Analysis of Freeway Improvements for Express Bus Service

Christopher R. Cherry
UC Transportation Center, Graduate Student Researcher
University of California, Berkeley.
2614 Dwight Way, Berkeley, CA 94720
Phone: (510)717-9834
E-mail: ccherry@ce.berkeley.edu

Eric Tang
Cambridge Systematics, Inc.
555 12th St. Suite 1600 Oakland, CA 94607
Phone: (510)873-8700
E-mail: etang@camsys.com

Elizabeth Deakin
Director, UC Transportation Center
University of California, Berkeley.
2614 Dwight Way, Berkeley, CA 94720
E-mail: edeakin@berkeley.edu

Alexander Skabardonis
Institute of Transportation Studies
University of California, Berkeley
109 McLaughlin Hall, Berkeley, CA 94720-1720
Phone: (510) 642-9166, Fax: (510) 642-1246
E-mail: skabardonis@ce.berkeley.edu

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ABSTRACT

In many urban areas, High Occupancy Vehicle (HOV) lanes have been provided to permit carpools and express buses to bypass congestion and offer a significant travel time advantage to commuters willing to share a ride or take transit. In many locations, however, HOV lanes are incomplete due to difficulties in securing right of way or funding. In other locations, existing HOV lanes are underutilized and/or express buses are undersubscribed, raising questions about their value. In this research we show how a Paramics microscopic traffic simulation model can be used to analyze proposed HOV lanes and their effects on express bus operation along an urban freeway corridor. We develop a Paramics application for Interstate 580 in the San Francisco Bay Area and use it to test alternative ways of providing HOV lanes. We evaluate the performance of the corridor under plausible scenarios of traffic growth. Traffic simulation models are usually used for detailed operations management. The case study shows that traffic simulation can be an effective preliminary planning and scenario testing tool for evaluating the likely performance of an infrastructure or operations improvements on express bus service.

OBJECTIVES

This paper describes the processes undertaken to develop and calibrate a model of the Interstate 580 (I-580) freeway corridor in the San Francisco Bay Area as part of an overall Regional Express Bus study. Transportation modeling involving the use of Paramics has been widely performed at Caltrans and this project, like others, is using the tool to replicate and simulate existing and future traffic conditions. As with any demand modeling activity, a rigorous calibration procedure is required that compares the model output to field-measured traffic performance. This is essential when dealing with microscopic stochastic simulation models, as there are a large number of input model parameters that may be difficult to replicate and vary by location.

Once the model is calibrated, alternative geometry, demand, and operations can be simulated to determine the relative improvement to the existing base case scenario. The improvement can then be evaluated to determine if it is financially justified. In this case a High Occupancy Vehicle (HOV) lane will be added to the network. This HOV lane is essential to the improved operation of a regional Express Bus plan because it will allow the buses to bypass heavily congested freeway segments and provide competitive service along the corridor. Currently, there are many gaps in the HOV network in the San Francisco Bay area. Simulating the creation of these lanes will help prioritize which gaps are most critical to the Express Bus plan and which gaps are most financially feasible. The I-580 freeway was chosen because it has the right of way required for various HOV configurations and it is considered a critical HOV gap for a successful Express Bus plan. An effective HOV configuration maximizes the throughput of both HOVs and Single Occupant Vehicles (SOV). More specifically, it is important to improve the throughput of people, not necessarily vehicles. This is where an Express Bus route in an HOV lane can really show improvement to a system. HOV lanes have been modeled rigorously using Paramics *(1)* but few have considered modeling the improvement to an Express Bus network.

This paper briefly describes the background of the freeway corridor site. The next section will discuss the Paramics model and the input and performance data that was assembled for the study. The calibration of the model will then be discussed and the performance of the existing network will be analyzed. Alternative HOV alignments will then be modeled and their performance compared to the existing base case. Finally, recommendations for future work and conclusions will be presented.

BACKGROUND ON THE I-580 CORRIDOR

Interstate 580, the corridor selected for our application, is a primary east-west transportation corridor connecting the San Francisco Bay Area and the Central Valley of California, serving commuter, commercial, and recreational traffic. Over the past several years, population growth in the Central Valley as well as in the cities of Dublin, Pleasanton, and Livermore, which line the corridor, has led to a dramatic increase in traffic congestion on the I-580. This segment of I-580 is now among the busiest freeway corridors in the San Francisco Bay Area.

The freeway study corridor consists of a 25-mile segment of westbound I-580 extending from Interstate 205 in the east to just west of Interstate 680 in the west. This portion of I-580 includes 13 off-ramps and 15 on-ramps. A map of the freeway corridor study site is shown in **Figure 1**. There are currently no HOV lanes along the entire segment. However, there are existing HOV lanes or planned HOV lanes on I-680, to which much of the westbound traffic on I-580 connects. The road currently contains four lanes in each direction plus a few weaving areas. Additionally, there is a wide median where an HOV lane could potentially be added if it is found to be justified.

The study period was for the morning peak extending from 6:00 to 10:00 AM. This time period encompasses the heavily directional peak flow patterns in the westbound direction. The case analysis was limited to the westbound AM peak period because our primary interest is to develop and demonstrate the analysis procedure rather than to develop a specific recommendation for the corridor itself.

BACKGROUND ON PARAMICS

The Paramics model is a comprehensive microscopic stochastic simulation model that can be applied to a wide set of freeway, arterial, and network situations *(1, 2, 3, 4)*. The software allows the analyst to visualize simulated traffic conditions in a network in order to identify problem areas and their potential causes. Individual vehicles are modeled in fine detail for the duration of their entire trip, providing traffic flow, travel time, and congestion information. The internal structure of the Paramics model *(5,6)* includes the following six software modules:

- **Modeller**, the core simulation and visualization tool;
- **Processor**, the simulation configuration tool which allows the user to set up multiple network simulations to be run in batch mode;
- **Analyzer**, the post simulation statistics viewing tool whose primary function is to display and compile reports on statistical data output from Modeller;
- **Programmer**, the API (Application Programming Interface) to Modeller;
- **Monitor**, the interface that calculates the levels of traffic emission pollution on a road network.
- **Estimator**, the OD matrix estimation package that works at the microscopic level

Paramics Modeller provides three fundamental operations: model building, traffic simulation with 3-D visualization, and statistical output, available through a graphical user interface. Many aspects of the transportation network can potentially be investigated including integrated urban and freeway networks, advanced signal control, roundabouts, public transportation, car parking, incidents, truck or HOV lanes, or special lane usage.

The Paramics general model input includes:

- Network characteristics: geometry, link description, signposting, lane restrictions, forced lane changes
- Demand data: origin/destination zone areas, level of origin/destination demand, breakdown by time period, vehicle type and vehicle proportion
- Assignment: link cost factors, coefficients of generalized cost equations, assignment techniques
- General configuration: time step duration, speed memory, mean target headway, mean reaction time.

The model output includes statistics at the network level (overall travel time, total travel distance, average speed), on a link-by-link basis (with the Analyzer modules which reports statistics such as traffic flows, queue lengths, delays speeds and densities) or at specific locations (instantaneous detector type of information).

CONSTRUCTION AND CALIBRATION OF THE I-580 PARAMICS MODEL

A comprehensive data set made available by Caltrans at the beginning of this study that provided the research team with all data needed to develop and calibrate the model. The Caltrans data included a compilation of hourly traffic counts at various freeway locations and ramps in the corridor, collected on various days over several years, as well as travel time and speed data coincident with these volume counts over the entire freeway study segment.

Constructing a Paramics I-580 network that reflected morning peak conditions required us to establish and calibrate parameters in four categories: network, demand, overall simulation configuration, and driver behavior. The I-580 Paramics network was to include the I-580 freeway itself, all interchanges along the segment, and small portions of the intersecting arterials. A road categories file, a component of the geometry files in Paramics, was developed based on the operating speed and number of lanes of the roads as well as their relative importance to the roadway network. The network was then coded as a series of links and the categories assigned to those links specify the configuration of the lanes.

For the simulation configuration, we selected 5 time steps per second, meaning that calculations in the simulation are conducted every 0.2 seconds. This value was adopted based on a previous study where it was determined that high density flows often require frequent time steps per second to properly represent operations *(7).* Following the same study, speed memory, which is number of time steps a vehicle remembers its speed, was set at 8.

Paramics controls the movement of individual vehicles in the network using three basic models: vehicle following, gap acceptance, and lane changing. These models are strongly influenced by two key user-specified parameters: mean headway and mean reaction time. The overall behavior of the model can be changed considerably by increasing or decreasing the mean target headway and the mean reaction time. Previous research concluded that a 0.98 mean target headway and a 0.6 mean reaction time is appropriate for a California road network *(8).* However, these are only starting values, since each network will have unique values due to variations in driver behavior and unmodeled or inadequately modeled roadway design features and network geometry. Choosing the correct headway and reaction times is an iterative procedure implemented during the calibration phase.

Demand parameters relate to the pattern origin-destination (OD) matrix that is required to run a simulation in Paramics. A pattern matrix defines travel patterns between distinct pairs of zones. In order to generate a pattern matrix for the I-580 Paramics network, data was extracted from an EMME/2 *(9)* planning model developed by the Alameda County Congestion Management Agency (ACCMA). This model is built upon nodes, which represent points of origin and destination in the region; and links, which represent major thoroughfares and connect the different nodes. o extract travel patterns for the Dublin/Pleasanton/Livermore area that is modeled in the I-580 Paramics network, all nodes and links within the area covered by the Paramics network were flagged in the EMME/2 model, links at the boundaries of the sub-area were identified as gateway links and were given a special identifier that would treat the gateway like a node with inputs and outputs for the sub-area. Only the AM peak matrices were used; matrices for single, 2 and 3 occupancy vehicles for the peak hour interval were aggregated into one.

The final OD matrix that was extracted from the ACCMA model was comprised of 26 zones. Zone boundaries were then created in the Paramics network based on the location of the zones in the EMME/2 model. Adjustments were made in the calibration phase to the network geometry, vehicle routing options, OD matrix and general configuration parameters.

Calibration procedures for Paramics and other microsimulation software packages have been documented for various projects *(10, 11, 12, 13, 14)*. Several of these projects include calibration of similar freeway sections in the same region as I-580; so many of their findings were used to build the base case for this project.

As a preliminary step, the OD matrix was visually compared to the observed volume counts to identify loading discrepancies on the network. Several of the links of the network did not have matching loading patterns and the OD matrix was adjusted to reflect the observed volumes on the system. Once this was done, the model was loaded and vehicle counts at locations along the freeway were compared to flows from the Paramics Analyzer module *(6),* using Caltrans' Report Analyzer tool *(15)* to extract Paramics link speed and flow results.

Examination of the reports generated by Paramics Analyzer and Report Analyzer indicated that freeway congestion patterns observed under field conditions were not being replicated in the model during the first iteration; the freeway capacity estimated by the model was lower than observed capacity. To represent actual field conditions, fine-tuning was required for those freeway links where congestion was shown to occur. The geometric parameter that was modified, on a link-by-link basis, was the link headway factor. Additionally, the mean headway factor was reduced as well as the mean driver reaction time. These adjustments increased the model-estimated capacity of the bottleneck section, as well as the timing and severity of the congestion. Additionally, driver awareness and aggressiveness parameters were adjusted upward to reflect actual driving behaviors.

Model performance was then compared to field data on traffic flow, link speeds, and travel times. **Figure 2** shows the compared flow rates for the observed calibration points. Bottlenecks were activated in the model to determine the maximum flow observed for a link, i.e., its capacity. The demand periods were adjusted so that the peak flow pattern occurred at the same times as those that were observed. The GEH statistic *(11 pg. 61)* was developed to determine if a microsimulation model's performance is within an acceptable range of existing conditions. If the GEH statistic for all of the observations is less than 4, the model is said to be calibrated. In this case, the GEH statistic was 0.94 for all of the peak flow volumes. Speeds were compared at the same points that the flow rates were compared, with a GEH statistic of 3.24 (Figure 2).

Travel time was compared for the length of the corridor with travel time runs conducted by Caltrans. The average westbound travel time during the AM peak period from the I-205 interchange to Foothill Road (the interchange west of I-680) was 33.45 minutes, with a standard deviation of 4.65 minutes. The average travel time observed within the model was 38.45 minutes, or a difference of +15%. This was deemed to be within an acceptable range, given the limited amount of field travel time data.

ALTERNATIVE HOV LANE CONFIGURATIONS

As soon as the model was calibrated to produce acceptable flow, speed, and travel time results for the existing network, it was used to test infrastructure and operations improvements.

Buses along I-580 currently operate in mixed flow, so that the buses experience the same speeds and travel times as other vehicles. As a result, the bus rider has no time saving advantage while riding in the mixed flow lanes. Additionally, bus schedule reliability is compromised by the irregularity of congestion and delay in the system. This can be especially detrimental to an express bus commuter service, whose frequency is often lower than that of typical urban buses and whose customers often must connect to additional transit services to reach their destinations. The need to transfer to and from low-frequency services requires much higher schedule reliability than would be needed in denser, more frequently served urban transit networks.

HOV lanes offer improved schedule reliability as a result of more predictable travel time. Use of the HOV also can improve service by permitting the HOVs to obtain a travel time advantage over the SOVs. This extra time can offset the additional time required by the HOVs to pick up and drop off their passengers, so that the HOV is competitive with the automobile. While many HOVs can be used by carpools and vanpools as well as by buses, in this case study we are primarily concerned with travel time savings for express buses, but we also consider the effects of carpool use of the lanes under different rules of operation.

California has both 2+ occupancy HOV lanes, in which vehicles with two or more passengers are allowed to travel, and more restrictive 3+ occupancy and bus-only lanes and ramps. In most applications, motorcycles and buses are allowed in the HOV lane.

To investigate plausible rules for our I-580 simulation, we referred to the literature and to traffic classification data. A study of a similar section of freeway in the Bay Area identified approximately 10% of vehicles as two occupant HOVs and 5% as 3+ occupant HOVs *(1)*. The vehicle class distribution for this freeway, based on historical counts from Caltrans, is consistent with that study (**Table 1**) We therefore use a first estimate of 10% 2 occupant HOVs, 5% 3+ occupant HOVs, and 1% buses as a starting point for the analysis.

Adding an HOV lane to the current freeway configuration would increase the capacity from four lanes to five lanes. At current traffic volumes and the vehicle class assumptions listed above, the additional lane should be able to accommodate all HOVs with excess capacity. In our HOV simulation we therefore allowed 15% of the cars to use the HOV lane, along with the 1% of vehicle that we assumed to be express buses. This vehicle mix and lane usage was accomplished in Paramics by specifying the percentages of different vehicle types and by restricting the HOV lanes to specified types.

Previous research has shown that drivers in HOV lanes behave differently from drivers in mixed flow lanes. The drivers in the HOV lanes tend to stay in their lanes longer and reduce erratic lane changing and passing movements. We used a Paramics developed HOV driver behavior plug-in that allows the user to adjust parameters for passing behavior and patience thresholds, ability to look ahead and see and respond to HOV lanes, and lane changing parameters, both for the HOV users and the SOV users around HOV lanes. The parameters used for this project were the same as those calibrated and used for another similar project on I-680 *(1)*.

Finally, we considered alternative HOV lane configurations. The most common HOV lane configuration in the San Francisco Bay area is a non-barrier separated lane on the inside (median) side of the road. The design allows for continuous lane changing throughout the section. In southern California, many HOV lanes have a “barrier” separation painted on the road surface that prohibits lane changing, allowing it only at specific weave sections. Typically there are many interchanges between weave sections, so an HOV using those intersections must enter the HOV lane well downstream of their origin interchange and/or must exit the HOV lane well in advance of their exit interchange. This undoubtedly reduces HOV lane use, but it does however eliminate last minute multi-lane crossing maneuvers.

Another, less common HOV lane configuration places the HOV lane in the outside shoulder lane. Having a shoulder HOV lane would facilitate safe and efficient HOV merging and diverging from the freeway section, but it presents some difficult weave considerations. This strategy has been used in several cities including Minneapolis and Seattle.

For each alternative, we report performance in terms of travel time savings for the entire 25-mile length of the freeway segment. While not all vehicles travel this entire length, the overall time savings do provide an indication of relative performance for the alternatives. A more detailed examination of link level performance would allow the analysis to extend to implementation phasing, etc.

Median HOV Lane

The first HOV strategy modeled using Paramics was the implementation of a non-barrier separated HOV lane in the median lane (**Figure 3**). The HOV lane was added to the median side of the roadway, providing an additional lane for 2+ HOVs, motorcycles, and buses. This alignment provides fluid movement from the beginning of the segment to the destination. Additionally, the lane allows continuous weaving between the HOV and the mixed flow lanes. This is beneficial in the sense that vehicles can move in and out of the HOV lane when necessary, but it can also create friction between the mixed flow and HOV lane. This friction can reduce the performance of the HOV lane because of vehicles slowing to try to exit the lane. It can also be a safety hazard in the case of highly differential speed between the mixed flow and HOV lanes, as vehicles must rapidly accelerate and decelerate as they enter and exit the lane. Many vehicles that must exit will stay in the HOV lane as long as possible and will choose to exit at the last minute to realize the maximum travel time savings. This can be hazardous as well as detrimental to maximization of traffic flow.

An HOV lane was coded into the Paramics network for the entire length of the I-580 study segment. Adding the fifth HOV lane to the existing four-lane section increased the freeway's capacity dramatically and not only sped up HOVs, but on many links allowed higher speeds and flows for the SOVs remaining in the mixed flow lanes. However, some of the corridor currently has high speeds (**Figure 2**) and flow rates (downstream of Tassajara Road), so in those sections the HOVs do not experience much travel time saving over the SOVs. Nor does the added capacity contribute to added throughput, as there is already excess capacity in these links - presumably the discharge capacity of the upstream bottleneck. The discharge capacity of the upstream bottleneck increases with the addition of the HOV lane, but only by the amount of HOVs that actually use the HOV lane and are thus out of the mixed flow lanes.

The Caltrans District 4 HOV Lane Report *(16)* states that about 85% of the vehicles that are eligible for an HOV lane will use it. Applying this rule of thumb in our analysis, we assume that 14% of all vehicles (85% of the 16% HOVs and buses) will use the HOV lane. This is consistent with the Paramics model results.

With the added lane, the average travel time during the peak experienced by mixed flow vehicles with from the I-205 interchange in the east to Foothill Road in the west was 32.23 minutes. The average travel time for vehicles traveling in the HOV lane was 22.47 minutes. This is a significant time savings for both the HOVs and the SOVs from the original travel time of 38.45 minutes (**Table 2**).

Barrier-Separated HOV Lane

A barrier separated HOV lane consists of a lane added in the median of the roadway (**Figure 3**). This barrier can take the form of paint striping that indicates that vehicles are prohibited from changing lanes in certain sections or it could consist of an actual hard barrier that is a physical separation from the mixed flow lanes. Both types of lanes perform in a similar manner, although there are different safety features and violation types for each type of barrier-separated HOV lane.

There are pros and cons to this design. A barrier separation reduces friction along the route, allowing the HOV lanes to operate in a much more freely flowing manner. It also allows vehicles to travel safely with much higher speed differentials between adjacent lanes. Also, barrier separated HOV lanes have to have weave sections where an HOV can exit or enter the HOV lane. These weave sections need to be strategically placed so that HOVs can remain in the HOV lane as long as possible and only exit in order to have enough time to cross the mixed flow lanes and exit the freeway. However, weave sections reduce the operational effectiveness of the HOV lane so the number of weave sections should be minimized.

One strategy is to strategically locate the weave sections to meet the needs of express bus service. That is, a weave section should be placed just upstream of the ramp that a bus needs to exit, with enough distance for the bus to comfortably cross the lanes to get to the exit. (A weave section placed too far upstream will cause the bus to travel in the mixed flow lanes too long, reducing its advantage over SOVs.)

To model this barrier separated HOV lane strategy, the Paramics network was edited to add the HOV lane as an entirely separate single lane link that merges and diverges with the mixed lane traffic. The weave sections operate primarily like the previously discussed median HOV lane weave sections. The weave sections were placed in locations that would serve the most interchanges without long distances in the mixed flow lanes. The locations were just upstream of interchanges with large off-ramp demand and just downstream of interchanges with large downstream demand.

The model-estimated travel time for HOVs and express buses in the HOV lane from the I-205 interchange to the Foothill Road interchange was 29.25 minutes. The travel time in the mixed flow lanes was 34.87 minutes. While the travel times are an improvement compared to mixed flow conditions, they are not as advantageous as the median HOV lane without barrier separation–largely due to 1) HOVs being stuck in the mixed flow lanes longer than they otherwise would, because of inability to move into the HOV lane except at specified locations, and 2) general slowing of traffic due to concentrated weave activity.

Shoulder HOV Lane

An alternative HOV alignment that has been used in some States is a shoulder HOV lane (**Figure 3**). Utilizing a shoulder HOV lane allows HOVs and buses to always stay in the right hand lane and exit without crossing all of the mixed flow lanes. This would enable an express bus to serve the entire corridor without ever driving in a mixed flow lane (except at merge and diverge points). The problem with this configuration is that SOVs must merge onto the freeway and quickly merge into the mixed flow lanes. This is problematic if the mixed flow lanes are congested and slow moving, while the HOV lanes are in a free flow state. The SOVs would enter the freeway at high speeds and be forced to slow rapidly to merge with the mixed flow lanes. This could severely hinder the flow of the HOV lane. Additionally, this HOV lane would experience some of the same friction effect of traveling next to slow moving traffic. In addition, HOVs from the mixed flow lanes would be allowed to merge into the HOV lane at any point, which could be dangerous with large speed differentials.

We modeled the shoulder lane configuration in Paramics and found a travel time for the HOVs of 30.48 minutes, as well as an SOV travel time of 33.65 minutes. This is the worst performance of the three alternatives for the HOVs, but the best performance for the SOVs. This result is presumably because the SOVs are not (much) affected by HOV weaving, but the HOVs are affected by SOVs at each on and off-ramp section. These sections are typically the most congested along this corridor. Because of this congestion at the shared locations, the HOVs and buses do not have a travel time advantage over the SOVs where there is the greatest opportunity to gain time.

Our modeling procedure may be partly responsible for the comparatively poor performance produced for the shoulder lane alternative. We assumed that the SOVs would be allowed to use the HOV lanes near on and off ramps. Observing the simulation results, we saw that SOVs sometimes would use the shoulder lane for a short distance to pass congestion. The HOV lane is then reactivated and the SOVs must quickly exit the shoulder lane. This causes a bottleneck at the points where the shoulder lane turns from a mixed flow to an HOV. Additionally, Paramics software has some difficulty modeling vehicles in the shoulder lane at merge and diverge points. Paramics gives warnings to the drivers of on and off ramps by way of signposting. This encourages drivers to get into and out of the shoulder lane based on merge and diverge patterns, not based on HOV status. Care must be taken when modeling signpost distance in conjunction with a shoulder HOV lane.

Overall, the travel time improvement of HOVs relative to SOVs is lower than for other HOV alternatives, but buses may still have an advantage depending on the number of times they need to stop along the corridor. If a bus is required to merge in and out of a median HOV lane frequently, it may not realize the improved travel time provided by the HOV lane because it will be spending much of its time in mixed flow lanes. With a shoulder lane, the bus will be able to exit and enter the freeway with minimum disruption from mixed flow traffic.

ALTERNATIVE GROWTH SCENARIOS

The regions surrounding this corridor are experiencing high levels of growth. This implication is that the traffic will likely grow quite rapidly in the coming years. This growth is likely to have major impacts on the amount of congestion experienced by the express buses, especially in the absence of HOV lanes.

In order to model this growth, two scenarios were simulated (**Table 2**). The first scenario increased the traffic by 5% throughout the corridor. This increase was modeled for all four cases: the base case, the median HOV lane, the barrier-separated HOV lane, and the shoulder HOV lane. Overall, the travel times followed the same trend as the current demand pattern. As expected, the travel time increased for both the SOVs and the HOVs. Again, the median HOV performed better in terms of travel time savings and advantage over SOVs, followed by the barrier-separated case, then the shoulder case. The median HOV travel time was 23.92 minutes compared to 37.52 minutes for the SOVs. This is a significant improvement and advantage. The HOV reduction in travel time is insignificant from the current demand level because of the excess capacity of the HOV lane. The barrier separated case actually performed better for the HOVs and worse for the SOVs than the shoulder HOV lane. This could be attributed to more concentrated vehicle merges into and out of the barrier separated HOV lanes.

The next scenario was a system wide 10% increase in demand. Similarly, this caused more congestion and increased the travel time for all vehicles. The travel time increase is most severe for the SOVs; in comparison HOVs still experience much shorter travel times (particularly with the median, and barrier-separated HOV lanes). Surprisingly, the barrier-separated HOV provides shorter travel times than the barrier-separated 5% growth case. This could be because the HOVs and express buses will utilize the HOV lane at a much higher rate and for the entire length of the corridor in the high demand case. In the lower demand cases, they might choose to exit the HOV lane because it is flowing freely in sections and then get stuck in congestion because of the barrier separation. The shoulder case provide less and less of an advantage as congestion gets worse on the mixed flow lanes. Again, the congestion occurs most heavily at the interchanges, where HOVs have to travel in mixed flow lanes with the shoulder lane case, thus reducing their overall travel time advantage.

Overall, this is an effective tool to identify the type of demand scenarios that produce the most problematic results. Combined with analysis of different geometric alternatives, policy can be enacted to attempt to control demand in a responsible manner.

CONCLUSION AND FUTURE DIRECTIONS

This case analysis has demonstrated that traffic operations microsimulation software can be an effective tool in evaluating alternative infrastructure improvements for HOVs Once the microsimulation base case has been set up and tested, it is relatively easy to test alternative configurations (e.g., various designs and locations for the HOV lane) and alternative operating rules (e.g., two vs. three person eligibility) for lane use. The analyses show that it is possible to analyze future improvements to an Express Bus system. With the results of these analyses, many inferences can be made to identify the effectiveness of an infrastructure or operations improvements. These results can then be compared to determine which alternative has the greatest improvement to Express Bus service as well as traffic operations as a whole.

In the case studied, three alternative alignments for HOV lanes were each shown to offer considerable benefits over mixed flow operations. For the case study conditions, a median continuous HOV lane offered the highest travel time savings as well as the greatest performance differential between mixed flow traffic and HOV traffic. The shoulder lane produced the smallest improvement for the HOVs (considering travel for the full length of the section studied) but the biggest improvement for the SOVs. However, if a bus had to exit and re-enter the freeway at several locations, much of the travel time savings could be lost by traversing through the mixed flow lanes, so the shoulder lane might be a preferred option.

Future work would include modeling specific scenarios that would identify bus routes and model their movement through mixed flow lanes while attempting to exit the HOV lanes. Scenarios can be analyzed to identify the most beneficial interchanges where the bus could exit as well as the most beneficial locations for weave sections into and out of the HOV lane. Additionally, the model could be fine tuned to identify specific areas where the greatest travel time improvement is likely to happen and focus the investment on those areas. Different demand scenarios can be modeled and policy can be implemented that would attempt to realize the most beneficial demand scenario. Additionally, alternative HOV lane rules, such as the allowance of tolled SOVs by converting the lane into a High Occupancy Toll (HOT) lane could be modeled. This would fill the excess capacity of the HOV lane and reduce the congestion on the mixed flow lanes. All of these improvements have differing effects on Express Bus service. Through modeling these improvements using microsimulation software, high-return alternatives can be identified and policy enacted to aid in the implementation of an efficient and competitive Express Bus system.

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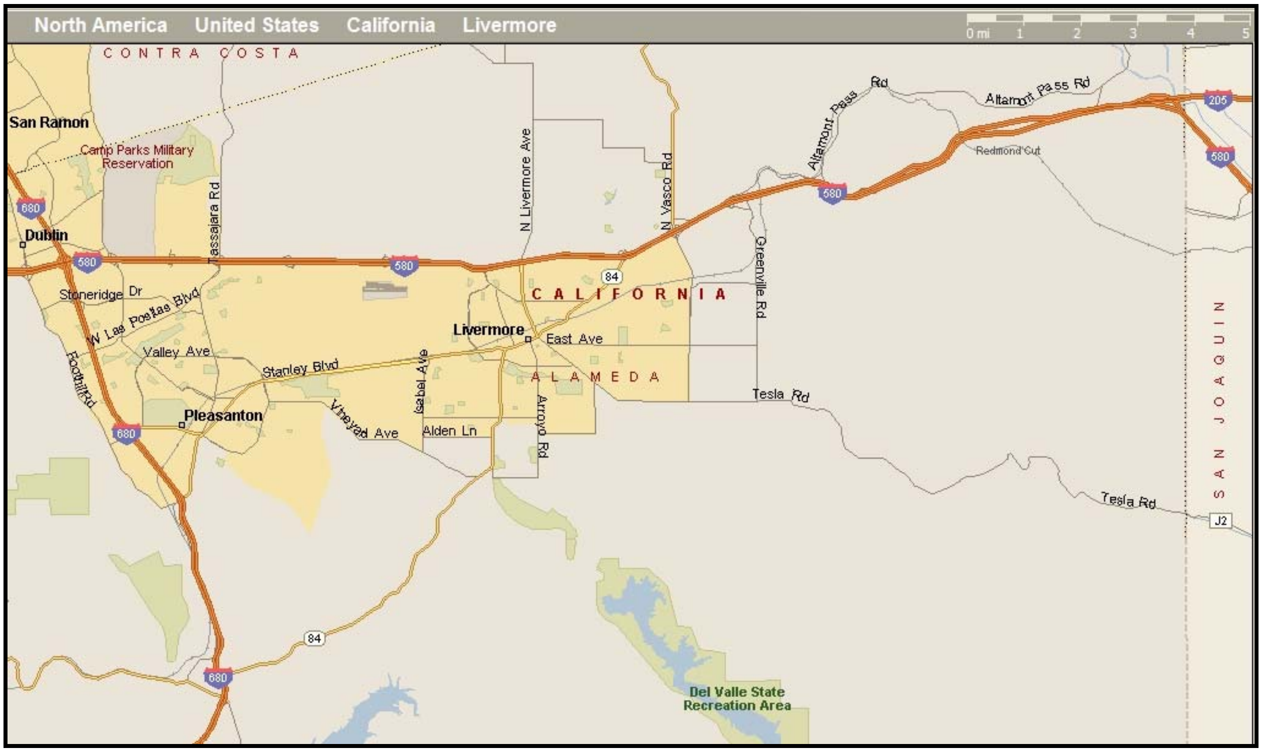


FIGURE 1 Map of the Freeway Corridor Study Site

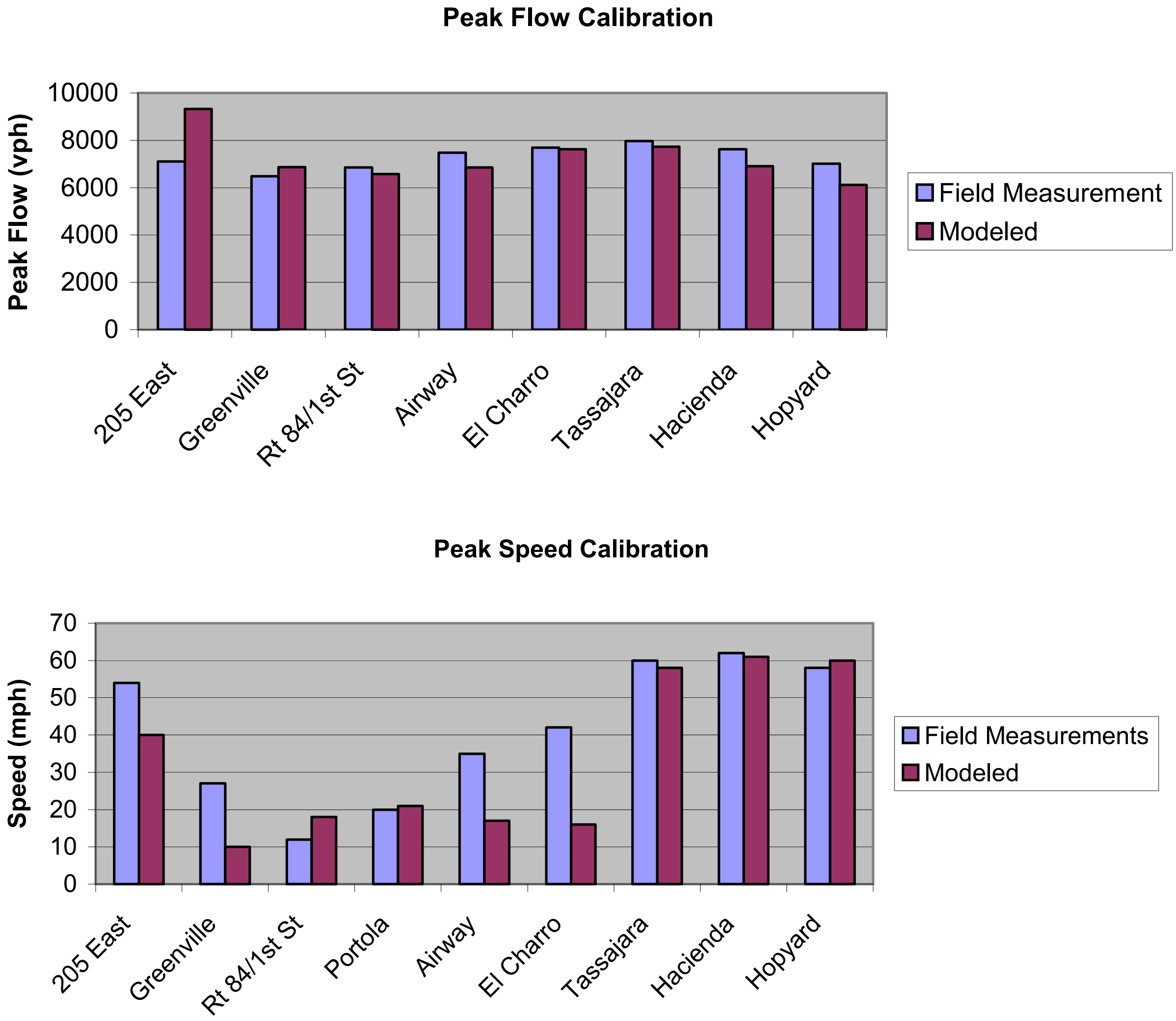
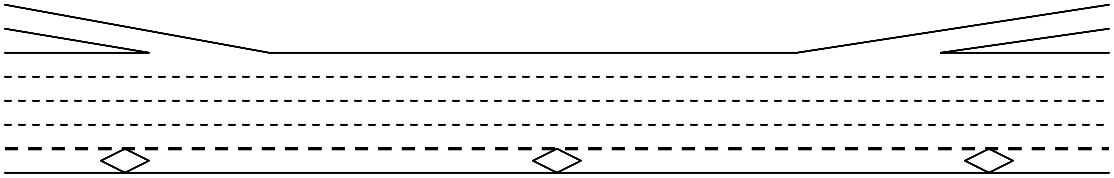
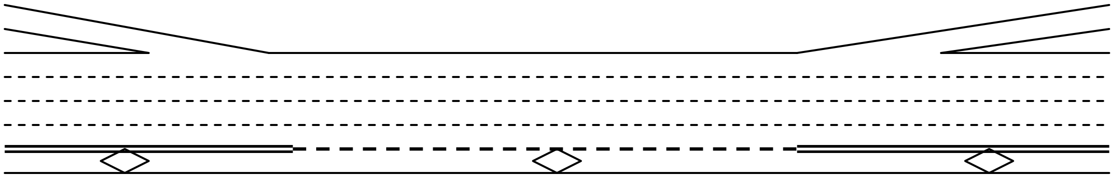


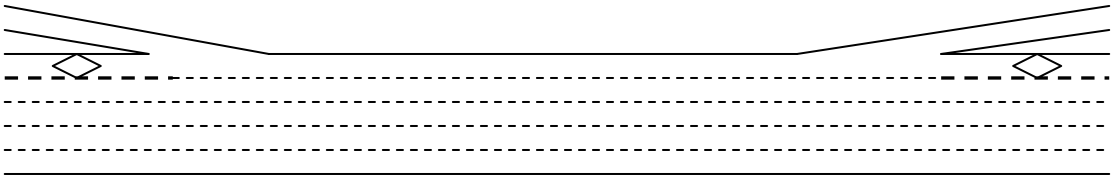
FIGURE 2 Modeled vs. Field Flow and Speed Comparison



Median HOV Lane



Barrier Separated Median HOV Lane



Shoulder HOV Lane

FIGURE 3 Alternative HOV Configurations

TABLE 1 Vehicle Fleet Composition

Type 1	SOV	70%
Type 2	2+ HOV	15%
Type 12	Light Truck	8%
Type 13	Medium Truck	3%
Type 14	Heavy Truck	3%
Type 15	Coach (Express Bus)	1%

TABLE 2 HOV Alternative Travel Time Comparison

	High Occupant Vehicles and Express Buses				**Single Occupant Vehicles**			
	Current Demand		**5% Growth**	**10% Growth**	**Current Demand**		**5% Growth**	**10% Growth**
Note: All Travel Times are in Minutes	**Average Travel Time**	**Standard Deviation**	**Average Travel Time**	**Average Travel Time**	**Average Travel Time**	**Standard Deviation**	**Average Travel Time**	**Average Travel Time**
Existing	38.45	3.32	40.03	42.62	38.45	3.32	40.03	42.62
Median	22.47	4.07	23.92	25.31	32.23	1.55	37.52	40.61
Barrier Separated	29.25	3.87	33.65	24.17	34.87	1.92	38.00	38.96
Shoulder	30.48	1.50	36.25	36.08	33.65	1.65	38.60	38.50