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Title:
Spatiotemporal Studies of Traffic Phenomenon on Freeways with Limited-access Special Lanes

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Publication Date:
January 2015

Series:
Research Reports

Permalink:
http://escholarship.org/uc/item/8j0585hg

Keywords:
Managed lanes, Bottlenecks, Traffic congestion, Barriers, Carpool lanes, High occupancy vehicle lanes, Toll lanes

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Michael J. Cassidy and Kwangho Kim

Research Report
UCB-ITS-RR-2015-01



January 2015

Spatiotemporal studies of traffic phenomenon on freeways with limited-access special lanes

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Abstract

Most special-use freeway lanes in the US, whether reserved for carpools, toll-paying commuters or both, are physically separated from the adjacent regular-use lanes by some form of barrier. Vehicle movements in and out of a special lane of this type are permitted only at select access points along the route. The barrier at each select point might open for a distance of 400 m or so. Limiting access in this way is said to reduce the "turbulence" that might otherwise occur were the special lane not to have a buffer, such that vehicles could instead enter or exit that lane anywhere along its length.

Yet, real freeway traffic studied in spatiotemporal fashion shows that access points are prone to become bottlenecks. The problem occurs when traffic in the regular lanes becomes dense, as commonly happens during a rush. Drivers then seek refuge in the special lane in greater numbers. Since the vehicular maneuvers through the access point are focused within a limited physical space, they can become disruptive and further degrade traffic. Degradation can occur both in the special lane and in the adjacent regular ones. The damage can be worse than what occurs when barrier are not used to limit special-lane ingress and egress. Policy implications are discussed.

Key words: *managed lanes, carpool lanes, toll lanes*

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1. Introduction

Special-use lanes that are reserved for select vehicle classes have long been a means of managing freeway traffic. These lanes can be used to prioritize certain classes, as when carpool lanes are used to promote travel by "high-occupant" vehicles (e.g. Chang, et al., 2008); or when lanes are set aside for drivers who are willing to pay tolls to reduce their own trip times (e.g. Loudon, 2009). Whether establishing the toll amounts to be paid or the number of onboard occupants that meets the definition of a carpool, access requirements are set in attempts to limit the use of special lanes. The objective is to keep rush-period travel conditions (e.g. vehicle speeds) better in a special lane than in the freeway's adjacent regular-use ones. The term "managed lanes" is thus often used to describe lanes of these special types (e.g. Wang, et al., 2012).

Of further interest, the use of special lanes to segregate vehicle classes can reduce disruptive interactions that would otherwise occur between the classes. The result can be higher bottleneck capacities (e.g. Cassidy, et al., 2009; 2010). Traffic safety may be enhanced as well. These benefits not only occur when segregating vehicle classes that are physically distinct, as when bus lanes are used to segregate buses from cars. Benefits can also accrue when carpool lanes are used to segregate car classes that have distinct numbers of onboard occupants, but are otherwise physically identical and thus share common performance characteristics (Menendez and Daganzo, 2007; Cassidy, et al., 2010).

As regards geometric design, most special lanes on US freeways are separated from adjacent regular lanes by some form of barrier. In these cases, select vehicle classes can enter and exit the special lane only at designated "access points," also known as "barrier or buffer openings," of the kind shown in Fig. 1a. These openings span distances that typically range from about 280 m to 460 m, depending upon the design standards of a particular jurisdiction (e.g. Fitzpatrick, et al., 2007).[1] These openings can occur at intervals of several kilometers or more. Limiting the ingress and egress locations is said to reduce "turbulence" in all lanes (Collier and Goodin, 2004), as compared against what supposedly occurs in the presence of non-separated special lanes, like the one shown in Fig 1b, which can be accessed and egressed anywhere along its length (e.g. Caltrans, 2003; ASSHTO, 2004). We take "turbulence" in this case to mean disruptive vehicle interactions across special-use and regular lanes.

Yet, the present paper shows that an access point to a special-use freeway lane can become a bottleneck due to the focused vehicle maneuvers that take place over its limited physical length. When conditions are ripe, these focused maneuvers can be disruptive. In the present cases, we observe that the problem occurs when rush-period travel conditions erode in the regular lanes, and drivers seek refuge by

[1] Newly-established standards now recommend that access points extend to more than 600 m in length (Caltrans, 2011). To date, we are aware of only two freeways in the US, the I-15 in Salt Lake City, Utah, and the I-85 in Atlanta, Georgia, where these longer lengths are in place (Perez, et al., 2012).

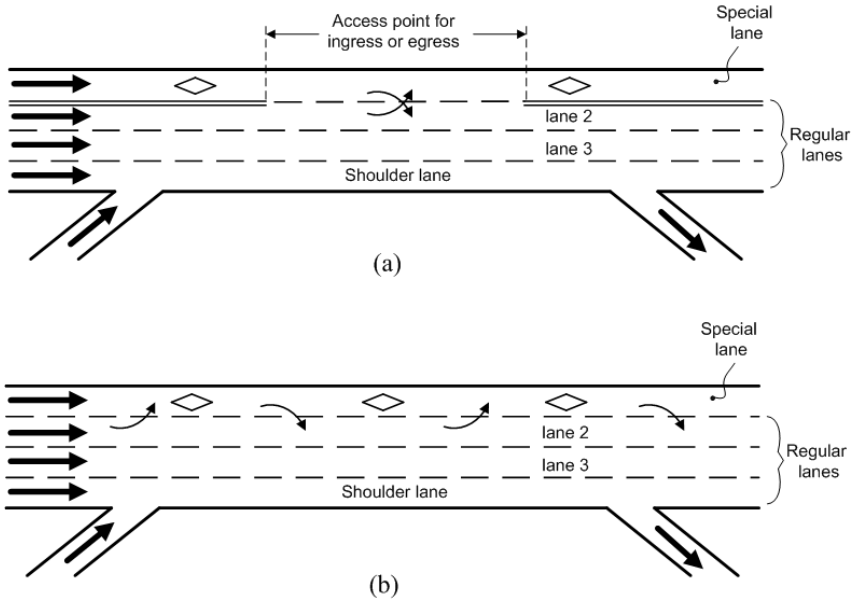

Figure 1 Access-types for freeways with special lanes: (a) limited access; (b) non-separated access

migrating into the adjacent special lane in greater numbers. We show that bottlenecks of this kind can severely diminish vehicle speeds and flows, both inside the special lanes and in the regular lanes as well. Though non-separated special lanes of the kind in Fig. 1b come with downsides of their own, it turns out that the damage done to traffic by access points can be worse.

Previous studies on special-use freeway lanes will be discussed in the following section. We will argue that access-point bottlenecks have not previously been reported in the literature, owing to analysis methods that looked only at the temporal changes in traffic data, while ignoring changes that occurred over space. The existence of access-point bottlenecks and their causes are unveiled in Sections 3 – 5 via a fuller, spatiotemporal analysis of traffic data from three US freeways. Implications are discussed in Section 6.

2. Background

Theoretical work in Menendez and Daganzo (2007) found that a freeway's non-separated carpool lane of the kind in Fig. 1b can have an unexpectedly favorable effect on traffic in all lanes. That earlier study predicted: that setting aside an erstwhile regular lane during a rush for the exclusive use of carpools can trigger reductions in vehicle lane-changing maneuvers; and that this, in turn, can "smooth" traffic and promote higher bottleneck discharge flows in the regular lanes that remain. This is a good thing: all else

equal, higher discharge flows mean that travelers spend less time on the freeway. This so-called "smoothing effect" was confirmed with real data from non-separated freeway carpool lanes in northern California; and the effect was shown to be significant in that discharge flow increased in some regular lanes by 20% (Cassidy, et al., 2010).

Yet, non-separated special lanes come with a downside of their own: they are especially susceptible to a so-called "frictional effect" whereby slow-moving, congested traffic in the regular lanes slows-down traffic in the adjacent special lane as well (e.g. see Jang, Ohm and Chan, 2012; Jang and Cassidy, 2012). Much discussion, and limited experiment, has been devoted to disentangling the convoluted causes of this effect. These likely include: reluctance among drivers in a special lane to adopt high speeds when adjacent to slow-moving, regular-lane queues, possibly out of perceived concerns for safety; and actual traffic disruptions that occur when cars maneuver between a special lane and a congested, slow-moving regular one (Guin, et al., 2008).

Whatever the causes, the frictional effect can be damaging. It can slow traffic in a special-lane to the point of diminishing its capacity (Jang, Ohm and Chan, 2012; Wang, et al., 2012). It can even cause well-intentioned policies to produce unintended and counterproductive consequences. An example of the latter was offered in Jang and Cassidy (2012). It assessed a policy aimed at improving speeds in freeway carpool lanes by forcing just 1% of traffic to migrate from carpool lanes to the adjacent regular ones; and showed that the frictional effect often caused the policy to backfire by slowing *all* traffic, including traffic in the carpool lanes.[2]

Efforts to combat the frictional effect have led to the wide-scale use of limited-access special lanes of the kind shown in Fig 1a. Studies show that the frictional effect on limited-access lanes is smaller than on non-separated ones.[3] Some studies even go on to show that the extent of this diminution varies with the form of partition used for a limited-access lane. So-called "buffer-separated" lanes that are partitioned by means of solidly-painted striping, and possibly accompanied by narrow shoulder separations, reportedly suffer more from the frictional effect than do "soft-barrier" lanes that are separated from regular traffic by plastic barriers. These, in turn, are reportedly more susceptible to the effect than are lanes that are separated by solid concrete barriers (Liu et al., 2011).

[2] Both theory and data showed that the expanded queues and vehicle slowing that the policy promoted in the regular lanes caused slowing in adjacent non-separated carpool lanes as well; i.e. the benefits to the carpool lanes that stemmed from reducing the demand for their use was outweighed by the deleterious impacts of the frictional effect; see again Jang and Cassidy (2012).

[3] One study (Jang, Ohm and Chan, 2012) goes so far as to claim that traffic in limited-access lanes is "almost indifferent" to traffic conditions in the adjacent regular lanes, though even visual inspection of the data suggests that the claim is exaggerated; e.g. see Figures 9 and 10 of the cited reference.

Yet, we will show that the bottleneck problems created by access points can outweigh the frictional effect at its worst. Mitigating the frictional effect by resorting to a limited-access lane can thus at times be like avoiding the frying pan by jumping into the fire.

In retrospect, little about the present findings is surprising. After all, the problem is a consequence of rational driver behavior: when regular-lane travel degrades, many drivers seek to reduce their trip times by maneuvering into a faster-moving special lane. And the flow disruptions caused by having to focus these maneuvers over the limited length of an access point is consistent with what has been observed at other types of freeway bottlenecks. These include bottlenecks that emerge at weaving sections and that generate maneuvers akin to those at access points (see Lee, 2008). In light of this, one might ask why the problem of access-point bottlenecks has scarcely garnered mention in the literature.[4]

The answer seems to lie in the fragmented way in which studies have been conducted on the subject. Most have focused on traffic data measured by detectors at isolated locations within limited-access lanes. These locations were commonly upstream of bottlenecks: one sees in the published data how special-lane traffic measured at a single detector location (i.e. at a single point along a freeway) can devolve over time from freely-flowing to queued conditions; e.g. see Figures 9 and 10 of Jang, Ohm and Chan (2012) and Figures 2, 3, and 6 of Liu, el al. (2011). Yet, the studies did not compare measurements taken across neighboring detector locations within a limited-access lane. Hence, no attempts were made to examine how time-varying changes in queued traffic propagated over space; and the bottlenecks from which the queues emerged, including perhaps access-point bottlenecks, therefore escaped notice.

Greater insights can come through analysis that is less fragmented, and more spatiotemporal in its approach. Illustrations follow. The presentations will be incremental, with macro-level analyses offered in Section 3 and finer details introduced in Sections 4 and 5.

3. Spatiotemporal Observations at Cursory Levels

The literature routinely reports that traffic conditions in a special lane are "expected to be quite different" from those in the adjacent regular-use ones (e.g. Wang, el al., 2012). We start by showing that this expectation can be reasonable in the case of a non-separated freeway carpool lane. We thereafter show how the story can be very different when a freeway comes with a limited-access carpool lane instead.

[4] In its conclusions, one report (Jang, Ohm and Chan, 2012) advocated the study of access points as part of some future effort. Tellingly, that reference cited only a need to assess the extent to which the frictional effect might occur at those access points. The possibility that access points might become bottlenecks passed without mention.

3.1 Non-Separated Case

The first case-study site is illustrated in Fig. 2a. It is a 4.4 km freeway stretch in California's San Francisco Bay Area. The site's median lane is reserved for the exclusive use of carpools each weekday afternoon starting at 15:00 h. For some hours prior to that time, the lane is available to all traffic. The lane is demarcated from the adjacent one by ordinary dashed painted lines; i.e., the carpool lane is a non-separated one of the kind shown in Fig. 1b. The site's vehicle detectors are shown as shaded circles in Fig. 2a. The locations for three of the detector stations are labeled D1– D3 for reference.

The shadings in Fig. 2b correspond to dimensionless versions of traffic density, termed "occupancies," that were measured by the detectors in the site's non-separated median lane for a 2-h period.[5] The darker shades in this spatiotemporal region denote high detector occupancies that are associated with congested traffic. The shadings in Fig. 2c denote the occupancies measured in the adjacent regular lane, henceforth termed "lane 2," for the identical 2-h period.

Visual inspection of Figs. 2b and c reveal that, prior to 15:00 h, traffic conditions in the two neighboring lanes are nearly identical. Queues (dark shades) emerged in both lanes at around 14:15 h, and ultimately expanded to locations upstream of D3.

However, the similarities across lanes abruptly ended at 15:00 h, when the median lane was set aside for carpool-use only. Congestion lightened noticeably in the newly-activated carpool lane (Fig. 2b), but persisted in lane 2 (Fig. 2c).[6] The above pattern was observed at the site, without exception, over numerous weekday afternoons.

Figs. 2b and c thus confirm that beyond 15:00 h when the carpool lane took effect, traffic conditions in that non-separated lane were indeed "quite different" from those in lane 2. If one were to believe the literature, then one might suppose that these distinctions across lanes would be even greater if the special lane were of the limited-access variety instead. After all, buffers and physical separations reportedly reduce "turbulence" across lanes (Collier and Goodin, 2004). However, this supposition would not be correct in general, as shown below.

3.2 Limited-Access Case

Fig 3a presents a 3.7 km freeway stretch in southern California. Its median lane is a buffer-separated one that is reserved for carpools at all times. Note that the site's vehicle detectors reside at locations that are again labeled D1 – D3 in the figure.

[5] The occupancies measured at each detector station are interpolated to obtain estimates over the entire length of the freeway stretch.

[6] Fig. 2b periodically displays narrow swaths of dark shading beyond 15:00 h, meaning that high detector occupancies (and vehicle slowing) occurred in the carpool lane, albeit only occasionally. This pattern was previously shown to be a result of the frictional effect; see Jang and Cassidy (2012).

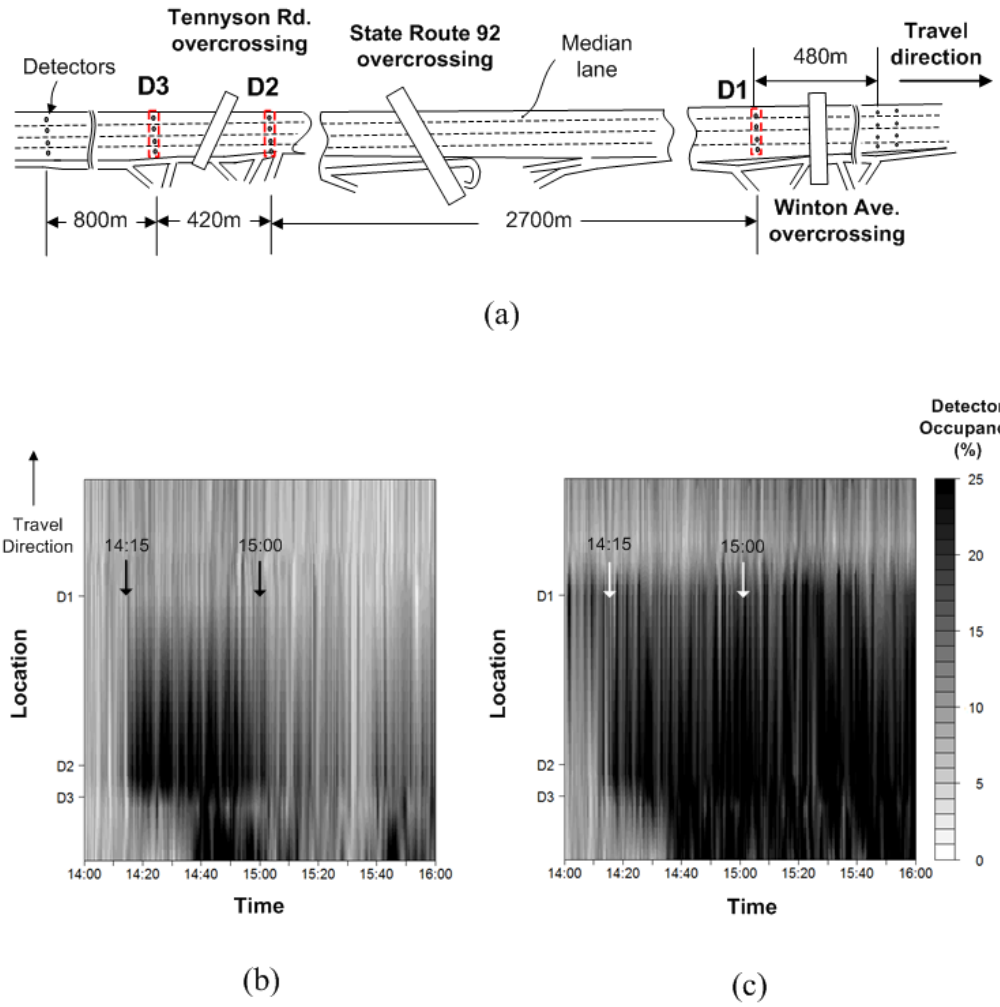

Figure 2 Non-separated Example (May 13, 2009)

(a) Northbound I-880 freeway, Alameda County, California

(b) Time-space-occupancy plot of carpool lane

(c) Time-space-occupancy plot of lane 2

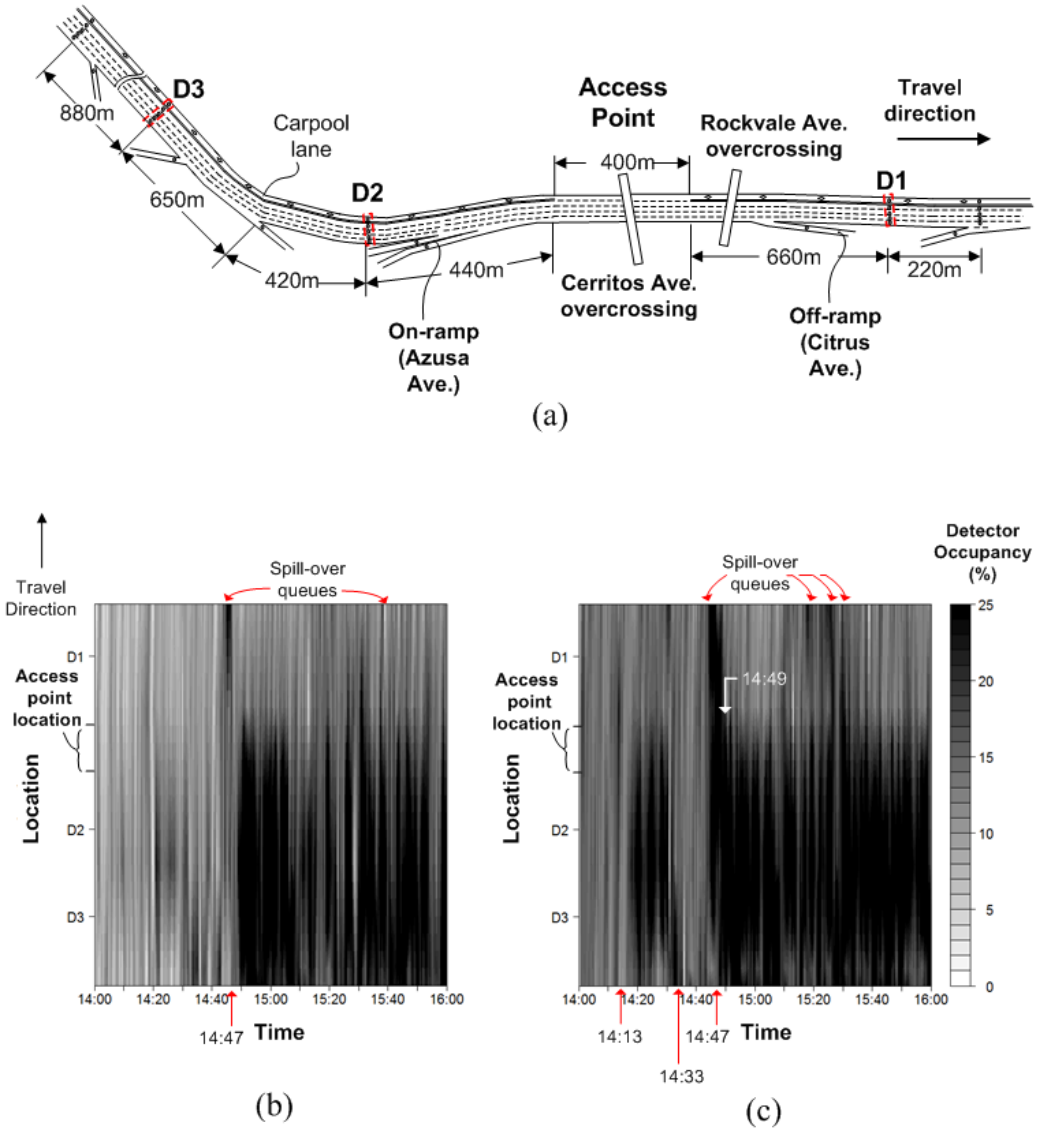

Figure 3 Limited-access Example 1 (September 26, 2013)

(a) Eastbound I-210 freeway, Los Angeles County, California

(b) Time-space-occupancy plot of carpool lane

(c) Time-space-occupancy plot of lane 2

Time-space-occupancy plots for that carpool lane and for adjacent regular-lane 2 are shown in Figs. 3b and c, respectively. These latter two figures display similarities, the most striking of these being: the persistent queueing that emerged somewhere between the detectors located at D1 and D2, starting at around 14:47 h; with free-flow conditions (lighter shades) that persisted for much of the time downstream.

That these patterns are common to the two lanes reveals that both share a common bottleneck. The bottleneck turns out to be the site's 400 m access point, as we shall see in the following section.[7]

4. Closer Inspections

The detector data used in Figs. 3b and c were augmented with measurements made from videos. (Cameras were installed for a single day on the overcrossings shown in Fig. 3a and vehicle counts of various kinds were manually extracted from the videos.) These data verify that growths in regular-lane density were accompanied or closely followed by (i) sudden increases in the rates that carpoolers abandoned the regular lanes by migrating leftward through the site's access point and into the carpool lane; (ii) flurries of rightward lane-changing as drivers of non-carpool vehicles evidently sought to avoid the resulting disruptions in lane 2, which spread congestion laterally across all regular lanes; and (iii) substantial reductions in the rates that regular-lane vehicles discharged from the site.

On the day shown here, the above mechanism occurred twice. The first was early in the rush when features (i) – (iii) emerged in the wake of rising regular-lane densities, but only briefly. When leftward migration through the access point abated shortly after having risen, regular-lane discharge flows rebounded immediately, and regular-lane queues dissipated soon thereafter.

The reprieve was only temporary, however. A short time later, traffic density climbed again in the regular lanes, this time thanks to a queue that briefly spilled-over from some other bottleneck downstream.[8] Features (i) – (iii) reoccurred at the site. This time around, leftward migrations through the access point not only grew in number, but persisted over the rush. Tellingly, regular-lane queues and reductions in discharge flow then persisted as well.

To make matters worse, a persistent queue then also formed in the carpool lane. It, like the regular-lane queues, was pinned at the access point and expanded upstream. The resulting discharge flow in the carpool lane was lower than what is commonly observed in non-separated carpool lanes located elsewhere in California.

[7] Data both from vehicle detectors and videos indicate that other possible causes of the bottleneck, namely the site's on- and off-ramps, were not culpable. Evidence exonerating the ramps is furnished in Appendix I.

[8] Thin, dark swaths that occasionally appear in the top portions of Figs. 3b and c reveal that short-lived queues periodically spilled-over from downstream. The cause of these spill-over queues is not germane to the present discussion.

The empirical evidence for the above is presented in the following sub-section. (The reader content with the summary offered above may skip the presentation of details to come in Section 4.1 without loss of continuity.) We thereafter verify that the bottleneck and its mechanism are reproducible features of the site across days.

4.1 Bottleneck and its Mechanism

The day's earliest growth in regular-lane density and the subsequent migration through the access point can be seen from joint visual inspection of Figs. 4a and b. The first of these figures presents a time series of the number of vehicles (i.e. the "accumulation") across all regular lanes, as counted at 10-s intervals over the 400-m portion of the site adjacent to the access point. Fig. 4b presents a cumulative curve of the leftward lane-changing maneuvers through the access point. This latter curve was plotted in oblique coordinates so as to magnify time-varying changes in its slopes, thus rendering the time-varying patterns in leftward lane-changing rates discernible to the naked eye. The reader can refer to Cassidy and Windover (1995) or Muñoz and Daganzo (2003) for further discussion on oblique cumulative curves.

Note how regular-lane accumulation began to rise steadily at around 14:12:30 h (Fig. 4a), and how leftward migrations then rose shortly thereafter at around 14:13 h (Fig. 4b). Some of these migrating carpoolers were evidently content to travel in regular lanes while they were freely flowing, but sought to abandon them once regular-lane traffic became dense.

These focused leftward maneuvers were evidently disruptive to traffic in lane 2, and Fig. 4c reveals how non-carpool drivers sought relief by maneuvering (rightward) out of that lane in heightened numbers. The figure presents an oblique curve of rightward maneuvers, made from regular-lane 2 to 3. These maneuvers were counted from video over the 400 m stretch that spans the access point. Note the surge in these lane-changes that began at around 14:13 h, coincident to the rise in leftward migrations.[9]

That flurry of rightward maneuvers occurred when regular-lane traffic had grown dense (see again Fig. 4a), such that the maneuvers were disruptive. The disruptions: spread congestion laterally across all regular lanes; and diminished the discharge flows in those lanes.

Evidence of the latter is visible in Fig. 4d. It presents an oblique cumulative curve of vehicle counts across the site's four regular lanes, as measured by the detectors at location D1 and the Citrus Avenue off-ramp; see again Fig. 3a. Note from Fig. 4d how flow (i.e. the curve's slope) temporarily fell to 6,510 vph, also at 14:13 h.

[9] A brief surge in rightward lane-changing was also observed earlier at around 14:04 h. That surge was different from the later ones in that it was fueled by a flurry of carpool-lane vehicles that exited the lane via the access point and headed for off-ramps downstream. Moreover, that surge occurred early in the rush when regular-lane accumulation was still low (see again Fig. 4a), such that the maneuvers were evidently not disruptive.

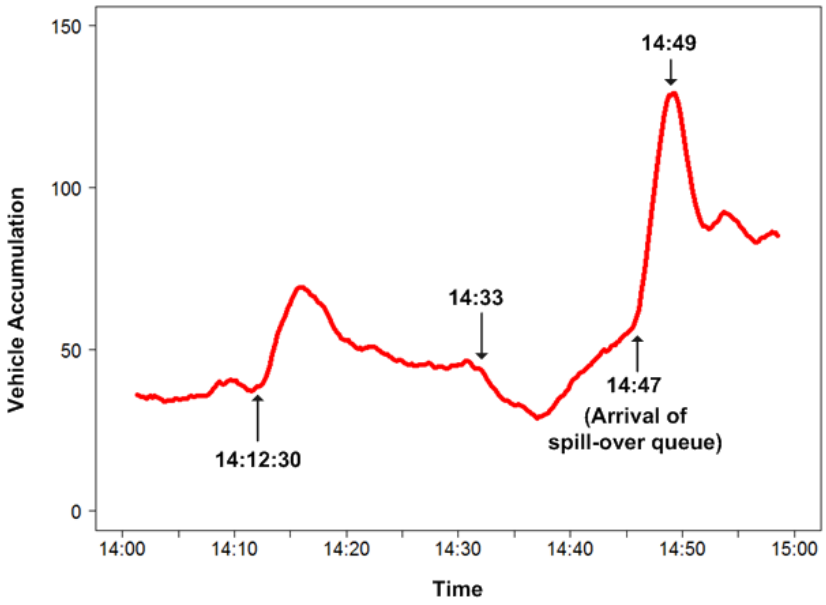

Figure 4(a) Time-series of vehicle accumulation across all regular lanes (I-210E; September 26, 2013)

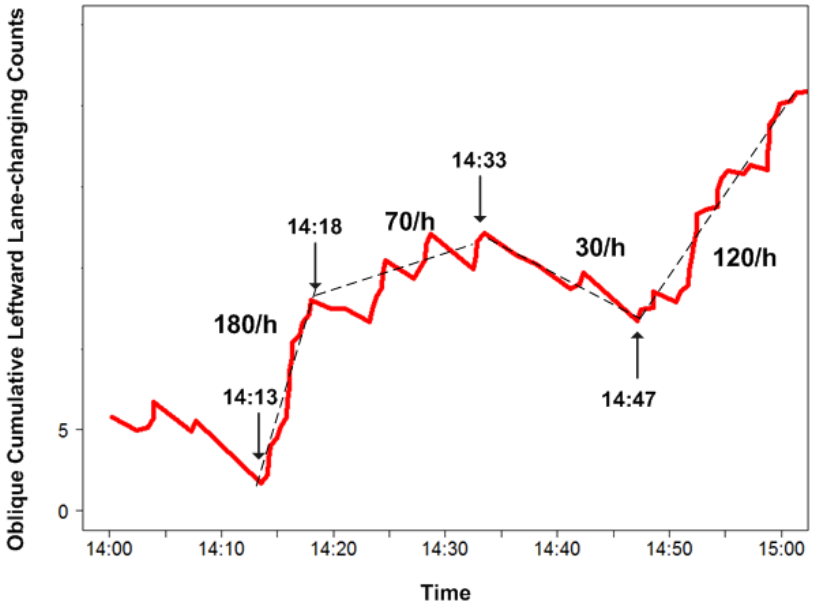

Figure 4(b) Oblique cumulative curve of leftward lane-changing maneuvers through the access point (I-210E; September 26, 2013)

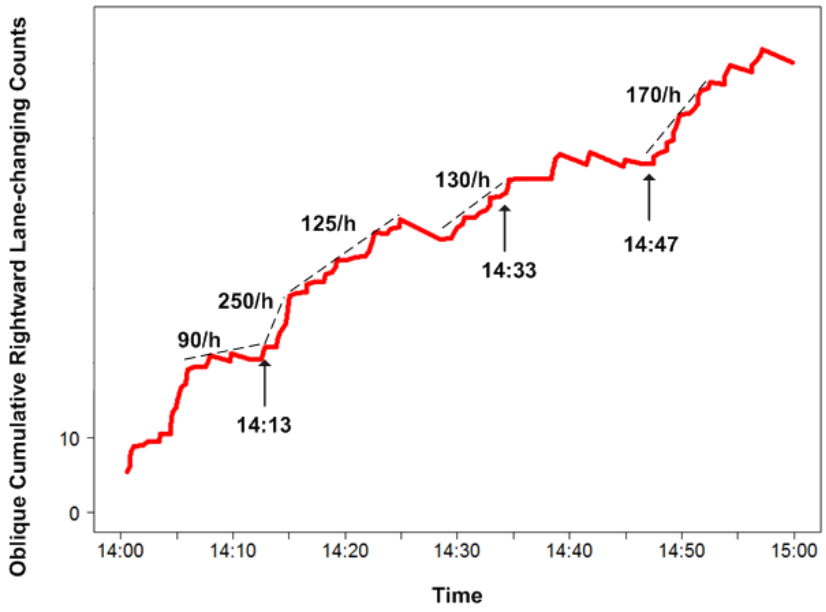

Figure 4(c) Oblique cumulative curve of rightward lane-changing maneuvers from lane 2 to lane 3 (I-210E; September 26, 2013)

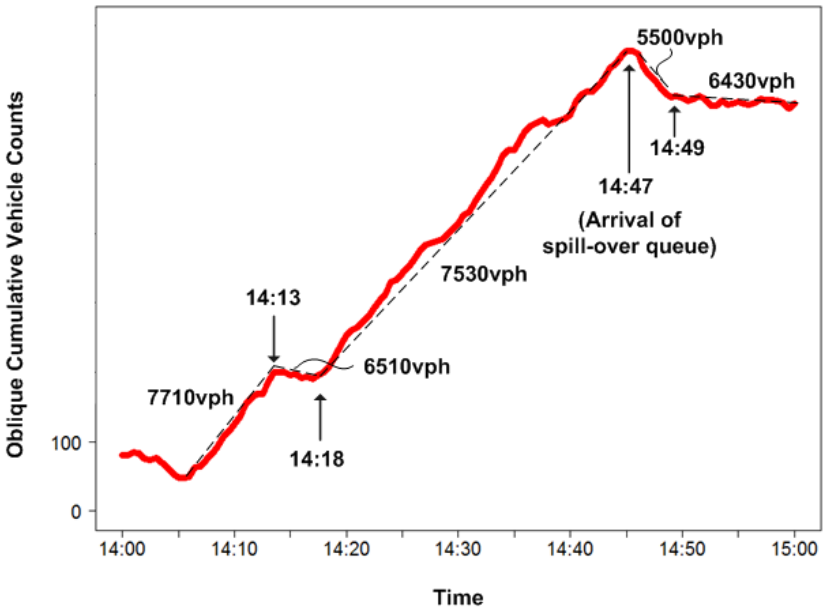

Figure 4(d) Oblique cumulative curve for all regular lanes combined at D1 and Citrus off-ramp (I-210E; September 26, 2013)

During this time, flow at D1 was not constrained by any spill-over queues from downstream. This can be confirmed for lane 2 using Fig. 3c and for the other regular lanes by referring to Appendix II. Hence, we find no explanation for the flow reduction at 14:13 h other than the disruptive presence of the access-point bottleneck.

Interestingly, this discharge-flow reduction persisted only until around 14:18 h, which is also the time when leftward migration through the access point diminished: Fig. 4b makes clear that at 14:18 h, leftward migration dropped from a high rate of 180/h to an average rate of 70/h. (Perhaps the regular lanes' surplus of carpools dissipated in the early rush.) With the restoration in discharge flow, the regular-lane queues dissipated soon thereafter at around 14:33 h. This is evident both from the shading pattern in Fig. 3c and the temporary drop in accumulation in Fig. 4a. [10]

Figs. 3c and 4a also show that a spill-over queue thereafter arrived on the scene at around 14:47 h. That queue re-triggered greater migration rates leftward and rightward, as evident in Figs. 4b and c. This time, however, the high migration rates persisted even after 14:49 h when the spill-over queue disappeared from the scene. And the regular-lane discharge flow thereafter remained at a low rate of only 6,430 vph, a 15% reduction from the rate of 7,530 vph measured prior to the spill-over queue; see Fig. 4d.

By this same time, flow in the carpool lane had grown as well. Thus, the heightened migrations into the carpool lane caused persistent queueing there, as evident in Fig. 3b. Average carpool speed in the queue fell to 54 km/h for the remainder of the rush. That speed is well below the standard of 72 km/h established by the US government (refer to section 1121 of SAFETEA-LU, 2005); and far lower than what would be expected due to the frictional effect, had the site's carpool lane been a non-separated one.[11]

Moreover, the queue discharge flow in the carpool lane was only around 1,500 vph, as measured by the detector in that lane at location D1. This rate is far lower than the highest flows measured in non-separated freeway carpool lanes in northern California. Flows in the latter case often exceed 1,800vph; see Cassidy, et al. (2010) for an example.

The data thus indicate that the access point created a bottleneck that severely degraded travel conditions, both for carpool- and regular-lane vehicles. This state of affairs was a re-occurring one for the site, as is shown below.

[10] Tellingly, the return to free-flow conditions at 14:33 h also brought a further reduction in leftward migration through the access point, as evident in Fig. 4b.

[11] Using Figure 5 of Jang and Cassidy (2012) along with the site's measured flows in the carpool lane and in lane 2, we estimate that carpool-lane speed at location D2 would have been about 90 km/h, had that carpool lane been a non-separated one.

4.2 Reproducibility

The site in Fig. 3a was studied over the afternoon rush periods of 10 additional days. On all days, the access point became a bottleneck with a mechanism consistent with the one previously revealed.[12] On 5 of those days, the bottleneck was interrupted so frequently by spill-over queues that the data from those days were excluded from further assessment.

Observations from the remaining 5 days are summarized in Table 1. Each day's measurements occurred during a period that extended from the initial emergence of the access-point bottleneck, to the arrival of the first spill-over queue from downstream. The daily durations of these periods are shown in the second column of Table 1. The table further shows how the access-point bottleneck always diminished regular-lane discharge flows and always created low speeds in the carpool lane. Also note how carpool-lane discharge flows were always lower than 1,600 vph.

Table 1 Reproducibility of access-point bottleneck on I-210E

Date	Bottleneck duration prior to first spill-over queue (h)	% reduction in regular-lane discharge flow	Carpool-lane average speed (km/h)	Carpool-lane discharge flow (vph)
March 13, 2012	0.4	7.9	66.0	1560
March 14, 2012	1.0	8.1	61.2	1470
March 15, 2012	0.9	6.8	66.9	1510
September 19,2013	0.5	5.5	65.6	1410
October 3, 2013	0.5	4.8	64.5	1450
Average	0.7	6.6	64.8	1480

[12] Proxy measures collected from vehicle detectors (only) were used to make this determination because video cameras were not available for additional days. Occupancies measured in lane 2 by the detector at location D2 served as proxies for regular-lane accumulation at the site. Differences in the carpool-lane vehicle counts at detectors D1 and D2 were used to obtain "net inflows" leftward through the access point, and these were the proxies used for leftward migration rates. Proxy measures for the day when videos were available were compared against Figs. 4a and b. The proxies were found to provide reliable signals in regard to changes in both, vehicle accumulation in the regular lanes and vehicle migration through the access point. Full presentation of these matters is furnished in Appendix III.

5. Additional Cases

Access points on two additional US freeways are studied below. Videos were not available for these sites. So, the studies relied solely on less-detailed traffic data from vehicle detectors. Those data reveal features that are consistent with a bottleneck mechanism like the one unveiled in the previous section. Although the shortage of detail in the data precludes us from ruling-out possible variations to that mechanism, the data are conclusive in one important respect: they reveal that rising densities in the regular lanes triggered damaging changes in the patterns by which vehicles maneuvered through the access points. The damage done to traffic at both sites was dramatic and persistent. The evidence follows.

5.1 Toll-Lane Example

Fig. 5a illustrates a 3.3-km freeway stretch in Minneapolis, Minnesota. The site's median lane is a limited-access one that is reserved at all times for carpools, along with regular, non-carpool vehicles whose drivers are willing to pay tolls. Figs. 5b and c present time-space-occupancy plots for the toll lane and for regular-lane 2, respectively. Note from the latter two figures how queues pinned at the access point emerged in both lanes by 7:03 h, and promptly expanded.

Much concerning the bottleneck mechanism and its effects are revealed in Figs. 5d – h. On this day, regular-lane density began to rise steadily at around 6:55 h, as evident in Fig. 5d, a time series of detector occupancies measured in lane 2 at location D2. Note that this initial rise in density began some 8 minutes prior to the queue formations previously revealed in Figs. 5b and c.

The pattern of vehicle movements through the site's access point changed in response to the rising accumulation. To see this, Fig. 5e presents an oblique curve of "net inflow" through that point. The curve's slopes reflect the cumulative differences between carpool-lane vehicle counts as measured by the detectors at D1 and D3 over each 30-s sampling interval. (Negatively-valued slopes denote periods when the rates of rightward maneuvers through the access point exceeded the leftward rates.) Note the upward shift in the curve's slope that began at around 7:02. This sudden rise in slope is in keeping with a sudden rise in leftward migration into the toll lane, as per the mechanism unveiled in Section 4.

A variation of this dynamic is also possible. The 7:02 change in slope could instead be caused by a reduction in rightward maneuvers through the access point. Perhaps the growing density in the regular lanes discouraged migration into them. And perhaps the resulting retention of toll-lane vehicles, in combination with whatever leftward migrations occurred through the access point, may have been disruptive.

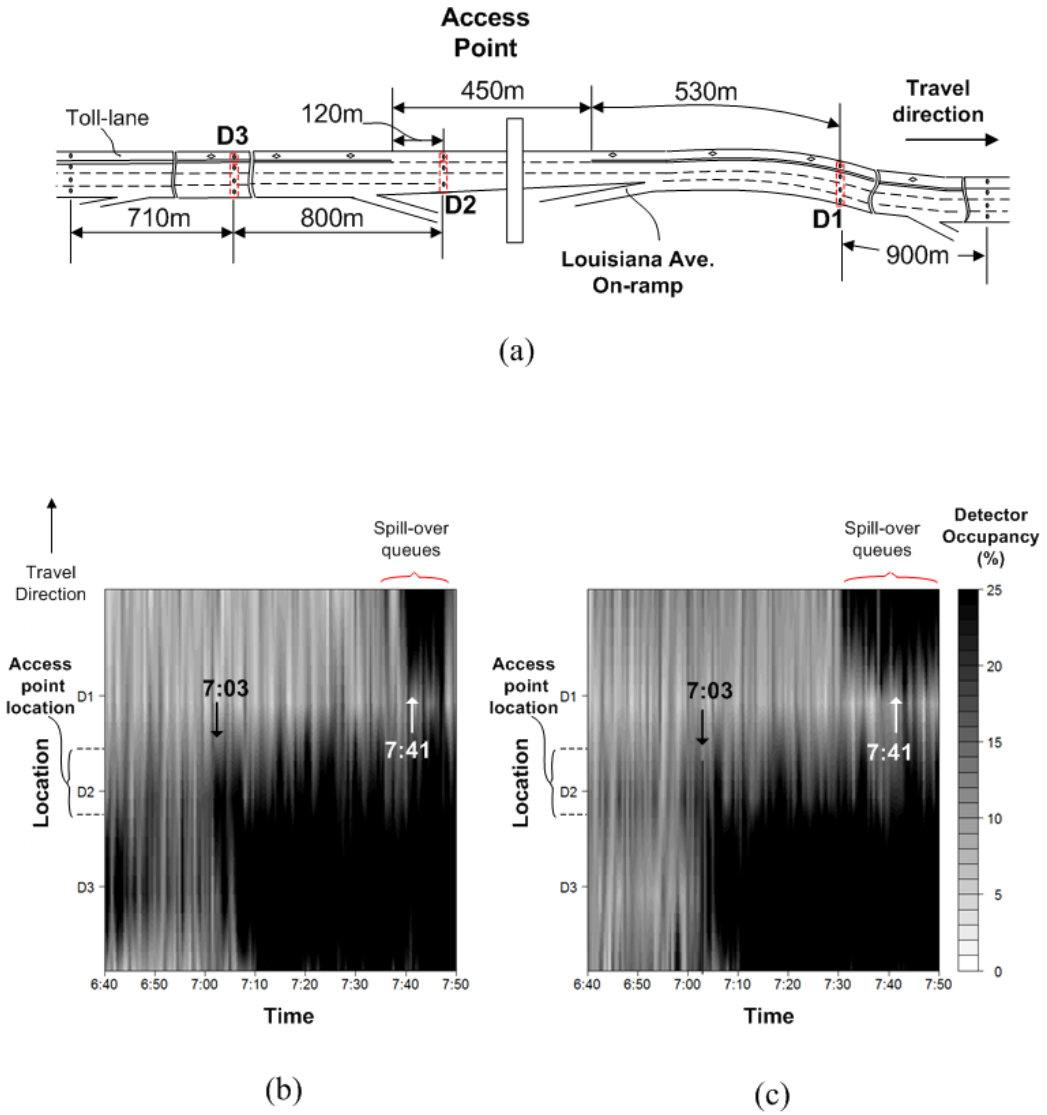

Figure 5 Limited-access Example 2 (September 24, 2013)

(a) Eastbound I-394 freeway, Minneapolis, Minnesota

(b) Time-space-occupancy plot of toll-lane

(c) Time-space-occupancy plot of lane 2

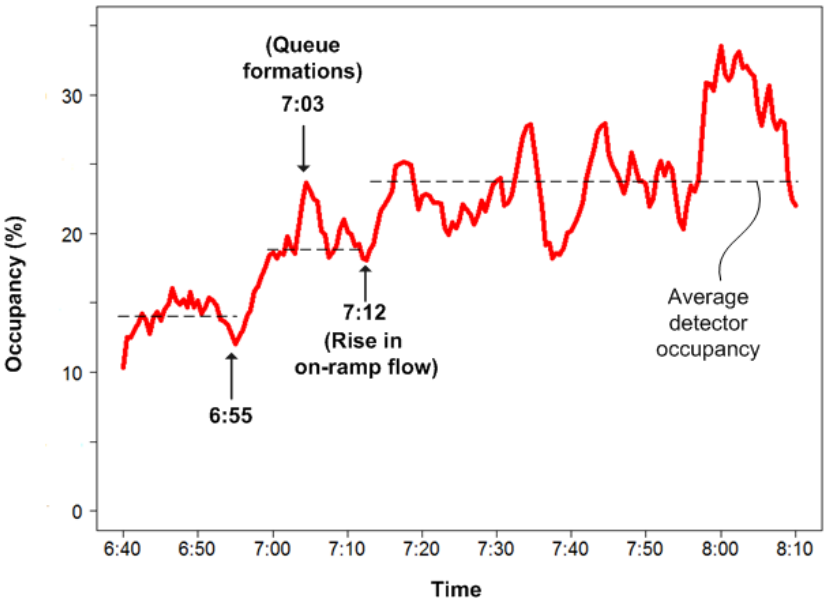

Fig 5(d) Time-series of occupancy for lane 2, measured at D2 (I-394E; September 24, 2013)

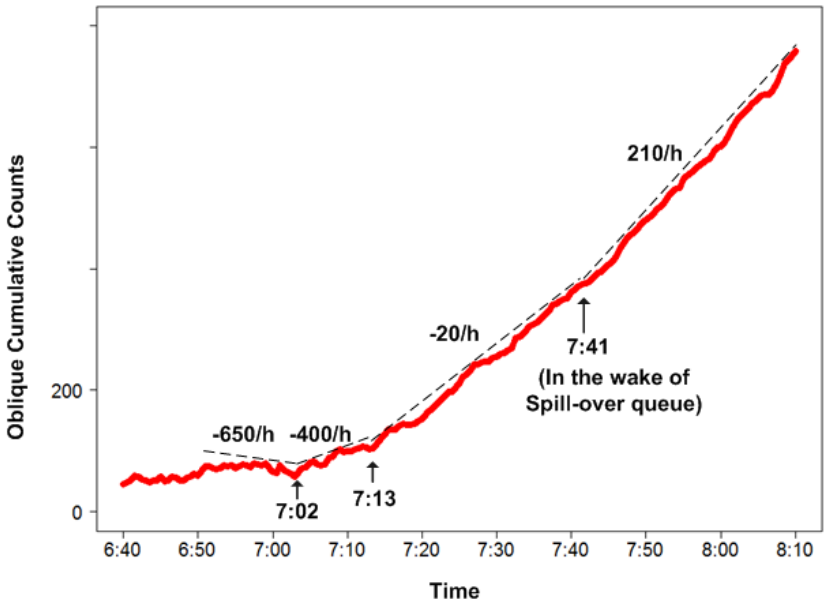

Fig 5(e) Oblique cumulative curve for net-inflows into toll lane using vehicle counts measured at D1 and D3 (I-394E; September 24, 2013)

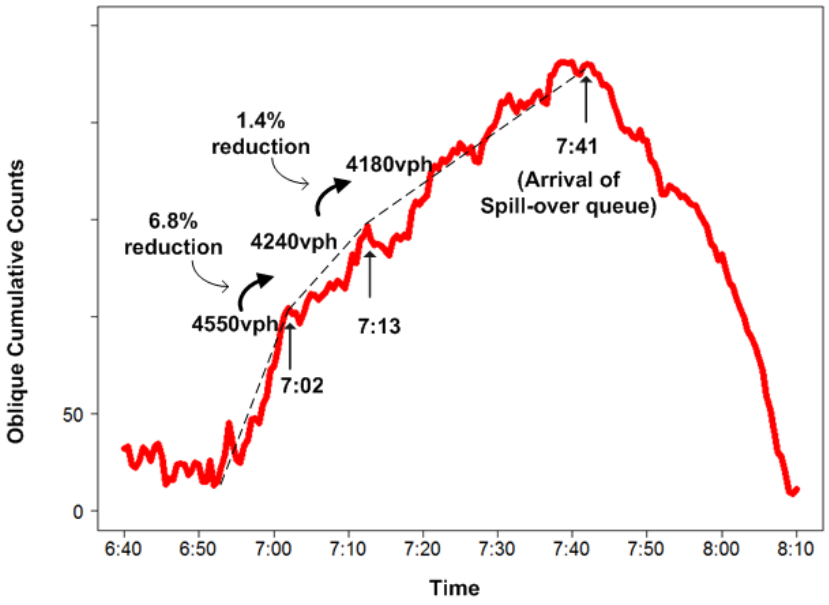

Figure 5(f) Oblique cumulative curve for all regular lanes combined at D1 (I-394E; September 24, 2013)

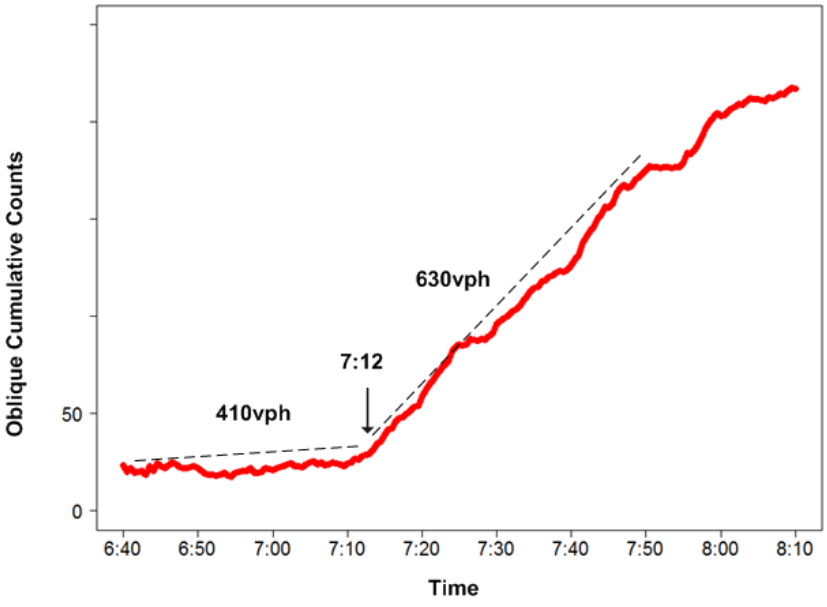

Figure 5(g) Oblique cumulative curve for on-ramp inflows at Louisiana Avenue (I-394E; September 24, 2013)

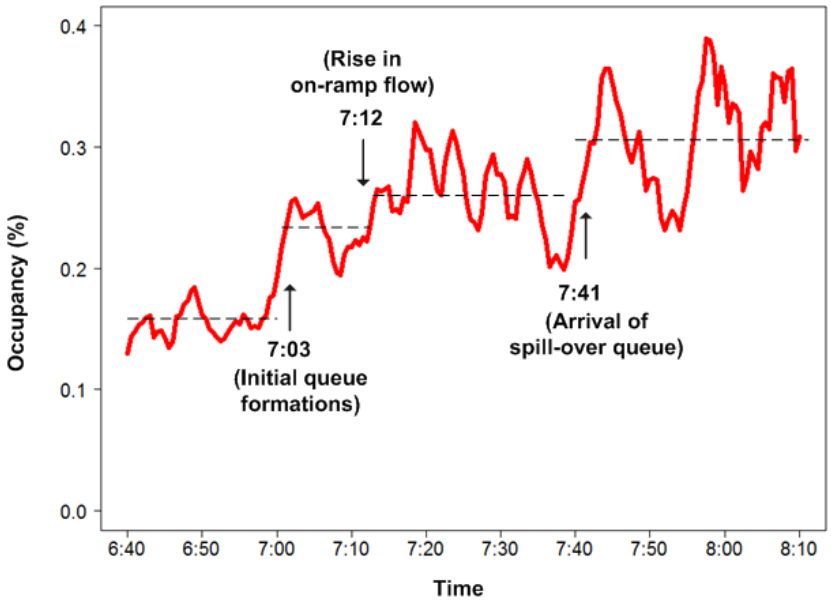

Figure 5(h) Time-series of occupancy for toll-lane measured at D2 (I-394E; September 24, 2013)

The uncertainty in this regard notwithstanding, it was the 7:02 change in access-point maneuvers that immediately preceded the queue formations; see again Figs. 5b and c. Moreover, regular-lane discharge flow fell by 6.8% at that same time; see Fig. 5f. Interestingly, the mechanism, with its telltale change in net inflow, reoccurred on two occasions later in the rush owing to two distinct events that occurred downstream of the access point.

The first of these events occurred at approximately 7:12 h, at which time inflow from the Louisiana Avenue on-ramp (see again Fig. 5a) abruptly rose from 410 vph to 630 vph and remained at the higher rate for the duration of the rush. That persistent rise in ramp flow is evident in Fig. 5g. Regular-lane density upstream immediately began to grow again as a result (see Fig. 5d). Within no more than a minute, net inflow through the access point began to grow as well (Fig. 5e); and regular-lane discharge flow diminished by an additional 1.4% (Fig. 5f).

The second event occurred when spill-over queues arrived some time later at around 7:41 h. Those queues thereafter remained in the regular lanes (Fig. 5c) and severely constrained their flows (Fig. 5f). Net inflow through the access point further increased in the immediate wake (Fig. 5e), even though a queue also spilled-over in the toll lane as well (Fig. 5b).

We find the final event that began at 7:41 to be particularly interesting in the following respect: the event suggests that when travel conditions erode in regular lanes, drivers are prone – perhaps reflexively – to seek refuge in a special lane, even when conditions in that latter lane are poor. This driver tendency means that an access point carries with it the potential to make a bad situation worse, just as we see for the present site at around 7:41 h.

And as was seen for the previous site, an access point can degrade conditions not just in the regular lanes, but in the special one as well. As cases in point regarding the latter matter, consider Fig. 5h. Visual inspection of that figure reveals that once the queue had formed in the toll lane, each later-occurring rise in net inflow through the access point caused that toll-lane queue to grow denser. Of course, average vehicle speeds in that lane diminished with each growth in its density.

Our final case study to follow has more to say regarding degradation in a special lane. It entails a case in which regular-lane traffic became so congested that heightened migration into the limited-access special lane did little to worsen that state of affairs. However, the focused migration did degrade conditions in the special lane, and did so significantly.

5.2 Final Illustration

The median lane of the southern California freeway stretch shown in Fig. 6a is a limited-access one that is reserved at all times for carpools. Visual inspection of the time-space-occupancy plot in Fig. 6c reveals that a queue in regular-lane 2 spilled-over to the site's access point from somewhere downstream at about 5:44 h. The oblique cumulative curve in Fig. 6d shows how net migration through the access point and into the carpool lane increased (by 130 movements/h) in immediate response to the arrival of that queue. Fig. 6b shows how a queue pinned at the access point emerged in the carpool lane at that same time. The carpool-lane queue thereafter persisted for nearly 3 hours, and eventually expanded to a length of more than 5 km. Average speed in that queue was only about 35 km/h.

6. Conclusions

The present findings show that access points to special-use freeway lanes are prone to become bottlenecks. Detailed traffic data extracted from videos reveal that sharp growths in migration into a special lane came in the wake of rising regular-lane accumulation. Less-detailed detector data unveil traffic patterns that are consistent with this. In that heightened vehicle migrations were funneled through limited space, and given that these migrations competed with other vehicular movements at the access points, traffic disruptions occurred. Queues and diminished discharge flows were the result. Often this degradation occurred in the regular lanes and in the special ones.

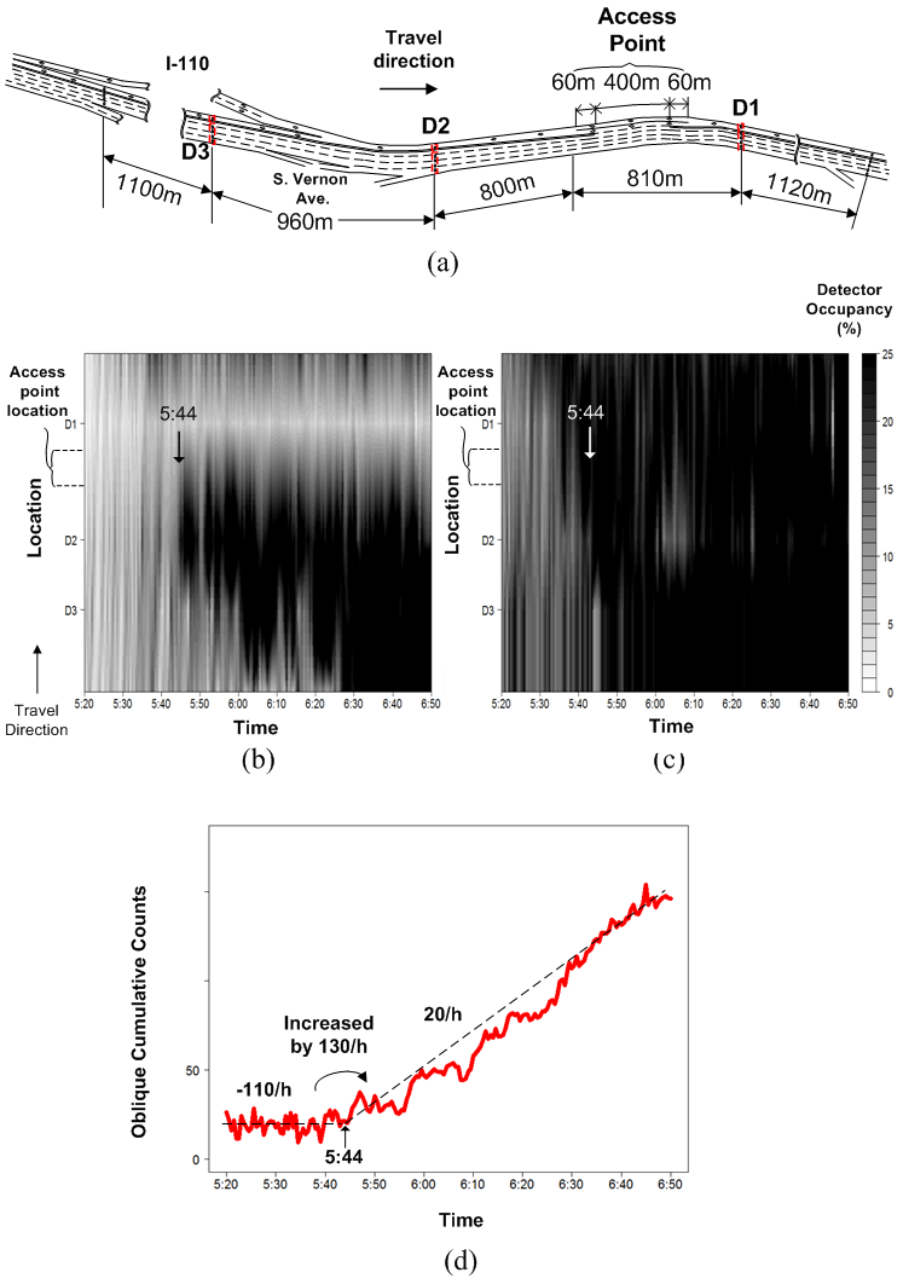

Figure 6 Limited-access Example 3 (January 29, 2014)

(a) Westbound I-105 freeway, Los Angeles County, California

(b) Time-space-occupancy plot of carpool lane

(c) Time-space-occupancy plot of lane 2

(d) Oblique cumulative curve of net-inflows using vehicle counts measured at D1 and D2

The problem seems to be a common one. The paper offers examples from three different freeways, and a further example at another site is furnished in Appendix IV.

Still, we cannot at present estimate just how widespread the problem may be. We have made no attempt to inventory some region in pursuit of an estimate of that kind. This would be a task better left to transport agencies that are charged with the stewardship of their regions and that enjoy jurisdictional authority over them. In an effort to be helpful, the present paper shows how an inventory of this kind might be performed. A good start would entail use of time-space-occupancy plots, like Figs. 3b and c, to identify congestion patterns that are common to regular- and to special lanes.

Yet, the intent of this study is less to proffer procedural recommendations than to motivate the need for inventories along these lines. Stated in slightly different terms, we believe that unveiling the potential problem of access points is useful in its own right. After all, limiting the access to special lanes has been widely touted as means of combatting the frictional effect. That far worse problems can be created by the access points to those lanes may be more than sad irony. It may be cause to reassess certain policies, including policies in regard to freeway toll lanes.

For example, the state of California plans in coming years to deploy hundreds of miles of toll lanes in the San Francisco Bay Area alone; and the plan calls for limited-access lanes for the area's most congested freeways (Caltrans, 2009). The latter decision may be a well-intentioned attempt to shield toll-lane traffic from the frictional effect. And unintended bottlenecks might be mitigated if lengthier access points are ultimately deployed, as is now recommended (Caltrans, 2011). Yet, longer access points may not eliminate the problem entirely.

Limited-access toll lanes might also be attractive to an agency because they require fewer roadside transponders to identify who is to be tolled. This can save costs to the agency, but should perhaps be weighed against the costs that access-point bottlenecks impart to society at large. Even crude estimates of the latter costs might be better than overlooking them entirely.

In cases when the societal costs of access-point bottlenecks are found to be too great, policies could be formulated to incentivize other options. For example, if toll-collection agencies were allowed to retain greater revenues by maximizing the speed differences between toll lanes and regular ones, those agencies might then advocate greater use of non-separated lanes, so as to eliminate access-point bottlenecks and their damaging effects on toll-lane traffic.

Acknowledgments

The authors are indebted to both Xiaoyue Cathy Liu, University of Utah, and Yinhai Wang, University of Washington, for directing us to sources for some of the raw data used in this report.

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Appendix I

Inspections of flows measured at on- and off-ramps near Azusa access point

This appendix is intended to further confirm that the bottleneck presented in Section 4.1 was not caused by ramps residing near Azusa access point but by the access point itself; see again Fig. 3(a) for the geometry of the study site. Recall that the site's bottleneck became first activated at the access point at 14:13 h and that this earlier activation sustained for around 5 minutes; see again Figs. 3(c) and 4(d) together. In addition, these latter figures reveal that the access point became an active bottleneck again at 14:49 h. Note also that this later activation of the bottleneck was induced by the arrival of a queue spilled-over further downstream of the access point.

Some researchers have applied oblique cumulative curves of vehicle counts to identify if a freeway bottleneck of interest is caused by surges either of on-ramp inflows or of off-ramp exit flows; see e.g. Cassidy and Rudjanakanoknad (2005) or Kim and Cassidy (2012). In line with these references, we shall examine oblique cumulative curves for input flows from Azusa on-ramp and exit flows into Citrus off-ramp; see Figs. A1(a) and (b), respectively.

Fig. A1 (a) shows that inflows from Azusa on-ramp sharply increased at 14:05 h and at 14:38 h, respectively. Each of these two surges, however, does not appear temporally correlated with either of the aforementioned two activations of the bottleneck; see again Figs. 3(c) and 4(d) together. In addition, the bottleneck's two activations happened in the midst of the periods when relatively low inflows (490 vph and 480 vph, respectively) entered from Azusa on-ramp; see again Fig. A1(a). Thus, we can safely say that the site's bottleneck was not attributed to Azusa on-ramp.

Similar inspections reveal that output flows exiting Citrus off-ramp were reduced from 720 vph to 470 vph (from 660 vph to 530 vph) once the bottleneck became active at the access point at 14:13 h (at 14:49 h); see again Fig. A1(b). Moreover, visual inspections of video data confirm that Citrus off-ramp itself did not generate any disturbance during the entire rush. These inspections together with the findings unveiled in Section 4.1 suggest that vehicles destined to Citrus off-ramp were subject to delays at the site due to the freeway queues originated from the access point.

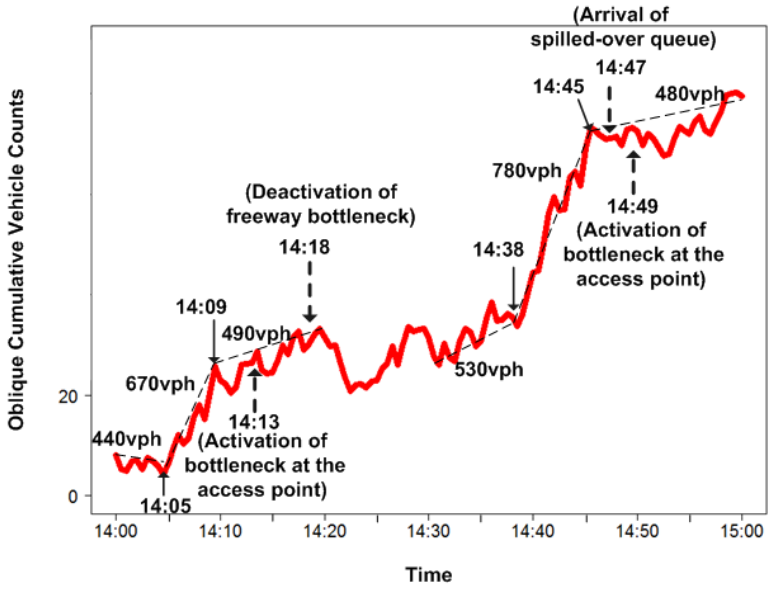

Figure A1 (a) Oblique cumulative curve for on-ramp inflows at Azusa Avenue (I-210E; September 26, 2013)

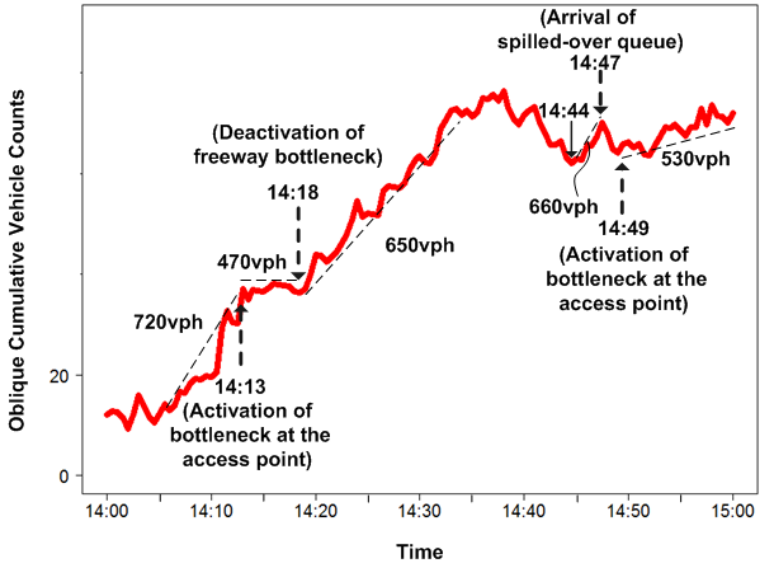

Figure A1 (b) Oblique cumulative curve for off-ramp exit flows at Citrus Avenue (I-210E; September 26, 2013)

Appendix II

Complementary inspections of queues' spill-over from downstream

We shall further examine here if the site shown in Fig. 3(a) was encroached by queue(s) that were spilled-over from the further downstream of Azusa access point during a particular afternoon. Recall that this issue has already been discussed in Section 4.1. However, this earlier discussion was only concerned about the traffic of carpool lane and lane 2; see again Figs. 3(b) and (c), respectively. Thus, we shall here inspect the traffic conditions of the remaining regular lanes as well.

Fig. A2 presents time-series of occupancy for lanes 3, 4 and 5 measured at D1 (i.e. at the immediate downstream of Azusa access point); see the figure's solid, bold-dotted, and light-dotted lines, respectively. Inspections from these lines reveal that occupancies of all the three general-use lanes were less than 20 % except the period spanning some minutes surrounding 14:47 h. Thus, these inspections further confirm that flows departing from the site were not restricted by spilled-over queues during most of the examined rush.

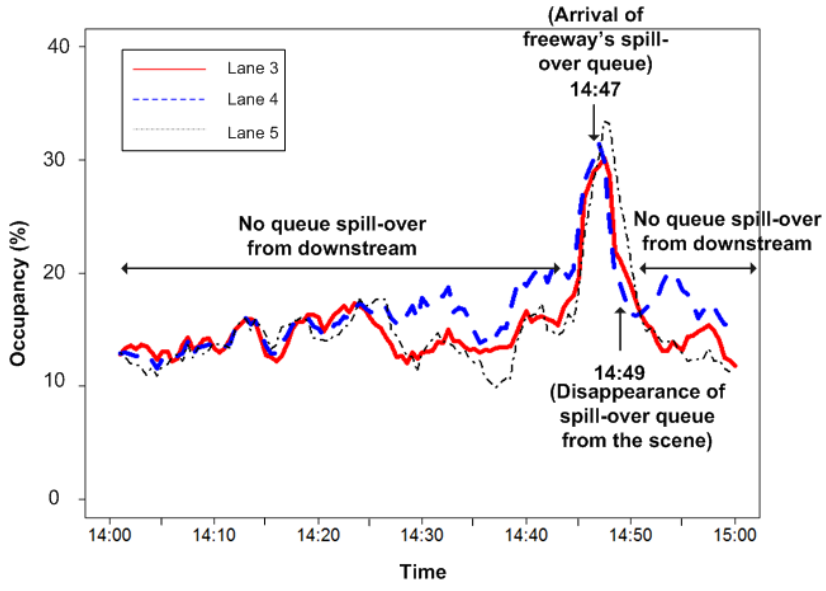

Figure A2 Time-series of occupancy for lanes 3, 4 and 5 measured at D1 (I-210E; September 26, 2013)

Appendix III

Testing the validity of proxy measures used to detect activations of a bottleneck

This appendix illustrates the effectiveness of proxy measures introduced to detect activations of a bottleneck at the site shown in Fig. 3(a). Recall that Section 4.1 revealed that activations of the site's bottleneck are characterized both by a sharp rise of the site's vehicle accumulation and by a surge of the leftward lane-changing maneuvers through Azusa access point; see again Fig. 4. Note, however, that the site's video images are not available during other typical days. Lack of video measurement, archived detector data were used to estimate proxy measures. These measures are (i) the net-inflow through the access point into the carpool lane and (ii) the detector occupancy at a suitable location.

Table A1 summarizes outcomes from testing the proxies. Note that the set of tested days are identical with what was used in Section 4.2 to confirm the bottleneck's reproducibility. The table's first and second columns present exactly when a bottleneck became activated at the access point. The third column presents how the net-inflow through the access point has increased once the bottleneck became activated. Note that each increase in the net-inflow was quantified by calculating the difference between 10 minute-averages of the net-inflow measured before and after each bottleneck-activation, respectively. Note that such a quantified increase in net-inflow reproducibly ranged between 200/h and 300/h on each of all the tested days.

Table A1 Summary of testing proxies to detect bottleneck activations at Azusa access point

Date	Bottleneck Activation Time	Increase in Net-inflow Into HOV-lane (/h)	Mean Occupancy (%) of Lane 2 Measured at D2		*p*-value ($H_0: \overline{\rho_b} = \overline{\rho_a}$ $H_1: \overline{\rho_b} < \overline{\rho_a}$)
			Before Activation $\hat{\rho}_b$	After Activation $\hat{\rho}_a$	
March 13, 2012	16:10	260	22	26	6.9E-03
March 14, 2012	15:05	200	25	36	1.6E-04
March 15, 2012	14:55	250	16	25	1.4E-04
September 19,2013	14:22	280	14	23	7.8E-05
October 3, 2013	14:52	260	26	33	1.1E-03
Average		250	21	29	1.7E-03

The table's fourth and fifth columns show two means of occupancy measured during 10 minutes before and after each activation-time, respectively in regular-use lane 2. These two means denoted by $\hat{\rho}_b$ and $\hat{\rho}_a$, respectively, were measured at D2 (i.e. at the immediately upstream of the access point). The table reveals that $\hat{\rho}_a$ was greater than $\hat{\rho}_b$ on each of all tested days. Finally, the sixth column furnishes *p*-values obtained from conducting *two-samples t-tests*. Note that the statistical inference for these *t*-tests was based on the null hypothesis that there was no difference between true means (denoted by $\overline{\rho_b}$ and $\overline{\rho_a}$, respectively) of occupancy corresponding to before and after activation. Against this null hypothesis was specified the alterative hypothesis that the latter mean was greater than the former one (i.e. $\overline{\rho_b} < \overline{\rho_a}$). Inferring from *p*-values less than 1% for all the tested days, we can confidently reject the null hypothesis for the alternative one.

To sum up, an increase of the net-inflow through the site's access point turns out to be a reproducible feature of the bottleneck created by the access point. Moreover, such an increase in net-inflow attendant to the bottleneck reproducibly fell within a somewhat narrow range. In this way, each increase in the net-inflow can effectively indicate the surge of leftward lane-changing maneuvers through the access point whenever regular lanes are degraded. In addition, queues originated from the access point invariably increased its immediate upstream detector's occupancy, particularly in lane 2. Such an increase of occupancy can be used to detect when the site's vehicle accumulation surges.

Appendix IV

Analyses on another example of limited-access

This final appendix furnishes another limited-access example. Fig. A3(a) presents a 2.7-km freeway stretch residing in Orange County, California. This site's median lane is a limited assess one that is reserved for carpools at all times. Figs. A3(b) and (c) show time-space-occupancy plots constructed for carpool lane and lane 2, respectively during an afternoon rush on a typical weekday. These latter figures reveal that freeway queues both on carpool lane and on lane 2 delineated distinctively different patterns of evolution during the rush before and after around 15:40 h.

Fig. A3(c) reveals that a queue spilled-over from downstream in the general-use lane arrived at Westminister access point at 15:39 h and thereafter swamped it. Since this prominent arrival of a spilled-over queue at the access point, net-inflow through it into the carpool lane sharply increased. This surge of the net-inflow can be confirmed by inspecting the oblique cumulative curve shown in Fig. A3(d). This latter figure reveals that there were increases of the net-inflow by the amount of 340/h (at 15:39 h) and additionally by 820/h (at 15:43 h). Notably, these rises of the net-inflow were accompanied by a persistent queue in the carpool lane; see Fig. A3(b) and note the darker shades persistently emerged from the access point since around 15:43 h. This persistent carpool-lane queue sustained upstream of the access point for around 3.5 hours, and the expanded queue's length eventually amounted to 4.4km. Average speed in that queue turned out to be only around 42.4 km/h.

A persistent increase of input flows through the site appears to fuel the expansion of the spilled-over queue in the regular lane beyond the access point. In this regard, Figs. A3(e) and (f) present oblique cumulative curves constructed for total flows combined across all the regular lanes at D3 (i.e. at the immediately upstream of the access point) and for on-ramp inflows at Westminister Boulevard, respectively. Fig. A3(e) shows that total input flows from all the regular lanes significantly increased by 690 vph at 15:36 h. Similarly, inflows from Westminister on-ramp surged by 380 vph at 15:37 h; see again Fig. A3(f). Notably, these surges of the site's input flows happened just within a few minutes prior to the aforementioned prominent arrival of the spilled-over queue at the access point.

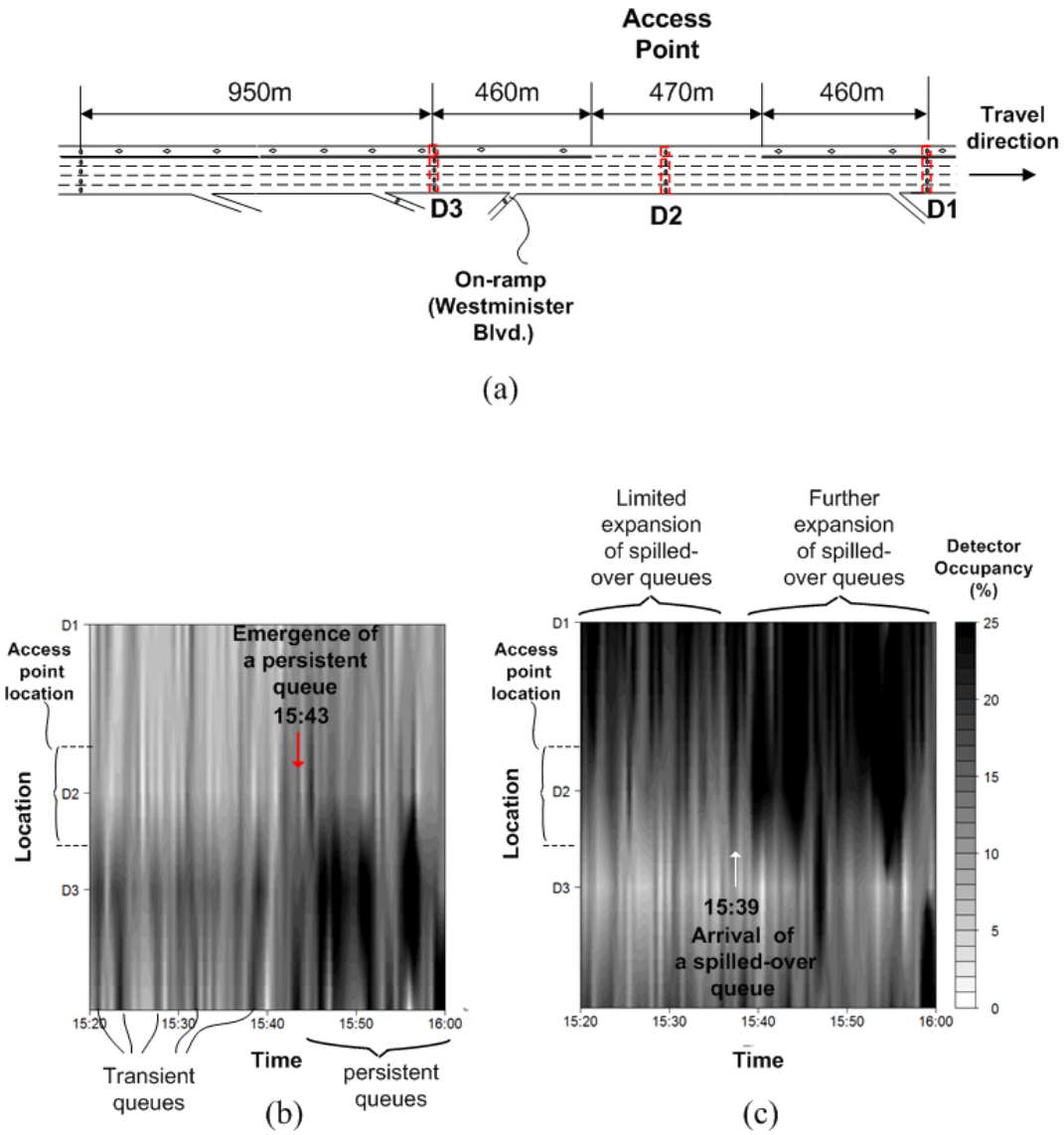

Figure A3 Additional example of limited-access (March 15, 2012)

(a) Northbound I-405 freeway, Orange County, California

(b) Time-space-occupancy plot of carpool lane

(c) Time-space-occupancy plot of lane 2

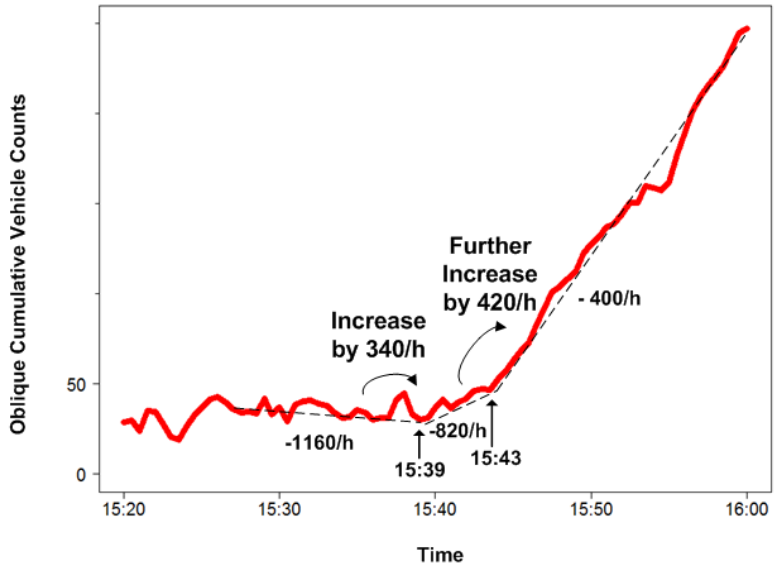

Fig A3(d) Oblique cumulative curve for net-inflows using vehicle counts measured at D1 and D3 (I-405N; March 15, 2012)

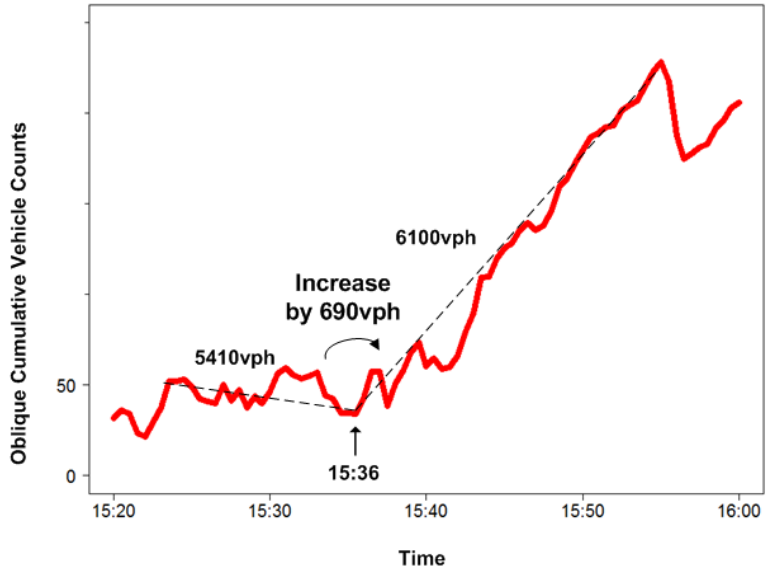

Figure A3(e) Oblique cumulative curve of vehicle counts for all general-use lanes combined at D3 (I-405N; March 15, 2012)

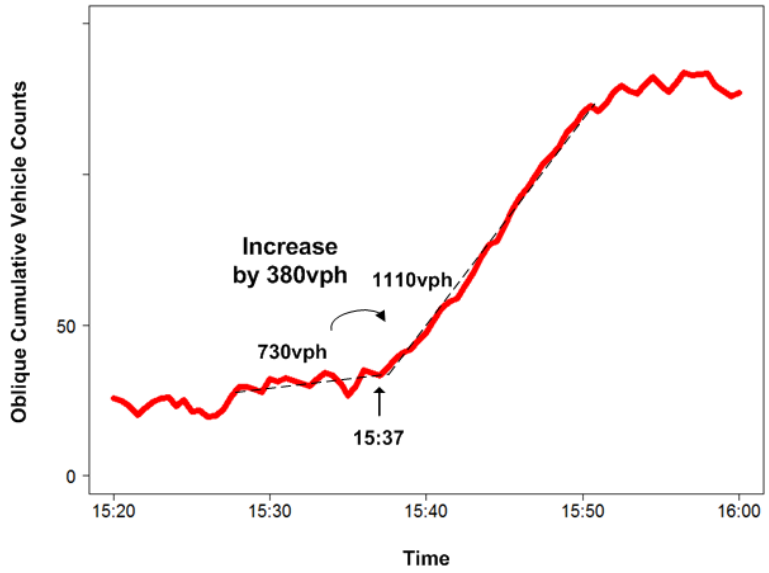

Figure A3(f) Oblique cumulative curve for on-ramp inflows at Westminister Boulevard (I-405N; March 15, 2012)

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