Traffic Interactions in Freeways with Carpool Lanes

By

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Abstract

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The dissertation presents findings in regard to the vehicular interactions that arise when carpools and regular vehicles are segregated in their own lanes. Empirical evidence shows that the presence of a carpool lane can diminish vehicular lane-changing maneuvers near bottlenecks, which in turn can increase bottleneck discharge flows in adjacent lanes. This so-called smoothing effect is so pronounced that in many cases even an underutilized carpool lane can increase total bottleneck discharge flows and therefore benefit all freeway commuters and not only carpoolers. Ironically, the congested regular-use lanes are often damaging to the carpool-lane travelers.

It is found that slow speeds in a carpool lane can be due to both, high demand for that lane and slow speeds in the adjacent regular-use lane. These findings imply that the current US policy to restrict most classes of Low-Emitting Vehicles (LEVs) from slow-moving carpool lanes can be counterproductive. The LEVs excluded from carpool lanes will thereafter contribute to congestion and slowing in the regular lanes, and this, in turn, can also reduce the speeds of those vehicles that continue to use the carpool lanes, despite the reduced use of those lanes.

Implications for all of the above findings are discussed. This includes discussion on constructive ways to amend the new regulation, and promising strategies to increase the vehicle speeds in carpool lanes by improving the travel conditions in regular lanes.
This dissertation is dedicated to my family, for all their love, support and encouragement.
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Chapter 1

Introduction

Carpool lanes are deployed on congested urban freeways for the exclusive use of vehicles that carry more than a predetermined number of occupants. On freeways with these special lanes, carpools and regular vehicles are segregated by reserving a lane for carpools during select hours. These lanes are often not physically separated, and thereby allow carpool vehicles to enter or exit the special lanes anywhere along their lengths. As a result, carpools and regular vehicles continuously interact. The work in this dissertation unveils two important findings regarding the vehicular interactions between carpools and regular vehicles on freeways with so-called non-separated carpool lanes.

First, real data show that reserving a lane for carpools on congested freeways induces a smoothing effect that is characterized by significantly higher bottleneck discharge flows (capacities) in adjacent lanes. The effect arises because disruptive vehicle lane-changing maneuvers diminish in the presence of a carpool lane. The effect is reproducible across days and freeway sites: it was observed, without exception, in all cases tested; and queueing analysis shows that the effect greatly reduces the times spent by people and vehicles in queues. The effect is so significant that even a severely underused carpool lane can sometimes increase a freeway bottleneck’s total discharge flow. Thanks to this smoothing effect, carpool lanes can benefit all freeway travelers including the ones in regular lanes. However, the reverse is not always the case: we find that congested regular-use lanes are often damaging to the carpool-lane travelers.

This second finding from the dissertation verifies that vehicle speeds in a carpool lane are negatively influenced by both, growing use of that lane and diminishing vehicle speeds in the adjacent regular-use lane. These dual influences are confirmed from months of data collected from all freeway carpool facilities in the San Francisco Bay Area. The findings do not bode well for a new US regulation stipulating that most classes of Low-Emitting Vehicles (LEVs) that are currently granted access to carpool lanes are to be expelled from slow-moving carpool lanes. Analysis shows that relegating some or all of these vehicles to regular-use lanes can significantly add to regular-lane congestion; and that this, despite the reduced use of the carpool lanes, can also reduce the speeds of those vehicles that continue to use the carpool lanes. The findings show that this counterproductive outcome can occur even when the newly-excluded vehicles constitute a small percentage of the traffic.
The following chapter summarizes previous related research. Chapter 3 reveals the existence of the smoothing effect and the mechanism causing it; confirms that the effect arises consistently, significantly and reproducibly across days and sites; and uses queueing theory to quantify its impacts at a specific site. Chapter 4 analyzes six-months of loop detector data collected from all freeway carpool facilities throughout the San Francisco Bay Area to verify dual influences on vehicle speeds in carpool lanes; and, in light of these influences, predicts the impacts of the regulation expelling LEVs from the carpool lanes. Concluding remarks are offered in Chapter 5.
Chapter 2

Related Research

Freeway carpool lanes tend to be underused, and as a consequence a number of studies report that these lanes unduly penalize non-carpool travelers by creating or worsening congestion in regular lanes. (e.g. Schofer and Czepiel, 2000; Chen et al., 2005; Kwon and Varaiya, 2008). And since an underutilized carpool lane wastes a freeway’s queue storage space, it extends the queue length in adjacent lanes (Daganzo and Cassidy, 2008).

As shown in this dissertation, however, even underutilized carpool lanes can increase bottleneck total discharge flows and thereby diminish freeway congestion.

This chapter provides a review of previous research showing that (i) vehicular lane-changing maneuvers have significant impacts on freeway bottleneck discharge flows (Section 2.1); and (ii) traffic speeds in neighboring lanes tend to be synchronized (i.e., roughly equal) when the lanes are congested (Section 2.2).

2.1 Effects of Lane Changes on Bottleneck Discharge Flows

Laval and Daganzo (2006) used traffic simulation to show that lane-changing maneuvers performed near bottlenecks can create voids in traffic, and that by propagating forward in traffic, these voids can reduce bottleneck discharge flows. Under dense traffic conditions, lane-changing vehicles can behave as moving-bottlenecks in their target lane during the period when they accelerate to the speed prevailing in that lane. The study suggested that the spatial distribution of lane changes and the difference in vehicle speeds across lanes are important determinants of bottleneck discharge flows.

Cassidy and Rudjanakoonknd (2005) observed substantial discharge flow reductions (so-called capacity drops) from a real-world merge bottleneck. They found that the mechanism of this phenomenon was initiated by the formation of a queue in the freeway shoulder lane near the on-ramp. Once the vehicle accumulation in this queue reached a critical value (reproducible from day to day), vehicle lane-changing rates increased

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1 Laval and Daganzo (2006) used a macroscopic model with microscopic lane-changing (i.e. a hybrid model) for the simulation experiments. Bottleneck discharge flow was defined as the sustained flow a bottleneck could discharge when the bottleneck was not affected by downstream traffic conditions while a queue formed upstream.
markedly as drivers sought to avoid the slow traffic in the queued shoulder lane. This behavior spread the queue laterally across all lanes, and was promptly followed by the reduction in bottleneck discharge flows.

Menendez and Daganzo (2007) developed a microscopic simulation model for car-following with lane-changing, and applied this model to study the impacts that carpool lanes have on traffic flow. The simulations predicted that the presence of a carpool lane can diminish lane changes, and that this, in turn, can smooth (and increase) bottleneck discharge flows. This is consistent with the above-cited work showing that disruptive lane-changing is a main cause for the capacity drop at bottlenecks without carpool lanes (Cassidy and Rudjanakanoknad, 2005; Laval and Daganzo, 2006). These findings are intriguing: if the smoothing effect turns out to be real, it would mean that carpool lanes can sometimes benefit all freeway commuters, and not just carpoolers; and the effect would open a door to new ways of managing freeway congestion.

2.2 Synchronized Traffic Speed

Koshi et al. (1983) examined vehicle speeds measured in individual lanes by a series of loop detectors in the Tokyo Expressway in Japan. The data indicated that oscillations in traffic speed frequently arise upstream of the bottleneck, and that the oscillations in two neighboring lanes become more synchronous as the oscillations propagate upstream. Kerner and Rehborn (1996; 1997) studied traffic data from three-lane German Highways and confirmed that vehicle speeds in different lanes of congested highways can become nearly identical.

Lee et al. (1998) used simulations to unveil the connection between vehicle lane changing and synchronization of vehicle speeds across lanes. That study showed that any increase in lane changing between two adjacent lanes induces synchronicity in traffic speed. Extending that earlier study, Kerner (2001) explained how lane changing can produce this speed synchronization across lanes. When one lane initially moves slower than its adjacent lane, drivers in that lane tend to maneuver into the faster lane as they seek to avoid slow traffic. This maneuvering increases the density in the faster lane and consequently reduce the speed in that lane. But lane changing alone might not explain synchronized traffic speed because synchronized speed is often also observed where there is little lane changing.

Previous empirical evidence has shown that synchronization of vehicle speeds can also be due to cautionary driver behavior. Even if there is little lane changing, drivers tend to travel at slower speeds and with wider spacings in response to queueing in adjacent lanes. The synchronized traffic speed due to this cautionary driver behavior was observed both at freeway diverge bottlenecks (Cassidy et al. 2002; Muñoz and Daganzo, 2002b); and at a freeway merge bottleneck (Cassidy and Rudjanakanoknad, 2005).
The above findings suggest that freeway carpool lanes can also become slow due to queued, slow adjacent regular-lane speeds. Preliminary evidence from recent studies (Chen et al., 2005; Guin et al., 2008; Menedez and Daganzo, 2007) showed that vehicle speeds in carpool lanes diminish soon after vehicle speeds in the adjacent regular-use lanes diminish.

This finding suggests that an attempt to increase the speed in a carpool lane by limiting access to it might be problematic. This is because adding more vehicles to congested regular-use lanes would have negative influences on carpool-lane speed. However, it is also true that carpool-lane speeds are positively influenced by reducing the number of vehicles that use that lane. Hence, in this respect, the carpool lane speed can be increased by reducing its use. These dual influences on carpool lane speed have implications for carpool lane operation because they act in opposite directions. The net impacts of these two countervailing influences have not previously been explored. In view of this, the present dissertation analyzes loop detector data from all freeway carpool facilities in the San Francisco Bay Area to quantify the impacts of these dual influences, and to shed light on the net outcomes due to these opposing influences.
Chapter 3

The Smoothing Effect

This chapter presents the findings from having analyzed data from all sites in the San Francisco Bay Area where relevant experiments could be performed. Detailed video data from a site with good vantage points reveal the existence of the smoothing effect and the mechanism causing it (Section 3.1). Detector data from all sites and numerous days confirm that the effect arises consistently, significantly and reproducibly across days and sites (Section 3.2). Queueing theory is then used to quantify its impacts at a specific site (Section 3.3).

3.1 The Effect and its Causal Mechanism

Traffic data collected from videos at the site in Figure 3.1 unveil: (i) the existence of the smoothing effect at a freeway merge bottleneck (see Section 3.1.1); and (ii) its causal mechanism (Section 3.1.2).

3.1.1 Existence

The freeway study site includes a median lane (lane 1) that is reserved for carpools on weekdays during the morning rush (5:00 to 9:00), and again in the afternoons (15:00 to 19:00); see Figure 3.1. The remaining lanes (labeled 2 through 4) are always available for general use. We examined a day (July 19, 2006) in which a queue formed in the early portion of the afternoon rush due to the site’s bottleneck, and before the carpool restriction went into effect; and we found that when this restriction eventually took effect in lane 1, the queue discharge flow (i.e., the rate that vehicles discharged from the bottleneck) markedly increased in adjacent lanes. The increase in these lanes was so significant, that the bottleneck’s net capacity increased, even though the carpool lane (lane 1) was underutilized.

Vehicle arrival times at locations X1, X2 and X3 were manually extracted from videos taken from the two over-crossings (for pedestrians and for Tennyson Rd.). As is customary, cumulative curves of vehicle count for all lanes combined (including all vehicles from the Tennyson on-ramp) were plotted on an oblique coordinate system (O-curves); see Figure 3.2. The curves were shifted in time so that superimposed curves
indicate free-flow traffic (flow = demand) and separated curves indicate delays; see Cassidy and Windover (1995) and Muñoz and Daganzo (2002a). Note that the slopes of the O-curves are the excess flows over a background flow (6800 vph in the present case) and that the wider the separation between curves the longer the delays.

In Figure 3.2, curves 2 and 3 are superimposed, and below curve 1. Thus, traffic was freely flowing between X₂ and X₃, but delays arose between X₁ and X₂; i.e. a bottleneck formed between the latter two locations. The curves at these two locations diverged for good at about 14:43 hrs when a disruption temporarily reduced the total flow at X₂. Less than 3 minutes later (at approximately 14:45:30) and well before the carpool restriction was activated, flow dropped further to about 6950 vph.² Thus, the carpool lane did not contribute to the bottleneck formation and the eventual flow drop. Instead, the videos show that the queue first formed in the shoulder lane, then spread to all lanes, and that the discharge flow then dropped, as is typical of merge bottlenecks without carpool lanes (see Cassidy and Rudjanakanoknad, 2005). Cassidy, et al (2009) furnish data supporting this statement. The carpool lane did begin to exert influence later in time, however; and the influence was favorable.

Figure 3.3 displays an O-curve for lane 1 (the carpool lane) measured at X₃. As one might expect, flow diminished both before and after 15:00 hrs, as LOVs exited the lane. Surprisingly, a comparison of Figures 2 and 3 from 14:52 to 15:10 reveals that the total flow across all lanes (including the carpool lane) remained quite steady at rates approaching 7000 vph, even as the carpool lane was being vacated.

These patterns indicate that the diminished carpool-lane flow was compensated by increased queue discharge flows (capacity) in adjacent lanes. The effect was sustained from then on, and this is underscored by extending the curves in Figures 3.2 and 3.3 beyond 15:10.

Figure 3.1. Study site: I-880 North, Hayward, California. Shaded segments were subject to video surveillance

² Dashed lines are shown in Figure 3.2 (and in other figures) to highlight average rates over a longer run. These longer-run periods were selected as in Cassidy (1998); i.e., using as few lines as possible while ensuring that no line deviates from the measured curve by a count of more than 15.
3.1.2 Cause

We now show that the increase in queue discharge flows in regular lanes was due to a decline in the lane changing rates directly upstream of the bottleneck (in the 0.4 km shaded segment of Figure 3.1), and that this decline was in turn caused by the carpool restriction. Lane-changing rates were extracted from videos.
To understand the connection between lane changing and queue discharge flow, we examined the lanes, one at a time, starting with lane 2. The boldfaced O-curve in Figure 3.4(a) shows the combined lane-changing maneuvers both in and out of that lane. Note that the lane-changing rate began to diminish minutes before 15:00 hrs, the carpool lane activation time (as highlighted by the downward-bending dashed line in the figure). An abrupt increase in the queue discharge flow from that lane (measured at X2) followed close on the heels of this event, as revealed by the thin O-curve of vehicle count (and highlighted by the upward-bending dashed line). Figure 3.4(b) reveals that a similar pattern was observed a few minutes earlier in lane 3: lane changing diminished and queue discharge flow rose very soon thereafter, beginning sometime around 14:52 hrs. The phenomenon was not observed in lane 4, however: as shown by Figure 3.4(c), the queue discharge flow in that lane remained steady.

Thus, we see that in each of the two lanes closest to the carpool lane, a reduction in lane-changing rate was closely followed by an increase in queue discharge flow. The timing of these events so close to 15:00 hrs strongly suggests that they were caused by the carpool restriction.

Appendix A takes a more detailed look at the data and shows that the observed patterns (including the 8-min discrepancy between the pattern changes in lanes 2 and 3) were indeed caused by the migration of vehicles away from the carpool lane, further solidifying the idea that the carpool restriction is at the root of the reductions in lane changing and improvement in discharge flow. The next section shows that the smoothing effect arises consistently and reproducibly at different sites.

Figure 3.4. Oblique cumulative curves of lane-changing and discharge flow (July 19, 2006); (a) Lane 2, Background rates = 1760 vph (thin curve) and 290/hr (bold curve)
Figure 3.4. (cont’d) Oblique cumulative curves of lane-changing and discharge flow (July 19, 2006); (b) Lane 3, Background rates = 1250 vph (thin curve) and 300/hr (bold curve); (c) Lane 4, Background rates = 1550 vph (thin curve) and 100/hr (bold curve)

3.2 Repeated Observations

We examined the entire network of carpool facilities in California’s San Francisco Bay Area during multi-week study periods, and identified all the sites in which a bottleneck was active for at least 30 mins before and after its carpool restriction switched on or off.
This filtering method is necessary, since we need to compare the bottleneck’s center-lane discharge flows with and without the carpool lane, while holding all else approximately constant. Although we found only two suitable sites (the site in Figure 3.1 and one additional site) multiple instances passed our filter at both of these sites. The smoothing effect arose in every instance. We show this for our first site in Section 3.2.1; and for the second site in Section 3.2.2.

3.2.1 Reproducibility across days: Site 1

This site was examined every weekday in Aug. and Sept. 2007, and eight instances suitable for testing turned up. These eight instances are in addition to the one used in Section 3.1; four came from late portions of the morning rush, and four from early portions of the afternoon rush. No other instances were found in which the bottleneck’s active period overlapped both the carpool lane’s active and inactive periods.

Table 3.1 summarizes the data. Each instance includes two 30-min periods; one with the carpool lane restriction and one without. The table presents the average bottleneck discharge flows of the two center lanes combined (just downstream of X2), for each of the sixteen 30-min periods. (Discharge flows from 5-min transition periods on each side of the carpool lane activation and deactivation instants are excluded.) The table shows that the smoothing effect arose without exception, and did so significantly and consistently. The rise in center-lane discharge flows ranged from 9.5% to 13%, with an average of 10.5%, in the early afternoons; and from 18% to 21%, with an average of 19.5%, in the late mornings. The late morning and early afternoon differences are significant, so something must be causing them. As we shall see momentarily, a similar discrepancy arises at the second site.

3.2.2 An additional site

The second site is shown in Figure 3.5. A bottleneck forms at the entrance to the curved section during the afternoon rush. The site was canvassed for suitable study instances from May through September 2007. Four instances were found: all during the afternoon rush. Two straddled the carpool lane’s activation time (at 15:00 hrs) and two its deactivation time (at 19:00 hrs).

Again, the smoothing effect emerged without exception; see Table 3.2 which presents the queue discharge flows of the two center lanes for each of the four cases. The effect is again significant and consistent: discharge flows increased by 8% and 12% in the beginning of the afternoon rush; and by 18% and 19% at the end of the rush; and the discrepancies between early and late measurements are significant as well.

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3 The bottleneck’s location, as well as its activation and deactivation times, were determined by jointly plotting oblique curves of vehicle count, together with oblique curves of detector occupancy, at each detector station shown in Figure 3.1, as described in Cassidy and Bertini (1999).
Table 3.1. Queue discharge flows from lanes 2 and 3 combined at I-880 North study site

<table>
<thead>
<tr>
<th>Observation Date</th>
<th>Flows with carpool lane (vph)</th>
<th>Flows without carpool lane (vph)</th>
<th>Increase due to smoothing (vph)</th>
<th>% increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Afternoons</td>
<td>15:05 ~ 15:35</td>
<td>14:25 ~ 14:55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007-08-02</td>
<td>3670</td>
<td>3350</td>
<td>320</td>
<td>9.5</td>
</tr>
<tr>
<td>2007-08-03</td>
<td>3690</td>
<td>3370</td>
<td>320</td>
<td>9.5</td>
</tr>
<tr>
<td>2007-08-23</td>
<td>3740</td>
<td>3400</td>
<td>340</td>
<td>10</td>
</tr>
<tr>
<td>2007-09-11</td>
<td>3650</td>
<td>3240</td>
<td>410</td>
<td>13</td>
</tr>
<tr>
<td>Late Mornings</td>
<td>8:25 ~ 8:55</td>
<td>9:05 ~ 9:35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007-08-21</td>
<td>3290</td>
<td>2750</td>
<td>540</td>
<td>20</td>
</tr>
<tr>
<td>2007-08-22</td>
<td>3530</td>
<td>2990</td>
<td>540</td>
<td>18</td>
</tr>
<tr>
<td>2007-08-23</td>
<td>3370</td>
<td>2830</td>
<td>540</td>
<td>19</td>
</tr>
<tr>
<td>2007-09-04</td>
<td>3430</td>
<td>2840</td>
<td>590</td>
<td>21</td>
</tr>
</tbody>
</table>

Note from Tables 3.1 and 3.2 that at both sites all the flows without the carpool lane are significantly higher (and that the smoothing effect is less significant) at the start of the afternoon rush than at the end of either the morning or afternoon rushes. The pattern suggests that early-afternoon drivers are more aggressive than drivers in the late stages of a rush, and are therefore less affected by lane changes, perhaps because they are trying to “beat the rush” for the remainder of their trips. If this is generally true, then the queue discharge flows during the beginning of any rush would increase less than in the late stages. This conjecture should be tested if more data become available.

Figure 3.5. Second study site: I-80 East, Richmond, California
Table 3.2. Queue discharge flows from lanes 2 and 3 combined at I-80 East study site

<table>
<thead>
<tr>
<th>Observation Date</th>
<th>Flows with carpool lane (vph)</th>
<th>Flows without carpool lane (vph)</th>
<th>Increase due to smoothing (vph)</th>
<th>% increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Afternoons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15:05 ~ 15:35</td>
<td>3880</td>
<td>3590</td>
<td>290</td>
<td>8</td>
</tr>
<tr>
<td>2007-05-30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007-07-23</td>
<td>3870</td>
<td>3450</td>
<td>420</td>
<td>12</td>
</tr>
<tr>
<td>Late Mornings</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8:25 ~ 8:55</td>
<td>3660</td>
<td>3100</td>
<td>560</td>
<td>18</td>
</tr>
<tr>
<td>2007-07-10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007-09-11</td>
<td>3350</td>
<td>2820</td>
<td>530</td>
<td>19</td>
</tr>
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3.3 The Real Impacts of Carpool Lanes on People and Vehicle Delay

This section explores the impacts of carpool lanes in light of smoothing. We compare the PHT and VHT for an afternoon at the site in Figure 3.1 under three scenarios: (i) no carpool restriction; (ii) a carpool lane with realistic consideration of smoothing; and (iii) the hypothetical (and unrealistic) case of a carpool lane that does not induce smoothing. Predictions were made with the queueing/kinematic wave model in Newell (1993). Details are provided in Appendix B. Inputs to the analysis were estimated from the site’s data: discharge flows were set equal to the average rates over multiple afternoons; and input flows were set equal to those measured at the upstream detector station during an afternoon when the queue did not grow beyond these detectors. This allowed us to measure upstream demand precisely, but corresponds to a day with lower than usual congestion. Thus, our results underestimate the differences that arise between our three scenarios on more typical days. Results are shown in Table 3.3.

Note from columns 2 through 4 which compare system performance with and without the carpool lane, that the carpool lane reduces PHT by 30% compared to the case of no carpool lane. This is reassuring, since PHT-reduction is a commonly-cited reason for deploying carpool lanes in the first place (Turnbull and Capelle, 1998; Bracewell, et al. 1999; Henderson, 2003). But more remarkably, and thanks to the smoothing effect, the carpool lane reduces VHT by 15%.

Let us now see what a conventional analysis (wrongly ignoring the smoothing effect) as in Dahlgren (1998, 2002) and Kirshner (2001) would have predicted. The result is shown in column 5. By ignoring the smoothing effect, one would incorrectly attribute
very large delays to the carpool lane. One would be predicting increases well in excess of 300% both for PHT and VHT when instead the carpool lane would reduce both. This example clearly shows that one cannot assess the real impacts of a carpool lane without accounting for smoothing. A question of interest then is: what fraction of traffic must be carpools to justify a carpool lane?

Queueing analysis also shows that the carpool lane is beneficial even when demands for that lane are quite low. The curves in Figures 3.6(a) and (b) show the PHT and VHT obtained at a 4-lane site like ours, with and without a carpool lane, as a function of the percentage of freeway demand that is comprised of carpools, $\alpha$. Note from Figure 3.6(a) that the carpool lane reduces PHT when $\alpha$ is as low as 17%; and from Figure 3.6(b) that only a slightly higher $\alpha$ (17.3%) is required to reduce the VHT. In the present case, $\alpha \approx 17\%$ corresponds to carpool-flows that are less than 1200 vph. So we see that, with smoothing, even a very underused carpool lane can reduce this freeway’s PHT and VHT, with its attendant externalities, and therefore be a win-win proposition for society.

Table 3.3. Predicted PHT’s and VHT’s

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<thead>
<tr>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
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</thead>
<tbody>
<tr>
<td>PHT (person-hrs)</td>
<td>2450</td>
<td>1900</td>
<td>– 30</td>
<td>10340</td>
<td>+ 322</td>
</tr>
<tr>
<td>VHT (vehicle-hrs)</td>
<td>1950</td>
<td>1700</td>
<td>– 15</td>
<td>9080</td>
<td>+ 365</td>
</tr>
</tbody>
</table>

Figure 3.6. Predictions with and without carpool lane as functions of $\alpha$, (a) PHT’s; (b) VHT’s
Chapter 4

Dual Influences on Vehicle Speeds in Carpool Lane

This chapter verifies that slow speeds in a carpool lane can be due to both high demand for that lane and slow speeds in the adjacent regular-use lane. The analyses performed in light of these dual influences show that a new US regulation attempting to increase speeds in a carpool lane by reducing its use can be counterproductive.

US policy had previously stipulated that access to carpool lanes should also go to a variety of vehicle classes that satisfy low emission standards, even when these so-called Low-Emitting Vehicles (LEV) carry small numbers of people. However, recent federal regulation has partially reversed this policy: many LEV classes are now to be expelled from a carpool lane when any portion of that lane (of unspecified physical length) exhibits vehicle speeds below 45 mph (72.4 km/hr) for more than 10% of its operating period. The regulation is aimed at increasing the carpool-lane speeds in so-called “degraded” facilities of this kind, and the reader can refer to SAFETEA-LU section 1121 (2005) for details on it. The regulation took effect in August 2005. States throughout the US are currently evaluating their freeway carpool facilities to determine which are degraded as per the regulation’s criteria. We will demonstrate in the ways described below why the regulation can be counterproductive.

Six-months of data were collected from all loop detectors in the network of freeway carpool facilities throughout the San Francisco Bay Area. On each of these facilities, the median lane is reserved for carpools (and formerly for various LEV classes as well) during weekday rush periods, and these carpool lanes are not physically separated from the regular ones. The data confirm that the dual influences on speed cited above are invariably felt by the carpool lanes (see section 4.1). Based upon the observed magnitudes of these two influences, the Bay Area site that would seem to be most favorably affected by the SAFETEA-LU regulation was analyzed using kinematic wave theory. Even for this site, we predict that all of its rush-period traffic, in or out of the carpool lane, will be damaged by the regulation; and real data support this prediction (section 4.2). Further analysis of a hypothetical, but more generic freeway system indicates that this wholesale damage can be expected in many instances (section 4.3).

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4 Naturally, LEVs in these classes would still be allowed carpool-lane access when these vehicles carry the prescribed number of occupants.
Promising strategies to increase the vehicles speeds in carpool lanes by improving the travel conditions in regular lanes are discussed (section 4.4), as are constructive ways to amend the new regulations (section 4.5).

4.1 Observed Influences

We first examine data from the site shown in Figure 4.1. According to the criteria of the SAFETEA-LU regulation, the site is the most “degraded” facility in the San Francisco Bay Area: carpool-lane speeds fall below 45 mph for more than 40% of the lane’s operating times, and do so for extended distances. The data for the illustration to follow were measured by the two inductive loop detectors circled in the figure. Note that these reside in the site’s median lane, which operates as the carpool lane during rush periods, and in the adjacent regular-use one. The data were collected during the carpool lane’s morning and evening operating times over a 6-month period extending from May through October 2009.

Figure 4.1. Example site: I-80 West, Berkeley, California

Figure 4.2 presents average vehicle speeds in the carpool lane, $V_c$, for different values of average speed in the adjacent regular-use lane, $V_r$, and detector occupancy (a dimensionless measure of density) in the carpool lane, $\rho_c$. The shading in this figure corresponds to the magnitude of the carpool-lane speed; the darker the shade, the lower the $V_c$. The data were measured over 5-min intervals. To construct the figure, the 5-min measurements of $V_r$ and $\rho_c$ were partitioned into cells at increments of 2 mph and 1%, respectively. The average $V_c$ was then computed for each cell.

Visual inspection of Figure 4.2 reveals a negative correlation between the carpool lane’s speed and its occupancy: note how the shades grow darker as the eye moves upward along a vertical line of some fixed regular-lane speed, $V_r$; i.e., $V_c$ diminishes as $\rho_c$ increases. Interestingly, we find from these data that low values of $V_c$ do not necessarily coincide with values of $\rho_c$ that are especially high: less than 2% of the data from this site coincide with $\rho_c$ that were greater than 20%. Scatterplots of $\rho_c$ vs carpool-lane flow indicate that $\rho_c$ below about 20% correspond to uncongested (albeit often slow-moving).
carpool-lane traffic.\textsuperscript{5} This state of affairs reveals that low $V_c$ is not a reliable indicator that the carpool lane is over-used. It turns out that low $V_c$ are largely due instead to low speeds in the adjacent regular-use lane.

To see this latter influence, note first the positive correlation between $V_c$ and $V_r$ visible in Figure 4.2: note how $V_c$ increases (shades grow lighter) when moving the eye rightward along some horizontal line of fixed $\rho_c$. To confirm the direction of causality in this relation, note as an example the time-series curves of $V_c$ and $V_r$ in Figure 4.3. These were measured by our two detectors during a 15-min period spanning the onset of a morning rush (on May 21, 2009). Notice both, the precipitous decline in $V_r$ that began at around 6:10:30 hr, and the comparable reduction in $V_c$ that began 1.5-min later at 6:12 hr.

![Figure 4.2. Average carpool-lane speeds at example site](image)

Constructing similar time-series curves at the site for all other days in our 6-month period, and then repeating this exercise for all other Bay Area sites, showed that: reductions in $V_r$ always preceded reductions in $V_c$. There were no exceptions. This temporal sequence of events establishes that reductions in regular-lane speeds, $V_r$, trigger reductions in carpool-lane speeds, $V_c$. To argue the reverse (i.e., that precipitous reductions in $V_c$ trigger similar reductions in $V_r$) would be to claim that an effect can precede its cause.

\textsuperscript{5} These scatterplots revealed the well-known concave relations between occupancy and flow (e.g., Edie and Foote, 1958; Greenberg, 1959; Greenshields, 1934; Lighthill and Whitham, 1955), in this case between $\rho_c$ and $V_c$. These relations began bending downward at occupancies, $\rho_c$, above about 20%. This indicates that $\rho_c \approx 20\%$ is the approximate boundary between congested and uncongested carpool-lane traffic.
This influence of $V_r$ on $V_c$ points to the inherent risks of the SAFETEA-LU regulation. The regulation may reduce vehicle density in the carpool lane, but the migration of LEVs can add to congestion in the regular lanes and this, in turn, can further reduce speeds in the carpool lanes. These unintended consequences are explored next.

![Figure 4.3. Time-series speeds in carpool lane and adjacent lane](image)

### 4.2 Case Study 1: Real Site

The 4-mile freeway stretch in Figure 4.4 will serve as our first case study. Earlier studies have found that, during each rush, a bottleneck arises at the downstream end of this site, as annotated in the figure (Cassidy et al., 2010). According to the SAFETEA-LU criteria, the site is degraded: speeds in the carpool lane fall below 45-mph for more than 35% of its operating times. This site was selected because, of all carpool facilities in the San Francisco area, it is the one that stands the greatest chance of benefiting from the SAFETEA-LU regulation. The first analysis to follow is based on measurements taken from the detectors circled in the figure. These data were collected over the 6-month observation period from May through October 2009.

![Figure 4.4. Case-study site: I-880 North, Hayward, California](image)
To explore these influences in more quantitative fashion, imagine that Figure 4.5(a) is a surface in which the $V_c$ are displayed on a third axis. Further imagine taking vertical slices through this surface at select $V_r$ (say at 10-mph increments from 20- to 60-mph). The relations between $V_c$ and $\rho_c$ can then be viewed for fixed $V_r$.

Cross-sectional views of this kind are presented in Figure 4.5(b). Each data point in that figure shows the $V_c$ vs $\rho_c$ in a cell. A best-fit line is shown for each data set corresponding to a select $V_r$. Each best-fit line reveals a well-defined relation between $V_c$ and $\rho_c$: note that the $R^2$-values annotated in the figure are all quite high. Note too that distinct best-fit lines were estimated for those data with $\rho_c > 16\%$, since these were found to fall into the congested traffic regime, as per the reasoning described in footnote 2. (Only 5% of the data from this site fell into this congested regime.) Finally, note from Figure 4.5(b) that, for uncongested carpool-lane conditions, the slopes of the best-fit lines range from $-1.33$ to $-2.52$. These were the steepest of any slopes observed across all carpool facilities in the San Francisco area. Stated simply, carpool-lane speeds on our case-study site are more sensitive to $\rho_c$ than are the carpool-lane speeds on any other site in the region. From this relative perspective, expelling LEVs from our site’s carpool lane would favorably impact $V_c$ to the greatest degree.

Analogous cross-sectional views are featured in Figure 4.5(c): it presents relations between $V_r$ and $V_c$ at specified values of $\rho_c$. Best-fit lines again reveal that relations are well-defined. The slopes of these lines, which range from 0.29 to 0.37 (see the figure), are the lowest of those observed across all Bay Area carpool facilities; i.e., the carpool-lane speeds in our case-study site are the least sensitive to speeds in the adjacent regular-use lane. This means that if congestion in regular lanes is worsened due to the migration of LEVs into those lanes, the resulting reductions in $V_c$ would be modest, relatively speaking.

Given that its $V_c$ is relatively sensitive to $\rho_c$ and relatively insensitive to $V_r$, it seems that the SAFETEA-LU regulation stands greater chance of producing favorable outcomes for our case-study site than for any other site in the region. Yet, we find that the regulation is detrimental to all commuters at our site. The evidence follows.
Figure 4.5. (a) Average carpool-lane speeds at case-study site; (b) carpool-lane speed, $V_c$, vs carpool-lane occupancy, $\rho_c$; (c) regular-lane speed, $V_r$, vs carpool-lane speed, $V_c$.

<table>
<thead>
<tr>
<th>$\rho_c$ (%)</th>
<th>$V_c$ (mph)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5%</td>
<td>50</td>
<td>0.99</td>
</tr>
<tr>
<td>7.5%</td>
<td>60</td>
<td>0.98</td>
</tr>
<tr>
<td>11.5%</td>
<td>40</td>
<td>0.97</td>
</tr>
<tr>
<td>15.5%</td>
<td>30</td>
<td>0.96</td>
</tr>
<tr>
<td>19.5%</td>
<td>20</td>
<td>0.95</td>
</tr>
</tbody>
</table>

For $V_r = 60$ mph:

- $\rho_c \leq 16\%$
- $\rho_c > 16\%$

For $V_r = 50$ mph:

- $\rho_c \leq 16\%$
- $\rho_c > 16\%$

For $V_r = 40$ mph:

- $\rho_c \leq 16\%$
- $\rho_c > 16\%$

For $V_r = 30$ mph:

- $\rho_c \leq 16\%$
- $\rho_c > 16\%$

For $V_r = 20$ mph:

- $\rho_c \leq 16\%$
- $\rho_c > 16\%$

Equations:

- $V_c = 0.29V_r + 53.92$ with $R^2 = 0.57$
- $V_c = 0.29V_r + 44.69$ with $R^2 = 0.92$
- $V_c = 0.30V_r + 26.68$ with $R^2 = 0.90$
- $V_c = 0.30V_r + 22.81$ with $R^2 = 0.91$
- $V_c = 0.37V_r + 33.00$ with $R^2 = 0.83$
- $V_c = 0.37V_r + 33.00$ with $R^2 = 0.83$
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- $V_c = 0.37V_r + 33.00$ with $R^2 = 0.83$
4.2.1 Preliminaries

Though LEVs are relatively few in number (they constitute only about 1.2% of our site’s commute-time traffic demand), their migration from the carpool lane can severely damage travel conditions in the regular lanes. To fix ideas, consider the idealized queueing diagram in Figure 4.6. It provides a reasonable description of commute traffic in the regular lanes in that most of their traffic travels through the single bottleneck at the downstream end of the site. Without loss of generality, assume that this bottleneck has a fixed capacity; i.e., the slope of the dashed curve of cumulative vehicle departures from the bottleneck vs time has a constant slope. Further assume that there is a fixed demand that exceeds bottleneck capacity during a portion of the rush, and a lower fixed rate thereafter; note the piecewise linear patterns of the solidly-drawn demand curves. Suppose that the lighter-drawn solid curve is regular-lane demand absent LEV migration, and that its darker counterpart is demand when LEVs are added to the regular lanes.

The differences in demand rates with and without LEVs in the mix may be modest, but the vertical displacements between the solid curves can obviously grow large if the congested period is long. This vertical divergence in demand curves reflects congestion’s added physical expansion due to the LEV migration. This expansion means that the infusion of LEVs into the regular lanes will cause the vehicles in these lanes to travel greater distances in congestion.

Figure 4.6. Hypothetical queueing diagram for regular lanes

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6 The vertical displacements between the demand curves in Figure 4.6 are the added excess numbers of vehicles that are stored upstream of the bottleneck (see Newell, 1982). The excess number of stored vehicles is smaller than the number of vehicles enveloped in congestion (see Lawson et al., 1997), though this detail is an aside to the present discussion.
Congestion subsides at the time when a (solid) demand curve re-converges with the (dashed) departure curve (Newell, 1982). Note from the figure how congestion persists for a greater duration due to LEV migration. This added duration means that more vehicles will encounter slowed, congested states.

For our first case-study site, we predict that LEV migration can add to congestion’s spatial extent by as much as 40%, and to its temporal extent by 15%. The methods used to predict these sizable expansions are described next.

4.2.2 Kinematic Wave Analysis

Predictions for the first case-study site were performed using the Cell Transmission Model (CTM). As described in Daganzo (1995), the CTM approximates kinematic wave analysis by modeling traffic in discrete space and time; i.e., analysis is performed for short, interconnected roadway segments, termed cells, in short time steps. Cell lengths of approximately 150-m and time steps of 5-sec duration were used in the present case.

Modest additions were introduced to the CTM logic so as to model two adjacent traffic streams (carpools and regular traffic) with distinct flows and speeds; see Appendix C of this dissertation for details on these modifications. For simplicity, it was assumed that a carpool-lane user travels from her on-ramp to the carpool lane (and from that lane to her off-ramp) without encountering delays in the regular-use lanes. This simplification could cause us to under-predict slightly the SAFETEA-LU regulation’s negative impacts.

Inputs to the analyses were estimated from data collected at the site from all the afternoon rush periods in August 2009. Averages were used for this purpose. Values of $\rho_c$ and $V_r$ were predicted for each cell and time step, and were used as inputs to Figure 4.5(a) to predict time-varying $V_c$ in each cell. The CTM simulations were performed for 5-hour periods that bracketed the afternoon rush.

4.2.3 Aggregate Predictions

We first present predictions for regular and carpool-lane traffic combined. The boldly-drawn curve in Figure 4.7 displays the total People Hours Traveled, the PHT, predicted for the afternoon rush. These are given as functions of the additional traffic quantities admitted into the carpool lane, over and above what is allowed access under the SAFETEA-LU regulation. These added quantities are expressed as percentages of the site’s total demand.

Note that the predicted PHT is nearly 3800 person-hrs when only vehicles that are approved under the regulation use the carpool lane (i.e. when the added quantity on the x-axis of Figure 4.7 is zero). Further note that PHT drops to 3390 person-hrs when an additional 1.2% of the demand use the carpool lane. Recall that 1.2% is the proportion
of rush-period demand that are LEVs, and that these vehicles were previously allowed carpool-lane access. Thus, we predict that the SAFETEA-LU regulation can increase a rush period’s PHT at the site by more than 400 person-hours, a 12% increase. In similar fashion, the thin curve in Figure 4.7 indicates that the regulation can increase the total rush-period Vehicle Hours Traveled, the VHT, by roughly 11%.

Interestingly, both curves in Figure 4.7 monotonically decrease over the range of added quantities shown. This means that the site’s commute conditions would improve, on the whole, not by tightening the carpool lane’s restrictions, but by easing them somewhat so that more vehicle classes would enjoy access to that lane.

![Figure 4.7 Predicted total PHT and VHT as functions of the added traffic proportions that are given access to the carpool-lane](image)

**Figure 4.7 Predicted total PHT and VHT as functions of the added traffic proportions that are given access to the carpool-lane**

### 4.2.4 Carpool-Lane Predictions

The curves in Figure 4.8 present time series of travel speeds predicted for the carpool lane only. The 4-hr period shown in the figure spans the carpool lane’s active period. Each curve depicts what can occur when a distinct quantity of additional traffic (e.g. LEVs) enjoy carpool-lane access. These added quantities are again expressed as percentages of the site’s total demand.

The speeds in Figure 4.8 are averages for the carpool lane taken over the site’s entire 4-mile length. Note how the average speeds gradually fall and then recover as congestion in the regular lanes gradually grows and then recedes on our 4-mile site. On most days, regular-lane congestion does not engulf this entire length. Rather, the site’s upstream end typically remains uncongested. Thanks to this uncongested portion upstream, the average carpool-lane speeds predicted over the 4-mile length tend to exceed 45 mph. Our predicted carpool-lane speeds at the downstream portion of the site, where congestion persists in the regular lanes, are significantly lower. (Slow downstream speeds are the reason that the facility was designated as a “degraded” one.)
Our predictions indicate that the SAFETEA-LU regulation can be damaging to carpool-lane speeds. To see this, note first the dashed curve that presents the speeds when only vehicles approved under the SAFETEA-LU criteria are admitted into the carpool lane. Further note the solid, bold curve that presents speeds when an additional 1.2% of the demand is admitted to that lane. The solid, bold curve lies mostly above its dashed counterpart and the implication of this is clear: we predict that speeds in the site’s carpool lane would be higher in the absence of the SAFETEA-LU regulation.

The solid, thin curve in Figure 4.8 describes speeds in the carpool lane when a greater portion of demand (3%) enjoys access to that lane. Note how the carpool lane’s speeds are predicted to increase when we admit greater (not lesser) quantities into it. It seems that reducing the spatial and temporal extents of congestion favorably impacts speeds in the carpool lane, even when the utilization of that lane is increased.

![Figure 4.8. Predicted average carpool-lane travel speeds over the entire 4-mile length](image)

**4.2.5 Changes in Travel Behavior?**

Our predictions until now have assumed that the LEVs expelled from the carpool lane will all migrate to the congested regular-use lanes. In reality, some of the newly-expelled commuters may choose not to travel in the site’s regular lanes during the rush. These kinds of behavioral changes are notoriously tricky to predict. Moreover, the changes can bring on costs that are equally tricky to assess. For example, an LEV-driver who diverts from the freeway to surface streets would typically suffer added costs of her own (as compared against the good-old-days prior to the SAFETEA-LU regulation), and could also impart added costs to others by adding to congestion on her new surface-street travel route.

To keep things simple (while still illustrating a key point), let us optimistically assume that fully one-half of newly-expelled LEV-users do not join congested traffic in the site’s regular lanes. In the same spirit of unbridled optimism, we will further suppose that these behavioral changes do not add any costs to the system. (Perhaps the erstwhile
commuters now stay home every day, and are somehow indifferent to their lifestyle change.) Despite these assumptions that are favorable enough to strain credulity, we predict that the SAFETEA-LU regulation would still be damaging to all commuters who remain on the site.

For illustration, the solid, bold curve in Figure 4.9 presents – for a second time – the time series of predicted average travel speeds in the carpool lane, when LEVs totaling 1.2% of the site’s demand are allowed access to that lane. The dashed curve shows the carpool lane’s speeds when: LEVs are expelled from it, and one-half of these expelled vehicles disappear from the scene. The dashed line still mostly falls below its solidly-drawn counterpart. The damage to the carpool lane is lessened (as compared against what we saw in Figure 4.8), but damage persists, nonetheless.

![Figure 4.9. Predicted average carpool-lane travel speeds over the site’s 4-mile length, with optimistic assumptions regarding the changes in travel behavior](image)

4.2.6 Empirical Verification

It so happens that California has opted not to renew the exemption that had formerly granted carpool-lane access to select classes of LEVs. The resulting prohibition, which took effect on July 1, 2011, has affected 85,000 LEVs statewide; See SB 535 (2010) for further details on this California policy. Consequently, the LEVs totaling 1.2% of our site’s traffic demand are now banned from its carpool lane. This new state of affairs affords us opportunity to test our predictions against real data. The data are limited: as of this writing, California’s new policy has been in effect for little more than 2 months. The preliminary assessment to follow is instructive nonetheless.

The curves in Figure 4.10(a) display time-series average speeds in our site’s carpool lane measured over the lane’s entire 4-mile length. The speeds were measured by the loop detectors in that lane (see again Figure 4.4) during the carpool lane’s afternoon operating periods in: June 2011, the month prior to LEV expulsion (solid curve); and July 2011, immediately following this expulsion (dashed curve). Averages over each month were
used, though data from periods that included major incidents were excluded. These incidents were identified from the site’s incident log (PeMS, 2011).

By comparing the measured curves in Figure 4.10(a) against the predicted ones in Figures 4.8 and 4.9, we see that our simulations over-predicted carpool-lane speeds. More to the point, we further see that our predictions regarding the damaging effects of LEV expulsion are in qualitative agreement with the real data. Note from Figure 4.10(a) how the dashed curve lies beneath its solid counterpart for most of the carpool-lane operating period. Thus, we see that the measured average speeds in the carpool lane did in fact diminish following LEV expulsion.

Travel conditions in the regular lanes erode as well, as migrating LEVs cause the regular-lane queue to expand spatially and temporally. This is evident in Figure 4.10(b). It presents time-series curves of the measured speeds averaged across all regular lanes. Averages over the month just before and just after the LEV expulsion are shown.

![Figure 4.10. Measured average travel speeds over the site’s 4-mile length before and after LEV expulsion: (a) carpool lane; and (b) averages across all regular lanes](image)

4.2.7 Closing Thought on this Case Study

Since our first case-study site was, relatively speaking, favorably disposed to the SAFETEA-LU regulation, the damage it does may be different (possibly even worse) at other sites in the region and elsewhere. This concern underscores the need for parametric assessments that are more general in nature. These come next.

4.3 Case Study 2: Hypothetical Congested Beltway

Consider a rotationally symmetric and fully-congested closed-loop beltway, with \( L \) lanes to serve traffic in a single direction, and where one of those lanes is reserved for carpools during part of the day. Our select facility is an idealization of a generic freeway network: the beltway’s uniform (rotationally-symmetric) congestion pattern approximates what can arise on a freeway system with multiple bottlenecks throughout;
and like an urban freeway, the beltway can have any number of access and egress points; see Daganzo and Cassidy (2008) for further discussion on the generic attributes of a beltway system.

Parametric analysis will now be used to predict how LEV-expulsion from the carpool lane can make congestion worse (denser) in the beltway’s regular lanes (sect 4.3.1). These predictions will be used jointly with the observed relations previously displayed in Figure 4.5(a) to estimate impacts on the carpool lane (sect 4.3.2).7

We will assume that inflows to the congested beltway are controlled in such way that its total density across all lanes is held constant, whether or not the carpool lane is active. This is a sound strategy: it would ensure that congestion outside the beltway (e.g. on access roads) is kept constant as well; see again Daganzo and Cassidy (2008) for further discussion on this matter.

We will further assume that the controlled (e.g. metered) on-ramps do not have bypass lanes for carpool-lane vehicles. This assumption will lessen the damage done by the SAFETEA-LU regulation. In the absence of on-ramp bypass lanes, severe congestion on the beltway’s regular lanes will limit the inflows of carpool-lane vehicles, and thus the utilization of the carpool lane itself. As a result, the damaging effects of slow regular-lane speeds on the carpool lane will be offset somewhat by low densities in that lane.

4.3.1 Regular-Lane Predictions

We borrow ideas from Cassidy, et al. (2009) for assessing impacts of bus lanes on regular (i.e., car) traffic in a beltway, and examine now the case of a carpool lane. It is assumed that traffic in each regular lane is described by a triangular-shaped fundamental diagram. Prior to the carpool lane’s activation, \( q = Q(k) \), where \( q \) is the flow in a lane and \( k \) is its density. Both \( k \) and triangular relation \( Q \) are inputs to the analysis.

When the carpool lane eventually activates, carpools use that lane, as do LEVs in the absence of any expulsion policy. Since the beltway’s total density is unchanged by this activation, the density in each of the \( L - 1 \) regular lanes becomes \( k_r = L/(L - 1) \cdot k \cdot (1 - p_c - p_l) \), where \( p_c \) and \( p_l \) are the fixed proportions of beltway demand that are carpools and LEVs, respectively. Total flow in those lanes becomes \( q_r = Q(k_r) \cdot (L - 1) \), where the superscript is used to denote a total flow across all the regular lanes.

If LEVs are expelled from the carpool lane and migrate to the regular ones, we similarly define \( k_{r, e} = L/(L - 1) \cdot k \cdot (1 - p_c) \) as the resulting density in a regular lane, and \( q_{r, e} = Q(k_{r, e}) \cdot (L - 1) \) as the total flow across those lanes. We can now explore impacts of LEV expulsion by comparing \( q_r \) with \( q_{r, e} \).

7 Had we chosen instead to use the relations from a different Bay Area facility (e.g. those in Figure 4.2), our predictions would have reflected even less favorably on the SAFETEA-LU regulation.
For illustration, Figure 4.11 presents comparisons for a freeway beltway with L = 4 lanes, including the carpool lane. The figure displays \( \Delta q_r = (q_e^R - q^R)/q^R \), the percent change in regular-lane flow due to LEV expulsion, vs \( \rho_r = q/q_{max} \), a regular lane’s flow normalized by its capacity, \( q_{max} \). Note that \( \rho_r \) is a measure of regular-lane congestion: it ranges from capacity flow (\( \rho_r = 100\% \)), and diminishes as the flow becomes progressively more constrained by denser congestion. The curves in Figure 4.11 correspond to distinct inputs, as explained below.

The two dotted curves in the figure (both the bold and lightly-drawn one) correspond to cases when \( pc = 10\% \). The dashed and solid curves correspond to \( pc \) of 15% and 20%, respectively. The extremes (10% and 20%) roughly bound the range of carpool-lane demand that we observed on so-called degraded facilities in the San Francisco Bay Area. The curves drawn bold correspond to cases with \( pl = 1\% \), which is comparable to the LEV levels on Bay Area freeways. The family of light curves correspond to \( pl = 3\% \), which could be viewed as a target that might be achieved through thoughtful policies to promote LEVs. Moreover, by including the case of \( pl = 3\% \), we can analyze what could occur should the SAFETEA-LU regulation ever become even more restrictive.

The curves confirm that, for all cases, LEV expulsion reduces regular-lane flow; i.e., denser congestion brought by LEV migration to these lanes further constrains their flow. This reduction is undesirable. It means that regular vehicles exit the beltway at diminished rates, and therefore reach their destinations later in time, with more delay. The curves further show how the negative impacts grow worse at lower \( \rho_r \), meaning that the LEV migration is especially damaging to regular lanes when those lanes are already congested. Congested regular-use lanes are, of course, the norm on freeway carpool facilities: congestion is typically a reason for installing a carpool lane in the first place.

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Figure 4.11. Curves of \( \rho_r \) vs \( \Delta q_r \) for a congested beltway with a carpool lane

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8 The fundamental diagram used for the analysis is suitable for a freeway lane: capacity, \( q_{max} = 2000 \) vehs/hr/lane; free-flow vehicle speed = 60 mph; and backward wave speed = 15 mph.
As expected, we see that the damage is also more extreme: when the carpool lane serves a small demand (the dotted curve of either hue lies below its dashed and solid counterparts); and when greater proportions of traffic are expelled from that lane (the lightly-drawn curves lie below the bold ones).

As in our first case study, the damage done in the regular lanes will likely damage the carpool lane as well. This matter is explored next.

4.3.2 Carpool-Lane Predictions

While the carpool lane is active, and absent any policy to expel LEVs, the average speed in a regular lane is \( V_r = \left( \frac{q^R}{L - 1} \right) / k_r \); and the density in the carpool lane is \( k_c = L \cdot k \cdot (p_c + p_l) \). With the expulsion of LEVs, the regular-lane speed is \( V_{cr} = \left( \frac{q^R}{L - 1} \right) / k_{cr} \), and carpool-lane density is \( k_{ec} = L \cdot k \cdot p_c \). The densities \( k_c \) and \( k_{ec} \) are converted to occupancies in the customary way (e.g. see Cassidy and Coifman, 1997). Speeds and occupancies are then used as inputs to the surface in Figure 4.5(a) to estimate the carpool-lane average speed without LEV expulsion, \( V_c \), and with this expulsion \( V_{ec} \).

Figure 4.12 presents \( \Delta V_c = \left( V_{ec} - V_c \right) / V_c \) vs \( \rho_r \) for our 4-lane freeway beltway. The curves reveal that carpool-lane speeds invariably diminish under LEV expulsion. The reductions are always modest (e.g. less than 0.5% for \( p_l = 1% \)), and this is no doubt due in part to our assumptions that are favorable to the SAFETEA-LU regulation. Yet reductions occur. In light of our favorable assumptions, the findings suggest that the regulation stands little chance of improving carpool-lane speeds in any circumstance. Moreover, the predicted speed reductions in the carpool lane come part and parcel with the worsened conditions predicted for the regular lanes. Everyone seems to suffer under the regulation. Possible remedies are discussed next.

![Figure 4.12. Curves of \( \rho_r \) vs \( \Delta V_c \) for a congested beltway with a carpool lane](image-url)
4.4 Alternatives

The findings in previous sections suggest that carpool-lane travel can be improved by improving travel conditions in the regular lanes. This means that strategies to regulate regular-traffic inflows to facilities (e.g. Cassidy and Rudjanakanoknad, 2005; Daganzo, 1996; Daganzo et al., 2002; Haj-salem and Papageorgiou, 1995; Papageorgiou and Kotsialos, 2002; Persaud et al., 2001) can be Pareto improving and can promote the use of more environmentally-friendly LEVs. This knowledge can be used to further justify the deployment of these strategies. There remain possible downsides to strategies of this kind, however; e.g. sometimes they transfer congestion to access facilities that have insufficient queue storage space (e.g. Cassidy, 2003). This section explores other options.

In some cases, it may be beneficial to transfer some of the regular traffic into a so-called “degraded” special lane. This might be achieved by admitting a wider spectrum of vehicle (e.g. LEV) classes into that lane. Or, one might deploy so-called High Occupancy Toll lanes, or HOT lanes into which access is given to those drivers of regular vehicles who pay a fee (Fielding and Klein, 1993). A more equitable policy might entail turn-taking over days, such that all commuters enjoy a turn in the special lane (see Daganzo and Garcia, 2000).

To explore impacts of policies of this kind, we briefly return to our rotationally symmetric, congested beltway. We define as $V_{ca}$ the carpool lane’s speed when it serves: carpools, LEVs and an added proportion of beltway traffic demand, $p_a$. Figure 4.13(a) presents $\Delta_a = (V_{ca} - V_c)/V_c$, the percent change in the carpool lane’s speed when $p_a=1\%$. Note that these speed changes are shown for different values of carpool-lane demand and occupancy. From the figure, we see how mitigating regular-lane congestion by relaxing slightly the restrictions to the carpool lane can improve speeds in that lane. However, the improvements are modest; i.e., always less than 1%, consistent with what we saw earlier in Figure 4.12.

Given that the above improvements are small, one might also look for opportunities to improve carpool-lane travel by increasing regular-lane capacities. As an example of how this might be done, we note that findings from both, theoretical work (Menendez and Daganzo, 2007) and natural experiments (Cassidy et al., 2010) indicate that the capacities of freeway bottlenecks can be significantly increased by discouraging, but not necessarily prohibiting, vehicle lane-changing maneuvers in bottleneck vicinities.

To explore impacts of something like this, we define as $V_{cr}$ the carpool-lane speed when the capacity of a regular-use beltway lane, $q_{max}$, is increased by a percentage $p_r$. Figure 4.13(b) presents the percent change in the carpool lane’s speed, $\Delta_c = (V_{cr} - V_c)/V_c$, when only high-occupancy vehicles are admitted to that lane and $q_{max}$ is increased by $p_r = 5\%$. Our select value of $p_r$ in this instance is small relative to the gains in bottleneck capacities reported in the above-cited references (and we found that larger values of $p_r$
produce larger predicted values of $\Delta_r$). Yet the predicted improvements shown in Figure 4.13(b) may themselves justify whatever experiments might be needed to refine strategies that increase bottleneck capacities.

![Figure 4.13](image)

Figure 4.13. (a) Curves of $\rho_r$ vs $\Delta_a$ when $p_a = 1%$; and (b) Curves of $\rho_r$ vs $\Delta_r$ when $p_r = 5%$

### 4.5 Amending the Regulation

Even if we can set aside the damages that will apparently result from the SAFETEA-LU regulation, we would remain puzzled by its logic. The regulation’s objective – to maintain a carpool lane’s speeds at or above 45 mph for 90% of its operating hours – seems off-target. After all, the literature indicates that a carpool lane’s attractiveness to commuters is based less on the magnitude of its speed than on the quality of travel that it provides relative to that of the adjacent regular-use lanes (Dahlgren, 1998; Jang and Chung, 2010; Li et al. 2007). From what we have seen, even slow-moving carpool lanes tend to perform well by this relative standard (e.g. see Wu et al. 2011). Moreover, carpool lanes are probably most attractive when regular-lane speeds are especially slow, even though the carpool-lane speeds would therefore be slow as well.

We are further puzzled by the regulation’s use of speed as its metric of choice. It seems that a facility can be classified as a “degraded” one based even on the speeds that occur over short segments of a carpool lane. The literature indicates that travelers are more concerned about the trip times over their entire journeys than they are about their shorter-run speeds (Ben-Akiva and Lerman, 1985; Brownstone, et al., 2003; Hensher, 2008; Hess et al., 2005).

In light of the above, it makes sense to change the regulation’s criteria to capture relative trip times over extended lengths of a carpool facility. The ratio of the average time to travel an extended distance in the carpool lane to that in the regular lanes might do for
this purpose. Mitigation measures could be prescribed for those facilities with trip time ratios that are persistently close to 1. However, expelling LEVs from the carpool lanes would seem not to be the best course of action in these cases.
Chapter 5

Conclusions

This dissertation has shown that carpool lanes passing through bottlenecks significantly increase the discharge flows in lanes adjacent to the carpool lanes. The effect is consistent with theory (Menendez and Daganzo, 2007); was consistently reproduced across days and sites; and is so pronounced that even an underutilized carpool lane can increase a bottleneck’s total discharge flow. Queueing analysis illustrates that carpool lanes with flow as low as 1200 vph can reduce not only people delay, but even vehicle delay. This indicates that the carpool lanes – even when underused themselves – can benefit travelers in the regular lanes. Ironically, the congested regular-use lanes are often damaging to the carpool-lane travelers.

Empirical evidence from across the San Francisco Bay Area indicates that slow carpool-lane speeds do not necessarily indicate that the lane is over-used. Typically, the slowness is due in part to congestion in the adjacent regular-use lanes. Carpool-lane drivers may be reluctant to travel fast when adjacent traffic is moving at slow, congested speeds. And when regular lanes are congested, lane-changing maneuvers made into and out of a carpool lane may become disruptive and diminish its speeds. This means that current US policy to restrict LEVs from slow-moving carpool lanes can be counterproductive because some or all of the LEVs will now add to congestion and slowing in the regular lanes.

Analysis of a real freeway stretch illustrates just how damaging the policy can be. Negative impacts were predicted for all commuters at that site, even if LEV-users were to adjust their travel behavior in highly-favorable ways. The predictions were in line with limited observations collected from the site. More generalized analysis of a hypothetical beltway suggests that these problems will be common to a wide range of freeways with so-called non-separated carpool lanes, despite our favorable assumptions.

The findings suggest that improved travel in a carpool lane will often not be realized by further restricting access to it. Policies that do this could in many instances prove to be recipes for disaster, whereby all commuters are made worse off. These concerns notwithstanding, there is something positive about the present findings. They indicate that carpool-lane travel can be improved by increasing regular-lane capacities and thus improving travel conditions in the regular lanes. The findings from the natural experiments in this dissertation show that this might be done by discouraging, but not
necessarily prohibiting, vehicle lane-changing maneuvers in bottleneck vicinities to induce the smoothing effect. The predicted improvements shown in Figure 4.13(b) may themselves justify whatever experiments might be needed to refine strategies to produce diminished lane changes.

Future work will be directed at developing and testing ways to discourage lane changes near bottlenecks. Roadside signing and (solid) painted lane striping might be used near certain bottlenecks to limit the disruptive impacts of lane changing. Disruptive lane changing might also be reduced in some cases by sorting drivers (and vehicle classes) across lanes according to their preferred travel speeds; or in other cases by inducing a more even distribution of flows across lanes; and these outcomes might be achieved by imposing lane-specific speed limits, based perhaps on real-time measurements of traffic. The above measures could be deployed on any freeway, whether or not it includes a carpool lane. For freeways with severely underused carpool lanes, one might even try to induce smoothing by rescinding carpool restrictions near bottlenecks at certain times only, e.g., as described in Daganzo, et al (2002). Though this latter dynamic strategy may be unconventional, simulations in Menendez and Daganzo (2007) indicate that it can significantly increase bottleneck capacity.

In closing, the presence of a carpool lane can reduce the delays not just for carpoolers, but for all freeway commuters, thanks to the smoothing effect; and thus carpool lanes can be beneficial to all commuters. The resulting reductions in congestion would benefit the environment as well. However, the present regulation to expel LEVs from the carpool lanes will likely backfire. Some or all of the expelled LEVs will thereafter use the regular lanes, which will expand congestion in those lanes and therefore slow traffic in the carpool lanes. Travel conditions for freeway commuters will therefore be worse, both in and out of carpool lanes. And this mismanagement can negate the benefits from the carpool lane. In locations (such as the state of California) where LEV expulsion has already taken place, corrective actions should be taken now. This would ensure that carpool lanes – an important public resource – will be managed in the best ways possible.
References


Freeway Performance Measurement System (PeMS) 2011. pems.dot.ca.gov


Appendix A

The Connection between the Carpool Restriction and Lane Changing Patterns

The evidence presented in this appendix indicates that favorable lane-changing patterns (i.e. patterns that ultimately induced the higher queue discharge flows in lanes 2 and 3) were triggered by the carpool restriction. This is explained with Figure A.1. It uses arrows to illustrate the time-varying lane-changing patterns measured over the 0.4-km stretch upstream of the I-880 bottleneck (the darker shaded area in Figure 3.1.) Thin, solid arrows denote initial lane-changing rates; thick arrows increased rates; and dashed arrows diminished rates. Note from the line-weights of the arrows how the lane-changing rates diminished when comparing the period before 14:52 (before the carpool restriction came into play) to the period after 15:05 (when the restriction was in effect), as was mentioned in the text. Let us now examine the sequence of events in more detail.

Consider first the vehicle maneuvers made out of lane 1 (the carpool lane) and into lane 2. This migration rate increased from 14:52 to 15:00 hrs, as depicted with the two boldfaced arrows that project from lane 1 to 2. We attribute this temporary increase to the impending carpool restriction since LOVs are required to vacate lane 1 by 15:00 hrs: early responses are to be expected since LOV-drivers risk fines for carpool violations. (The pattern is shown with real data by means of the bold cumulative curve in Figure A.2.)

The impending carpool restriction also discouraged drivers from maneuvering into lane 1 from lane 2. These movements started to decline at 14:57, and continued to diminish after the carpool lane activated, as depicted with the dashed and dotted arrows from lane 2 to 1. (The thin cumulative curve in Figure A.2 confirms this pattern with real data.)
The imbalance in lane-changing rates between lanes 1 and 2 created crowded conditions in lane 2 promptly after 14:52. (This can be seen from the time series of vehicle accumulation in Figure A.3.) The crowding had two effects. First, for a time it pushed vehicles from lane 2 into lane 3. As shown by the thicker arrows in Figure A.1, this push subsided at 15:00 hrs, when the heightened migration from lane 1 subsided as well. Second, the crowding discouraged maneuvers made into lane 2 from lane 3, as depicted with the dashed arrows from lane 3 to 2. (Measurements quantifying these latter patterns are furnished in Figure A.4.)

In summary, we see that all the changes in the detailed traffic patterns between 14:52 and 15:05 hrs can be traced back to the carpool restriction. Since we cannot think of another plausible explanation, we conclude that the changes are indeed caused by the restriction.9

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9 One might conjecture that the discharge flows increased in the center lanes because the carpool restriction forced aggressive LOV drivers (who travel at small headways and thus generate higher discharge flows) out of lane 1. This conjecture is not supported by the data, however. For example, joint inspection of Figures 3.4(a) and A.2 reveals that the queue discharge flow in lane 2 did not increase when migration out of lane 1 began at 14:52 (i.e., during the period 14:52 – 15:00, any aggressive drivers who migrated from lane 1 to 2 did not affect lane 2’s queue discharge flow). Rather, this discharge flow increased only after the combined lane changing in and out of lane 2 had subsided.

Figure A.2. Cumulative curves of lane changes between lanes 1 and 2 (July 19, 2006)
Figure A.3. Vehicle accumulation in lane 2 (July 19, 2006) measured over the 0.4-km darker shaded segment in Figure 3.1

Figure A.4. Cumulative curves of lane changes between lanes 2 and 3 (July 19, 2006)
Appendix B

PHT and VHT Predictions for Site 1 (I-880)

This appendix presents our queueing analysis for site 1; see Figure B.1. Given are: (i) the demands on the freeway at $X_U$, denoted $q_f'(t)$ (veh/hr), (ii) the fixed metered inputs from the on-ramps, denoted $q_U$, $q_M$ and $q_D$; (iii) the discharge flows past $X_D$ (immediately upstream of the Tennyson onramp), (iv) the fixed fraction of both LOVs and carpools exiting at $X_M$, $\beta$, and (v) the fixed fraction of total flow that is comprised of carpools, $\alpha$. See Table B.1 for these values.

Delays are calculated assuming that: (i) there is no delay beyond $X_D$; (ii) carpools entering from the on-ramps experience no significant delays as they access the carpool lane and do not create a more restrictive bottleneck in doing so; (iii) carpools exiting at $X_M$ are already in the General Purpose (GP) lanes prior to arriving at $X_U$; and (iv) all vehicles delayed in GP lanes obey the kinematic wave theory with the parameters of Table B.1.

![Figure B.1. I-880 study site with added notation](image)

We use the queuing representation of kinematic wave theory proposed in Newell (1993). Some care is required because the system exhibits two distinct phases: before and after carpool-lane deactivation. We consider first the scenario with a carpool lane that does not induce smoothing because it turns out to be the most complex. As a preliminary step, we construct a queuing diagram (Figure B.2) that only keeps track of those vehicles delayed in the GP lanes and destined for $X_D$: LOVs before 19:00 hrs (phase 1) and all vehicles after 19:00 hrs (phase 2). The delay of other vehicles will be calculated as a side product.
Table B.1. Estimated inputs

<table>
<thead>
<tr>
<th>Input variables (Units)</th>
<th>$q_f(t)$ (vph)</th>
<th>$q_U$ (vph)</th>
<th>$q_M$ (vph)</th>
<th>$q_D$ (vph)</th>
<th>$\beta$ (%)</th>
<th>$\alpha$ (%)</th>
<th>$\Delta p$ (hrs/km)</th>
<th>LOV average person Occupancy</th>
<th>Carpool average person occupancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value(s) estimated from data</td>
<td>5400-6300</td>
<td>500</td>
<td>700</td>
<td>700</td>
<td>12</td>
<td>17.5</td>
<td>0.043</td>
<td>1</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Triangular-shaped fundamental diagram (estimated from data): free flow vehicle speed = 105 km/hr, jam density = 75 vehs/km/lane, GP-lane capacity (discharge flow) = 1,900 vph/lane (with smoothing), or 1,740 vph/lane (without smoothing or without carpool lane).

Note that the two phases are separated by a brief transition with curves shown by dotted lines. During this transition carpools and LOVs mix across all four lanes, and the change in discharge flow propagates upstream from $X_D$. This takes about 4 minutes. Since the transition is so short relative to the rush, it does not have to be modeled precisely. Thus the dotted curves are drawn linearly.

In the first phase, prior to 19:00, the $V$-curve displays the known cumulative number of desired departures at $X_D$ for all LOVs, ending with vehicle $N_A$ at point $A$. In the second phase, after the transition, the cumulative count $V(t') - N_A$ at some time $t' > 19:00$ hrs includes all vehicles with desired departures between 19:00 and $t'$, including all the carpools present on the freeway at 19:00 and destined for $X_D$. This cumulative count is known from the data.

The $D$-curve is constructed in the conventional queuing way using as the service rate the discharge rate of the GP lanes minus the inflow from the Tennyson on-ramp. Note that its slope changes at 19:00 as the number of GP lanes changes from 3 to 4. The area between curves $V$ and $D$ is only the delay to those vehicles in the GP lanes destined for $X_D$.

To obtain the delay to all vehicles including those exiting via the off-ramp at $X_M$, we construct the departure curve at $X_M$ which isolates the delay between $X_U$ and $X_M$ (darker area in the figure). This construction is easy because the horizontal distances between the $M$- and $D$-curves in the two phases are the known vehicle delays in the segment from $X_M$ to $X_D$ (Lawson, et al, 1997). Knowing the $M$-curve, we can now compute the total delay in the system. Since only a fraction $1 - \beta$ of the vehicles experiencing delay in the $X_U$ to $X_M$ segment is captured in the figure (the figure ignores the fraction $\beta$ that exits at $X_M$), the total delay in that segment is the darker area shown factored upward by the quantity $1/(1-\beta)$. To this we add the lighter shaded area in the figure and the delay to the
carpool lane vehicles. The latter was estimated as the product of the (i) carpools' average extra pace, \( \Delta p \), (see Table B.1.), and (ii) their vehicle-miles traveled on the site.

To convert this total delay into VHT, we add the free-flow travel hours; i.e. the product of the vehicle-kilometers traveled and the free-flow speed, both known. To obtain PHT, averages for the number of occupants per LOV and per carpool (known from earlier field observation, Caltrans, 2004) were used to convert VHT to PHT on both the upstream and downstream parts of our freeway. This concludes the analysis of the most difficult case.

The case of a carpool lane with smoothing, and the case of no carpool restriction were analyzed in similar, but simpler fashion. For the case of no carpool restriction, the queueing analysis was of a FIFO system with a single bottleneck capacity (commensurate with four freeway lanes and no smoothing). The case of a carpool lane with smoothing was also analyzed using a single capacity for the (3-lane) bottleneck, because the rush-hour queue predicted in this case did not persist beyond the carpool lane deactivation time.

Figure B.2. Queueing diagram for the case of a carpool lane without smoothing
Appendix C

Modifications to CTM for Case Study 1

This appendix describes refinements made to the Cell Transmission Model (CTM) to perform analysis on two adjacent traffic streams – carpools and regular vehicles – with distinct flows and speeds. Only the alterations to the CTM framework are described. Readers interested in full details on the CTM can refer to Daganzo (1995).

The CTM was modified to accept additional demand inputs, namely; the proportions of total demand that are comprised of carpools and LEVs, $p_c$ and $p_l$, respectively. To model the distinct (carpool and regular) traffic streams, parallel sets of cells were used. Each cell in its set was connected by links as per the CTM’s original logic.

Each cell that happened to represent either an on- or off-ramp was linked to both sets of cells. It was assumed that on-ramp (i.e. merging) vehicles bound for the carpool lane entered that lane within the length of its merge cell. Similarly, these vehicles exited the carpool lane and reached its off-ramp within the length of its diverge cell. Thus, the merge and diverge maneuvers for carpool-lane vehicles occurred without delay and without disrupting regular traffic.

At each on-ramp, traffic advanced into two intermediate cells: the fraction $p_c + p_l$ entered the intermediate cell designated for carpool-lane traffic, and the fraction $1–p_c – p_l$ entered the other intermediate cell designated for regular traffic. The traffic in each intermediate cell then merged into its (carpool or regular) cell at predetermined ratios, $\alpha$, as shown in Figure C.1(a). Exiting traffic was handled in analogous fashion: diverging traffic in each lane set merged into intermediate cells at ratio $\beta$, as shown in Figure C.1(b).

When performing the simulations during the period when the carpool lane was active, each cell of the carpool lane adopted a fundamental diagram estimated from real data taken from the case-study site. Recall that carpool-lane speed, $V_c$, were determined for each carpool cell and time step via Figure 4.5(a) given the values of $\rho_c$ and $V_r$ that were generated from the CTM simulations.
Figure C.1. Representation of (a) on-ramp; and (b) off-ramp in the modified CTM