Safety Evaluation of High-Occupancy Vehicle (HOV) Facilities in California

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High Occupancy Vehicle (HOV) lanes have been implemented on urban freeways to mitigate continuously growing traffic congestion and improve overall mobility within metropolitan freeway systems. HOV lanes allow vehicles carrying more passengers to bypass the congested General Purpose (GP) lanes thereby encouraging the use of carpools and public transportation to move more passengers per lane with a fewer number of vehicles. In California, HOV lanes were first introduced in 1970’s and increasingly implemented in congested freeway segments in Southern and Northern California metropolitan regions. As of 2005, HOV lanes comprised 1,305 (directional) lane-miles of freeway, with 895 lane-miles located in Southern California, 410 lane-miles in Northern California, and 950 additional lane-miles of HOV lanes have been proposed for construction.

Since their inception, two configurations for HOV lanes—continuous and limited—have emerged in California (figure 1, pg 2). Continuous access HOV lanes allow vehicles to enter or exit the HOV facility continuously along the freeway such that lane changing maneuvers are not concentrated at specified location; on the other hand, the traffic operation in the continuous HOV lane is more frequently interrupted by the lane changing vehicles. Limited access HOV lanes, which are predominant in Southern California, are in operation 24 hours a day, seven days a week.
The present study evaluated traffic collision patterns in continuous and limited access HOV lanes and investigated the attributes accounting for safety performance of HOV lanes.

A statewide comparison of limited and continuous access HOV facilities was conducted. Collision data from the Traffic Accident Surveillance and Analysis System (TASAS) between year 1999 and 2003 along 824 miles of freeways with HOV facilities were examined, including 279 miles of HOV lanes with continuous access and 545 miles with limited access.

For the purpose of comparing the collision distributions in different HOV facilities, only the collision data during the peak hours were analyzed since the continuous access HOV lanes operate as regular lanes outside of the peak hour period.

Rear-end and sideswipe collisions together comprised over 90 percent of all collisions in both facilities. In continuous access HOV lanes, 57 percent of collisions were rear-end and 34 percent were sideswipe collisions. In limited access HOV lanes, 64 percent were rear-end, and 26 percent were sideswipe collisions (figure 2).

The difference in types of collisions observed in continuous versus limited access HOV lanes could be due to the difference in traffic movements inherent to continuous and limited access HOV facilities. Compared with the traffic in limited access HOV lanes, the traffic in continuous access HOV lanes are more likely to be exposed to continuous interaction with traffic in adjacent lanes, and thus there is a greater occurrence of sideswipe collisions. On the other hand, the traffic in limited access HOV lanes are prohibited from changing lanes except at ingress/egress areas and tend to have more interaction with vehicles in the back or front than those in adjacent lanes such that they experience a greater number of rear-end collisions.

The distribution of collisions in the HOV lane and its adjacent lane was examined to determine whether there is a consistent pattern of collisions between the two different types of HOV facilities. The lane adjacent to the HOV lane is called the left lane by its definition within TASAS.

A higher distribution of both Property Damage Only (PDO) and injury related collisions was observed in the HOV and left lanes of the HOV facilities with limited access. It can be seen that the limited access facilities have a considerably higher percentage of collisions, PDO or injury, concentrated in the HOV and left lanes (figure 3).

The differences observed in collision distribution could have been the result of the difference in lane utilization of traffic. To investigate this phenomenon further, a more detailed analysis was conducted for a selective list of routes, for which detailed geometric and traffic data were available. These freeway segments were suggested by regional transportation engineers from California Department of Transportation (Caltrans). The routes were included in the detailed analysis on the basis that these routes shared similar traffic patterns, according to local district engineers who were familiar with the configurations and operations of these freeway segments.
In November, 2006 California voters approved a $20 billion bond measure to improve transportation. Subsequently, the California Department of Transportation (Caltrans) launched an ambitious ‘corridor management program’ to design and implement operational improvements, emphasizing ramp metering and arterial signal coordination, incident management, traveler information and demand management (including using tolls), in order to reduce congestion in 2025 by 40 percent [1]. TOPL (Tools for Operations Planning) is a suite of software tools for specifying such operational improvements and for quickly estimating the benefits such improvements are likely to provide. Products of the TOPL group, including software, are available at the TOPL website [2].

TOPL focuses on operations in freeway corridors. A corridor is a road network consisting of a freeway and surrounding arterials. A network is a collection of links interconnected by nodes. A link is a homogeneous section of a freeway, a ramp, a freeway interconnect, or an urban street. A link is characterized by its geometry (length, number of lanes) and fundamental diagram, which expresses the flow of vehicles through a link as a function of the number of vehicles in the link and its downstream neighbors. A node specifies the logic controlling vehicle flows between its incoming and outgoing links. For instance, at the merge junction of an on-ramp and a freeway link, the node specifies the algorithm used to meter the on-ramp flow; at a diverge junction of an off-ramp and a freeway link, the node specifies the turning movement; and at a signalized intersection, the node specifies the algorithm that determines the various green and red phases.

TOPL simulation programs are based on the dynamic macroscopic cell transmission model (CTM) of a freeway corridor. The choice of CTM is dictated by its sound theoretical properties and the ease with which operational improvements can be represented [3, 4].

TOPL provides three simulation programs: CTMSim, FwyModel, and Aurora. CTMSim and FwyModel simulate a single freeway and associated on- and off-ramps; Aurora simulates a freeway corridor. This article describes how Aurora functions for a single freeway.

Aurora

An Aurora freeway application requires the construction of a configuration file. The file specifies (1) the freeway geometry expressed as a sequence of variable-length, variable-lane links; (2) the fundamental diagram for each link; and (3) the on-ramp demand profiles and off-ramp split ratios, all of which for California freeways can be directly obtained or estimated from PeMS data [5] (Several configuration files are available from the TOPL website.) Given a configuration file, Aurora will generate flow, speed and density space-time contours and several performance measures that can be compared with PeMS data. Users can develop and test their own ramp controllers, and compare their performance with other built-in controllers.

Aurora is interactive, so a user can see the temporal evolution of the freeway state, halt the simulation and change some parameters like the fundamental diagram to simulate an incident, or switch certain controllers on or off; and then resume the simulation. Interactivity also helps with model calibration, by adjusting fundamental diagrams, on-ramp demands and off-ramp split ratios as necessary.

I-880 Case Study

Aurora’s usefulness to Caltrans’ corridor management program is illustrated by a case study of I-880N, a 45-mile long freeway in the San Francisco Bay Area stretching north from San Jose to Oakland. The map in figure 1 shows the location of two major bottlenecks.

The recurrent bottlenecks are visible in the measured speed contour plots for four consecutive days in figure 2. Figure 3 (see pg 9) is a screen shot of a display window of the Aurora simulation of I-880N for the base case. The continued on page 9
HOV facility and geometric attributes, including shoulder width, length of the access, and the proximity of the access to its neighboring ramps. The same collision data set from the eight routes was used for this part of the analysis.

1. Shoulder width
Effects of shoulder width on safety performance are illustrated (figure 5) with the observed collision rates for the eight freeway segments plotted versus the corresponding shoulder width. The plot indicates that collision rates diminish with an increase in shoulder width, regardless of the type of access associated with the HOV lane. The group of limited access does exhibit a higher collision rates when compared to the group of continuous access with comparable shoulder width.

2. Total (Shoulder + HOV Lane + Buffer) width
The total width is defined as the lateral space including the shoulder, the HOV lane and buffer. A scatter plot (figure 6) of collision rate versus total width was constructed and a trend line for each type of HOV facility was estimated based on the scatter plot. Narrower total width was associated with a higher collision rate in both types of HOV lanes. Notably, the trend line for the limited access, shown as a black line, exhibits remarkable resemblance to the trend line of the continuous access, a grey line, but with a vertical shift upward. The pattern implies that given the same amount of total width, employing continuous access HOV lanes can result in fewer numbers of collisions; more shoulder width can be allocated to the HOV lane with continuous access since it does not require a buffer.

3. Spatial collision patterns
Continuous Risk Profile (CRP) method, which can generate a variation of risk measurement interpretable as the number of collisions per unit distance along a freeway, was applied to investigate the spatial distribution of collisions along the freeway. The CRP plots (figure 7) for HOV and left lanes of the eight routes were constructed to examine the spatial distribution of collision concentration locations along the freeways. Using CRP analysis, the followings were observed.

- In the continuous access facility:
  - Each of the peaks accompanies a peak in adjacent left lanes.
  - This implies that the factors causing the concentration of collisions appear to have equal influence on both HOV and left lanes.
- In the limited access facility:
  - Some of the peaks are observed only in either HOV or left lane.
  - These peaks were often found at locations where HOV lane is separated by buffers from the adjacent GP lanes where lane change is prohibited.
  - This indicates that lane change maneuvers are not necessarily a collision causative factor at this location of collision concentration.

### Table 1: List of eight study sites.

<table>
<thead>
<tr>
<th>Facility Type</th>
<th>County</th>
<th>Freeway</th>
<th>Length (Mile)</th>
<th>Operation Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>Contra Costa</td>
<td>I-80E</td>
<td>10</td>
<td>Weekdays, 5–10AM &amp; 3–7PM</td>
</tr>
<tr>
<td>Contra Costa</td>
<td>I-80W</td>
<td>9.8</td>
<td>Weekdays, 5–10AM &amp; 3–7PM</td>
<td></td>
</tr>
<tr>
<td>Alameda</td>
<td>I-880N</td>
<td>7.4</td>
<td>Weekdays, 5–10AM &amp; 3–7PM</td>
<td></td>
</tr>
<tr>
<td>Santa Clara</td>
<td>SR-101S</td>
<td>13.5</td>
<td>Weekdays, 5–10AM &amp; 3–7PM</td>
<td></td>
</tr>
<tr>
<td>Limited</td>
<td>Los Angeles</td>
<td>I-105E</td>
<td>15.7</td>
<td>24 Hour</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>I-105W</td>
<td>14.3</td>
<td>24 Hour</td>
<td></td>
</tr>
<tr>
<td>Los Angeles</td>
<td>I-210E</td>
<td>11.6</td>
<td>24 Hour</td>
<td></td>
</tr>
<tr>
<td>Los Angeles</td>
<td>I-405S</td>
<td>9.3</td>
<td>24 Hour</td>
<td></td>
</tr>
</tbody>
</table>

Using traffic volume data from the Freeway Performance Measurement System (PeMS), collision per million Vehicle Miles Traveled (VMT) was calculated by dividing the number of collisions by total operation hours, average hourly traffic volume and lane-mile for HOV and left lanes. Higher PDO collision rates were observed in both HOV and left lanes of the HOV facility with limited access. The combined injury related collision rates for the HOV and left lane was higher for the limited access. However, the injury related collision rate for the left lane alone was higher for the continuous access HOV facility. All the differences except for the difference of injury related collision rates in left lanes were statistically significant at the 95 percent level of confidence (figure 4).
4. Ingress/Egress analysis

To understand the potential impacts of traffic movements near ingress/egress areas and nearby freeways, a detailed analysis is carried out for a number of sites. The site samples were obtained from 24 different ingress/egress sections along the four limited access HOV lanes, for which per lane traffic volumes were available. No apparent systematic relationship can be identified between the collision rates and the distance from ingress/egress to the nearby on- or off-ramps. However, three locations showed significantly higher collision rates than the average collision rate in limited access HOV lanes. It was found, after inspecting the configurations of these three locations, that these three ingress/egress segments were associated with the following common features:

1. They were located within 0.3 mile of the nearest on- or off-ramp,
2. They had short access lengths (0.25 mile), and
3. They possessed high traffic volume in the HOV lane during peak hours (1000–1200 vehicles per hour versus 700–800 vehicles per hour on average).

Summary of Findings and Future Research

The findings from this research show that the HOV facility with limited access offers no safety advantages over the one with a continuous access. The combined collision rates of the HOV and its adjacent lane were higher for the HOV facility with limited access.

The relationship between collision rates in HOV lanes with respect to its shoulder width, length of the access, and the proximity of the access to its neighboring ramps were studied. HOV facilities with shoulder width greater than 8ft displayed significantly lower collision rates regardless of access type. Based on the analysis of total width and crash rates, it can also be inferred that facilitating HOV lane with continuous access may result in lower collision rate, given the same total width of right of way. Furthermore, it was found that limited-access HOV facilities with a combination of short ingress/egress length and a close proximity to the nearest on- or off-ramp tends to exhibit markedly higher collision rates than other limited access freeway segments.

For the evaluation of the relationship between the collision rate and the total width, the present study did not attempt to quantify the effect of individual width element if given the same total width. This is a critical question that needs to be further explored because it can be used as a guideline for allocating spaces where the right-of-way is limited. In addition, additional study sites should be included to evaluate the relationship between the length of ingress/egress and its proximity to the neighboring on or off ramps. These remain the topics of future research.

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PeMS - Performance Management System: https://pems.eecs.berkeley.edu/
Automated Bus for Bus Rapid Transit Debuts on City Street

Sarah Yang
UC Berkeley Media Affairs

The thought of a bus moving along city streets while its driver has both hands off the wheel is alarming. But a special bus introduced today (Friday, Sept. 5), steered not by a driver, but by a magnetic guidance system developed by engineers at the University of California, Berkeley, performed with remarkable precision.

The 60-foot research bus was demonstrated along a one-mile stretch of E. 14th Street in San Leandro that was embedded with a series of magnets. Special sensors and processors on board the bus detected the magnets in the pavement and controlled the steering based upon the information it received. The driver maintained control of braking and acceleration, but the steering was completely automated, allowing the bus to pull into stops to within a lateral accuracy of 1 centimeter, or about the width of an adult pinky finger.

Researchers say such precision docking would help shave precious seconds off of the time to load and unload passengers at each stop, adding up to a significant increase in reliability and efficiency over the course of an entire bus route. For example, precision docking could potentially negate the need to deploy wheelchair ramps and make passenger queuing more efficient.

Moreover, the ability to more precisely control the movement of the bus reduces the width of the lane required for travel from 12 feet - the current standard - to 10 feet, researchers say.

The California Department of Transportation (Caltrans) has provided $320,000 to fund this Automated Bus Guidance System demonstration project, conducted by the California Partners for Advanced Transit and Highways (PATH) program based at UC Berkeley.

"Today’s demonstration marks a significant step in taking the technology off of the test track at UC Berkeley’s Richmond Field Station towards deployment onto real city streets," said Wei-Bin Zhang, PATH transit research program leader at UC Berkeley. "We have seen increasing interest among transit agencies in this technology because of its potential to bring the efficiency of public bus service to a level approaching that of light rail systems, but at a much lower overall cost."

California PATH researchers have been studying magnetic guidance systems as a means of controlling vehicle movement for nearly 20 years with significant funding from Caltrans and the U.S. Department of Transportation. They have showcased how the technology can control a platoon of passenger cars speeding along high occupancy vehicle (HOV) lanes in Southern California, as well as industrial vehicles such as snowplows and tractor trailers in Northern California and Arizona. Today’s test run along E. 14th Street marks the first application of magnetic guidance technology for use in transit buses on a public road.

“It is our mission to improve mobility across California, and maximizing transportation system performance and accessibility through this technology helps us to achieve our mission,”
said Larry Orcutt, chief of the Caltrans Division of Research and Innovation. “The rising cost of fuel has created greater interest in public transit. This technology could convince more people to get out of their cars and onto buses, and as a result, reduce congestion.”

In the system demonstrated today, sensors mounted under the bus measured the magnetic fields created from the roadway magnets, which were placed beneath the pavement surface 1 meter apart along the center of the lane. The information was translated into the bus’s lateral and longitudinal position by an on-board computer, which then directed the vehicle to move accordingly. For a vehicle traveling 60 miles per hour, data from 27 meters (88 feet) of roadway can be read and processed in 1 second.

Zhang added that the system is robust enough to withstand a wide range of operating conditions, including rain or snow, a significant improvement to other vehicle guidance systems based upon optics. Researchers also pointed out that magnetic guidance technology allows for a bus to safely follow closely behind another. Extra vehicles, much like extra cars on light rail trains, could thus be added during peak commute times.

AC Transit puts the cost of its BRT proposal at $273 million, while a comparable light rail system would cost around $2 billion. Zhang said that adding the magnetic guidance technology to AC Transit’s proposed BRT project would help it run more like a light rail system for an additional $5 million. The Valley Transportation Agency has also compared the costs of BRT and light rail systems for its planned Santa Clara Alum Rock Transit Improvement Project. The estimated cost for BRT came in at $128 million, compared with $393 million for light rail.

AC Transit is joining Caltrans and the U.S. Department of Transportation in funding the next stage of the Automated Bus Guidance System project as it becomes part of the federal Vehicle Assist and Automation Program. The project will expand to AC Transit routes along Interstate 880 and the San Mateo Bridge, and to a dedicated BRT route in Eugene, Ore.

“Ultimately, it’s up to the community to decide which transit option is best for its members,” said Zhang. “Our job is to develop the technology that can help improve whatever form of transportation is used.”
California PATH publications (which include research reports, working papers, technical memoranda, and technical notes) can be obtained from:

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window is divided into two halves. The right-hand side displays contour plots of flow (top), density (middle) and speed (bottom). The left-hand side displays five performance plots: (instantaneous) travel time, VMT, VHT, delay and productivity loss. Comparisons with measurement data from PeMS indicate that the simulation conforms well to measurement. For example, the contour plots of figure 3 clearly show the two major bottlenecks in figure 2. Similarly, the delay in the morning peak is much larger than the afternoon peak, which is to be expected, because the morning commute direction is north. These and other comparisons lend confidence in the analyses of two scenarios that follow.

On 27 September, 2007, there was a serious accident at 3:40PM. The accident is simulated in Aurora as a reduction in the capacity (two of four lanes were shut down) from 3:40PM until 4:45PM. Figure 4 shows the simulation, with the density contour replaced by the measured speed contour from PeMS. The location and time of occurrence of the accident is indicated by X. The two ellipses mark the increased delay and congestion caused by the accident, in comparison with the base case of figure 3. The reduction in capacity causes the demand to be infeasible, triggering and spreading congestion as theory predicts [3].

Figure 5 shows how ramp metering reduces the congestion caused by the accident. The freeway is maintained in free flow. The dotted ellipses are in the same locations as the solid ellipses of figure 4. Of course, free flow on the mainline is partly paid for by delay on the ramps. Nonetheless, there is a net reduction in delay as summarized in figure 6. The figure plots hourly delay (including delay on the ramps) for three scenarios: base case (blue), accident with no metering (red), and accident with metering (green). The area between the red and green plots is the net delay savings due to ramp metering.

A more dramatic scenario is illustrated in figure 7, which simulates the impact of a two percent increase in demand (all on-ramp flows are increased by two percent relative to the base case). The morning congestion no longer disappears by mid-day as in the base case of figure 3, and as a result congestion in the afternoon peak is worse. Nevertheless, ramp metering keeps the mainline free flowing as indicated in figure 8. The net effect is summarized in the hourly delay plots of figure 9, which is analogous to figure 6. The very large increase in congestion from a two percent increase in demand implies that traffic flow on I-880N is close to capacity, in which case ramp metering benefits are much greater than if demand is well below capacity.

**Configuration Tools**

To investigate new scenarios for a freeway for which a configuration file is available at the TOPL website, a user can simply start with that file and edit it to create a new scenario. However, in order to investigate a new freeway the
user must create a configuration file from scratch. Recall that the configuration file requires (1) the network specification of the freeway in terms of links (freeway sections and ramps) and nodes; (2) the fundamental diagram for each freeway link; (3) the pattern of on-ramp demands and off-ramp turn movements.

TOPL provides three tools to create a configuration file. The first tool accepts from the user the freeway name, the direction, the beginning and end post miles, and a range of dates (e.g. 2007). The software queries the PeMS data warehouse, extracts the freeway configuration, and constructs the network specification. It then determines those days within the specified range for which PeMS has 'good' data, which means that at least 90 percent of the data are observed (rather than imputed). The second tool processes the good data, and obtains an estimate of the fundamental diagram for each link in the network. Details of the statistical procedures used are provided in [6]. An example of a fundamental diagram produced in this manner is shown in figure 10. The third tool imputes ramp data that are frequently missing. While all three tools can be used with very little user intervention, the user must exercise judgment because sometimes critical detector data are missing.

**Future Directions**

TOPL provides software tools that can be used to rapidly advance the selection of operational improvements for freeway corridors. Until now TOPL effort has concentrated on the automatic generation of calibrated freeway models. For arterials, TOPL provides models of signalized intersections. However, progress in the automatic calibration of arterial models has been retarded by the absence of data, and much effort will be devoted to these models in the near term. In this connection, TOPL has started a promising new effort to directly measure urban street data [7].

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[5] https://pems.eecs.berkeley.edu/


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**Figure 6** Plots of hourly delay: base case (bottom), with accident (top) and under metering (middle).

**Figure 7** Simulation of a two percent increase in demand.

**Figure 8** Simulation of the increased demand under metering.


A. Muralidharan. Imputation for the Link-Node CTM. http://path.berkeley.edu/topl/.

Figure 9 Plots of hourly delay: base case (bottom), with increased demand (top) and under ramp metering (middle).

Figure 10 Estimate of the fundamental diagram from data from VDS 400669
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