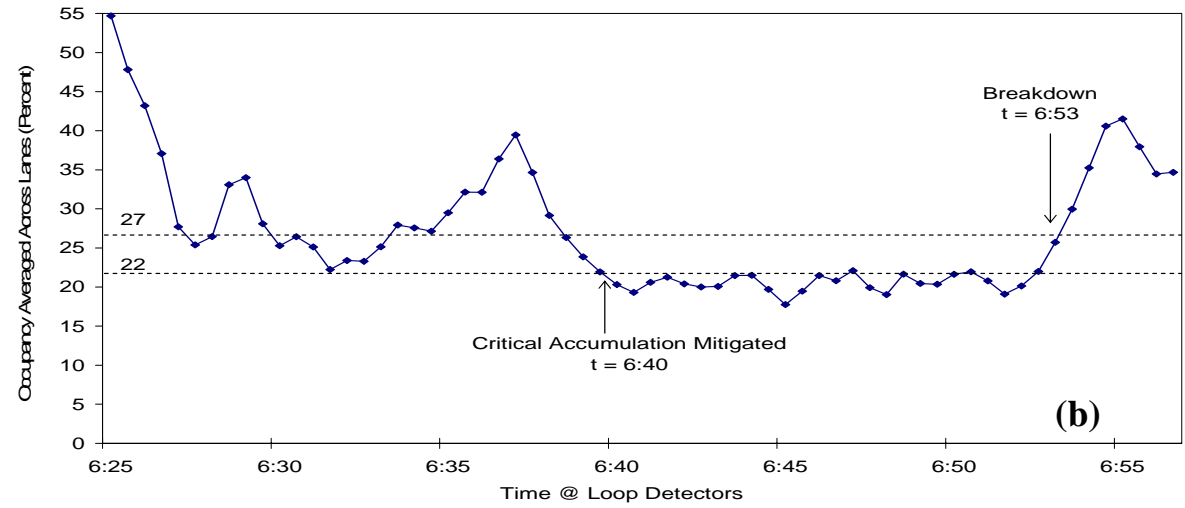(c)   Oblique cumulative curve of lane-changing counts
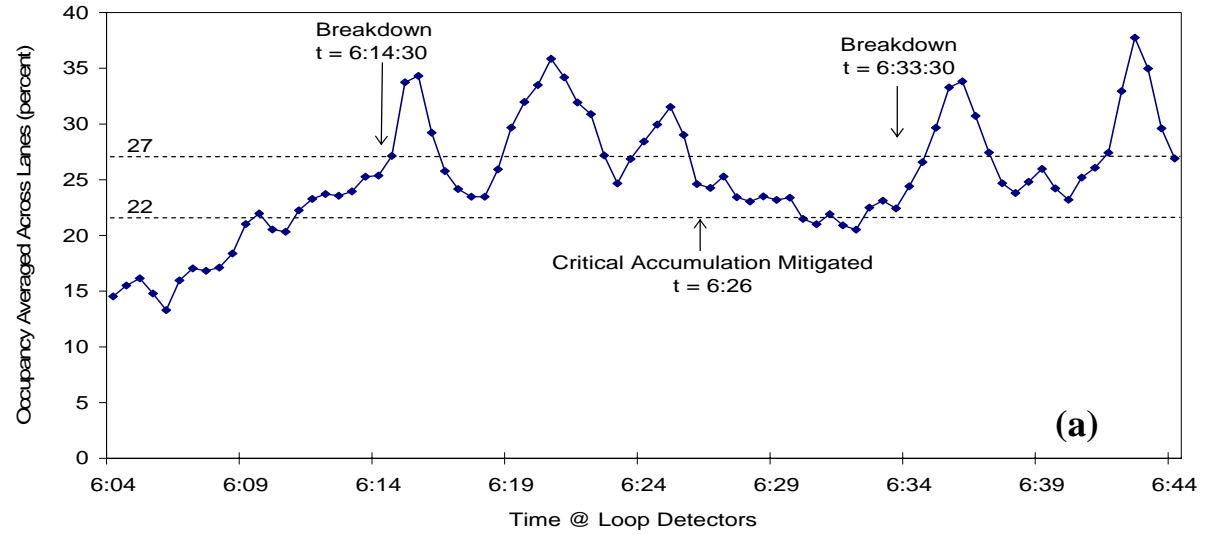
Figure 7 Time series of detector occupancies

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