Chapter 4

Spatiotemporal Effects of Segregating Different Vehicle Classes on Separate Lanes

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Abstract The paper explores some of the impacts of setting aside road lanes for the exclusive use of select vehicle classes. We examine first the case of lanes that are reserved for carpools, and then extend the analysis to bus-only lanes. In doing so, the paper makes three contributions. The first is methodological: it illustrates the importance of analyzing freeway data in full spatiotemporal detail. The second is physical: data reveal that carpool lanes are not as damaging as previously reported. In fact, these lanes are found to smooth traffic in adjacent lanes so much (by diminishing disruptive vehicle interactions near bottlenecks) that even substantially underutilized carpool lanes can increase bottleneck discharge flows. The third contribution is theoretical: it uses the smoothing phenomenon to show how the judicious deployment of bus-only lanes on freeways and city streets can favorably affect not just buses, but also cars.

1. Introduction

Empirical assessments of road traffic are numerous and date back at least as far as the 1930's. Many, if not most of these studies examine time series of vehicle flows, speeds, etc. from a single milepost on a road, while ignoring (or not collecting) measurements at neighboring mileposts. This kind of purely temporal analysis seems to have advanced the belief that special-use lanes are a common cause of traffic congestion; see for example the study of freeway carpool lanes in Chen et al. (2005) published in earlier proceedings of this symposium series.

The present paper begins (in Section 2) by illustrating how the real effects of a special-use lane can be misjudged if one ignores the spatial component of the facility on which the special lane is deployed. This section redoes the Chen et al. (2005) study spatiotemporally and shows that none of the carpool lanes in that study were creating congestion.[1] To look into this finding more deeply, Section 3 refines the analysis for one of these carpool lanes at a bottleneck location. Despite being underutilized, the carpool lane is observed to smooth and increase flow through the bottleneck, and thereby reduce congestion. The physical reasons for this beneficial smoothing effect are identified. They strongly suggest that the effect should be even more pronounced for bus-only lanes. In view of this, Section 4 quantifies the benefits of segregating buses from cars on separate lanes in urban areas, recognizing the smoothing effect. Section 5 discusses the implications of our findings.

2. Methodological Contribution: Spatiotemporal Analysis

Section 2.1 gives background on the Chen et al. (2005) study. (Since that study was titled An Empirical Assessment of Traffic Operations, it will be referred to from now on by its acronym, EATO.) The spatiotemporal reassessments are given in Sections 2.2 – 2.4.

2.1 Background

The EATO study used time series of vehicle speeds and flows (by lane) as metrics to assess the carpool lanes' impacts on freeway traffic. Like in many other studies, these data were measured at single detector stations, and were not analyzed together with data from neighboring detectors. EATO identified periods when queues persisted atop a detector, and correlated these with carpool-lane operating times. But this methodology of examining only data from single detector stations can not identify the locations where these queues initially formed. To see how this missing information colored the analysis, refer to Figs. 1a – 1f. These charts reproduce the speed time series data in Fig. 8 of EATO and characterize all of the carpool facilities it studied. Our charts include additional annotations to aid in their interpretation.

On all the freeways of Figs. 1a – 1f, the median lane is reserved for carpools on weekdays during the afternoon rush, from 15:00 to 19:00. This period is demarcated by vertical lines in each chart. In all cases, speeds are lower during that period than outside it, both in the carpool lanes (dark curves) and in the adjacent General Purpose (GP) lanes. Our concern is with the impacts that special lanes

[1] The carpool lanes for all of the sites in Chen et al. (2005) are set aside during rush hours to serve only vehicles (mostly cars) that carry more than a predetermined number of occupants. Note too that previous studies of traffic, on various other facility types, and with various other objectives in mind, have also shown the value of performing analysis in spatiotemporal fashion (e.g. Kerner 2002; Treiber and Helbing 2002; Kerner and Klenov 2003; Kurata and Nagatani 2003).

have on those vehicle classes excluded from using them, and we therefore focus on the (larger) speed drops in the GP lanes.[2]

The EATO study claims without examining demand effects that queues arose in these GP lanes because they were eventually in short supply; i.e., demand among Low Occupancy Vehicles (LOVs) presumably grew while the median lane was unavailable for their use, and this supposedly pushed the GP lanes into the congested regime. The evidence of this mechanism is said in EATO to come after 19:00 hrs because by this time, when each lane-use restriction had been lifted, the speeds reportedly increased. EATO's conclusion is that speeds rose because the median lane was no longer squandered on carpools.

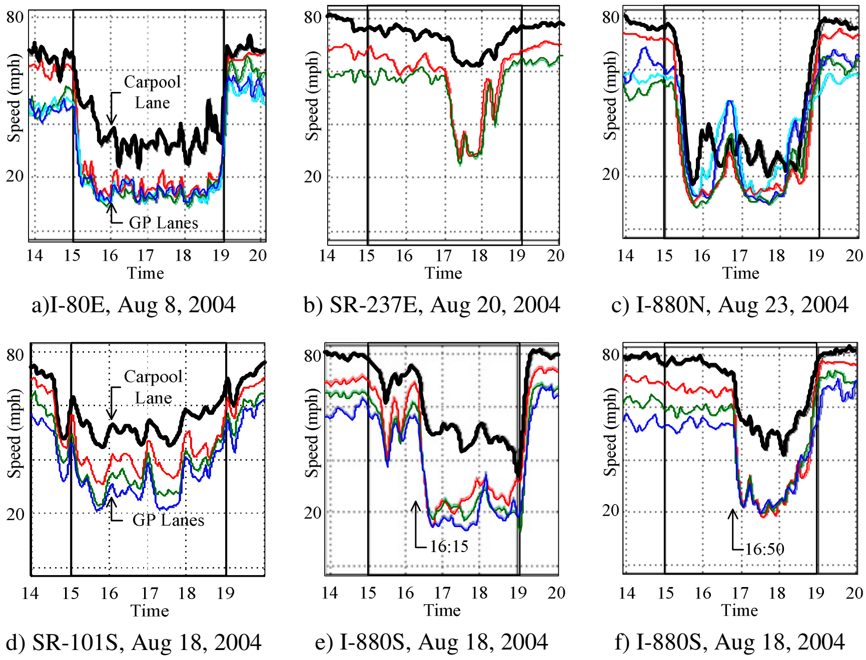

Fig. 1. Time-series diagrams of speed furnished in EATO

The evidence from the above figure, however, is not as stated in EATO. In four of the cases (Figs. 1b, 1c, 1d and 1f) speeds began to recover *before* the carpool restriction expired at 19:00, and in three of these (Figs 1b, 1d and 1f) recoveries began around 18:00 - an hour before the restriction's expiration time. One cannot conclude from EATO's data that lifting the carpool restriction increased the speeds (removed the queues): an effect cannot precede its cause. The more plausi-

[2] The observed speed reductions in the carpool lanes turn out to have a rather insignificant impact on carpool-vehicle delay (see Cassidy et al. 2006).

ble explanation is that congestion eased because demand declined at the end of the rush.

Of course, lack of evidence around 19:00 does not mean that the carpool lanes could not be causing other problems at other times. Since, however, the single-detector station methodology is inconclusive, we now reassess the events of Fig. 1 in spatiotemporal detail. Section 2.2 examines the cases e and f; Section 2.3 cases a, b and d; and Section 2.4 case c.

2.2 Cases 1e and 1f

The last two charts of Fig. 1 come from neighboring detectors on the same freeway (southbound Interstate 880, labeled I-880S in the charts) during the same day and time, though EATO did not analyze their spatiotemporal relationship. (It mistakenly states that the data were from different freeways.) Note how speed dropped much earlier at one detector location than at the other, suggesting that the queue formed at a specific location.

Fig. 2 reveals that location: it presents a spatiotemporal plot of occupancy from all the detectors along the relevant stretch of I-880, including the two detectors in EATO. Note in interpreting the figure that: (i) Fig. 2 spans the same observation period as Figs. 1e and 1f; (ii) occupancies of about 20 percent or more denote the presence of queues; and (iii) occupancies below 20 percent imply no queues, i.e. that flow *is* demand. The downward-slanting, diagonal pattern separating light and dark shadings (labeled queue growth in Fig. 2) shows that the queue started locally at Post Mile (PM) 18.7, around 15:30 hrs. The queue then grew, eventually causing the speed reductions visible in Fig. 1e around 16:15, and then the reductions of Fig. 1f around 16:50.

The accident log maintained by the state police indicates that this queue was triggered by a vehicle collision, and not by the carpool lane. An archival record of that collision can be found at http://pems.eecs.berkeley.edu.

Fig. 2 also shows that after the collision was removed, a second bottleneck became active at PM 26.7 from 17:30 onward: the shading reveals a queue upstream of this location, with freely flowing conditions downstream. Note that PM 26.7 is the location of a merge. Later in the rush, but still prior to 19:00, the back of the queue gradually receded forward toward this second bottleneck for lack of demand, and eventually dissipated. Thus, the gradual speed recoveries seen in Figs. 1e and 1f were due to a reduction in traffic demand, and not to the expiration of the carpool restriction. The speed recovery at PM 26.7 (Fig. 1e) coincided with the expiration of the carpool restriction only by chance, and this could have been a confounding factor in EATO.[3]

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[3] Although the expiration of the lane-use restriction could have slightly accelerated the queue's dissipation, Fig. 2 shows that the queue was already well on its way to dissipating, and likely would have done so at around 19:00 hrs – even if the lane-use restriction had not expired.

We examined this freeway for nine additional weekdays (in July and August, 2004). On four of these days, a queue did not arise at all. On each of the five other days, a small queue did form, and always did so locally at the merge bottleneck near PM 26.7.

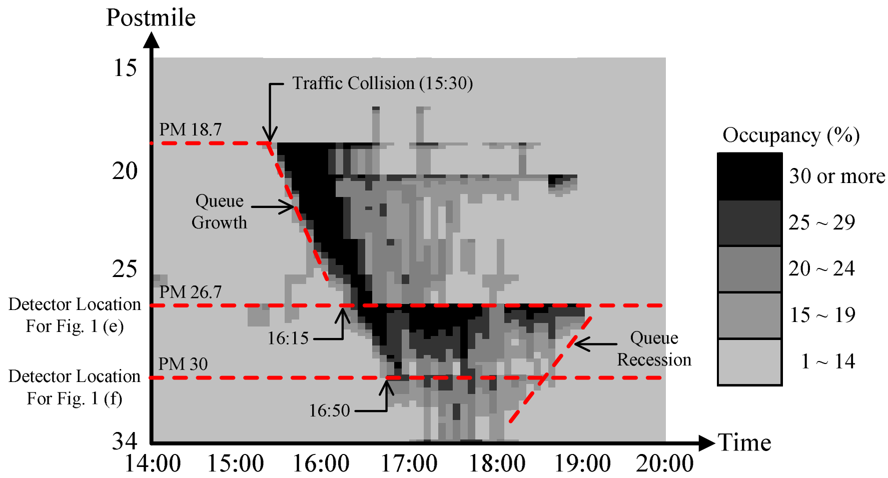

Fig. 2. Time-space-occupancy plot, I-880S (Aug 18, 2004)

It may be tempting to blame this bottleneck (near PM 26.7) on the carpool lane because the lane was underutilized: flow in the lane remained at, or slightly below, 1500 vph while the carpool restriction was in force. However, assigning culpability to the carpool lane would have been premature because the bottleneck discharge flows in the other lanes actually increased while the carpool restriction was in force. We investigate this phenomenon in Section 3.

2.3 Cases 1a, 1b and 1d

As in the previous cases, spatiotemporal analyses of the three sites in Figs. 1a, 1b and 1d uncovered no evidence that the carpool lanes were adding to freeway congestion. To the contrary, the loop detector data from the site in Fig. 1d suggest that the carpool lane reduced congestion slightly by increasing the bottleneck discharge flows in other lanes (see again Section 3). Analysis also shows that the site of Fig. 1b became congested because of construction activity downstream of the chart's measurement location; and that the site was not congested on days when this roadwork did not occur. For further details, see Cassidy et al. (2006).

2.4 Case 1c

Fig. 3 displays a time-space-occupancy plot for a long stretch of the freeway I-880 (northbound) that includes the detector station used in Fig. 1c, and spans the same period. Once again, the occupancies show that a queue started at definite points in space and time: namely, at PM 26, the location of a merge, and 15:00 hrs.[4] Since the queue formed at about the time when the carpool restriction took effect, and since there were good vantage points near the merge, we used videos to determine both: the mechanism of queue formation; and the subsequent effect of the carpool lane. The unexpected findings are presented in the following section.

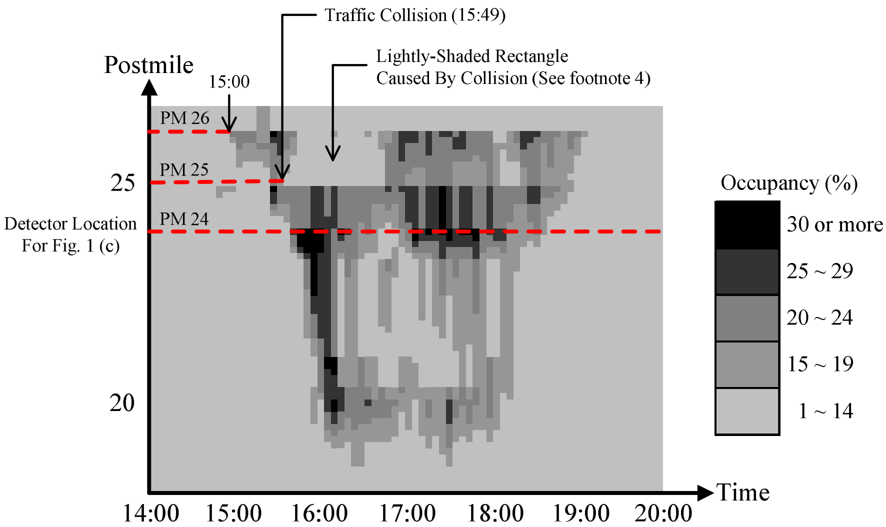

Fig. 3. Time-space-occupancy plot, I-880N (Aug 23, 2004)

3. New Physical Finding: The Smoothing Effect

The freeway geometry in the vicinity of PM 26 (I-880N) is displayed in Fig. 4. Video cameras were erected on the over-crossings, and these recorded traffic during part of an afternoon rush (on July 19, 2006). The video data unveil the carpool-lane effect on both the bottleneck's formation (Section 3.1), and its discharge flow (Section 3.2).

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[4] The lightly-shaded rectangle pinned at the bottleneck was the result of a collision that occurred at 15:49 and PM 25; see again http://pems.eecs.berkeley.edu.

3.1 Bottleneck Formation

Vehicle arrival times at locations X_1, X_2 and X_3 were manually extracted from the videos and, as is customary, cumulative curves of vehicle count were plotted on an oblique coordinate system (O-curves), as shown in Fig. 5. Note that the slopes of the O-curves are the excess flows over a background flow, which is 6800 vph in the present case; and that the curves in Fig. 5 were constructed in such ways that superimposed curves indicate free-flow traffic (flow = demand) and separated curves indicate delays: the wider the separation the longer the delays (see Cassidy and Windover 1995; Muñoz and Daganzo 2002).

In Fig. 5, curves 2 and 3 are superimposed, and below curve 1. Thus, traffic was freely flowing between X_2 and X_3, but delays existed between X_1 and X_2. These two curves diverged for good at about 14:43 hrs when a disruption reduced the flow at X_2. Less than 3 minutes later (at approximately 14:45:30) flow dropped further to about 6950 vph. The video data establish that this flow reduction was triggered by a queue that first formed in the shoulder lane due to pulses of merging vehicles, and then spread to all lanes; the carpool lane had no role in this.

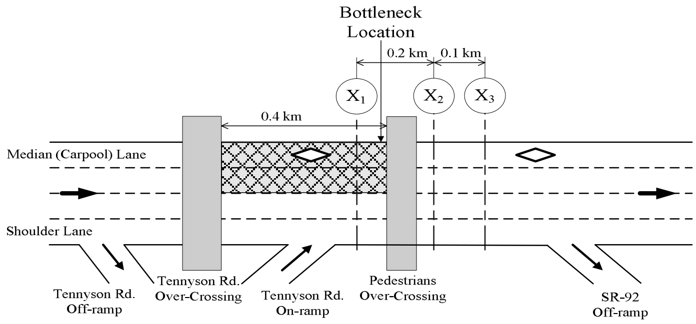

Fig. 4. I-880N freeway geometry

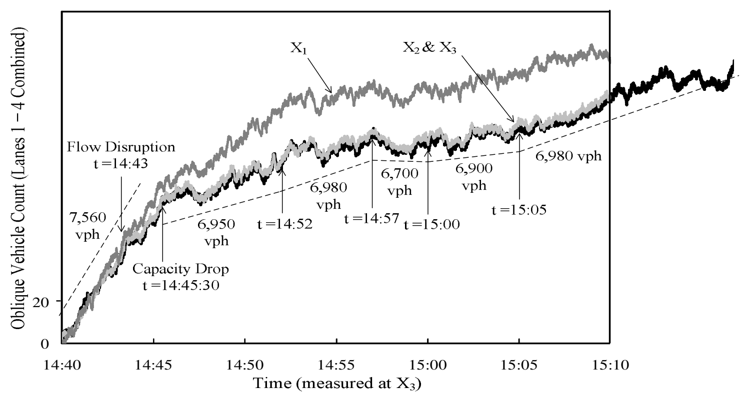

Fig. 5. O-curves at X_1 through X_3 (July 19, 2006)

To illustrate, Fig. 6 presents two O-curves of the bottleneck discharge flows at location X_2: one for the shoulder lane (in boldface) and another for the three remaining lanes combined. Note how the flow in the shoulder lane suddenly diminished from 2060 vph to 1,790 vph at 14:43 hrs (the time when queuing began in Fig. 5) without any effect on the remaining lanes. The videos clearly reveal that disruptions began in the shoulder lane at 14:43 because vehicles decelerated to make room for merging traffic from the on-ramp; this is the cause of the first reduction in flow.

Fig. 6 also shows that the capacity drop that occurred around 14:45:30 coincided with a flow reduction in the adjacent lanes, signifying that the queue had by then spread across the entire width of the freeway. This traffic pattern is typical of merge bottlenecks *without* carpool lanes (Cassidy and Rudjanakanoknad 2005) In short, the carpool lane did not trigger the bottleneck. As we show below, moreover, the lane did not impede bottleneck flow and prolong congestion, despite being underutilized.

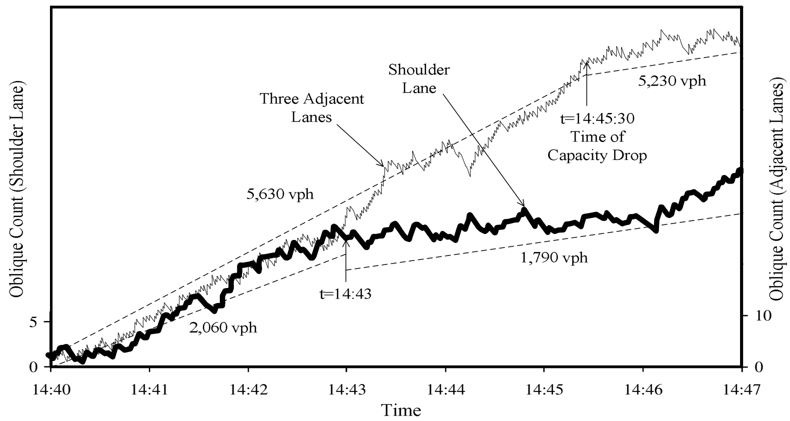

Fig. 6. O-curves of shoulder lane and adjacent lanes at X_2 (July 19, 2006)

3.2 Subsequent Effect of the Carpool Lane

The video data reveal that drivers (of LOVs) began avoiding the median lane shortly before the carpool restriction went into effect; and that these driver responses began after the capacity drop had already occurred. This is evident in Fig. 7, which displays the cumulative number of vehicular lane changes, both in and out of the median (carpool) lane, as counted from the videos over the 0.4-km-long shaded segment in Fig. 4. Note from the boldface curve how maneuvers out of the median lane were steady while the capacity was dropping during the period from 14:43 to 14:45:30 hrs; and then how these maneuvers increased from 14:52 to

15:00 hrs. This later period likely marks when LOVs began migrating from the lane due to the impending carpool restriction – particularly since the curve also shows that the rate of this lane changing returned to the earlier low value (210/hr/km) once the carpool restriction went into effect at 15:00. Note too that maneuvers into the carpool lane (shown by the thin curve in Fig. 7) were also steady while the capacity was dropping; and that these maneuvers diminished over time: the rate eventually declined from 380/hr/km, to 60/hr/km soon after the carpool restriction took effect.

Fig. 8 shows how these lane changes affected carpool-lane utilization. It displays the lane's O-curve measured at X_3. Note that flow in the lane was 1920 vph immediately following the capacity drop, and that flows steadily diminished thereafter. Note too how the times marking the onsets of reduced flows (from 14:52 to 15:05 hrs) coincide with the lane-changing patterns of Fig. 7. So, what effect did the lane changing and flow reductions in the carpool lane have on the bottleneck?

A visual comparison of Figs. 8 and 5 from 14:52 hrs onward reveals that the reductions in carpool-lane use, though substantial, had almost no effect on bottleneck discharge rate. The carpool-lane flow (Fig. 8) eventually dropped to 1370 vph, and yet the total flow across all lanes (including the carpool lane) shown in Fig. 5 remained quite steady (at rates approaching 7000 vph). The bottleneck's total discharge flow returned to its highest rate (6980 vph) after 15:05, when carpool-lane flow was lowest (1370 vph). This indicates that the diminished carpool-lane flow was compensated by increased queue discharge flow (capacity) in the adjacent GP lanes. Note too from Fig. 7 that during this period (from 15:05 onward), lane changing to and from the carpool lane was lowest (270/hr/km), indicating that lane changing played a role in producing the higher GP-lane flows.

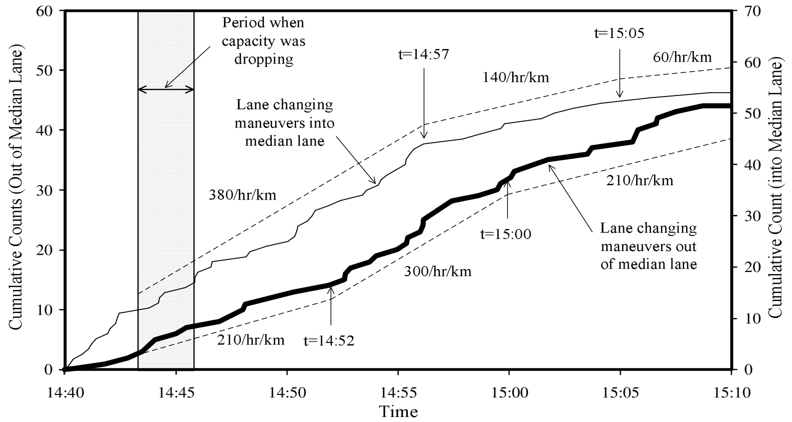

Fig. 7. Cumulative curves of lane changing into and out of median (carpool) lane (July 19, 2006)

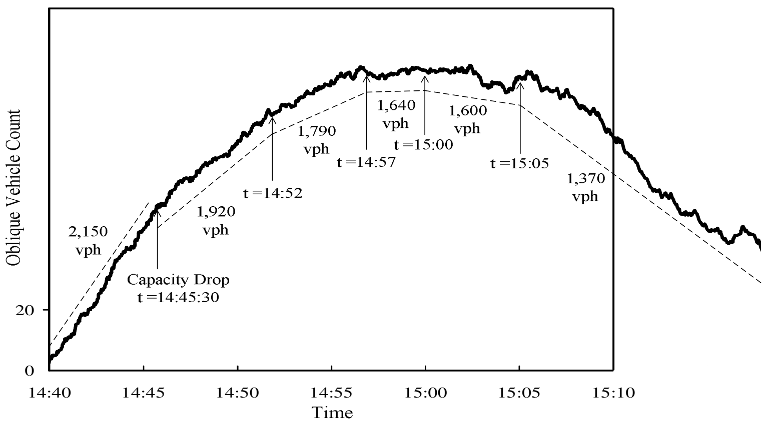

Fig. 8. O-curve of median (carpool) lane at X_3 (July 19, 2006)

This effect was predicted in Menendez and Daganzo (2007), where it was shown through simulation experiments that a carpool lane's presence can diminish disruptive vehicle lane changes, and that this in turn can smooth (and increase) bottleneck flows. This prediction, moreover, was consistent with an earlier analysis, which had shown that disruptive lane changes were a main cause for the capacity drop at bottlenecks without carpool lanes (Laval and Daganzo 2006). The present findings confirm that the so-called smoothing effect arises in real traffic; that it is linked to lane changing;[5] and moreover, that it can persist for extended durations. To underscore the latter point, some of the curves in Figs. 5 and 8 are shown for an extended period beyond 15:10.

Furthermore, the effect is reproducible. Loop detector data from the entire network of freeway carpool facilities in the San Francisco Bay Area were examined for several months. The smoothing effect arose on other days, both for the site in Fig. 4 and for another site, without exception, whenever conditions were suitable for observing the effect. And the effect was always significant: smoothing was found to increase the discharge flows in lanes adjacent to the carpool lanes by as much as 20%. (The reader can refer to Cassidy et al. 2008, for further details on the effect's reproducibility and significance.) Thus we find that carpool lanes always increase the discharge rate (i.e. capacity) of a bottleneck's GP lanes.

Given that smoothing is due, at least in part, to reductions in disruptive lane changing, its benefits should be even more pronounced when segregating more distinct vehicle classes, such as buses and cars. (Laval and Daganzo 2006, shows that lane-changing involving vehicles with low acceleration capabilities, such as buses, create large capacity drops.) This matter is pursued next.

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[5] Further details on this mechanism of smoothing, including a lane-by-lane analysis, are furnished in Cassidy et al. (2008).

4. Theoretical Application: The Effect of Bus Lanes

This section shows how the deployment of bus-only lanes can in some cases improve the flow of cars. Because we do not yet know how to predict the magnitude of the smoothing effect for roadways with cars and buses (this is a topic of ongoing research), we will predict its system-wide impacts parametrically. We will do this for rotationally symmetric closed-loop beltways with access and egress via on- and off-ramps because as explained in Daganzo and Cassidy (2008), this is the least favorable environment for a special-use lane.

To begin, define q_{max} (cars/hr) as the capacity of a single lane devoted to cars, and q^B_{max} (buses/hr) as the capacity of a lane devoted to buses. We call the ratio $p = q_{max}/q^B_{max}$ the passenger car equivalent (pce) of a bus because if we count each bus as p cars, then the capacity of a bus lane (in pce's/hr) is the same as that of a car lane. We expect $p \cong 2$.[6] We also denote by $q^M_{max} = (1 - r)\cdot q_{max}$ the capacity of a mixed traffic lane in pce's/hr, where r is a dimensionless parameter. We expect $r > 0$ because of the smoothing effect.[7]

Section 4.1 uses these definitions to examine the capacity of beltways where buses are segregated and where they are mixed. Section 4.2 then compares the flow of cars in the two scenarios when queues are allowed to exist on the beltway.

4.1 Beltway Capacities with and without Bus Lanes

Consider an L-lane, uncongested and rotationally symmetric beltway with on-ramp/off-ramp pairs and with a fixed fraction β of the flow (downstream of each on-ramp) exiting via each off-ramp. We assume that the transit agency supplies enough buses and drivers to sustain the same fixed service frequency, q_B, whether or not any of the beltway's L lanes are reserved for buses. In this way, bus passengers experience the same out-of-vehicle delay in the mixed and segregated scenarios, and we can focus on bus passenger in-vehicle travel time: the People Hours Traveled, or PHT. We also assume that buses tend to remain on the beltway during our analysis period, and therefore do not create significant cross-modal conflicts by entering or exiting.

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[6] Unfortunately, the literature does not furnish information to help us choose suitable values for p. Handbooks like the Highway Capacity Manual (2000), for example, furnish pce's for buses operating in mixed traffic (only), which is not what we seek here.

[7] This parameter should depend on the mix of buses vs. cars, and be largest when the traffic stream includes significant numbers of both. The use of this parameter simplifies the analysis and distinguishes the present work from other multi-class traffic models. The latter include gas-kinetic theories (Hogendoorn and Bovy 2000), and first-order continuum theories (Chanut and Buisson 2003; Logghe and Immers 2008; van Lint et al. 2008).

We now compare the beltway's maximum possible steady-state car outflows that can exit via all the off-ramps (the beltway capacity) under the two scenarios. Since these total outflows are a fixed fraction of the beltway's circulating car flows (measured downstream of each on-ramp merge), we focus for the moment on the latter.

Consider first the segregated scenario. We look for $l < L$, the number of lanes to be set aside for buses. This number should satisfy the capacity constraint $lq_{max} \geq pq_B$, to prevent buses from being delayed. If $lq_{max} \geq pq_B$, buses will not overflow to the car lanes. Therefore, the maximum car flow downstream of each beltway merge is $q_{max} \cdot (L - l)$. To maximize this flow, choose the smallest integer l that satisfies: $lq_{max} \geq pq_B$. The result, l^*, should leave a gap in the inequality smaller than the capacity of one lane, such that $l^* q_{max} - pq_B = uq_{max}$, where $u \in [0, 1)$ is the under-utilization level of one of the bus lanes. Since all other lanes, including those devoted to cars, can operate at capacity, the beltway's maximum pce flow would be $q_{max} \cdot (L - u)$ in the segregated scenario.

If vehicle classes are mixed on the other hand, the beltway's maximum pce flow would be $(1 - r) \cdot q_{max} \cdot L$. Thus by setting aside bus lanes to segregate vehicle classes, the extra pce flow circulating on the beltway can be as large as $q_{max} \cdot (Lr - u)$. This extra flow is composed of cars only, since bus flow, q_B, is fixed. Therefore it can produce up to $\beta q_{max} \cdot (Lr - u)$ extra units of car outflow per off-ramp, improving the beltway's ability to serve cars if $Lr > u$. We expect values of r comparable with 0.2 to arise when the traffic stream contains a significant fraction of buses that make many stops. (This is common in cities that rely heavily on buses to meet their transportation needs.) With r this large, we see that separating modes can increase the rate at which a beltway serves cars, even for beltways with just a few lanes. This would reduce the PHT of car users.

Recall that our segregation strategy does not affect the PHT of bus users because it keeps invariant both: the bus service frequency, q_B, and the bus speed on the (uncongested) beltway. Therefore, if a beltway can be metered to operate at capacity, segregating street space when modes are very different can improve mobility for everyone, even in the worst-case situation of a symmetric beltway.

Cities are often congested, however. In these cases, taking buses out of queued traffic and placing them in their own lanes would enable the buses to travel faster, so that fewer buses would be needed to maintain some target q_B. This would leave more road space for cars. The following section shows when and how deploying bus lanes in queued traffic can increase the mobility of car users.

4.2 Bus Lanes on Beltways with Queues

Suppose that a beltway cannot be metered very restrictively, so that queues form on it. We show here that even in this case, segregation can increase the beltway's flow (and therefore its input and output flows). This is a good thing because delays and queues of cars would then diminish outside the beltway (e.g. on its on-ramps and connecting streets), without increasing on the beltway itself; while bus users would also benefit by enjoying higher travel speeds.

We now evaluate the circulating car flow in both scenarios, holding the bus flow and the car density constant across scenarios.[8] It is assumed in this section that traffic in a congested lane is described by a fundamental diagram (FD) relating flow to density (both in pce's); that this congested branch, $q = Q(k)$, is the same for buses or cars when traffic is segregated; and that the branch is $(1–r)\cdot Q(k)$ when traffic is mixed.

Consider first the mixed scenario. Take q_B and q^M as given, where q^M is the beltway's total flow of cars and buses (expressed in pce's). Since bus flow, q_B, is invariant to the scenario, the queued car flow *per lane* in the mixed scenario is $q_C^M = (q^M – pq_B)/L$.

We now derive a similar expression for the car flow per lane in the segregated scenario, q_C^S, when the facility is congested. To do this, we first express a lane's car density in the mixed scenario, k_C^M, in terms of q_B and q^M, since this density is to be held constant across scenarios. We know that the combined density of buses and cars (in pce's) per lane in the mixed scenario is: $k^M = Q^{-1}(q^M/L\cdot(1–r))$; and since queued traffic in the mixed scenario is first-in, first-out, we have: $k_C^M = L\cdot k^M\cdot q_C^M / q^M = ((q^M – pq_B)/q^M)\cdot Q^{-1}(q^M/L\cdot(1–r))$.

When the beltway is converted to the segregated scenario, we would again deploy a sufficient number of bus-only lanes to prevent bus queues from forming: $l^* = [q_B \cdot p / q_{max}]^+$, where $[\ ]^+$ is the ceiling operator. If we define k_C^S as the car density in each of the beltway's $L – l^*$ lanes allocated to cars, we have $k_C^S = k_C^M \cdot L /(L–l^*)$, since car density must be invariant to the scenario. Note that the formula is a function of q_B and q^M. Thus, the total flow of cars in the segregated scenario, $q_C^S\cdot(L – l^*)$, is: $Q(k_C^S)\cdot(L – l^*)$, which is also a function of q_B and q^M. To see how and when bus-only lanes favorably affect cars, we now compare the above flow with its counterpart in the mixed scenario, q_C^M, for different values of q_B and q^M.

Figs. 9a and 9b display $\Delta =(q_C^S – q_C^M)/q_C^M$, the percent increase in beltway car flow when operation is converted to a segregated scenario, vs $\rho = q^M / (L\cdot q_{max}\cdot(1–r))$, the percent of capacity utilized by queued cars and buses in the mixed scenario. The curves are given for various bus flows, expressed as percentages of beltway capacity in mixed traffic, $s = q_B /(L\cdot q_{max}\cdot(1–r))$, for $p = 2.5$, $L = 3$, $r = 0.1$, 0.2.[9] These figures show that if bus flow is sufficiently high, a bus-only lane increases car flows; particularly of course when the smoothing effect is large, as in Fig. 9b. Note too that when there are benefits, they grow as ρ moves further from

8 Daganzo and Cassidy (2008) recommends holding car density constant to ensure that congestion outside the beltway is held constant as well. Metering could be used to this end.

9 In Fig. 9a, s = 12% corresponds to a bus flow of about 650 buses/hr, which approaches the peak-hour directional rate reported for New York's Lincoln Tunnel (Levinson et al. 2003); s = 8% corresponds to a bus flow slightly in excess of 400/hr, which reportedly occurs, for example, in Seoul, Korea (Kim 2003); and s ≤ 5% correspond to more modest bus flows reported in many cities of the world (Levinson and St. Jacques 1998).

100%, indicating that reserving lanes for buses can be especially beneficial *to cars* when traffic is very congested. The qualitative reason for these gains is that to maintain bus flow when buses have been released from the grip of congestion, one needs fewer buses, and since fewer buses require fewer dedicated lanes, segregation leaves proportionally more room for cars.

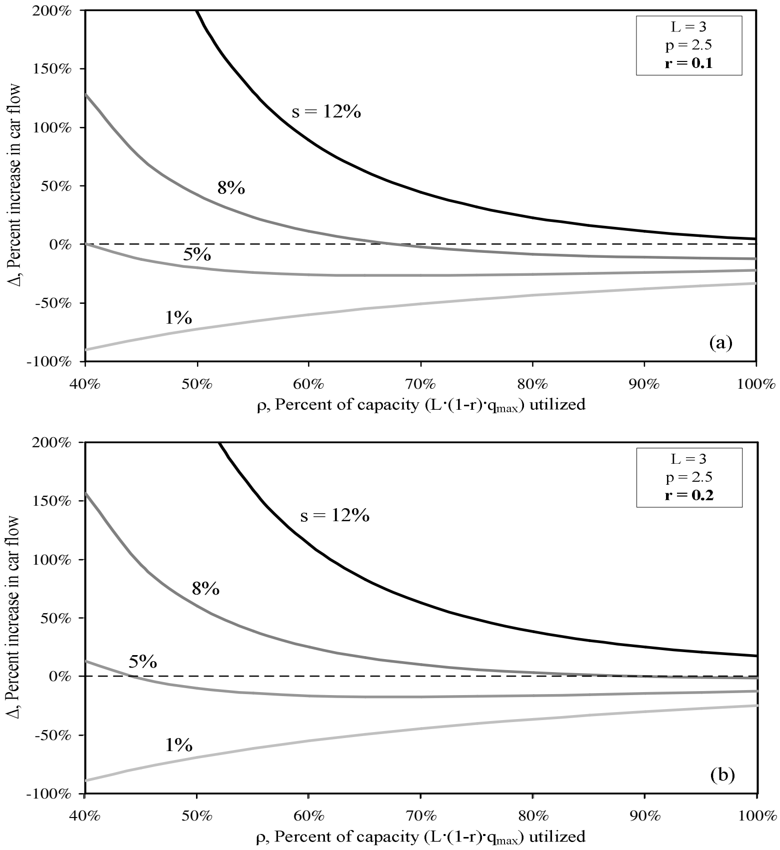

Fig. 9. Curves of ρ vs Δ for a congested freeway. The selected Q has a free flow vehicle speed = 95 km/hr, q_{max} = 2000 cars/hr, and a congested wave speed = 25 km/hr: a) $r = 0.1$ and b) $r = 0.2$

Segregation can also be used on dense networks of city streets with numerous parallel lanes by consolidating all the bus routes onto bus-only lanes. To illustrate the effect of this approach when one or more of L lanes are reserved for buses, Figs. 10a and 10b show curves of Δ vs ρ for $L = 5$ and with a FD suitable for city streets. (In this city-street context, car density could be held invariant to scenario via perimeter control strategies, such as signal metering or pricing, as proposed in Daganzo 2007) The figures show that bus-only lanes can produce significantly higher car flows even for $s = 5\%$.

Note how the curves for s = 12% cross other curves. This happens because for s = 12%, two lanes are set aside for buses to prevent bus queues from forming. Figs. 10a and 10b show that taking this much space away from cars is beneficial to them only when congestion reaches certain levels (i.e. when ρ < 80% and 95% for r = 0.1 and 0.2, respectively). Once again, the gains in queued car flow increase as ρ diminishes: the more congested the street network, the greater the attractiveness of bus-only lanes.

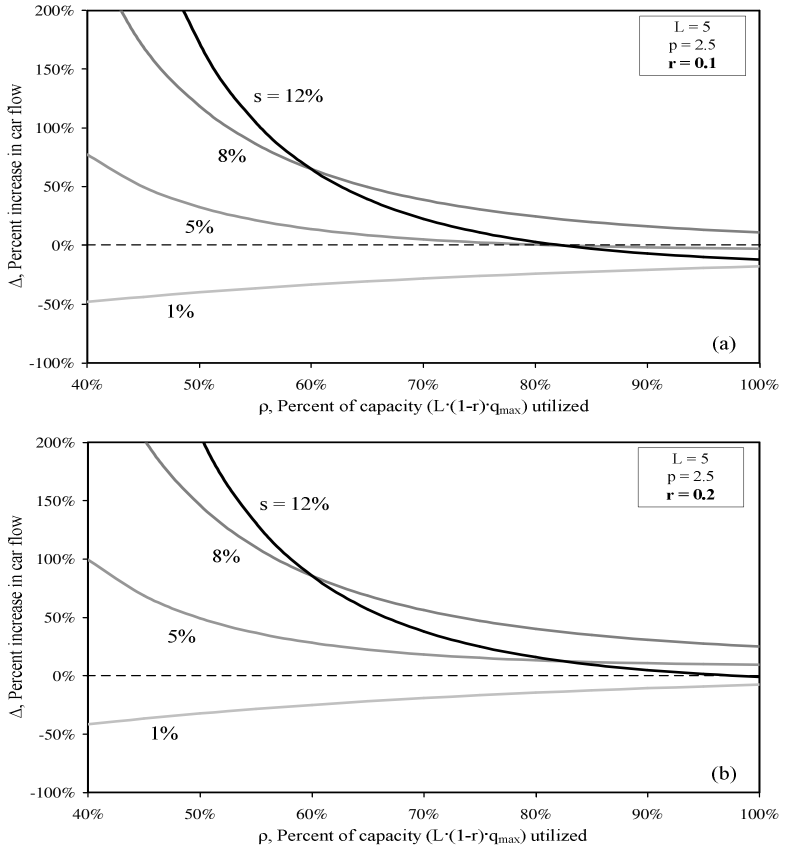

Fig. 10. Curves of ρ vs Δ for a congested city street network. The selected Q has a free flow vehicle speed = 55 km/hr, q_{max} = 1800 cars/hr, and a congested wave speed = 25 km/hr: a) r = 0.1 and b) r = 0.2

Of course, the bus-side of the system benefits even more from segregation. Not only does the bus agency benefit by maintaining the stipulated q_B with fewer vehicles and drivers, but by bypassing the car queue, the bus passengers enjoy a reduction in PHT. What we have shown is that these bus benefits can sometimes be achieved while benefiting car users as well.

5. Summary and Conclusions

There are many possible causes of roadway traffic congestion, including accidents, roadwork activity, high merge demands and special-use lanes; and one needs to rule-out all other possibilities before attributing congestion to any one cause. This paper has shown that analysis of time series data alone, without also considering a system's spatial component, will not provide a complete picture of how special-use lanes affect traffic, and can produce misleading results. Contrary to an earlier study, we found that carpool lanes are not creating congestion on five freeway sites in the San Francisco Bay Area. These lanes may instead be reducing congestion. Spatiotemporal analysis of real data showed that underutilized carpool lanes that run thorough bottlenecks can increase the bottleneck discharge flows by smoothing them, as predicted in Menendez and Daganzo (2007). A carpool lane with this desirable property could not only reduce total PHT, but also the PHT among LOVs, and could therefore become a win-win proposition for society.

Since the smoothing effect is at least partly due to vehicular lane changing, it should be stronger when special-use lanes are deployed to segregate vehicle classes with markedly different performance characteristics. Findings from our parametric analyses in Section 4 are cause for optimism: they reveal that bus-only lanes can in some cases not only benefit bus operation, but can also improve car travel. Field experiments to confirm this phenomenon are being planned.

References

Cassidy, M.J. and Windover, J.R. (1995). Methodology for assessing dynamics of freeway traffic flow. *Transportation Research Record,* 1484, 73-79.

Cassidy, M.J. and Rudjanakanoknad, J. (2005). Increasing the capacity of a merge by metering its on-ramp. *Transportation Research Part B,* 39, 896-913.

Cassidy, M.J., Daganzo, C.F., Jang, K. and Chung, K. (2006). Empirical reassessment of traffic operations: Freeway bottlenecks and the case for HOV lanes. *UCB-ITS-RR2006-6,* Institute of Transportation Studies, University of California.

Cassidy, M.J., Jang, K. and Daganzo, C.F. (2008). The smoothing effect of carpool lanes on freeway bottlenecks. *87th Transportation Research Board Annual Meeting CD-Rom*, Washington D.C.

Chanut, S. and Buisson, C. (2003). Macroscopic model and its numerical solution for two-flow mixed traffic with different speeds and lengths, *Transportation Research Record,* 1852, 209-219.

Chen, C., Varaiya, P. and Kwon, J. (2005). An empirical assessment of traffic operations. *Proceedings of 16th International Symposium on Transportation and Traffic Theory*.

Daganzo, C.F. (2007) Urban gridlock: macroscopic modeling and mitigation approaches. *Transportation Research Part B,* 41, 49-62.

Daganzo, C.F. and Cassidy, M.J. (2008). Effects of high occupancy vehicle lanes on freeway congestion, *Transportation Research Part B,* 42, 861-872.

Highway Capacity Manual (HCM) (2000). Transportation Research Board, National Research Council, Washington, DC, USA.

Hoogendoorn, S.P. and Bovy, P.H.L. (2000). Continuum modeling of multiclass traffic flow, *Transportation Research Part B,* 34, 123-146.

Kerner, B.S. (2002). Empirical macroscopic features of spatial-temporal traffic patterns at highway bottlenecks, *Physical Review E,* 65, 46138, 1-30

Kerner, B.S. and Klenov, S.L. (2003). Microscopic theory of spatial-temporal congested traffic patterns at highway bottlenecks, *Physical Review E,* 68, 36130, 1-20

Kim, H.J. (2003). Performance of bus lanes in Seoul: some impacts and suggestions, *IATSS Research,* 27, 36-45

Kurata, S. and Nagatani, T. (2003). Spatio-temporal dynamics of jams in two-lane traffic flow with a blockage, *Physica A,* 318, 537-550

Laval, J.A. and Daganzo, C.F., (2006). Lane-changing in traffic streams. *Transportation Research Part B,* 40, 251-264.

Levinson, H.S. and St. Jacques, K.R. (1998). Bus lane capacity revisited, *Transportation Research Record,* 1618, 189-199.

Levinson, H.S., Zimmerman, S., Clinger, J. and Gast, J. (2003). Bus rapid transit: systhesis of case studies, *Transportation Research Record,* 1841, 1-11.

Logghe, S. and Immers, L.H. (2008). Multi-class kinematic wave theory of traffic flow, *Transportation Research Part B,* 42, 523-541.

Menendez, M. and Daganzo, C.F. (2007). Effects of HOV lanes on freeway bottleneck. *Transportation Research Part B,* 41, 809-822.

Muñoz, J.C. and Daganzo, C.F. (2002). Fingerprinting traffic from static freeway sensors. *Cooperative Transportation Dynamics,* 1, 1.1-1.11.

Treiber, M. and Helbing, D. (2002). Reconstructing the spatio-temporal traffic dynamics from detector data, *Cooperative Transportation Dynamics*, 1, 3.1-3.24.

Van Lint, J.W.C., Hoogendoorn, S.P. and Schreuder, M. (2008). Fastlane – A new multi-class first order traffic flow model, *87th Transportation Research Board Annual Meeting CD-Rom*, Washington D.C.