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Authors

Brownstone, David
Chu, Lianyu
Golob, Tom
et al.

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UNIVERSITY OF CALIFORNIA, BERKELEY

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EVALUATION OF INCORPORATING HYBRID VEHICLE USE OF HOV LANES

Final Report

David Brownstone[1]
Lianyu Chu[2]
Tom Golob[1]
K.S. Nesamani[1]
Will Recker, P.I.[1]

[1] Institute of Transportation Studies, University of California, Irvine
[2] California Center for Innovative Transportation, University of California, Berkeley

ABSTRACT

This report presents a method to investigate the operational and environmental effects of the policy of allowing qualified single-occupancy hybrid vehicles to use dedicated High-Occupancy Vehicle (HOV)/carpool lanes in California.. The method combines the traditional planning method with microscopic simulation modeling. The planning method is used for demand estimation and analysis and the microscopic traffic simulation modeling method is used for accurate measures of the system. The study employs a microscopic traffic simulation model that is capable of evaluating the HOV/hybrid system and providing detailed outputs that are not available in conventional static models. The study also includes detailed emissions modeling in order to estimate accurate emissions by integrating emission models into microscopic simulation models. An important aspect of the study involves predicting future hybrid vehicle demand; hybrid demand models are developed based on consumers' automobile choice behavior analysis. This is modeled both with standard network calculations employing network assignments sensitive to time savings from HOV lane use as well as using estimates of the locations of households owning hybrid vehicles and the O-D matrices for the hybrid drivers. We use these results to modify existing models to enhance their accuracy for hybrid vehicles. The updated models are then be applied to data from the recent Caltrans 2000-2001 Statewide Household Travel Survey and the 2001 National Household Travel Survey (NHTS). These survey data allow us to locate the households and trip destinations of likely hybrid vehicle owners. Results from previous studies of demand for toll lanes have established monetary values of saved travel time that can be applied to estimated time savings from network simulations to forecast incentives for purchase of hybrid vehicles. We also develop a supply-side model to estimate availability and prices of hybrid vehicles by body type and manufacturer and price in order to forecast penetration of hybrid vehicles. A total of four different scenarios were constructed. With the assumption that the total demand for all scenarios remains the same and the hybrid-HOV policy results in some solo drivers switching to hybrid vehicle drivers, these four scenarios are evaluated in terms of a set of operational performance measures and air quality measures. The key findings from this study are summarized as follows:

- The initial wave of single occupant hybrid vehicles entering the HOV lanes do not have a substantial negative impact on HOV lane operations.
- A hybrid demand exceeding 50 thousand statewide will have significant impact on the HOV lane operations in OC.
- From the air quality perspective, a high share of hybrid vehicles will cause fewer emissions.

Keywords: HOV, Hybrid Vehicle, Environmental Effects

EXECUTIVE SUMMARY

Federal and State governments are investing billions of dollars in building and promoting usage of High Occupancy Vehicle (HOV) lanes through various programs. HOV lane construction has become a major freeway improvement strategy. However, there still remain questions on the effectiveness of HOV systems. With the passage of the Federal Transportation bill on August 10, 2005 and Assembly Bill 2628 (AB 2628) on September 23, 2004, qualified single-occupancy hybrid vehicles were permitted to use dedicated High-Occupancy Vehicle (HOV)/carpool lanes in California. This policy was expected to reduce air pollution by encouraging drivers to use less fuel as well as ease traffic congestion through more efficient use of the reserve capacity on the HOV lanes.

For policy makers, how the policy impacts the performance of the traffic system (both on HOV lanes and on general-purpose lanes) is of interest. The traditional method to evaluate possible impacts of a new policy is to use a transportation planning model. However, this method is not appropriate for the evaluation of the hybrid-HOV policy since its impacts involve both demand forecasts and traffic flow and are likely to be confined to localized sections of the freeways involved. This project proposes an improved method to investigate the operational and environmental effects of the policy. The method combines the traditional planning method with microscopic simulation modeling. The planning method is used for demand estimation and analysis and the microscopic traffic simulation modeling method is used for accurate measures of the system.

The study site is the Orange County (OC) freeway network located in Southern California. The microscopic simulation software used in the project is Paramics. The Paramics simulation model is developed and calibrated based on observed data. The demand for the model is originally extracted from the Orange County Transportation Analysis Model (OCTAM) and further fine-tuned in Paramics OD estimator. The hybrid demand is obtained from a hybrid demand model that is developed based on consumers' automobile choice behavior analysis.

Based on the understanding of the hybrid-HOV policy applied in California, four scenarios were constructed. With the assumption that the total demand for all scenarios remains the same and the hybrid-HOV policy results in some solo drivers switching to hybrid vehicle drivers, these four scenarios are evaluated in terms of a set of operational performance measures and air quality measures. The key findings from this study are summarized as follows:

- The initial wave of single occupant hybrid vehicles entering the HOV lanes do not have a substantial negative impact on HOV lane operations.
- A hybrid demand exceeding 50 thousand statewide will have significant impact on the HOV lane operations in OC.
- From the air quality perspective, a high share of hybrid vehicles will cause fewer emissions.

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1. INTRODUCTION

High-Occupancy Vehicle (HOV) lanes have been regarded as a cost-effective and environmentally friendly option to help move people along congested routes. The Federal Highway Administration (FWHA) encourages the installation of HOV lanes as an important part of an area-wide approach to help metropolitan areas address the needs they have identified for mobility, safety, productivity, environmental, and quality of life.

Since having the first HOV toll bypass on San Francisco-Oakland Bay Bridge in 1970 in California, HOV systems have been extended statewide. Federal and State governments are investing billions of dollars in building and promoting usage of HOV lanes through various programs (Poole and Orski, 2003). Currently, there are about 2,500 miles of HOV lanes in the US and there are about 1,300 HOV lane miles in California alone.

HOV lane construction has become a major freeway improvement strategy. Many states, including California, have demonstrated the effectiveness of HOV lanes and are in the process of completing the HOV lane network.

In spite of wide adoption of policies relating to HOV facilities by many states, Metropolitan Planning Organizations (MPOs) and cities, there still remain questions on the effectiveness of HOV systems. Questions include HOV facility's cost-effectiveness and its impact on air quality. These questions apparently arise from concern that the conversion to a HOV lane might cause more congestion and higher emission by worsening the traffic condition on general-purpose lanes. In reality, HOV lanes may not be an appropriate option for every situation, and their benefit and impact may vary by the location and situation. However, the benefit of HOV systems has not been well quantified mainly due to the lack of analysis tools quantifying the benefit of HOV systems. In particular, air quality impact has not been accurately measured.

With the passage of the Federal Transportation bill on August 10, 2005 and Assembly Bill 2628 (AB 2628) on September 23, 2004, qualified single-occupancy hybrid vehicles were permitted to use dedicated High-Occupancy Vehicle (HOV)/carpool lanes in California. This proposed policy was expected to cut down the amount of air pollution by encouraging drivers to use less fuel as well as ease traffic congestion through more efficient use of the reserve capacity on the HOV lanes. This policy allows only the most fuel efficient (45 mpg or higher) and cleanest hybrid vehicles (Ultra low emission vehicle) to use HOV lanes irrespective of number of occupants. Currently, there are only three qualified models of hybrid vehicles: Honda Civic Hybrid, Honda Insight, and Toyota Prius.

For policy makers, how the policy impacts the performance of the traffic system (both on HOV lanes and on general-purpose lanes) is of interest during the policy planning process. Policy makers still want HOV lanes to be attractive for carpoolers and hope that the policy will not deteriorate the performance of HOV lanes significantly. However, one statistic shows that HOV lanes in Orange County reached almost their capacity (1,650 vehicles per hour) by carrying an average of 1,568 vph in 1998 while HOV lane utilizations in LA County and San Francisco Bay Area are 1,013 and 930 vehicles, respectively (Legislative Analyst Office, 2000). This implies that an understanding of current and future demand on HOV lanes is the key to success of HOV/hybrid proposal.

The traditional method to evaluate possible impacts of a new policy is to use a transportation planning model. HOV is a demand management policy that motivates solo drivers to switch to carpool in order to save travel time. In addition, HOV is a traffic management strategy since HOV drivers select HOV lanes or general-purpose lanes based on traffic conditions. As a result, the hybrid-HOV policy will dynamically impact the whole traffic system and thus the planning level study is not appropriate since it is an analysis based on BPR functions and it can not capture driver behaviors.

Alternatively, with the advancement of computer technologies and traffic modeling capabilities, microscopic simulation modeling has become an increasingly popular and effective tool for analyzing a wide variety of dynamic problems not amendable to study by other means. Microscopic traffic simulation emulates traffic systems at a level that includes detailed specification of roads, individual drivers, and vehicles. Micro-simulation has many applications, including ITS evaluation (Chu, L. et al 2004a), construction management (Chu, L. et al 2005), operational improvement, emission (K. S. Nesamani et al 2007), corridor management plan (Ban, J. X, et al 2007), traffic control studies (Liu, H. X. et al 2002, Chu, L. et al 2004b), policy investigation (Breiland, C., et al 2006), etc. Similar to planning studies, it can guarantee that the same demand pattern is applied both “before” and “after” the deployment of a policy in order to provide an objective evaluation. It can be used either before or after implementation of a policy or strategy. Its shortcoming is that the results of the evaluation may be influenced by theoretical limitations of its base traffic models.

This project proposes an improved method to evaluate hybrid-HOV policy. The method combines the traditional planning method with microscopic simulation modeling. The planning method is used for demand estimation and analysis and the microscopic traffic simulation modeling method is used for accurate measures of the system.

This report is organized as follows. Section 2 presents the methodology. Section 3 describes the study site. Section 4 explains the method for hybrid demand estimation. Section 5 provides the details of micro-simulation modeling followed by details of evaluation study and result analysis in Section 6. Policy implications and conclusions are given in Sections 7 and, 8, respectively. Finally, some recommendations are offered in Section 9.

2. METHODOLOGY

The study method is illustrated in Figure 1. The microscopic simulation model for the study site was built and then calibrated against the baseline traffic conditions. In the simulation model, the demand of the baseline model was originally extracted from the regional planning model and then further fine-tuned using the Paramics OD estimator tool. The traffic analysis zone level distribution of hybrid demand was estimated using socio-economic data and DMV records. Based on the California hybrid vehicle bill, different scenarios were designed and their corresponding travel demands were estimated according to the baseline demand, hybrid demand distribution, and hybrid population of each scenario. Next, the calibrated simulation model is simulated under different scenarios and simulation results will be analyzed and compared in order to show the effects of the policy under different hybrid population.

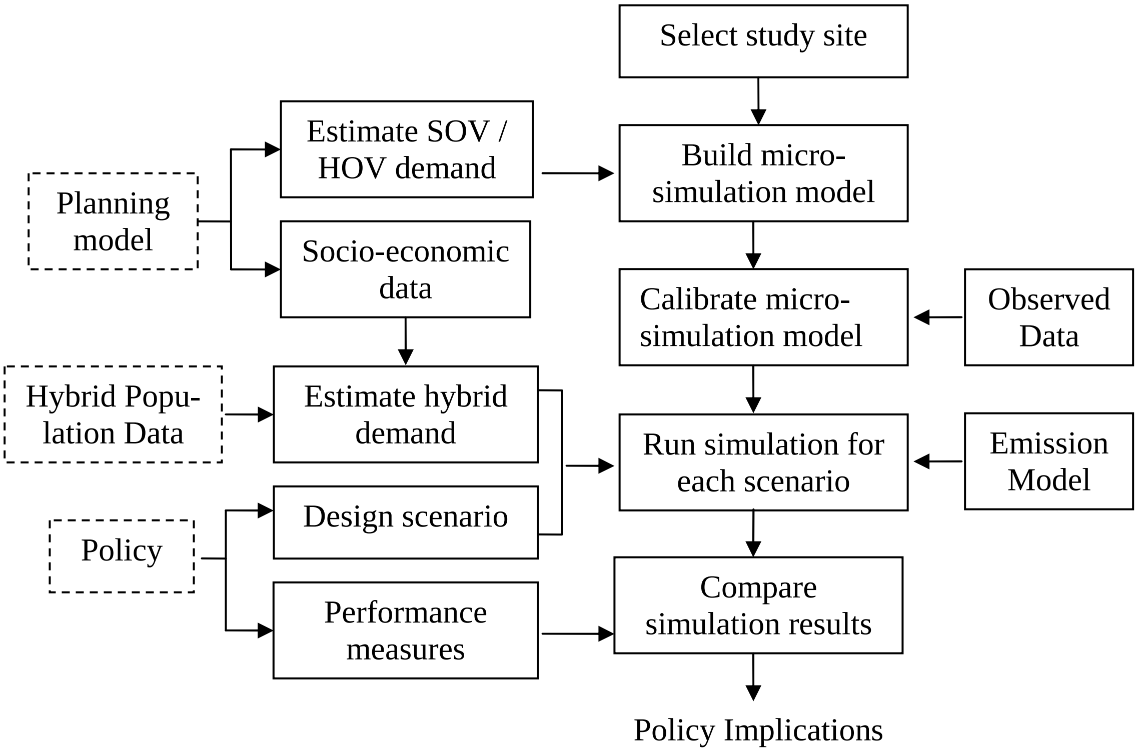


Figure 1. Methodology

The study involves three important modeling components:

(1) Microscopic simulation modeling

(2) Emission modeling

(3) Demand modeling

1. Microscopic simulation modeling

This study employs a microscopic traffic simulation model that is capable of evaluating the HOV/hybrid system and providing detailed outputs that are not available in conventional static models. Microscopic simulation is appropriate for investigating the hybrid-HOV policy since microscopic simulation models are designed to emulate the movement and behavior of individual vehicles on urban and highway road networks. With the majority of HOV lane delays related to vehicle-to-vehicle interactions, microscopic models are well suited to study the impacts of hybrid-HOV policies.

2. Emission modeling

This study also includes detailed emissions modeling in order to estimate accurate emissions by integrating emission models into microscopic simulation models. Current computer models lack sufficient detail required to properly predict emissions inventories at different scales. Shortcomings of these models/data include inaccurate characterization of actual driving behavior and a disregard of important vehicle operating parameters that affect emissions. The emissions model employed in this study is a new generation of models that can accurately predict the energy and air quality impacts of transportation systems, operating at the micro-, meso-, and macro-scale levels-of-detail.

3. Demand modeling

The demand matrix for the study network for Single Occupancy Vehicle (SOV), HOV, and hybrid vehicles are estimated from a suite of socio-economic models. The hybrid demand estimation is a particularly important aspect of this study.

3. STUDY SITE

The study site for this research is located in Southern California. Figure 2 shows the map of Orange County, California. Orange County is a densely populated portion of the Greater Los Angeles metropolitan area, with 3 million inhabitants in 800 square miles with 1.8 million cars registered. As can be seen from the map in Figure 2, the freeway network is quite dense and serves both internal and through traffic.

The study network includes all the major freeways in Orange County: I-5, I-405, SR-55, SR-22, SR-57, and SR-91 except the southern part of I-5 (from county line to La Novia Ave located at City of San Juan Capistrano) and I-605. Toll roads with express lanes—SR-73, SR-241, SR-261, north of SR-133, SR-91— are not included in the model.

This network also contains a well-developed set of access-controlled HOV lanes on the I-405, I-5, SR-55, SR-91 and SR-57 freeways. The HOV lanes have freeway-to-freeway connectors at the junctions of the I-5 and SR-55, I-5 and SR-57, I-5 and SR-91, I-5 and I-405, I-405 and SR-55 and SR-57 and SR-91 freeways.

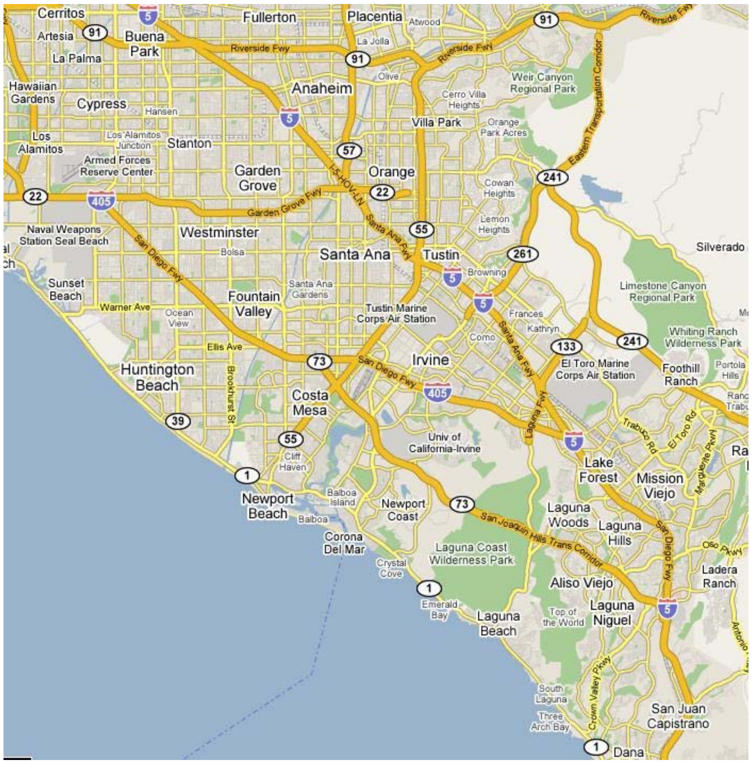


Figure 2. Study Site in Southern California (source: google)

4. HYBRID DEMAND MODELLING

The target of the hybrid demand estimation is to predict the number of hybrid vehicles for all transportation planning zones based on their respective socio-economic characteristics.

4.1 Methodology

An important aspect of this study is to predict future hybrid demand. The HOV/hybrid system is expected to promote the use of hybrid vehicles by providing travel time savings and travel reliability. How these benefits affect the hybrid vehicle market is a key component to predicting future hybrid vehicles on HOV lanes. While benefit from the HOV/hybrid system is estimated by supply side analysis using the microscopic simulation model, the hybrid vehicle demand requires an automobile market analysis. In this study, hybrid demand models are developed based on consumers' automobile choice behavior analysis.

Allowing hybrid vehicles to use HOV lanes can affect traffic congestion, overall fuel usage and vehicle emissions through at least four channels. First, most consumers who already have (or who would have otherwise purchased) hybrids will switch from regular to HOV lanes whenever they can as part of their normal driving. This could affect emissions from other vehicles by reducing congestion in the regular lanes.

Second, hybrid owners might change the routes or destinations of their existing trips so that they can take advantage of HOV lanes. This would shift patterns of traffic congestion among routes. Increased congestion could occur on routes with HOV lanes, both in the HOV lanes and in the regular lanes used to access HOV lanes.

Third, hybrid owners might make more or longer trips since using HOV lanes would reduce their travel times. If these new trips were substitutes for trips that would have been made in a non-hybrid household vehicle, then this would lead to reduced emissions and fuel usage. UCI researchers have modeled such effects in terms of household purchase of alternative-fuel vehicles, using stated preference data. Previous results showing a substitution effect for limited-range electric vehicles could be greater for hybrid vehicles without range and refueling restrictions.

Finally, households might be more inclined to purchase a hybrid vehicle by the prospect of reduced travel times from HOV lane usage. This effect could lead to the largest impact on traffic congestion and reduction in emissions and fuel usage, since the hybrid will replace many trips previously made in gasoline and diesel vehicles. We will also need to account for a rebound effect, whereby reduced operating costs and reduced travel times can lead to an increases in the number of miles driven by the household.

The first two channels are modeled with standard network calculations employing network assignments sensitive to time savings from HOV lane use. We also estimate the location of households owning hybrid vehicles and the O-D matrices for the hybrid drivers. DMV registration data are used to give the location of current hybrids.

The last two channels require more complex modeling of household vehicle demand and utilization. UCI researchers have specified and estimated relevant models using data from the mid 1990s, but their models were complicated by their emphasis on limited-range electric and natural gas vehicles. Assuming that consumers treat hybrids identically to other high capital and low operating cost vehicles, the models required are similar to those being developed at UCI and UC Davis to model the effects of California's Greenhouse Gas law. We use these new results to modify the existing UCI models to enhance their accuracy for hybrid vehicles. The updated UCI models are then be applied to data from the recent Caltrans 2000-2001 Statewide Household Travel Survey and the 2001 National Household Travel Survey (NHTS). These survey data allow us to locate the households and trip destinations of likely hybrid vehicle owners. Results from UCI studies of demand for toll lanes have established monetary values of saved travel time that can be applied to estimated time savings from network simulations to forecast incentives for purchase of hybrid vehicles. We also develop a supply-side model to estimate availability and prices of hybrid vehicles by body type and manufacturer and price in order to forecast penetration of hybrid vehicles.

4.2 Model development

Since collecting new data at the zone level is prohibitively expensive, we used existing socio-economic data from Orange County Transportation Analysis Model (OCTAM) model obtained from Orange County Transportation Authority (OCTA). OCTAM is a large travel demand model consistent with Southern California Association of Governments (SCAG) model, which covers all of Los Angeles, Orange, Ventura counties and western portion of Riverside and San Bernardino counties. OCTAM has 2940 traffic analysis zones (TAZ) of which about 1282 zones are external to OC (including cordon stations). OCTAM model classifies the links based on the facility type such as freeway, HOV facility, toll road, primary arterial, secondary arterial, collector and Smart Street.

The socio-economic data include population, number of workers, average household size, and median income to serve as the basis for prediction at the zone level. The study area is very diverse, with household median incomes ranging from $17,000 to $96,000 in 2001 dollars across approximately 2900 traffic analysis zones.

Gas-electric hybrid vehicles have only been available commercially for the past few years, but even today supplies were limited and many buyers have to endure long waits to purchase these vehicles. Therefore, the stated preference method was applied based on a previous study (Brownstone et. al., 2000), in which survey respondents indicate their choices among a set of hypothetical vehicles that include gasoline-electric hybrids. In this study, data were used from the 2002 California Vehicle Survey (CVS) conducted for the California Energy Commission (CEC) by Morpace International.

The focus of the survey was on vehicle choice from among hypothetical gasoline, hybrid electric, and diesel fuel/technology types. The choice tasks were relatively simple. Three-alternative choice sets using one each of the three fuel/technology types were constructed using the following attributes: purchase price, fuel cost, annual maintenance cost, acceleration, gradability, and purchase incentive. Fuel cost was expressed in terms of annual fuel cost, assuming that the vehicle is driven 10,000 miles. Acceleration is 0-60 time in seconds. "Gradability" is defined as the maximum sustainable speed on an upgrade. Purchase incentive is a categorical variable with four levels: none, use of diamond (HOV) lane, no sales tax on purchase, and free public and metered parking. The incentive attribute was varied only for hybrid and diesel fuel types. Each survey respondent received eight choice tasks.

This survey has approximately 1,000 responses from Southern California, which were used to fit a multinomial logit model including all design attributes. It was found that all cost variables had the expected negative sign. Respondents with annual household income greater than $40,000 were less sensitive to purchase price and operating cost, but more sensitive to acceleration. Respondents strongly prefer gasoline to either hybrid or diesel fuel, and the only "no sales tax on purchase" showed a significant positive effect. Note that sales tax in California averages 7 percent of the purchase price, so this incentive is typically larger than the rebates frequently used by U.S. automobile makers to get consumers to buy their cars.

Unfortunately, the model described in the previous paragraph cannot be used directly for forecasting since it requires information on the body types of all the vehicles held by the household. These data were used in our forecast model based on the survey data, whereas these were not available at the census tract level. Hence, the forecasting model was simplified as shown in Table 1. This model contains attributes for diesel vehicles because they were part of the choice experiment. However, this research do not predict shares for diesel vehicles since currently no such vehicles meet California's strict emission standards and further, they were not available in the California market.

Since the coefficient on fuel cost for high income households was zero in this model, the model predicts that only low income households will purchase hybrid vehicles. This problem was due to the design of the stated preference experiment—respondents were simply asked to choose one of the listed vehicles for their next vehicle transaction. They were not given the option of purchasing a used vehicle, which is in fact what most low-income households choose in real life. Therefore, the model in Table 1 needs to be interpreted as explaining choice given that the household has decided to purchase a new vehicle.

Table 1. Multinomial Logit Estimates for Stated Preference Choice Model

Variable	Coefficient	t-statistic
Price(/$10000) * (Income less than or equal to $40K)	-0.5936	-4.22
Price(/$10000) * (Income greater than $40K)	-0.1534	-2.38
Fuel Cost[a] * (Income less than or equal to $40K)	-1.0423	-2.52
Fuel Cost[a] * (Income greater than $40K)	0.0025	0.01
Hybrid	-1.1602	-14.90
Diesel	-2.0594	-21.06
Hybrid * Household with 2 or more members	-0.1876	-2.67
Diesel * Household with 2 or more members	0.1109	1.21
Gas * Household with 1 or more workers	-0.3789	-5.03
Gas * Household with 2 or more workers	-0.1660	-2.94

Notes: [a.] Annual fuel cost assuming 10,000 miles ($/10000)

Therefore, the model in Table 1 needs to be supplemented with a model to predict the probability that a household chooses to purchase a new vehicle, since the only hybrid vehicles currently available are new. This study used the 2001 National Household Transportation Survey (NHTS) to fit a model of new car purchases. The NHTS is a household-based travel survey conducted every five years by the U.S. Department of Transportation. Prior to 2001, the portion of the NHTS focusing on local trips was known as the National Personal Transportation Survey (NPTS) and the long-distance travel portion of the survey was called the American Travel Survey. There are 2,583 California (CA) households in the 2001 NHTS sample, representing 9.9% of the total base sample of 26,038. (The 2001 NHTS survey also contains nine add-on samples for specific geographical regions, all of which are outside of California.) The survey was conducted over a period of fourteen months ending in May 2002, and it contains data on all household vehicles and their utilization. The 2001 NHTS is described in detail in exhibits, reports, and codebooks maintained on the NHTS website (ORNL, 2004).

Table 2 gives the results of fitting a binomial logit model for whether a household purchased a new car in the last year. This model is fit using all 24,615 NHTS households with vehicles, and only 5.3% of this sample purchased a new car. As expected, higher income households and those with more workers are more likely to purchase new vehicles.

The purpose of this modeling effort is to predict the demand for high-mileage hybrid vehicles that qualify for a sticker to use the HOV lanes. These vehicles are primarily the Toyota Prius and the Honda Civic Hybrid; the new hybrid SUVs from Ford and Toyota do not qualify. Hence, the model in Table 2 was applied to predict the probability that a household will purchase a qualifying hybrid given that they purchase a new car. It was difficult to get reliable data on purchase prices of the Prius and Honda Civic Hybrid since these cars typically are in short supply and sell above list price. Based on anecdotal experiences from known purchasers of a Prius, the price of the hybrids was set at $22,000 and the price of the competing gas vehicles at $18,000. Based on tests conducted by Popular Mechanics (2006), the fuel cost of the hybrid vehicles was set at 20% below the gasoline model.

Given the above assumptions about the relative costs of hybrid vehicles, our prediction for the probability that a household will purchase a qualifying hybrid is just the product of the choice probabilities from the logit models given in Tables 2 and 3. Of course, this model is specified at the individual household level, but it is required to produce forecasts for the approximately 2,900 traffic analysis zones in our study area. One approach is to create synthetic households in each traffic analysis zone so that the joint distribution of the exogenous variables in our choice models matches the joint distributions of these variables in each zone. Unfortunately, the demographic variables easily available at the zonal level were not identical to those used in estimating the choice models, and no distributional information was available for these variables within a zone.

Table 2. Binomial Logit Estimates for New Car Purchase Model

Variable	Coefficient	t-statistic
Household Income between $40K and $79K	0.318	4.32
Household income greater than $80k	0.950	13.36
Exactly one vehicle in household	-0.277	-3.66
3 or more workers in household	0.338	3.83
Exactly 2 children in household	0.382	4.31
3 or more children in household	-0.506	-5.51
Constant	-0.868	-5.82

Therefore this study has used the California sub-sample of the public use microsample from the 2000 Census (PUMS) as our forecast base population. This data set has approximately 600,000 household samples on all of the required exogenous variables that enabled us to compute the probability of each household purchasing a hybrid vehicle. This was further aggregated into 62 different geographic regions (the smallest geographic breakdown available in these data), and computed the same aggregate sociodemographic variables that were available at the traffic analysis zone level. We then used these 62 “synthetic” zones to fit a linear regression model shown in Table 3 to predict the share of hybrid vehicles in each zone. Note that this relatively simple aggregation procedure captures the qualitative trends from the underlying disaggregate models. In particular, hybrid share was predicted to be higher when average income and household size were larger. The same methodology was used to produce zonal predictions for hybrid vehicle shares can also be used to predict other important zonal characteristics.

Table 3. Regression Model for Share of Hybrid Vehicles

Variable	Coefficient	t-statistic
Median Household Income /$10k	0.012364	11.25
Average Household Size	0.002286	1.46
Average Workers per Household	0.018347	2.96
Average Workers / Median Household Income	-0.06142	-2.90
Constant	0.186429	26.72
Number of observations	62	
R-squared	0.9866	
Root MSE	0.00248	

5. MOCRO-SIMULATION MODELLING

5.1 Micro-simulation model selection

The microscopic simulation model used in the project is Paramics, a scalable, high-performance microscopic traffic simulation package developed in Scotland (Gordon D. et al, 1996). Paramics is well suited to study hybrid-HOV policies due to its ability to model both existing (e.g., loop detectors) and emerging (e.g., adaptive ramp meters) infrastructures. In addition, Paramics provides users with Application Programming Interfaces (API) through which users can access the core models to customize and extend many features of the underlying simulation model without having to deal with the underlying proprietary source codes.

5.2 Network construction

5.2.1 Network construction procedure

A microscopic simulation network is built based on a wide range of input data, including data of network geometry, driver behavior, vehicle characteristics, transportation analysis zones, travel demands, traffic control systems, and traffic detection systems. The procedure followed in this study is as follows:

(1) Determine the configuration of the most basic inputs to the model, including the definition of link types, vehicles, and demand structures (i.e. how many demand tables). Although these can be modified later, it is better to make them to be as good as possible from the front end;
(2) Code the skeleton network based on background images;
(3) Code traffic control;
(4) Add zones and demands.

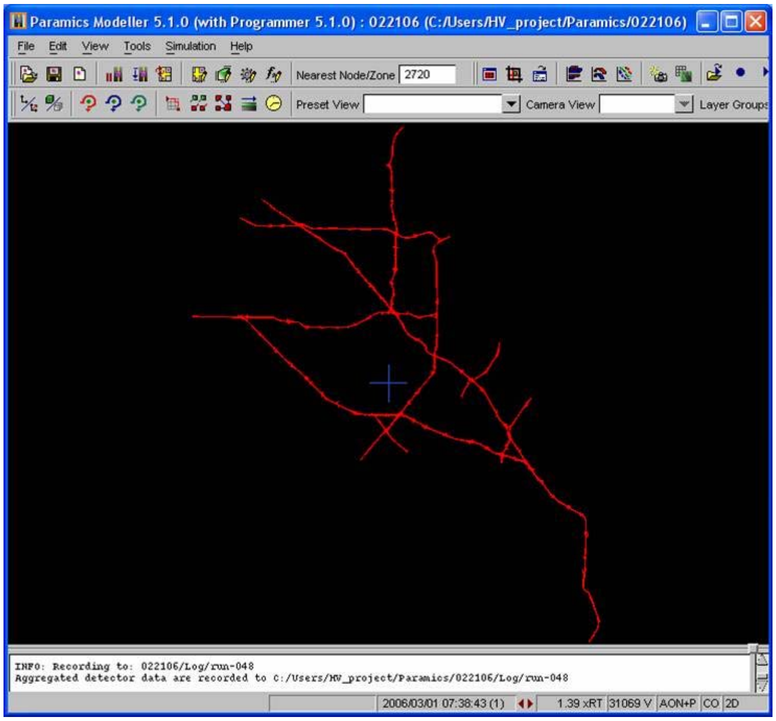
5.2.2 Network construction

As shown in Figure 3, the study network was coded in Paramics based on aerial photos, as-built maps, geometric data and photo logs from Caltrans. Table 4 shows the kind of data that can be obtained from each geometric data source. In order to ensure model accuracy, field trips were made to confirm the network geometry wherever necessary.

Table 4. Geometry Data for Network Coding

	Data Type	Data	Sources
Freeway Data	As-built map	Number of lanes, locations of detectors, on-ramps, off-ramps and lane drops	(1) Caltrans (2) 3-D view of Windows Live Local
	Photolog	number of lanes, locations of on-ramps, off-ramps, signs, and lane drops	Caltrans http://video.dot.ca.gov/photolog/
	Aerial photos	Curbs, number of lanes	(1) Caltrans Digital Highway Inventory Photography Program (DHIPP) (2) Google Map (3) Windows Live Local (4) http://www.terraserver-usa.com
Arterial Data	As-built map	Number of lanes, , lane assignment, locations of detectors	(1) Cities (2) 3-D view of Windows Live Local
	Aerial photos	Curbs, number of lanes	(1) Google Map (2) Windows Live Local (3) http://www.terraserver-usa.com

To model the buffer-separated HOV lanes common in Southern California, the HOV lanes and mixed-flow lanes were coded as two separate links at points where there was buffer between HOV and mixed-flow lanes, and as a single link between ingress and egress points (non-buffered). Ramp meters were added to all applicable on-ramps and set to the field-metering rate, and loop detectors were placed to collect data across the network. The zone structure of a simulation network was matched to the planning model.



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INFO: Recording to: 022106/Log/run-048
Aggregated detector data are recorded to C:/Users/HV_project/Paramics/022106/Log/run-048
```

Figure 3. Coded Network in Paramics

5.2.3 Time period of simulation model

Due to the large size of the study network, the model was calibrated to represent only traffic conditions during the morning peak period.

5.3 Calibration data preparation

5.3.1 Data sources

Freeway performance data were collected from three data sources:

(1) Performance Measurement System (PeMS). PeMS is a system to collect, filter, process, aggregate, and examine loop detector data from freeways in the State of California (Chen et al., 2002). PeMS provides volume, occupancy, and speed data collected from loop detector systems of Caltrans.
(2) Caltrans census database, which includes flow data collected by Caltrans employees once or twice a year using tube counters or loop detectors
(3) Caltrans Tach runs, which collect travel time data along freeways

5.3.2 Hourly flow data

Average hourly flow data during the morning peak period were prepared for all entrance and exit ramps, freeway mainline vehicle detection stations (including both general purpose lanes and HOV lanes) based on data from PeMS. For those locations without data, hourly flow data obtained from the Caltrans census database were used. Hourly flow data are major data we used for OD estimation and model calibration.

5.3.3 Bottleneck identification using speed contour maps

A congested freeway may contain physical bottlenecks as well as "hidden" bottlenecks. The former is defined as a location that initiates traffic congestion and the latter is a location that initiates traffic congestion only under a certain demand pattern. The feature of a bottleneck is that its downstream is free flow and its upstream is jammed. Hidden bottlenecks are usually located either downstream or upstream of a regular bottleneck. There are broadly two methods to study/identify the bottleneck locations: floating car method, and Speed Contour Maps (SCM). SCM is a two-dimensional surface plot on the space-time plane based on time-dependent speeds at several locations along a stretch of freeway.

Based on PeMS, bottlenecks were analyzed using spatial analysis (i.e. speed contour function) and bottleneck analysis tools (Chen et al., 2002; Chen, 2003). To accurately identify recurrent freeway bottlenecks, speed contours from different days were analyzed to remove non-recurrent bottlenecks caused by incidents. This time-consuming process was performed manually. Due to the variation of traffic congestion from day to day, bottlenecks obtained this way may not be reliable. To overcome this limitation, a speed contour map based on percentile-based speeds was used for identifying bottlenecks.

1. Percentile Speed Data

The speed data we use in this study are obtained from PeMS, which obtains measured speeds directly from double loop systems or estimates speeds for single loop systems. Since PeMS has archived a large amount of speed data (several years) for each freeway detector, how to better utilize these data to obtain "representative" speeds becomes a critical issue. Intuitively, using data from multiple days instead of a single day would be beneficial, but the question is how to generate a "representative" speed from a set of candidate speeds. The average speed might be one option, while speed from a typical day is another. However, speed data from the former method may be biased by incorrect speeds from some days (i.e., outliers), while speeds from the latter method may be biased by incidents occurred in the typical day. This research makes use of percentile speeds as the "representative" ones.

Denote *i*, $\forall i = 1,2,\cdots,N$, is the index of a freeway detector and *N* is the total number of detectors within the studied portion of freeway. Also denote *t* the discrete time interval (e.g., 5 minutes) $\forall t = 1,2,\cdots,T$ and x_i is the postmile (PM) of detector *i*. Further $v_d(i,t)$ is the speed of detector *i* at time *t* on the *d*-th day for $d = 1,2,\cdots,D$, and *D* is the total number of days. Given the notation above, the *p*-th percentile speed, denoted as $v^p(i,t)$, can be defined as follows:

$$P(v(i,t) \le v^p(i,t)) \ge p, \forall i = 1,\cdots,N, t = 1,\cdots,T \, . \tag{1}$$

Here P represents the *probability* and $v(i,t)$ the *random* speed at location i at time t. Further, since we have in total D days, $v^p(i,t)$ can be computed as follows:

$$
\begin{aligned}
&v^p(i,t) = \hat{v}_k(i,t) \text{ such that} \\
&k = [p \cdot D] + 1
\end{aligned}
\tag{2}
$$

Here $\{\hat{v}_d(i,t) \mid d = 1, \cdots, D\}$ is a non-decreasing re-ordering of the list of multiple day speeds $\{v_d(i,t) \mid d = 1, \cdots, D\}$. Also, $[a]$ denotes the integral part of a real value a.

From Equation (1), if the p-th percentile speed at detector i at time t is 35 MPH, the probability of speed at this particular location at time t lower than 35 MPH is at least p*100%. In other words, if speed lower than 35 MPH is considered as a bottleneck, it implies that for over p*100%, this location will be a bottleneck. Therefore, percentile speeds can be used to describe the probability of a location being a bottleneck, which can not be modeled by such other means as average speeds. In addition, the percentile-based method provides more flexibility for bottleneck identification and calibration. Since the percentile is the probability of having a bottleneck at the given location and time, the percentile-based method allows one to consider bottlenecks either aggressively or conservatively. For example, an aggressive approach may use a lower percentile (e.g., 15%), which will result in more bottlenecks; a conservative approach may use a higher percentile resulting in fewer bottlenecks. The decision may depend upon such factors as resource limitations, etc.; but in any case, both aggressive and conservative bottleneck analysis results can be presented to decision makers to make more informed decisions.

2. Speed contour maps

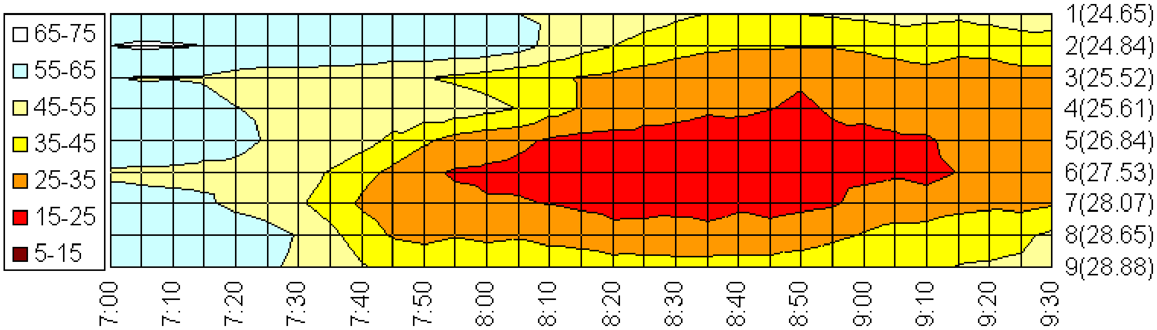
Based on the aforementioned method, “representative” speeds were obtained and then used to construct a percentile speed based speed contour map for the studied portion of freeway. To demonstrate the methods for bottleneck analysis, we use a small example in this section. We collected observed data for a small segment of freeway and drew the following speed contour maps:

(1) speed contour map based on average speeds;
(2) speed contour maps from single days with and without incidents; and
(3) 15-th, 50-th, and 85-th percentile speed contour maps

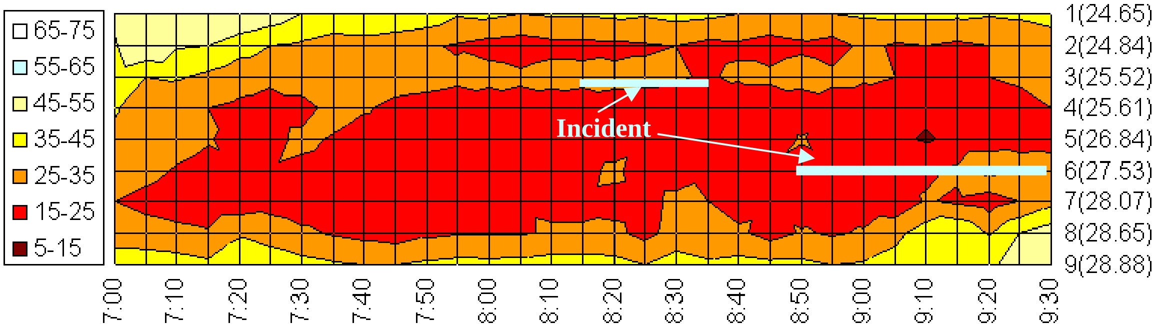
These contours are shown in Figure 4(a) – 4(f). The segment of freeway contains nine detectors and the direction of travel is from Detector 1 to Detector 9. The value in the parenthesis by each detector in the figures indicates its postmile. Data were collected from 7:00 AM to 9:30 AM for 20 days and one bottleneck can be observed. Here we assume speed is constant from a detector to its nearest downstream detector at a given time instant. First, in Figure 4(b), the locations and starting and duration times of two incidents are also depicted. From Figure 4(b) and 4(c), we can see that due to possible incidents or day-to-day traffic variations, speed contour maps from single day data could vary significantly. Thus, for heavily congested corridors, a "typical" day may not be easily identified; or even if it can, the data may not be reliable. From Figure 4(d) – 4(f), we can clearly see that both the spatial extent (queue length) and time duration of the bottleneck shrinks as percentile increases. Also note that the speed contour map based on average speeds, in this case, is similar to the 50-th percentile speed contour map, but they are not exactly the same. For example, the bottleneck duration is longer in the 50-th percentile speed contour map.

The 50-th percentile speed contour map in Figure 4(e) will be used to represent the typical traffic condition of the studied freeway section. Based on visual assessment, we can see that there is one major bottleneck between postmile 24.84 and 28.88. The bottleneck starts at Detector 8 at about 7:40 AM. The congestion gradually extends to upstream of Detector 8. As indicated in Figure 4(e), at 8:30 AM, the queue length at Detector 8 is about 28.65-24.84=3.81 miles and the time duration (until congestion clears) is about 30 minutes.

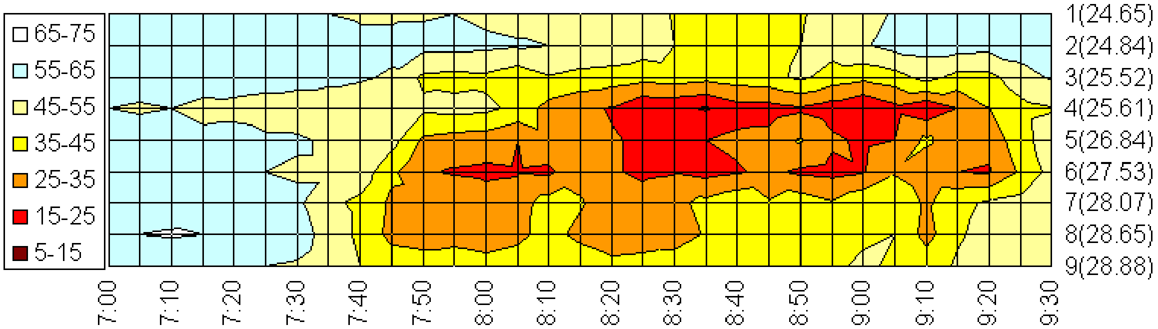
From Figure 4, since a speed contour map is indexed by *i* and *t*, it can be represented as an *N* by *T* matrix. Denote the matrix as *S*, and *S*(*i*, *t*) is the speed of sensor *i* at time *t*, $\forall i = 1,2,\cdots,N$, $\forall t = 1,2,\cdots,T$. Such a matrix representation of speed contour maps makes the bottleneck identification and calibration easily to conduct, which will become evident in later sections.



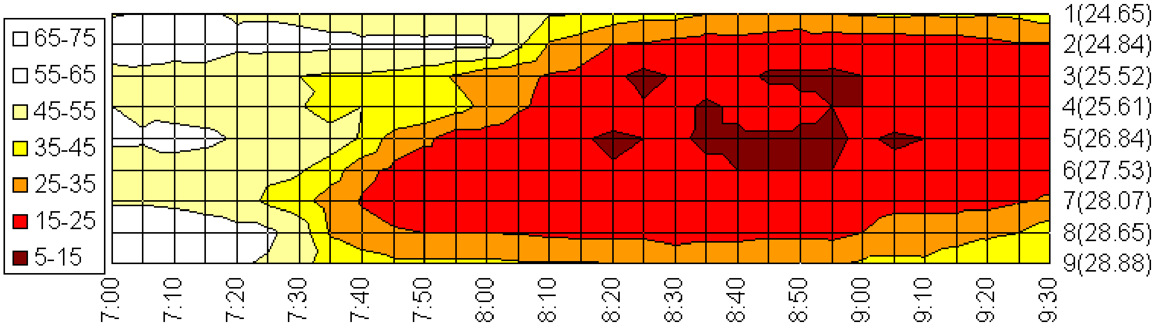
(a) Average Speed



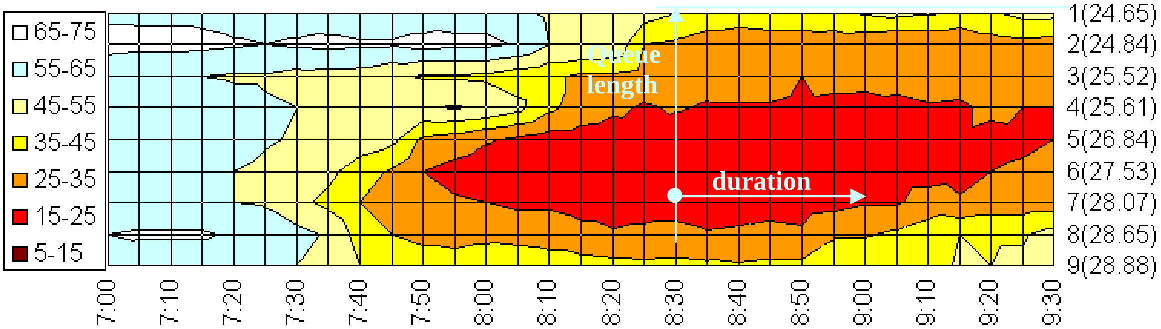
(b) Single Day – With Incident



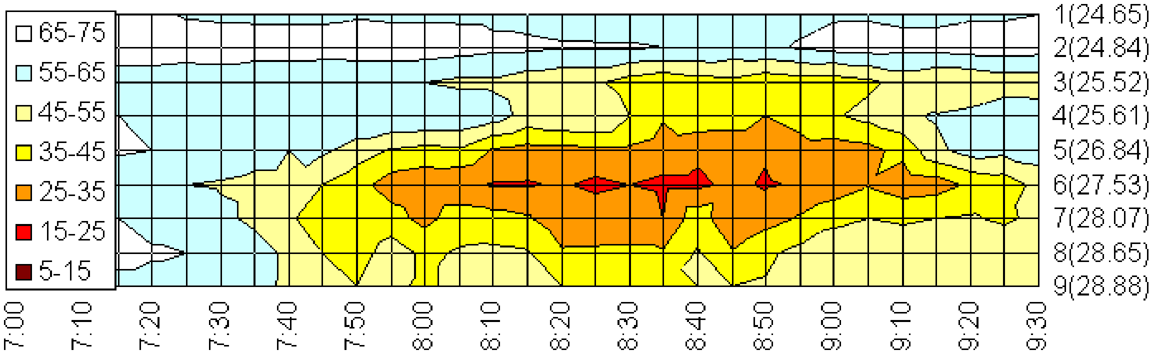
(c) Single Day – Without Incident



(d) 15-th Percentile Speed



(e) 50-th Percentile Speed



(f) 85-th Percentile Speed

Figure 4. Illustration of SCM from Observed Data

3. Preparation of 50th speed contour maps

Based on 5-min speed data on freeway mainlines for 3 months (only Tuesday to Thursday), the 50th percentile speed contour maps were further prepared for the following model calibration studies.

5.4 Model calibration

The objective of model calibration is to ensure that the simulation model of a network represents the network's real-world traffic conditions. In the model calibration process, model parameters were adjusted until reasonable (qualitative and quantitative) correspondence between the model and field-observed data was achieved.

5.4.1 Model calibration procedure

After a network was coded, its coding errors were checked and fixed as needed. Most network coding errors were fixed by loading the OD table obtained from the planning model and observing the simulation for obvious problems (blocked links, underutilization of links, low throughput, etc.).

The next step is to calibrate the simulation model. The procedure used to calibrate the Paramics simulation network is illustrated in Figure 5. The following four steps are the most critical issues when performing the model calibration:

(1) Calibration of driving behavior models
(2) Initial calibration / setting of route choice models
(3) OD demand estimation
(4) Network performance calibration and validation

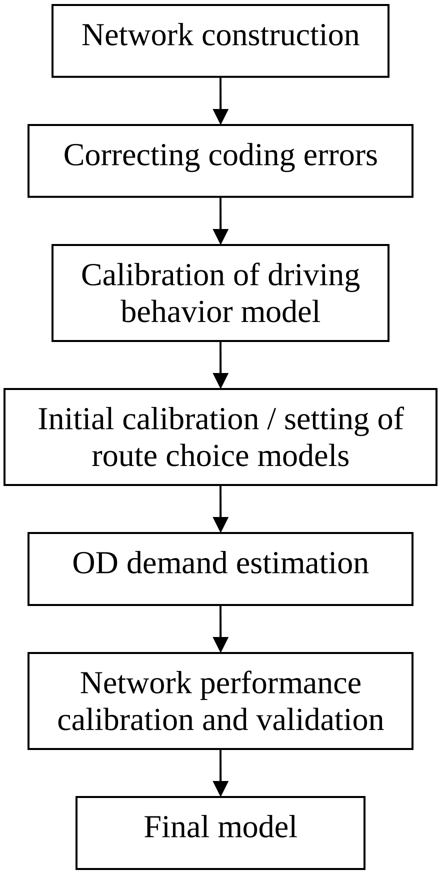


Figure 5. Model Calibration Procedure

5.4.2 Calibration of Driving Behavior Models

The calibration of driving behavior models was performed based on a sub-network. The purpose of this step of calibration is to provide a set of good global parameter settings. There are four global variables that affect DVU (Driver-Vehicle Unit) behavior: mean target headway, mean reaction time, time-step, and speed memory. Mean target headway and reaction time are two major parameters for Paramics' car-following model. Simulation time-step determines how detailed the simulation is. A certain value of speed memory is required to ensure the following vehicle to respond to the activities of the leading vehicle appropriately. Although Paramics provides a set of default values for these variables, the calibration of a simulation model usually requires them to be refined.

It was found that the following parameter values generate the best results based on studies on sub-networks:

(1) Mean target headway: 0.9
(2) Mean Reaction Time: 0.8
(3) Timestep: 5
(4) Speed memory: 6

Note that these parameters can be adjusted locally in the model fine-tuning step to fit the average driving behavior, which is greatly dependent on the geometry of the freeway. For example, we used Caltrans photo log files to investigate the merging pattern at some ramps and freeway interchanges. Then, the adjustment is performed to match the simulation result to the observed congestion patterns.

5.4.3 Initial calibration of route choice model

There are three steps to calibrate the route choice model in Paramics.

(1) Definition of generalized cost function
(2) Selection of route choice model
(3) Calibration of core parameters of the selected route choice model

1. Generalized cost function

Travel cost is represented by a combination of factors that drivers are assumed to take into account when choosing routes. In Paramics, the base cost for links is calculated using the following generalised cost equation:

$$cost = a*T + b*D + c*P \qquad (3)$$

where:

a is time coefficient in minutes per minute (default 1.0)
b is distance coefficient in minutes per kilometre (default 0.0)
c is toll coefficient in minutes per monetary cost (default 0.0)
T is free-flow travel time in minutes
D is the length of the link in kilometres
P is the price of the toll in monetary cost units

The most important parameters are *a* and *b*, i.e., parameters associated with time and distance, respectively. Tolls can also be considered where a monetary value is charged for the use of specific sections of road and thus can be used to model a drivers' willingness to pay. By default, Paramics favours travel time; however, users may need to investigate various combinations based on the study network.

A traditional method to determine parameter values of the generalized cost function is sensitivity analysis of routes between major OD pairs of the target simulation network. For example, parameter settings of the simulation network are: a = 0.75; b = 0.25, c = 1. The reason to have the parameter for toll is because it was found that some long-trip vehicles may not stick to the freeway mainline until the exit close to their destination zone. Due to specific geometric features at an interchange and/or traffic congestion, it may bring more time-saving if drivers exit at the off-ramp of an interchange and then go back to freeway mainline through the on-ramp at the same interchange. However, in reality, this almost never happens. To overcome this unrealistic behaviour in simulation, a two-minute toll was applied to all on-ramps and off-ramps in order to avoid the above-mentioned behavior.

2. Selection of route choice model

Paramics has three route choice models, all of which are based on the generalized cost function described above. They are: all-or-nothing assignment, stochastic assignment, and dynamic feedback assignment.

(1) All-or-nothing assignment assumes that there is only one path from an origin to a destination and the path has the lowest cost. The familiarity settings for each type of vehicles are indirect parameters of the method. The definition of generalized cost function is the key to the method.
(2) Stochastic assignment in Paramics assumes that different drivers perceive different costs from a decision node to the destination. The perceived cost is calculated based on the given perturbation factor with a random number assigned to the vehicle, and the shortest perceived route is chosen at the decision node. Parameter of the method includes perturbation of each vehicle type. The familiarity settings for each type of vehicles are indirect parameters of the method.
(3) Dynamic feedback assignment routing method assumes travelers select route based on instantaneous traffic information. It has two parameters—feedback period and compliance rate (i.e. familiarity). The dynamic feedback routing method updates link costs at a certain feedback period and a certain percentage of travelers determined by the compliance rate are regarded as familiar drivers and can change paths when en-route.

The selection of route choice model is based on features of the target network and the scope of the project. The use of appropriate route choices becomes critical especially when both freeways and parallel streets are included in the study network. Usually, the combination of two or three routing methods is applied to a complicated simulation model (a simple simulation model may include only one active routing method), in which:

(1) Different types of vehicles may use different route choice models.
(2) Part of a certain type of vehicles may use different route choice models.

The developed simulation model includes all three routing models.

(1) Familiar drivers for all vehicle types use dynamic feedback assignment;
(2) Trucks use all-or-nothing assignment;
(3) HOV vehicles use both stochastic assignment and dynamic feedback assignment.

3. Initial calibration of core parameters of the selected route choice model

Fundamentally, the calibration of the route choice behavior model is conducted on a network level. Core parameters of the route choice model can be calibrated using either aggregated data or individual data obtained from driver surveys.

For the study network, all three routing methods are applied and thus there are three routing parameters: (1) perturbation; (2) familiarity; (3) feedback cycle. The first two parameters are vehicle type specific; the third parameter is global. Their initial settings can be obtained either from a similar network that has been calibrated, or from sensitivity analysis of routes between major OD pairs of the target simulation network.

For the study network, the initial settings for these parameters are as follows: (1) perturbation = 2% for HOV and 0% for SOV; (2) familiarity = 10%; (3) feedback cycle = 2 minutes. These parameters are subject to change in the model calibration process.

In addition, there is one more routing parameter in this study. In order for HOVs to have a greater propensity to select HOV lanes as their path during simulation, the costs for HOV lanes were set to a lower value than that of mixed-flow lanes. Paramics has a global/local cost factor parameter that can be used to set link costs. In this study, the global cost factor of HOV links was calibrated to match HOV lane use percentages observed in the field.

5.4.4 OD demand estimation

Based on initial setting of core parameters of the selected route choice models, OD matrix was estimated. OD matrix estimation involved the following steps in the study:

(1) Obtain the pattern OD matrix from OCTAM (Orange County Transportation Analysis Model) model obtained from Orange County Transportation Authority (OCTA);
(2) Fine-tune OD matrix using Paramics OD estimator;
(3) HOV demand estimation.

1. Obtain pattern OD matrix

Traditional sub-area analysis was conducted to extract the study area. This includes all the facilities in the network; however, the focus of this research was to consider freeway and HOV facility only network. Hence, this study has applied a special type of sub-area extraction called “multi-modal, multi-class assignment (MMA)” was employed using TransCAD, a transportation planning software package. This study applied a special type of sub-area extraction called “multi-modal, multi-class assignment (MMA)” using TransCAD, a transportation planning software package. MMA analysis requires inputs such as link count and base OD matrix. In MMA, the analyst needs to define the links of interest and TransCAD keeps track of the number of vehicles that enter and leave these links. In this study, OCTAM travel demand matrices were used as base matrix. Since the study network is a “freeway only” network, zones were created at each on- and off-ramp. After selecting links that were freeway, HOV lane, or freeway exits, the MMA procedure was executed and produced an OD matrix with 265 zones.

Once MMA was performed in TransCAD, the resultant OD matrices were transferred to the coded Paramics network using a lookup table matching Paramics zones with TransCAD zones. A simple MATLAB code was written to conduct the work.

Figure 6. OCTAM Travel Demand Model

2. Fine-tune OD matrix

OD matrices extracted from the planning model were not sufficient enough to directly utilize in micro simulation models since the traffic assignments are different in two models. Paramics OD estimator was used to improve the quality of the OD matrices obtained from the regional travel demand model. Paramics OD estimator optimized the pattern OD matrix using link flows, turning movements and cordon flows. Generally, OD matrices were adjusted based on loop detector data and census data. The performance measure used in OD estimation was GEH[1] statistic (UK Highway Agency, 1996).

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[1] The GEH formula gets its name from Geoffrey E. Havers, who invented it in the 1970s while working as a transport planner in London, England. Although its mathematical form is similar to a chi-squared test, is not a true statistical test. Rather, it is an empirical formula that has proven useful for a variety of traffic analysis purposes.

$$GEH = \sqrt{\frac{(obs - sim)^2}{(obs + sim)/2}} \qquad (4)$$

By adjusting the target values and intensity regularly, it has estimated the OD matrix of which about 70 percent of the individual links with GEH statistics of less than 5.

3. HOV demand estimation

To this point, SOV demand was the focus of estimation. The main focus of this research is to evaluate the performance of HOV lanes; hence, it is necessary to estimate HOV demand. Unlike SOV vehicles, HOV vehicles can use both HOV lanes and general purpose lanes; therefore, a different OD estimation approach was adopted. The main source of information for this method is from Caltrans District 12 HOV Annual report from 2002 to 2005. Table 5 shows the peak period and peak hour flow for 11 locations in the study area. Share of HOV demand was estimated as 21.7 percent, which was arrived by trial and error ranging from 14.5% and 25%.

Table 5. Share of HOV Demand at Different Locations in the Study Area

			Peak period (6:30 - 9:00)			Peak hour (6:30-7:30)		
Name	Freeway	PM	HOV volume	Total volume	Percentage	HOV volume	Total volume	Percentage
Los Alisos Boulevard	I5 NB	18	4365	31995	13.6	1883	13122	14.3
Tustin Ranch Road	I5SB	R28.3	5805	26021	22.3	2741	10957	25.0
Main St	I5SB	33.1	4807	25021	19.2	1995	10628	18.8
Harbor Blvd	I5SB	37.4	3754	20951	17.9	1833	9099	20.1
Broadway St	I5SB	38.7	4304	21368	20.1	1785	9183	19.4
Von Karman	I 405 NB	7.4	2887	28182	10.2	1320	11625	11.4
Ward St	I 405 SB	13.2	3846	30094	12.8	1598	12749	12.5
Walnut Ave	SR 55 SB	14.2	4492	19051	23.6	1999	8607	23.2
Warner Ave	SR 55 SB	R 8.5	5284	23665	22.3	2345	10310	22.7
Yorba Linda Blvd	SR 57 SB	18.3	3729	16134	23.1	1571	6785	23.2
Harbor	SR 91 WB	3.3	3377	18018	18.7	1636	7818	20.9

5.4.5 Network performance calibration and validation

Based on estimated demand tables, the simulation model was further fine-tuned to match speed plots and travel time data from the real-world. The purpose of this calibration step was to match the network performance in terms of replicating the real-world conditions.

Table 6 shows the criteria and measures used to calibrate the network, which is similar to FHWA’s calibration criteria (Dowling, R. et al 2004).

Since traffic congestion varies daily and there are incidents that occur here or there, it is hard to use a fixed set of flows on all mainlines and ramps as flow calibration targets for the big network. As a result, our model calibration efforts could only roughly match flows. In the final calibrated model, 70% of all measurement locations have GEH values less than 5.

Table 6. Model Calibration Criteria

Criteria and Measures	FHWA targets
Hourly flow: Model Vs Observed GEH Statistic – Individual Link Flows GEH < 5	> 85% of cases
Speed: Model Vs Observed Match bottleneck locations	To analyst’s satisfaction
Visual audits: Individual Link Speeds Visually acceptable Speed-Flow relationship	To analyst’s satisfaction
Bottlenecks Visually acceptable Queuing	To analyst’s satisfaction

The focus of the model calibration efforts was capacity calibration. Capacity calibration involved the fine-tuning of the link specific parameters in order to best reproduce observed traffic capacities in the field. Local link parameters include signposting and signrange, headway factor, reaction time factor of a link, and lane choice parameters. The capacity calibration usually starts at the beginning of a freeway segment and moves downstream to uncover otherwise hidden bottlenecks.

Bottleneck matching was an important step in calibration of the network since bottlenecks can significantly impact the performance of an entire network. The result of capacity calibration is to match major bottlenecks of the network. Appendix A shows the observed and simulated 50-th percentile speed contour maps for HOV lanes in the study network.

6. EVALUATION

6.1 Scenario design

Several states are considering hybrid-HOV bills—Virginia was the first state to pass one. California has the busiest and most extensive HOV lane network in the country. California’s proposed version of the law includes many freeway performance checks to try and minimize the negative operational impacts of single occupant hybrid vehicles. For example, California’s hybrid-HOV law requires that the California Department of Transportation (Caltrans) must determine whether or not HOV lane breakdown has occurred on any of the state’s HOV lanes after 50,000 “HOV lane access” permits are issued to hybrid vehicles. It also states that the maximum allowed HOV lane access permits is 75,000.

The model that was calibrated was actually the base scenario for the study. In the scenario, hybrid vehicles are not allowed into HOV lanes, which corresponds to the time before California’s bill AB 2628 was passed. The shares of SOV and HOV were 78.3% and 21.7% respectively on the Orange County freeway network. The performance of the base scenario was used as reference to evaluate other scenarios.

Based on the understanding of California’s hybrid-HOV law, four scenarios were constructed. The assumption of the study is that the total demand for all scenarios is constant and the hybrid-HOV policy results in some solo drivers switching to hybrid vehicle drivers. As shown in Table 7, each scenario has different SOV and hybrid percentages. These scenarios are explained as follows:

(1) Scenario 1: Compared to the base scenario, this scenario allows eligible hybrid vehicles as of November 2005 to use HOV lanes. The hybrid demands were directly obtained from Section 4. This scenario helps to analyze the impact of allowing initial share of hybrid vehicles in HOV lanes. It also assumes that the proposed hybrid-HOV policy has no influence on hybrid sales. Share of HOV 2+ were fixed and added share of hybrid vehicles were deleted from single occupant vehicles.

(2) Scenario 2: This scenario corresponds to the condition when there are 50,000 hybrid vehicles in California. According to California’s Hybrid-HOV bill, AB 2628 requires that Caltrans should conduct a study of statewide HOV lane operations after it has been notified that the 50,000th hybrid permit has been issued.

(3) Scenario 3: This scenario corresponds to the condition when there are 75,000 hybrid vehicles in California. This is the maximum number of hybrid vehicles allowed as per the bill AB 2628.

(4) Scenario 4: This scenario was constructed to understand what could happen if the total hybrid vehicles reaches 100,000. This would give an idea to policy makers about the future performance of the network.

Table 7. Proportion of Vehicles in Different Scenarios

Scenario	SOV (%)	HOV (%)	Hybrid (%)	HOT (%)
Base Case	78.3	21.7	0.00	N/A
Scenario 1	76. 8	21.7	1.56	N/A
Scenario 2	76.2	21.7	2.16	N/A
Scenario 3	75.1	21.7	3.24	N/A
Scenario 4	74.0	21.7	4.32	N/A

In Section 4, the total number of hybrid vehicles in each transportation analysis zone was estimated using socio-economic characteristics. The next step was to develop the OD matrix similar to SOV and HOV demand. To achieve this, a three-step process was adopted.

(1) The proportion of total hybrid vehicles originated from each zone over the total demand was calculated.

(2) It was assumed that the OD pattern for Hybrid vehicles would be similar to the existing pattern for SOVs. A principal reason for this assumption is that most of the hybrid users are converting from the existing SOV demand.

(3) Total hybrid demand from each zone was subtracted from the total SOV demand of respective zones to match the overall demand.

According to DMV's hybrid vehicle registration records in Nov 2005, the following data were obtained:

(1) The total number of hybrid vehicles is 36,000

(2) The percentage of California hybrid vehicles in Orange County, based on DMV records, was about 10%.

It was assumed that

(1) Orange County keeps the same share of hybrid vehicles relative to the whole of California

(2) Hybrid demand distribution pattern remains the same in Orange County

Then, the hybrid vehicle demand for Scenario 3 and 4 were further estimated based on the total hybrid vehicles in these two scenarios.

6.2 Performance measures

In this study, three levels of performance measures were used. The first level was at the overall system performance, while the second level was at the corridor level performance analyses for both HOV lane and general purpose lanes. Finally, it was evaluated with respect to local and global pollutants, as well as from safety perspective. The overall system performance measures include:

1. Vehicle Hours Traveled (VHT)
2. Vehicle Miles Traveled (VMT)
3. Average travel speed

6.2.1 Corridor Level Performance Measure

According to California's proposed hybrid-HOV law, Caltrans has the authority to remove "individual HOV lanes, or portions of those lanes" if traffic conditions exceed a level of service (LOS) C, which corresponds to a traffic stream density greater than 26 vehicles per mile per lane. Based on Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU), HOV lanes should not be degraded and the speeds in one or both of the peak hours should not be less than 45 mph for more than 18 out of 180 days.

This benchmark of operational degradation provides a convenient measure to test whether any of the HOV lanes breakdown with the addition of single occupant hybrid vehicles and was used as the primary measure of effectiveness (MOE) in this study. California's hybrid-HOV law also recognizes that HOV lane travel time is an important measure of whether or not performance in an HOV lane has broken down. However, the bill was not specific as to how much change in travel time should be considered significant; noting only that a consistent increase was grounds for suspending the program. As travel time was the incentive offered by hybrid-HOV bills, changes in HOV lane travel time were important, and HOV lane travel times in excess of twenty percent were considered significant. In this study travel time was measured in terms of speed.

The HOV lane and general purpose lane performance measures include:

1. Average corridor speed
2. Speed distribution
3. LOS
4. Vehicle miles traveled (VMT)

A Paramics plug-in was developed to gather such MOE data as speed and densities for both HOV lane and general purpose lane between a pair of loop detectors that were spaced one-to-five miles apart. This gives detailed performance of the each section and makes it easy to capture the congestion patterns since congestion can be highly localized. After the detector stations were established, there were 46 general purpose segments and 42 HOV lane segments in the Paramics network as shown Table 8.

Table 8. Number of HOV and Mainline Sections by Corridor

Freeway	Direction	Distance (miles)	Mainline Section	HOV section
I-405	NB	22	4	5
	SB	22	4	4
I-5	NB	34	7	7
	SB	34	6	7
SR-55	NB	15	4	3
	SB	15	3	3
SR-57	NB	11	3	3
	SB	11	3	4
SR-91	EB	8	3	4
	WB	8	3	3
SR-22	EB	12	3	N/A
	WB	12	3	N/A

6.2.2 Air Quality & Safety Performance Measure

The Comprehensive Modal Emission Model (CMEM), developed by University of California, Riverside along with University of Michigan and Lawrence Berkeley National Laboratory, was used to evaluate the performance of different scenarios with respect to air quality. This model can predict emissions for a wide variety of light duty vehicles under various states of condition (properly functioning, deteriorated and malfunctioning). The model estimates second-by-second emissions as well as fuel consumption in various vehicle operating conditions (idle, cruise, acceleration and deceleration) based on power demand. It splits the entire emission process into vehicle operation and emission production. It also takes into consideration of starting conditions (cold start, hot start) and off-cycle. Tailpipe emissions are calculated as follows using fuel rate (FR), engine-out emission indices ($g_{\text{emissions}}/g_{\text{fuel}}$) and time dependent catalyst pass fraction (CPF)

$$\text{Tailpipe emissions} = FR^* (g_{\text{emissions}}/g_{\text{fuel}})^* \, CPF \qquad (5)$$

The model consists of six modules that predict engine speed, air-to-fuel ratio, engine power, fuel use, engine out emissions and catalyst pass fraction. Inputs to the model are second by second speed, road grade and accessory use (air conditioning) apart from these 55 vehicle specific variables (e.g., vehicle mass, engine size, engine displacement, transmission type). It can be integrated with other microscopic traffic simulation models such as Paramics, FRESIM, NETSIM, and CORSIM. In this study following pollutants were measured:

(1) Carbon monoxide (CO)
(2) Hydrocarbon (HC)
(3) Nitrogen oxide (NOx)
(4) Carbon dioxide (CO2)
(5) Fuel consumption

6.3 Results and analysis

Once the model was calibrated, simulations were performed for different scenarios for 1 hour and 30 minutes. Because traffic takes some time to build up in the network, the first 30 minutes of simulation time was considered as warm-up time and only the last one hour of the simulations were analyzed. Different plug-ins developed by UCI researchers were enabled to collect different performance data.

6.3.1 Overall System Performance

The results of the micro simulation model of the alternative scenarios for VMT, VHT and average speed is shown in Figure 7. The figure illustrates the percentage change in alternative scenarios with respect to the base case (as a reference point). This measures the overall system performance and congestion level in the network. All the alternative scenarios increase the speed and decrease the VHT compared to the base case. Scenario 1 has the greatest increase in speed. In terms of VMT, scenario 4 appears better (with a 0.9 percent increase) due to the high share of SOV vehicles diverted to HOV lanes reducing the congestion level in the adjacent general purpose lanes and thereby increasing the VMT.

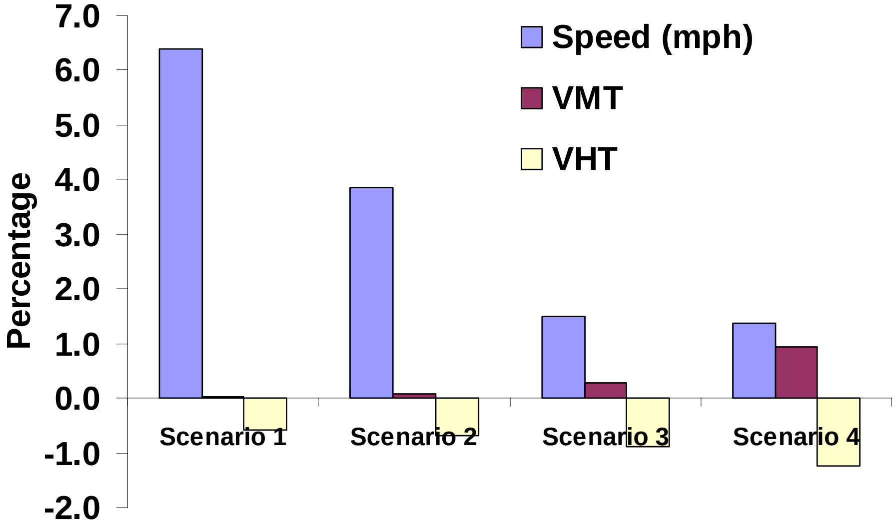


Figure 7. Overall Performance of the Network

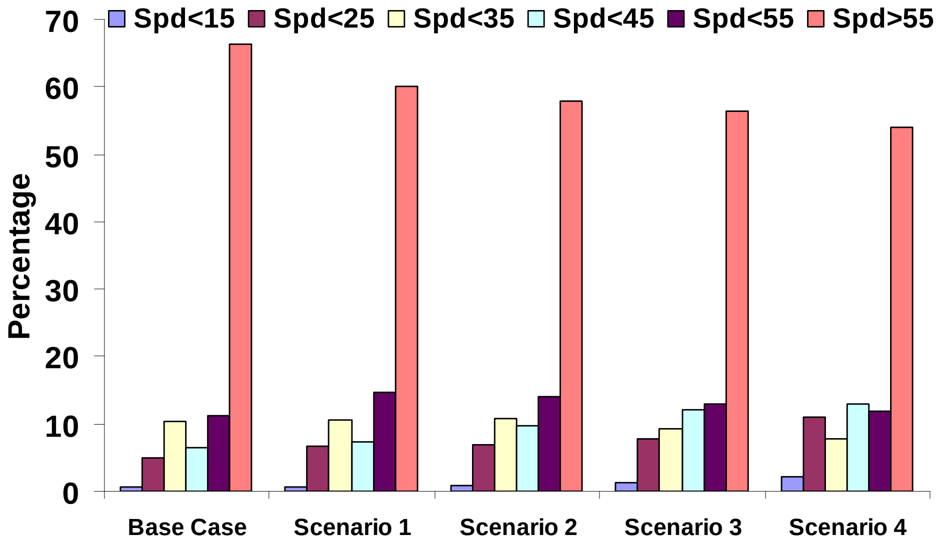


Figure 8. Speed Distributions of HOV Lanes

Corridor level analyses were performed to understand the degree of operational degradation by allowing SOHV (Single Occupant Hybrid Vehicles) into the HOV lanes. This also compares the performance of HOV lanes and general purpose lanes. Main factors considered in this study were average speed of each corridor, speed distribution within a corridor and level of service. As mentioned in the previous section each corridor was divided into number of section to analyze the performance in detail.

Figure 8 shows the speed distributions of HOV lanes in different scenarios and represents speed at both temporally and spatially. Speed is divided into 10 mph interval and x-axis shows the percentage of time spent in different speed ranges. It indicates that most of the OC network has higher average speed in base case. It can be clearly observed from Figure 10 that with increase in traffic flow in HOV lanes it degrades the performance of HOV lanes. In Scenarios 3 and 4, the share of vehicles with speed less than 45 mph has increased.

To meet the SAFETEA-LU requirements, the percentage of sections and time periods with speed greater than 45 mph were analyzed, as illustrated in Figure 9. In the base case about 77 percent of sections in HOV lanes had speeds greater than 45 mph. From scenario 3 less than 70 percent of sections have speed greater than 45 mph, which indicates the degradation of the HOV lane performance.

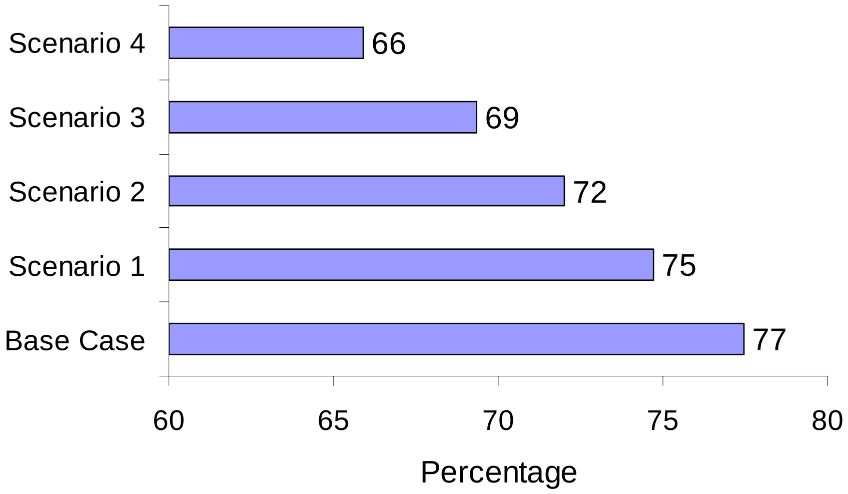


Figure 9. Percentage of Section and Time Period with Speed greater than 45 mph

Level of service (LOS) indicates the quality of the services provided by the given facility. “LOS A” represents better facility and “LOS F” represents the worst level of service. In this study LOS was assigned based on the density. Figure 10 demonstrates the level of service distribution in HOV lanes for the different scenarios. In the base case, the LOS A sections were close to 15 percent whereas in scenarios 3 and 4 the share of LOS F has increased significantly.

Figure 11 describes the percentage of sections with densities greater than 26 vehicles per mile per lane—the maximum allowable required by California’s bill AB 2628. In the base case, density in more than 80 percent of the sections was less than 26 vehicles per mile per lane. In scenario 1 this has been reduced to 70 percent. For scenarios 3 and 4 this has been further reduced to 60 percent and less, which shows significant degradation in HOV lanes.

6.3.2 Corridor Level Analysis

In this section, detailed analyses were performed at each corridor level. This analysis compares the performance of the HOV lanes with the adjoining general purpose lanes in the network in terms of speed and LOS.

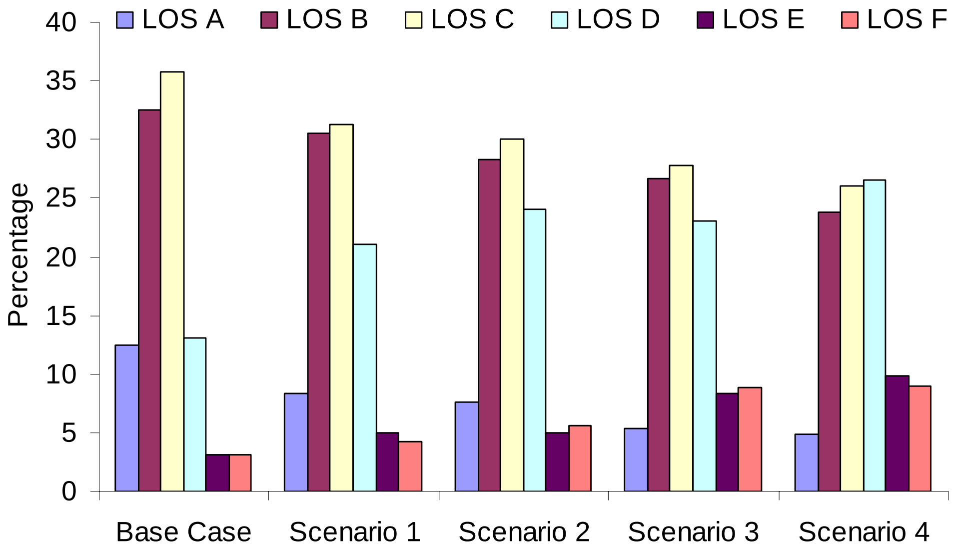


Figure 10. Level of Service Distribution in HOV lanes

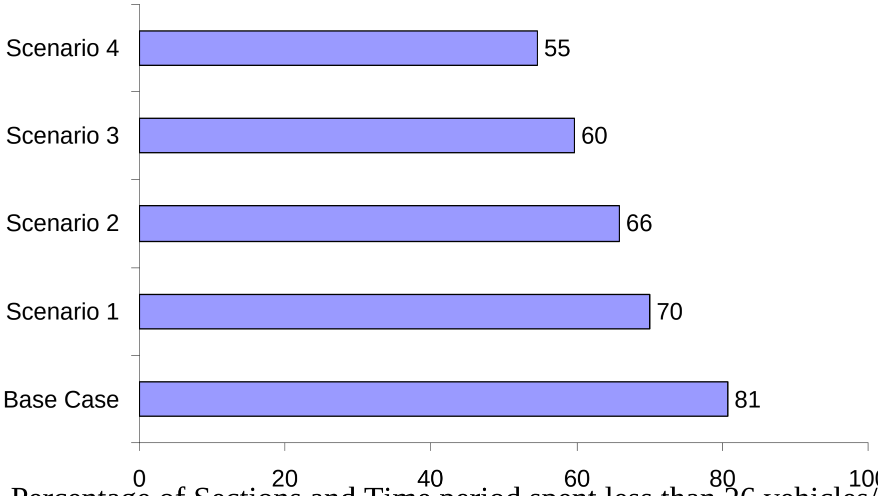


Figure 11. Percentage of Sections and Time period spent less than 26 vehicles/mile/lane

Freeway I-5: Freeway I-5 is the longest freeway in the study network—about 34 miles. It has 4 to 6 lanes each direction in mainline and 1 to 2 lanes in HOV sections. To understand the performance of the corridor, it was divided into 7 sections with an average interval of 5 miles. In the I-5 NB base case, the speed difference between HOV and general purpose lanes is about 10 mph as described in Figure 12; this speed differential has narrowed to almost similar speeds in scenario 4. In running the simulations it was observed that I-5NB has two major bottlenecks, namely Alicia Parkway before the I-405 interchange, and Red Hill before the SR-55 interchange. The main causes for these bottlenecks were weaving and merging. LOS B was apparent in more than 60 percent of the HOV lanes up to scenario 2; this was reduced to less than 50 percent beyond scenario 3.

In I-5 SB, the major bottlenecks were at the interchanges of SR-22, SR-55, and SR-57. Average speed in that section was reduced to as low as 18 mph. This is mainly due to HOV lanes having dropped from two lanes to one.

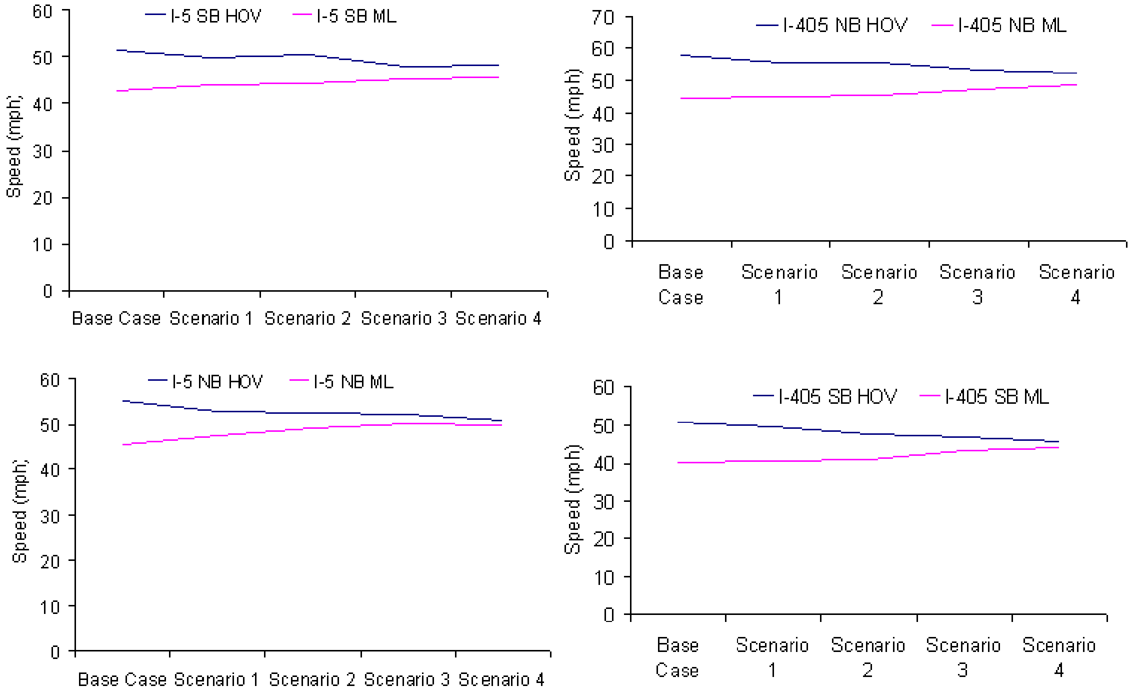
Freeway I-405: Freeway I-405 is next longest (second to I-5). It is about 22 miles long and has 4 to 6 lanes in mainline and, for the most part, only one HOV lane. HOV sections predominately have free flow speed. A major bottleneck was observed on I-405 NB at the merging location of SR-133 and I-405 NB, due to merging vehicles from SR-133. Average speed at this location was reduced to 33 mph.

During the morning peak period, I-405 SB is congested for long periods. Here, a major bottleneck is caused by weaving from I-405 to Fairview and SR-73. This bottleneck extends all the way back to Westminster Blvd. In the base case, most of the sections were operating at LOS D to F. In about 40 percent of the sections, speed was less 45 mph.

Freeway SR-55: Freeway SR-55 is about 15 miles long and has from 2 to 5 general purpose lanes and one HOV lane. There is a major bottleneck at the interchange of SR-55 NB and I-405. In the case of HOV lanes, there is almost free flow in all scenarios; hence, it could be observed that some of the demand from general purpose lanes could be accommodated, and improve the overall corridor speed, without substantial compromise on HOV benefits until scenario 3. The proposed policy may have some benefits on SR-55 NB

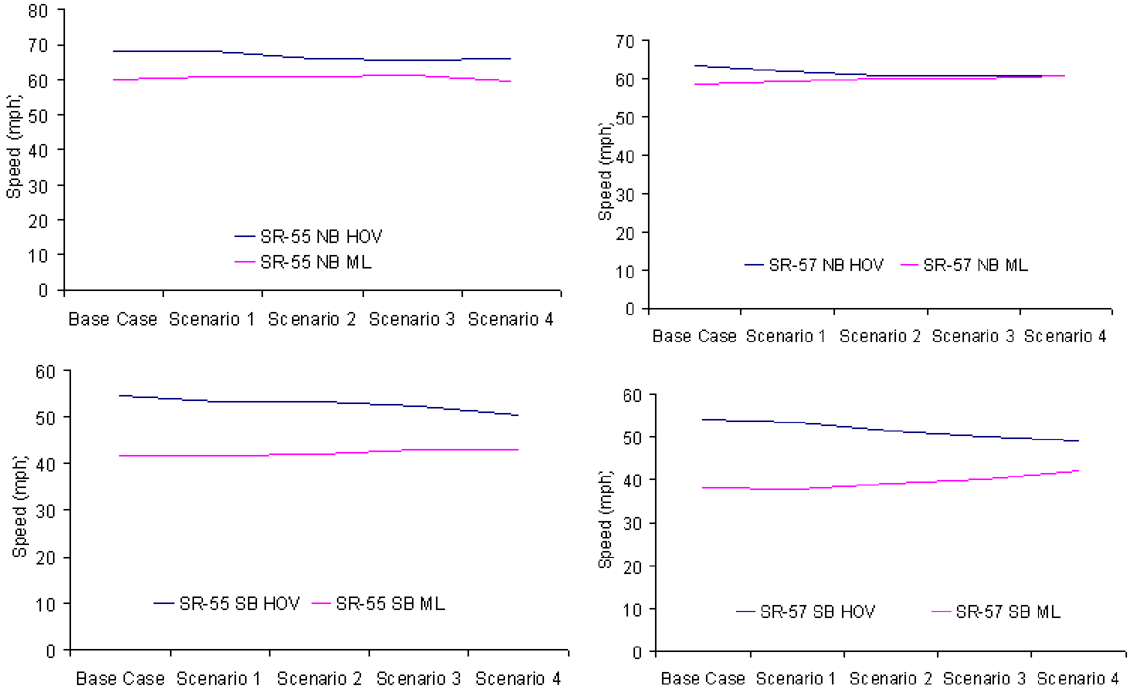
In the SR-55 SB base case, the speed difference between HOV lanes and general purpose lanes was about 15 mph. A major bottleneck at SR-55 SB was at the interchange of I-5 and SR-55 SB, and this extends to Katella. Speeds in general purpose lanes improved marginally until scenario 3, after which significant deterioration occurred. It was observed in the simulation that when the HOVs attempt to leave the HOV lane, they encounter heavy congestion in the general purpose lanes, making it difficult to merge and causing the HOV lane to become congested.

Freeway SR-57: SR-57 is located in the northern portion of OC and is about 11 miles long. During the morning peak hour there was no measurable speed difference between the HOV lane and general purpose lanes on SR-57 NB, which can be observed from figure 12. On average, speed was greater than 55 mph in all the scenarios.



(a) Freeway I-5

(b) Freeway I-405



(c) Freeway SR-55

(d) Freeway SR-57

Figure 12. Comparison of HOV and General Purpose Lane Speed

On SR-57 SB, there were two major bottlenecks—at the intersections of SR-91 and I-5, respectively. Along this corridor, both HOV and mainlines were congested, mainly due to weaving and merging associated with two major interstate highways. Along the general purpose lanes, speed was less than 45 mph at more than 90 percent of the sections. With scenario 4, both HOV and general purpose lanes totally break down due to the stop-and-go nature of traffic.

6.3.3 Air quality performance

As part of this research, CMEM was used to estimate emissions (CO, HC, NO_x, CO_2) and fuel consumption. Figure 13 compares the relative improvement of different pollutants over the base case. CO and HC are principally emitted by gasoline vehicles, while diesel vehicles emit significant share of NO_x emissions. CO_2 is directly proportionate to fuel consumption. Overall, scenario 4 performs better merely because of the high share of hybrid vehicles.

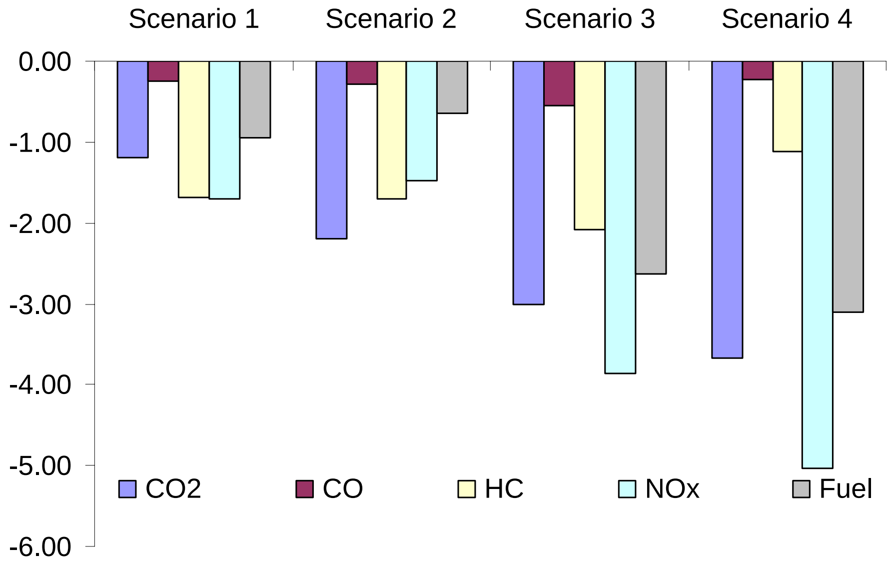


Figure 13. Comparison of Different Pollutants with respect to Base Case

7. POLICY IMPLICATIONS

To understand the policy implication of the “Hybrid HOV Bill”, the research team analyzed different scenarios in detail. First, we determined the criteria for the analysis. HOV lane operation is a facility used to encourage drivers to carpool. So, HOV lanes must provide sufficient benefits to carpoolers. Higher driving speed and better LOS on HOV lanes are expected to keep HOV lanes attractive. From a management perspective, policy makers may prefer maximizing Vehicle Miles Traveled (VMT) or minimizing Vehicle Hours Traveled (VHT) across the network in order to make full use of system capacity.

Currently, the average speed difference between HOV lanes and general purpose lanes is about 10% – 30% across the different freeways. If the criteria are to: (1) maintain the speed difference between HOV lanes and general purpose lanes by about 20 percent, and (2) ensure that more than 75 percent of the HOV lanes have speed greater than 45 mph, only Scenario 1 meets the criteria. This scenario marginally increases the mainline speed. The average speed difference between HOV lanes and mainlines can reach 30 percent on some corridors (e.g., SR-57 SB & SR-91 WB).

If the criteria are to: (1) maintain an average speed difference of about 15 percent throughout the network, and (2) keep at least 50 percent of HOV lanes at level of service of C (26 vpmpl) or better, Scenario 2 (i.e., 50K hybrid vehicles throughout the state) meets the above criteria. In this scenario, the average speeds for HOV lanes and general purpose lanes are 57 mph and 48 mph, respectively. Mainline sections have speed greater than 45 mph in about 70 percent of the network. This policy may more effectively utilize the hybrid HOV bill.

If the criteria are to: (1) maintain at least 10 percent of speed difference between HOV lanes and general purpose lanes, and (2) reduce at least 1% in VHT, Scenario 3 may be a better option. In this scenario, about 70 percent of the overall network (including HOV and general purpose lanes) has speed greater than 45 mph. Further, this scenario also reduces about 4,900 vehicle-hours traveled due to the increase of the general purpose lane speed.

If the criterion is to maximize the VMT throughput throughout the network, Scenario 4 (i.e., 100K hybrid vehicles) is the choice. During the morning peak period, this scenario increases VMT by about 18,000 vehicle miles traveled compared to the base case. Under Scenario 4, HOV lane performance is degraded and the speed differential between HOV lane and general purpose lanes is reduced significantly along most corridors. Although this scenario maximizes VMT and increases the general purpose lane speed by about 5%, the HOV lanes no longer offer trip reliability and offers no time incentives for carpools, buses or vanpools. Correspondingly, the HOV lanes effectively lose the ability for demand management.

8. CONCLUSIONS

This study introduces a microscopic simulation method to investigate the operational and environmental effects of the proposed California hybrid-HOV law that allows single occupant hybrid vehicles into the HOV lane. The study has constructed four scenarios, each with a different share of hybrid demand based on the market penetration. The OC freeway network was used for analyzing these scenarios based on a set of operational, performance, and air quality measures. The key findings from this study are summarized as follows:

- According to simulation results from Scenario 1, the initial wave of single occupant hybrid vehicles entering the HOV lanes does not have a substantial negative impact on HOV lane operations.
- After having 50K statewide hybrid vehicles (Scenario 2), the policy would degrade the performance of HOV lanes significantly, while marginally increasing the mainline speed.
- From the air quality perspective, a high share of hybrid vehicles will cause fewer emissions.

These findings must be considered within the context of the limitations of the modeling employed in the study. First, the demand forecasts associated with "early adopters" are notoriously unreliable. In this case, the market for hybrid vehicles is in the early stages of development, and it is unclear how this demand is being shaped both by supply limitations on the part of the manufacturers as well as by factors other than the typical economic considerations that form the foundation of automobile purchase and use decisions. Second, even with conventional travel modes, extracting traffic assignment and Origin-Destination information from regional planning models that is accurate at the microscopic level demanded by microsimulation models is subject to unknown (and probably high) error. Finally, the microsimulation model used in this study has a particular limitation pertaining to the modeling of the buffer-separated type of HOV facilities found in Orange County. Currently, access/egress decisions for eligible users of buffer-separated carpool lanes is handled as a route choice problem in Paramics. Because carpool-bound vehicles are constrained to follow these prescribed routes—the current implementation forces vehicles into the first access point possible—simulated vehicles can be observed to block mainline general purpose lanes in order to make these maneuvers. The current handling of this situation is flawed—the forced route choice behavior can lead to unrealistic congestion, particularly under peak conditions where the HOV lanes are most heavily utilized. Subject to these limitations, the results of the analysis indicate that a hybrid demand in excess of 50,000 vehicles statewide will have significant impact on the HOV lane operations in Orange County.

9. RECOMMENDATION & IMPLEMENTATION STRATEGIES

Allowing single-occupancy Hybrid vehicles access to California's HOV facilities is but one of many possible policy alternatives that potentially could make more efficient use of existing HOV lanes, ostensibly without degrading HOV performance to a level that impedes its intended function. For example, a priority-based HOV lane operation policy that would allow access to the HOV lanes by a wide range of vehicles, including SOVs, on a priority basis is one such alternative. Such a policy should be based on letting the maximum numbers of vehicles use the HOV lanes without allowing the lanes to become congested. In some areas, where/when the HOV capacity is underutilized, this may facilitate the use of HOV lanes as High Occupancy Toll (HOT) lanes. Economists have long promoted road pricing as an effective tool for managing congestion on urban freeways. California has used tolls to help pay for large bridge projects and some new freeways, but since the 1990s the development of practical radio frequency (RF) transponders spurred interest in wider application of pricing. It has been proposed that, because many HOV lanes have excess capacity, a natural application is to allow single-occupancy vehicles to pay a toll to use the HOV lanes and avoid congestion in the regular lanes. As long as the toll is set high enough to prevent congestion in the HOV lanes, these HOT lanes can potentially improve the efficiency of the existing freeway system. Dynamic management of the lanes will require fully instrumented HOV facilities including vehicle sensors, electronic message signs and ability for the users to pay tolls through transponders. The HOV lane managers must have the ability to monitor the traffic and communicate to the users via the signs the type of vehicles that are allowed to use the facility at any given time. For example, buses could have the highest priority, while SOVs who are paying a toll would have the lowest priority. In congested peak hours, only “3 plus” or “4 plus” HOV may be allowed.

As noted in the foregoing, the current implementation of HOV lanes in Caltrans District 12 features “buffers” between points of entry/exit to/from the HOV facility that prohibit the free movement of vehicles between the HOV- and general-use lanes. The argument for such a configuration is generally based on safety considerations associated with the presumed significant disparity in speeds between the respective traffic streams, particularly during peak period flow conditions. However, HOV lanes have been implemented in parts of northern California without separation; apparently without noticeable degradation in safety. The argument in favor of the type of HOV operation implemented in northern California is generally based on two considerations: 1) the absence of buffers affords greater flexibility to HOV traffic in making maneuvers into and out of the HOV lanes, and 2) the absence of buffers allows for the use of HOV lanes by general traffic during off-peak periods, more effectively utilizing the full capacity of the facility.

Serious consideration any of these alternatives should be accompanied by detailed simulations of their potential impacts. Before this can take place, several modeling improvements will be required: 1) refining our ability to extract reliable dynamic Origin-Destination information from regional planning models, perhaps in conjunction with loop detector data; 2) development of a better behavioral foundation for predicting traveler responses to alternatives they have yet to experience; and 3) model improvements relative to driver behavior in the access/egress of buffer-separated HOV facilities.

ACKNOWLEDGEMENTS

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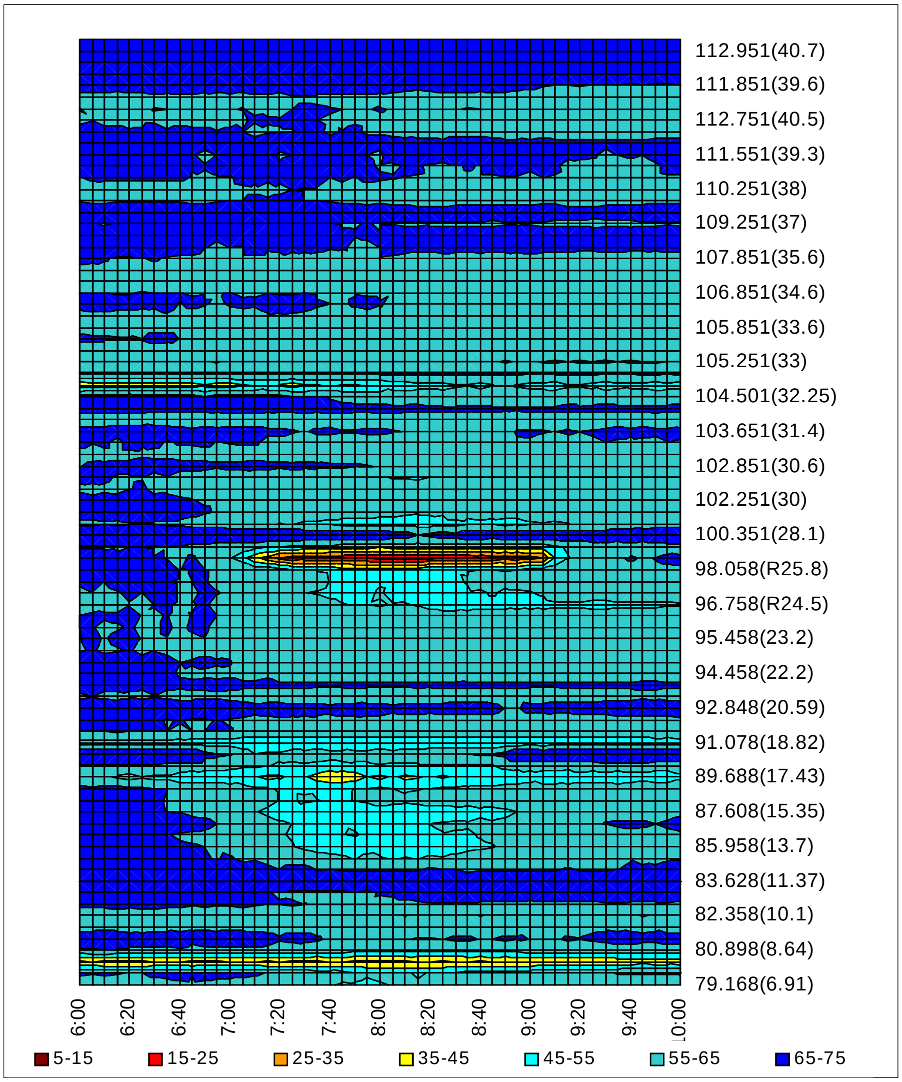
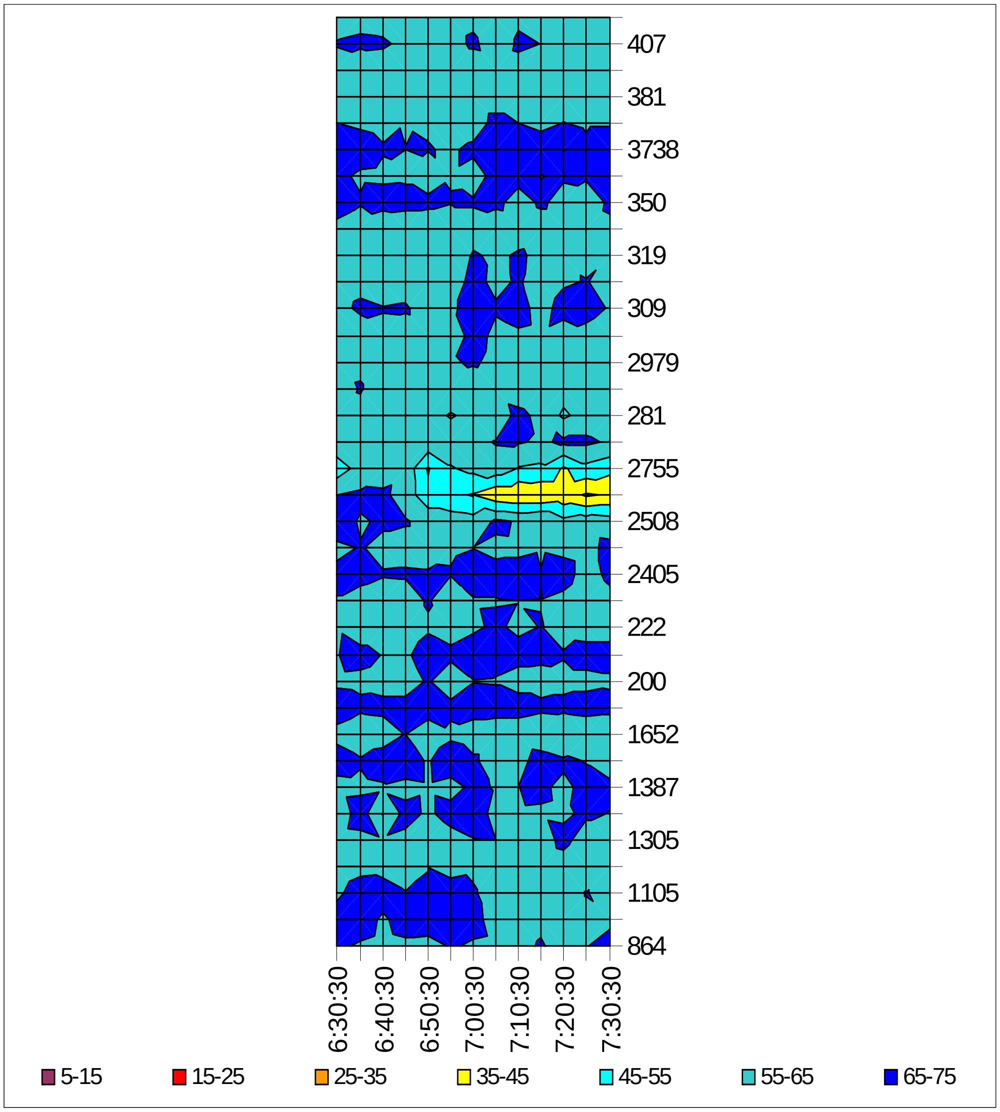
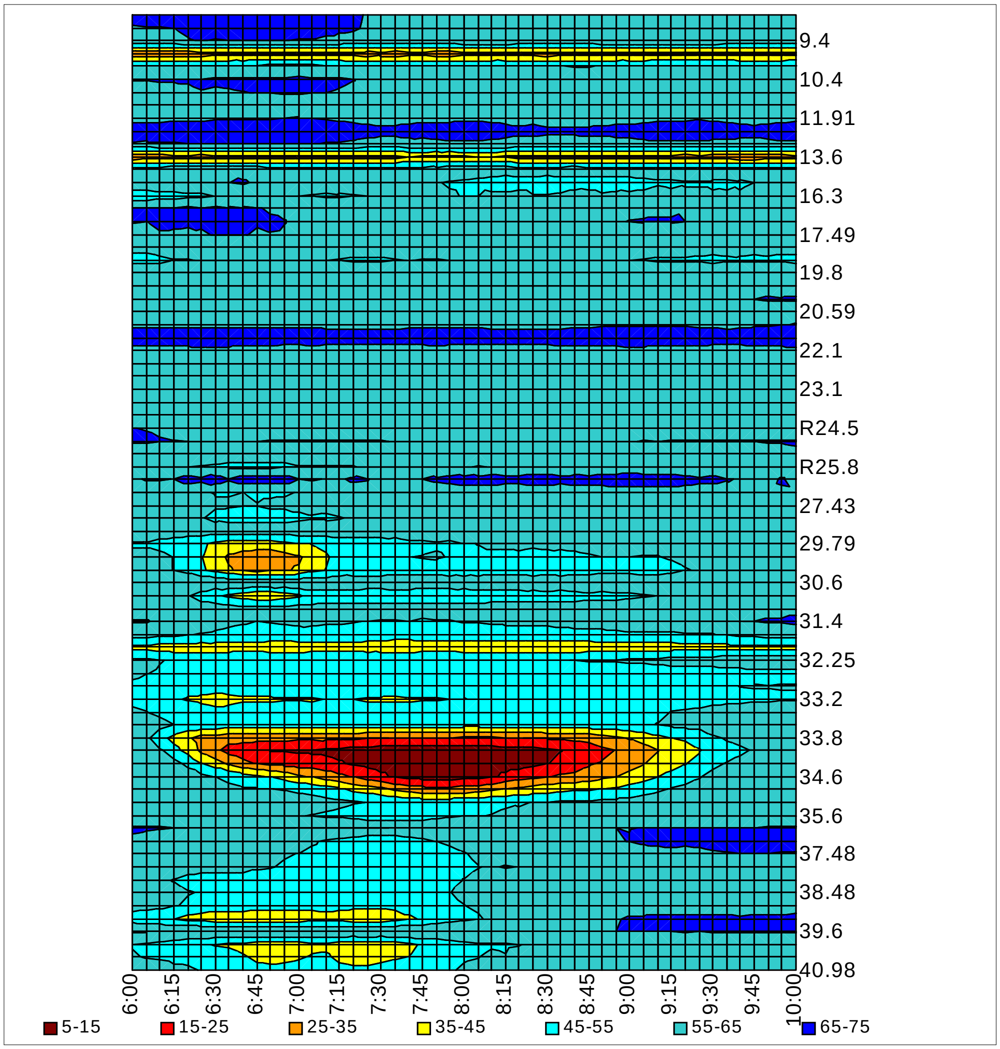
APPENDIX A



5NB HOV Speed Contour: Observed



5NB HOV Speed Contour: Simulated



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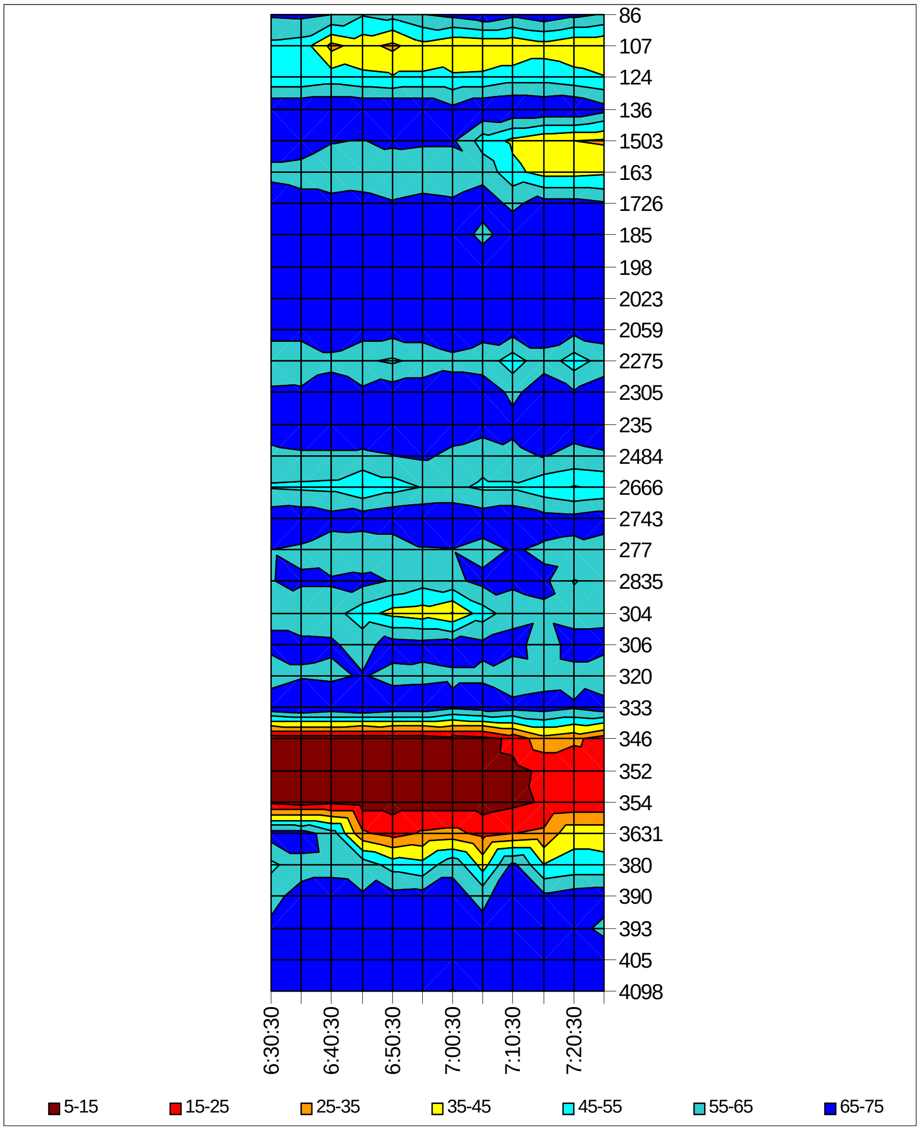

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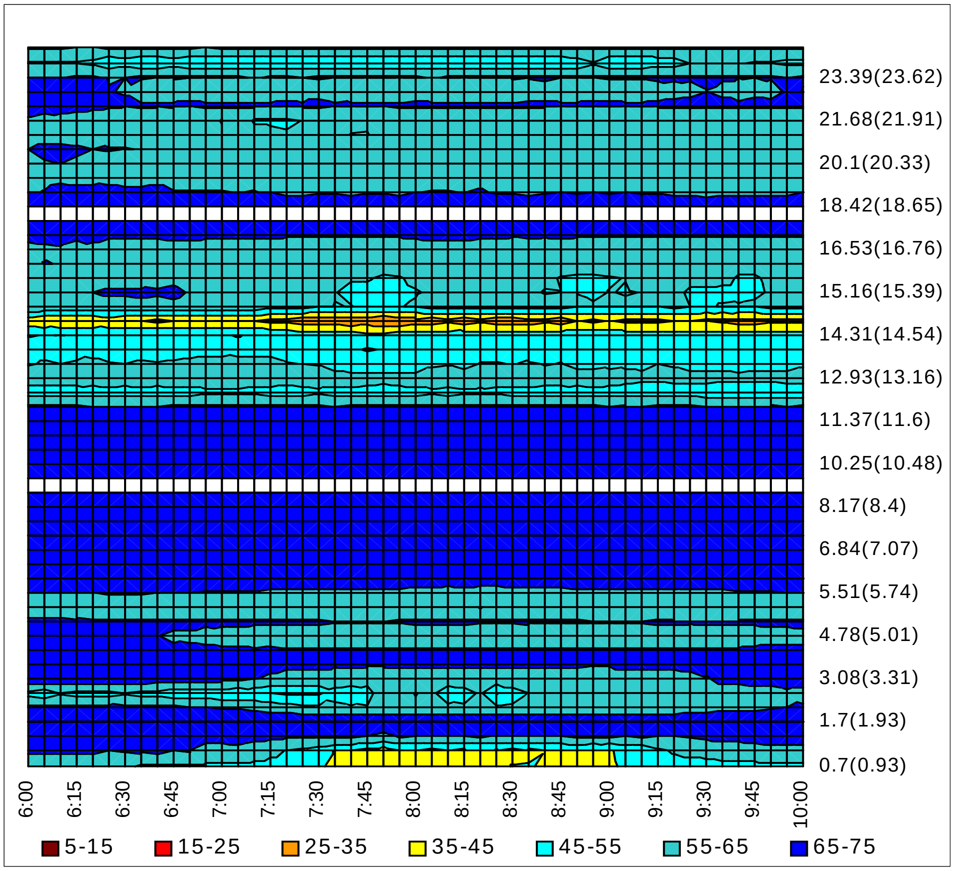

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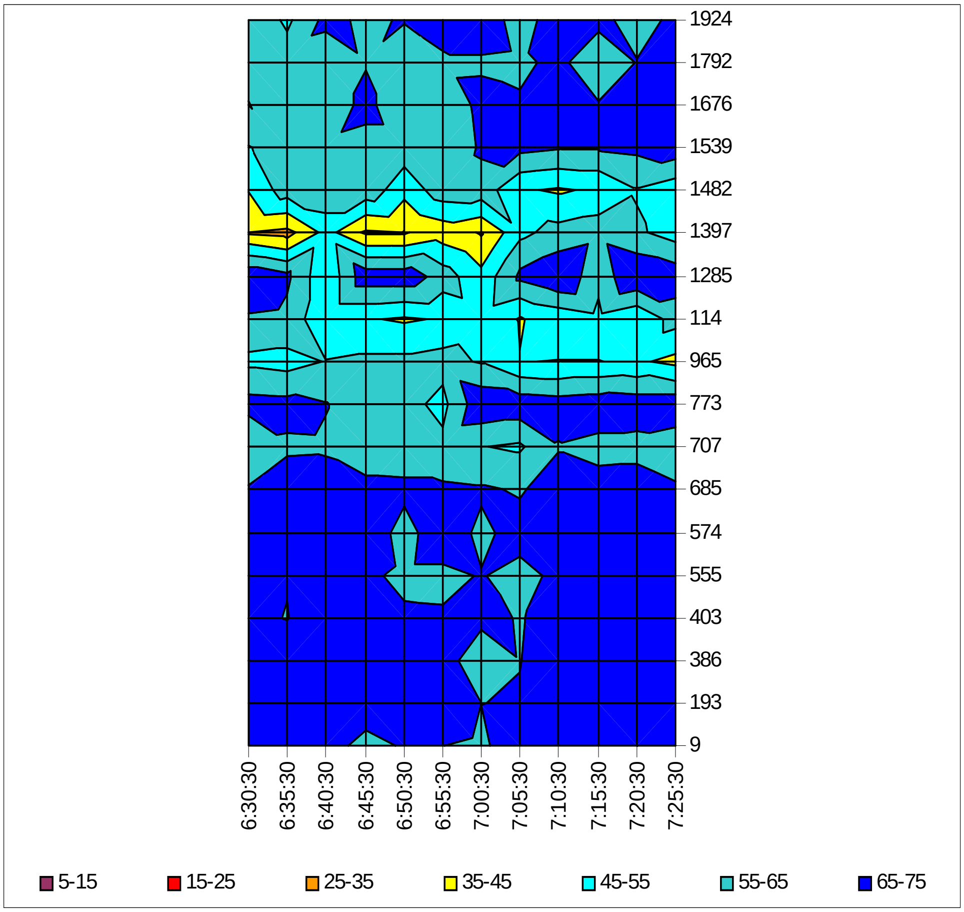

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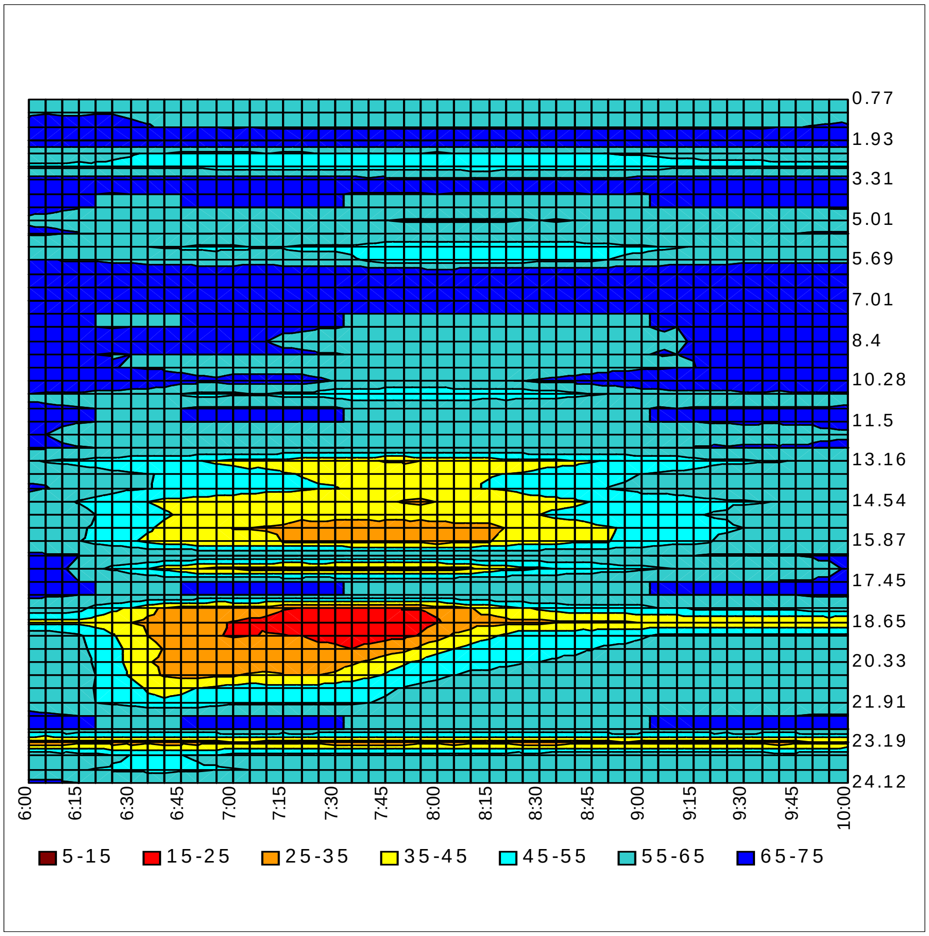

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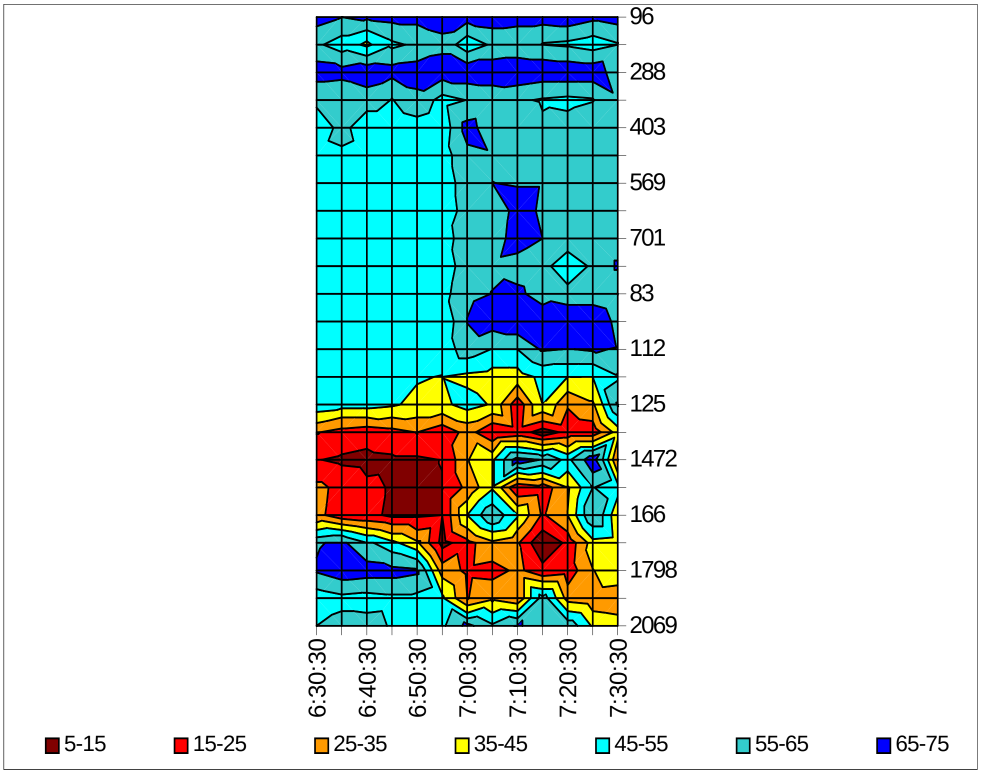

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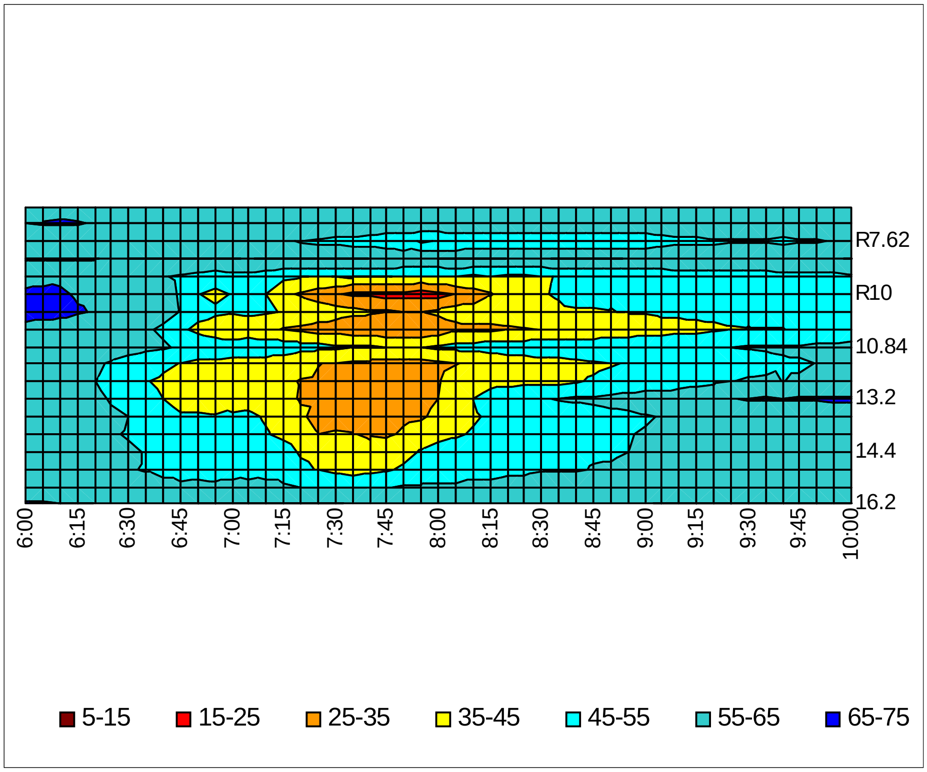

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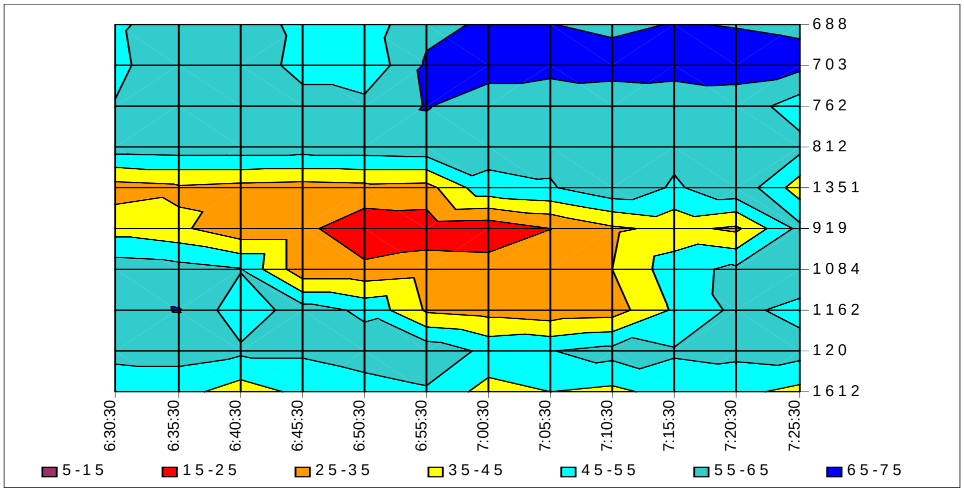

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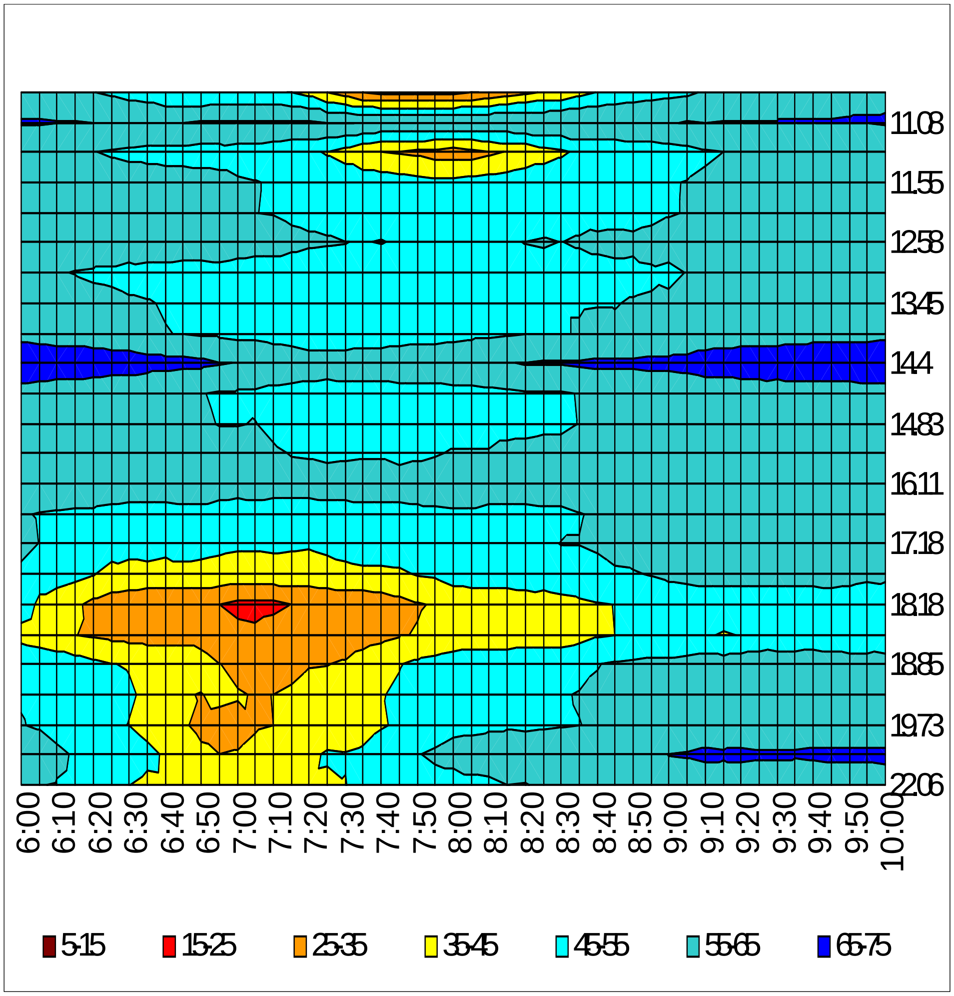
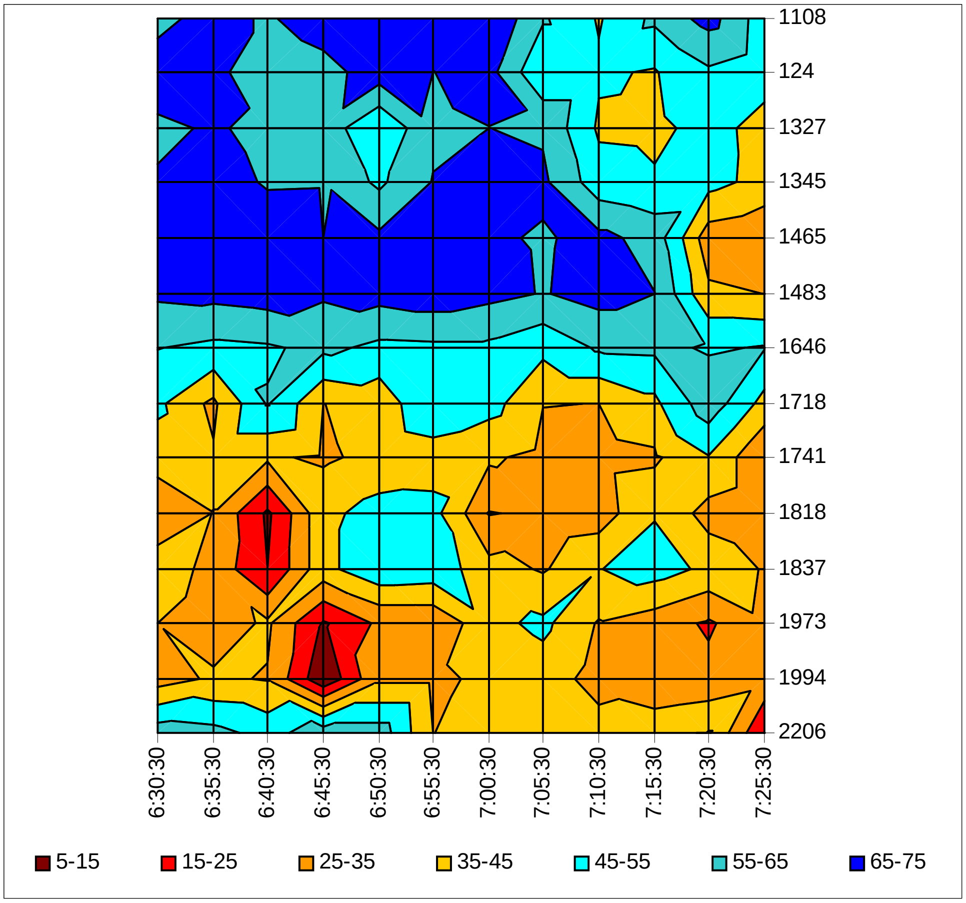


57SB HOV Speed Contour: Observed



57SB HOV Speed Contour: Simulated