JOURNAL OF TRANSPORTATION
SYSTEMS ENGINEERING AND INFORMATION TECHNOLOGY
Volume 10, Issue 2, April 2010
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: J Transpn Sys Eng & IT, 2010, 10(2), 30−41.

RESEARCH PAPER

Policy Implications of Incorporating Hybrid Vehicles into High-Occupancy Vehicle Lanes

NESAMANI K S[1,*], CHU Lianyu[2], RECKER Will[1]

1 Institute of Transportation Studies, University of California Irvine, 653 East Peltason Dr, Irvine, CA 92697-3600, USA
2 California Center for Innovative Transportation, University of California Berkeley, 653 East Peltason Dr, Irvine, CA 92697-3600, USA

Abstract: High-occupancy vehicle (HOV) lanes have been regarded as a cost-effective and environmental friendly option to help move people along congested routes. In spite of wide adaptation of policies, the effectiveness of HOV systems has been criticized for its under-utilization. A California statewide policy that allows hybrid vehicles to use HOV lanes was adopted under the expectation that vehicular emissions would be reduced by encouraging drivers to use fuel efficient vehicles as well traffic congestion would be eased through the more efficient use of the reserved capacity on the HOV lanes. To test the validity of this expectation, the impacts of the policy on the freeway network in Orange County, California was investigated using a method that combines a traditional planning model for demand estimation and analysis with a calibrated microscopic simulation model for accurate measures of system performance. The policy was analyzed in terms of overall system performance, corridor level performance and air quality. The key findings from this study are that the policy can be expected to have significant negative impact on HOV lanes that do not have reserve capacity. The maximum number of hybrid vehicles that the Orange County HOV system can absorb without significant degradation is about 50,000, and within this limitation, the policy can be expected to be successful in reducing emissions by allowing hybrid vehicles into HOV lanes.

Key Words: urban traffic; high-occupancy vehicle; hybrid vehicles; micro-simulation; travel demand modeling; emissions

1 Introduction

Federal and State governments are investing billions of dollars in building and promoting usage of High-Occupancy Vehicle (HOV) lanes through various programs[1]. The main motive behind this policy is to better manage the transportation system, moving more people by buses and carpools, saving travel time, reducing congestion, and improving air quality. The Federal Highway Administration (FWHA) encourages the installation of HOV lanes as an important component of an area-wide approach to help metropolitan areas address the needs that the agency has identified for mobility, safety, productivity, environment, and quality of life. In recent times, HOV lane construction has become one of the major freeway improvement strategies. Many states such as California, which is the state with the longest HOV lane miles in the US, have demonstrated the effectiveness of HOV lanes and are in the process of completing the HOV lane network[2].

Despite wide adoption of policies relating to HOV facilities by many states, Metropolitan Planning Organizations (MPOs) and cities, one criticism to HOV lanes is that they are under-utilized[3]. Based on California Assembly Bill 2628 (AB 2628) passed on September 23, 2004 and the Federal Transportation bill passed on August 10, 2005, California allows the three most fuel efficient (45 mpg or higher) hybrid vehicles (i.e. Toyota Prius, Hybrid Honda Civic, and Honda Insight) to use HOV lanes, irrespective of number of occupants. This policy was expected to reduce vehicular emissions by encouraging drivers to use fuel efficient vehicles as well as ease traffic congestion through the more efficient use of the reserved capacity on the HOV lanes. As a statewide policy, it is applied not only to such regions as the San Francisco Bay Area, where there is substantial reserve capacity on HOV lanes, but also such regions as Orange County, CA, whose HOV lanes have almost reached their nominal capacity of 1,650 vehicles per hour, carrying an

Received date: Jun 15, 2009; Revised date: Nov 9, 2009; Accepted date: Nov 25, 2009
*Corresponding author. E-mail: ksnesa55@hotmail.com

DOI: 10.1016/S1570-6672(09)60031-3

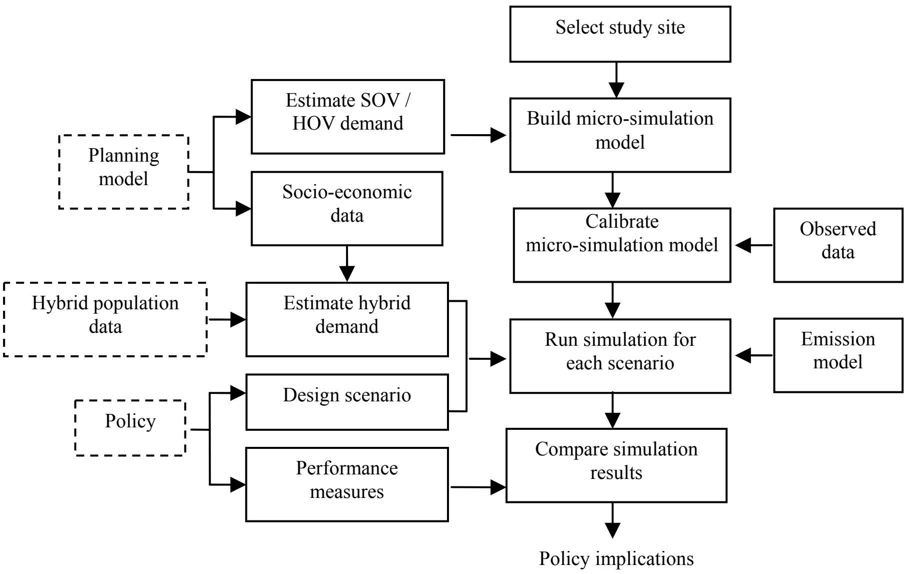

Fig. 1 Study methodology

average of 1,568 vph in 1998[4]. Hence policy makers are of interest to learn how this policy impacts the performance of the traffic system (both on HOV lanes and on general-purpose lanes).

Traditionally, transportation planning models have been used to evaluate possible impacts of a new policy. As HOV is a demand management policy that motivates solo drivers to switch to carpool, it is a candidate for such an analysis. However, HOV is also an advanced traffic management strategy because HOV drivers are capable of selecting HOV lanes or mixed-flow lanes based on traffic conditions. As a result, the hybrid-HOV policy in question could dynamically impact the whole traffic system and thus a planning-level study is not appropriate because it is an analysis that typically is based on BPR (Bureau of public roads) functions that cannot capture dynamic traffic condition and driver behavior.

Alternatively, with the advancement of computer technology and traffic modeling capability, microscopic simulation modeling has become an increasingly popular and effective tool for analyzing a wide variety of dynamic problems not amenable 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[5], construction management[6], operational improvement, emission[7], corridor management plan[8], traffic control studies[9,10], policy investigation[11], and so on. Similar to planning studies, it can guarantee the same demand pattern to be applied for both before and after the deployment of a policy to provide an objective evaluation. However, the limitation of the method is that evaluation results may be influenced by theoretical limitations of its base traffic models.

This paper proposes an improved method to evaluate the hybrid-HOV policy. The method combines a traditional planning method—used for demand estimation —with microscopic simulation modeling—used to provide accurate measures of the traffic system.

The remainder of the paper is organized as follows. Section 2 explains the methodology of the study, while Section 3 describes details of the simulation modeling of the study site. Section 4 designs several scenarios based on the hybrid-HOV policy and evaluates the results. Section 5 provides policy implications based on evaluation results. Section 6 concludes and discusses the limitations of the paper.

2 Methodology

The methodology adopted in this study is illustrated in Fig. 1. The study involved three important modeling components that are (a) microscopic simulation modeling; (b) demand modeling and (c) emission modeling. The microscopic simulation model for the study site was developed and then calibrated against the baseline traffic conditions. In the simulation model, the baseline demand was originally extracted from the regional planning model and then further fine-tuned using the Paramics OD estimator tool. Based on the California hybrid-HOV bill, different scenarios with different hybrid populations were designed and their corresponding hybrid demands were estimated. Then, the calibrated model was simulated under different scenarios and simulation results were analyzed and compared to show effects of the policy. This study also includes detailed emissions modeling to estimate accurate emissions. The emissions model employed in this study is a new generation model that can accurately predict the energy and air quality impacts of transportation systems, operating at the micro-, meso-, and macro-scale levels-of-details.

Study site. Orange County, CA, is a densely populated portion of the Greater Los Angeles metropolitan area, with 3 million inhabitants in an 800-square-mile area with 1.8 million motor vehicles registered. The study network includes all of the major freeways in Orange County—I-5, I-405, SR-55, SR-22, SR-57, and SR-91—all of which are well covered by loop detectors. These busy freeways contain a variety of HOV lane configurations, including freeway-to-freeway HOV lane connectors, exclusive HOV lane ramps, and limited ingress/egress points. The southernmost 10 miles of I-5 that do not have HOV lanes, I-605, and all toll roads with express lanes are not included in the study network.

3 Simulation modeling

Microscopic simulation is used for investigating the hybrid-HOV policy since microscopic simulation models are designed to emulate the movement and behavior of individual vehicles on urban and freeway 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. This section elaborates in detail the various stages of network construction and calibration.

3.1 Model construction

The microscopic simulation model used in this research is Paramics, a scalable, high-performance microscopic traffic simulation package developed in Scotland[12]. Paramics has ability to model both existing and emerging transportation infrastructures and intelligent transportation systems (ITS) strategies. In addition, Paramics provides users with application programming interfaces (API) through which the core models can be accessed to customize and extend many features of the simulation model without having to deal with the underlying proprietary source codes.

Figure 2 shows the study network coded in Paramics. It was built based on a wide range of input data, including roadway geometry, vehicle characteristics, traffic control systems, and traffic detection systems. To model the buffer-separated HOV lanes (common in Southern California), the mixed-flow lanes and HOV lanes were coded as two separate links wherever required. Non-buffered sections were coded as a single link between ingress and egress points. Ramp meters were added to all applicable on-ramps and set to their respective field metering rate, and loop detectors were placed to collect data across the network. Because the network has freeways only, its vehicles' origin and destination (OD) zones were typically placed at on-ramps, off-ramps, and the two ends of each freeway. The network has a total of 200 HOV lane miles and 800 mainline lane miles (most freeway mainline have 4–6 lanes), which makes it one of the largest networks coded in a micro-simulation platform.

3.2 Model calibration

The objective of any model calibration is to ensure reasonable (qualitative and quantitative) correspondence between the simulation model and field observation. Model calibration follows the procedure described in this section. The model was calibrated to represent traffic conditions during the morning peak period.

3.2.1 Calibration data preparation and data analysis

The coverage and accuracy of data are important for model calibration. Both flow and speed data were collected from the California Department of Transportation (Caltrans) Performance Measurement System (PeMS)[13].

At any given time, only about 50% of loop detectors were found to be reporting accurate data; to supplement these gaps we used data from four different years (i.e., from 2002 to 2005). Some on-ramp and off-ramp locations had no data at all even within the four-year period; they were estimated based on either Caltrans census dataset or an estimation based on mainline loop detector data. Due to these data collection problems and other inaccuracy issues, the flow data obtained were not consistent at some locations; such inconsistencies were removed by manual adjustments.

Speed data were collected to identify any bottlenecks in the freeway network. The 50th percentile speed contour maps drawn based on 5-min speed data collected from freeways for three months (only Tuesday to Thursday's were considered) were used to identify recurrent freeway bottlenecks[8].

3.2.2 Route choice

As the study network is a "freeway only" network, most OD pairs have only one path for non-HOV vehicles. Alternatively, HOV-eligible vehicles can select either the HOV lanes or mixed-flow lanes. Based on the HOV drivers'

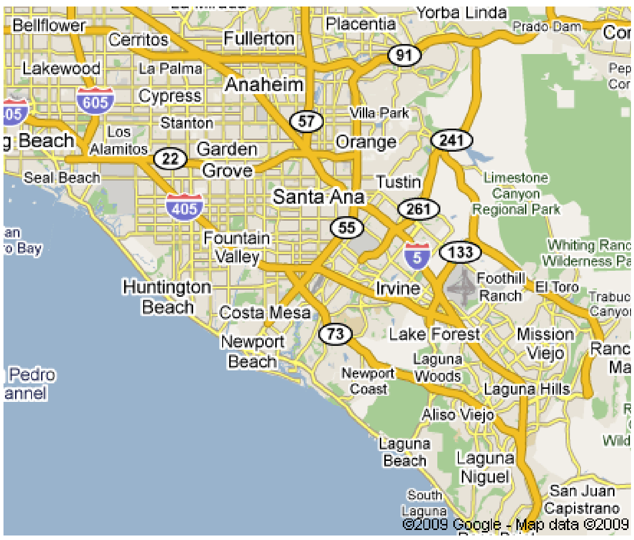

Fig. 2 Study area and coding in PARAMICS

travel pattern analysis during the morning peak period, it was found that while most HOV-eligible vehicles choose HOV lanes, some choose mixed-flow lanes, and others flip between HOV lane and mixed-flow lanes based on perceived traffic condition along both routes. To account for this observed behavior, we applied both a stochastic route choice model and a dynamic feedback route choice model to HOV-eligible vehicles. The stochastic route choice model, which assumes that different drivers perceive different costs from a decision point to the destination, captures the route choice behaviors of the first two groups of HOV drivers. The dynamic feedback route choice model, which assumes travelers select route based on instantaneous traffic information, captures the route choice behaviors of the last group of HOV drivers.

3.2.3 Demand estimation

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

(1) Obtain pattern OD matrix

The Orange County transportation analysis model (OCTAM) obtained from Orange County Transportation Authority (OCTA) was used to extract the pattern OD matrix of the study network, which is a "freeway only" network with 265 zones. We applied a special type of sub-area extraction method called "multi-modal, multi-class assignment (MMA)" using TransCAD, a transportation planning software package. The resultant OD matrices from MMA were transferred to the coded Paramics network using a lookup table matching Paramics zones with TransCAD zones. A simple MATLAB code was written to complete the work.

(2) Fine-tune OD matrix

OD matrices extracted from planning models generally are not accurate enough for microsimulation applications. To improve accuracy, the Paramics OD estimator was used to optimize the pattern OD matrix using link flows, turning movements and cordon flows. The performance measure used in OD estimation was GEH statistic[14].

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

For simplicity, this procedure was applied only to the estimation of the single occupancy vehicle (SOV) demand.

(3) HOV demand estimation

Due to the size of the study network, a practical assumption for HOV demand estimation is to have a fixed HOV percentage of all vehicles applied to the whole network. Unlike SOV, HOV can use either HOV lanes or mixed-flow lanes (or both). Every year Caltrans collects HOV vehicles' lane choice data at 11 locations in Orange County; these data were used to calibrate the HOV percentage[15]. In the final model, the share of HOV demand was estimated as 21.7%. (The Caltrans figures for the 11 stations range from 14.5% to 25%.)

3.2.4 Network performance calibration and validation

Based on estimated demand tables, the simulation model was further fine-tuned to match observed speed plots and flow data. Our calibration criteria are similar to FHWA's calibration criteria[16]. Because of: (a) the complexity introduced from the large size of the model, (b) the above-mentioned observed data issue, (c) day-to-day traffic congestion variation, and (d) random occurrence of incidents, use of a fixed set of flows on mainlines and ramps as flow calibration targets proved inappropriate. As a result, our calibration targets were as follows:

(1) Maximize the percentage of measurement locations having GEH values less than 5; this, instead of meeting the 85% criteria based on the FHWA's calibration guideline;

(2) Match major bottlenecks of the network.

Calibration results revealed that there was a good match between the simulated and the observed 50-th percentile speed contour maps for both mixed-flow lanes and HOV lanes in about 70% of all measurement locations, and these locations had GEH values less than 5[17].

3.2.5 Emission model

To understand the impact of proposed policy on air quality the comprehensive modal emission model (CMEM), developed by University of California, Riverside along with University of Michigan and Lawrence Berkeley National Laboratory, was used. This model can predict second-by-second fuel consumption and tailpipe emissions of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxide (NOx) and carbon dioxide (CO_2) for a wide variety of vehicles under different operating conditions (idle, cruise, acceleration, and deceleration) based on power demand. Tailpipe emissions are calculated as follows using fuel rate (FR), engine-out emission indices (g emissions/g fuel) and time dependent catalyst pass fraction (CPF)[18].

$$\text{Tailpipe emissions} = \text{FR} \cdot (\text{g emissions/g fuel}) \cdot \text{CPF}$$

This model was validated using different driving cycles. It can be easily integrated with other microscopic traffic simulation models such as PARAMICS, FRESIM, NETSIM, and CORSIM. In this study, CMEM plug-in developed for Paramics was used to estimate the emissions and fuel consumption directly during simulation runs.

4 Evaluation

4.1 Scenario design

The base scenario is the calibrated model, where hybrid vehicles were not allowed to use HOV lanes. This scenario corresponds to the timeframe before California's bill AB 2628 was implemented. California's hybrid-HOV law requires that Caltrans must determine whether 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 states that the maximum allowed HOV lane access permits is 75,000.

Four scenarios were constructed as follows:

Scenario 1 corresponds to the condition when there are 36,000 hybrid vehicles, equivalent to the actual number of eligible hybrid vehicles as of November 2005. This scenario analyzes the impact of initial wave of hybrid vehicles into HOV lanes.

Scenario 2 corresponds to the condition when there are 50,000 hybrid vehicles.

Scenario 3 corresponds to the condition when there are 75,000 hybrid vehicles (maximum number of hybrid vehicles allowed by bill AB 2628).

Scenario 4 corresponds to the condition when/if the total hybrid vehicles reach 100,000. This scenario used to give policy makers an idea what will happen if the allowed hybrid vehicles continue to grow.

4.2 Hybrid modeling

It is important to model the movement of vehicles and the interaction among them. Hence, in this study new vehicle category called hybrid was created using the physical characteristics of vehicle such as dimensions, top speed, power, crawl speed, color, and so on. The newly created vehicle category was allowed to use HOV lanes.

The hybrid vehicle demands for various scenarios were estimated according to the following five-step procedure.

(1) The hybrid demand for each Traffic Analysis Zone (TAZ) was estimated first based on a household-level choice model. The multinomial Logit and binomial Logit models were developed based on such socio-economic data as population, number of workers, average household size and median income[19]. These models were used to predict the number of households that would purchase new hybrid vehicles and their preferred choices. This was further aggregated to estimate the share of hybrid vehicles in each TAZ. Department of Motor Vehicles (DMV) registration data in November 2005, which shows California had 36,000 hybrids and approximately 10% of them were in Orange County, were used to validate the estimated hybrid demand. It was found that the DMV data were matched well.

(2) Based on the hybrid vehicle demand for each TAZ and the total demand from planning model, the proportion of hybrid vehicles of the total demand expected to originate from each TAZ was calculated. Based on the relationship between Paramics zones and Planning TAZs, the proportion was assigned to the Paramics zone level.

(3) The hybrid demand pattern matrix was estimated based on hybrid registration data from DMV in November 2005. It was observed during the peak period that predominantly hybrid vehicles were driven by solo drivers. Further, in absences of any data regarding the number of drivers shifting to hybrid vehicles, it was assumed only solo drivers switched to hybrid vehicles. However, authors are aware of the fact that there are other motivating factors to switch to hybrid vehicles such as environmental conscientious, economical benefits, and so on. Hence, hybrid vehicle demand was regarded as having the similar OD pattern as SOV demand.

(4) Assuming that the hybrid demand pattern matrix and the percentage share of hybrid vehicles in Orange County with respect to California remains the same (which is 10%), the hybrid demand matrices for all scenarios were obtained by scaling up or down the hybrid demand matrix. The scale was equal to the total issued HOV lane access permits under each scenario divided by 36,000, which is the total permits in November 2005.

(5) It was assumed that the total demands for all scenarios were constant and thus the SOV demand matrix were updated by subtracting the hybrid demand matrix to match the total demand. Table 1 indicates the percentage of SOV, HOV, and hybrids in each scenario.

4.3 Performance measures

The performance of each scenario was evaluated in term of: (a) overall system performance, (b) corridor-level performance, and (c) air quality. The overall system performance measures include vehicle hours traveled (VHT), vehicle miles traveled (VMT) and average travel speed. Corridor level performance measures include level of service (LOS) and speed. LOS indicates the quality of the services provided by the given facility, and California's hybrid-HOV law states that Caltrans has the authority to remove "individual HOV lanes or portions of those lanes," if traffic condition exceeds level C. Speed is used since SAFETEA-LU (Safe Accountable Flexible Efficient Transportation Equity Act: A Legacy for Users) from FHWA, which requires that HOV lanes speed should not be degraded for 10% of the time in one or both of the peak hours. In other words, HOV lanes should keep speed higher than 45 mph for 90% of the peak periods for the California case.

To analyze corridor performance, each corridor was divided into number of sections spaced about five miles apart. This segmentation allows detailed performance of each section to be computed and makes it easy to capture those congestion patterns that are highly localized. A Paramics plug-in was developed to collect the actual section density for LOS calculation and probe vehicle speeds for section speed

Table 1 Proportion of vehicles in different scenarios

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

Table 2 Number of HOV and ML sections by corridor

Freeway	Direction	Distance (miles)	ML 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	-
	WB	12	3	-

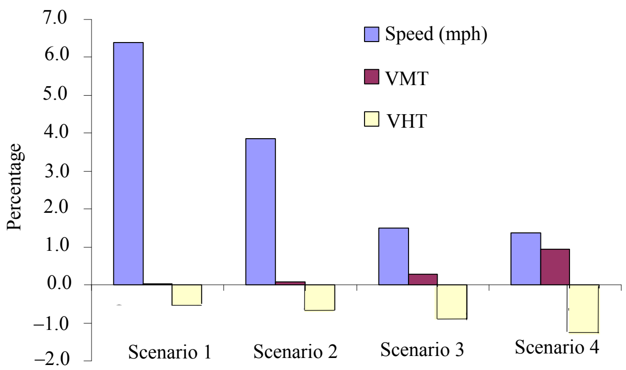

Fig. 3 Overall performance of the network

estimation. There were a total of 46 mixed-flow segments and 42 HOV lane segments in the Paramics network as shown in Table 2.

Current emission rate models (EMFAC, MOBILE) cannot estimate emission inventories at micro-scale level. Hence the CMEM, was used to evaluate the performance of different scenarios with respect to air quality[18]. The key input to the CMEM model includes vehicle activity (second-by-second speed, acceleration, and grade) and fleet composition was directly obtained from PARAMICS simulation run. In this model, vehicles are divided into 31 categories based on technical characteristics of vehicles and emission control systems, which include 14 categories of normal-emitting cars, 9 categories of normal-emitting trucks, 5 categories of high-emitting trucks, and 3 categories of heavy duty diesel vehicles[18,20]. However, this model does not have hybrid vehicle category and hence in this study hybrid vehicles were represented by low emission vehicle/technology for comparison purposes across different scenarios.

4.4 Results and analysis

Simulations were performed for different scenarios for 1 hour and 30 minutes. The first 30 minutes of simulation were considered as the warm-up period for vehicles to fill in the network, and only the last one hour of the simulations were analyzed. Although not consistent with field observation, it is assumed that there are no HOV lane violations during simulation.

Different plug-ins were enabled to collect different performance measures data. The performance of the base scenario was used as reference to evaluate other scenarios. Five runs were conducted per scenario to generate statistically meaningful results. The results from the median run are used for analysis.

4.4.1 Overall system performance

Figure 3 illustrates the percentage change of VMT, VHT, and average speed in alternative scenarios with respect to the base case. All scenarios show an increase in the average speed and VMT and a decrease in VHT compared to the base case. With the increase of hybrid vehicles from Scenario 1 to 4, VMT and VHT are seen to improve gradually. Scenario 4 outperforms all other scenarios in terms of VMT and VHT. However, the average speed increase of Scenario 4 (from 34.3 to 34.6 mph) is only 1.4%, which is very marginal and also is the worst compared to other scenarios. Scenario 1 performs the best in terms of average speed.

Ostensibly, Scenario 4 outperforms in terms of VMT and VHT because the capacity of the network is better utilized by degrading HOV lane's performance. The speed difference between HOV lane and mixed-flow lanes is reduced significantly along most corridors, as shown in Fig. 4. Although this scenario still increases the mixed-flow lane speed by about 5%, the HOV lane no longer offers trip reliability and has no time incentives for carpools, buses or vanpools.

4.4.2 Corridor level performance

As shown in Fig. 4, HOV lane speed is degraded gradually with the increase of hybrids, especially on such congested freeways as I-5, I-405, SR-55 SB and SR-57 SB. For example, the speed difference between HOV and mixed-flow lanes in the I-5 NB base case is about 10 mph; this has narrowed down to almost similar speeds in Scenario 4. I-405 SB is the most congested corridor in the morning peak and the base case simulation result indicates that most of the sections are in LOS D to F and about 40% of them have speeds less than 45 mph. Obviously, hybrid vehicles receive no measurable benefit from the policy on these already-congested corridors. Moreover, allowing them to use HOV lanes may cause the existing traffic congestion to get even worse due to the introduction of additional lane changes.

Figure 5 demonstrates the LOS distribution in HOV lanes for the different scenarios. Even in the base scenario, there are some sections with LOS E and F. It was found that most of these sections are located at major bottlenecks of the network

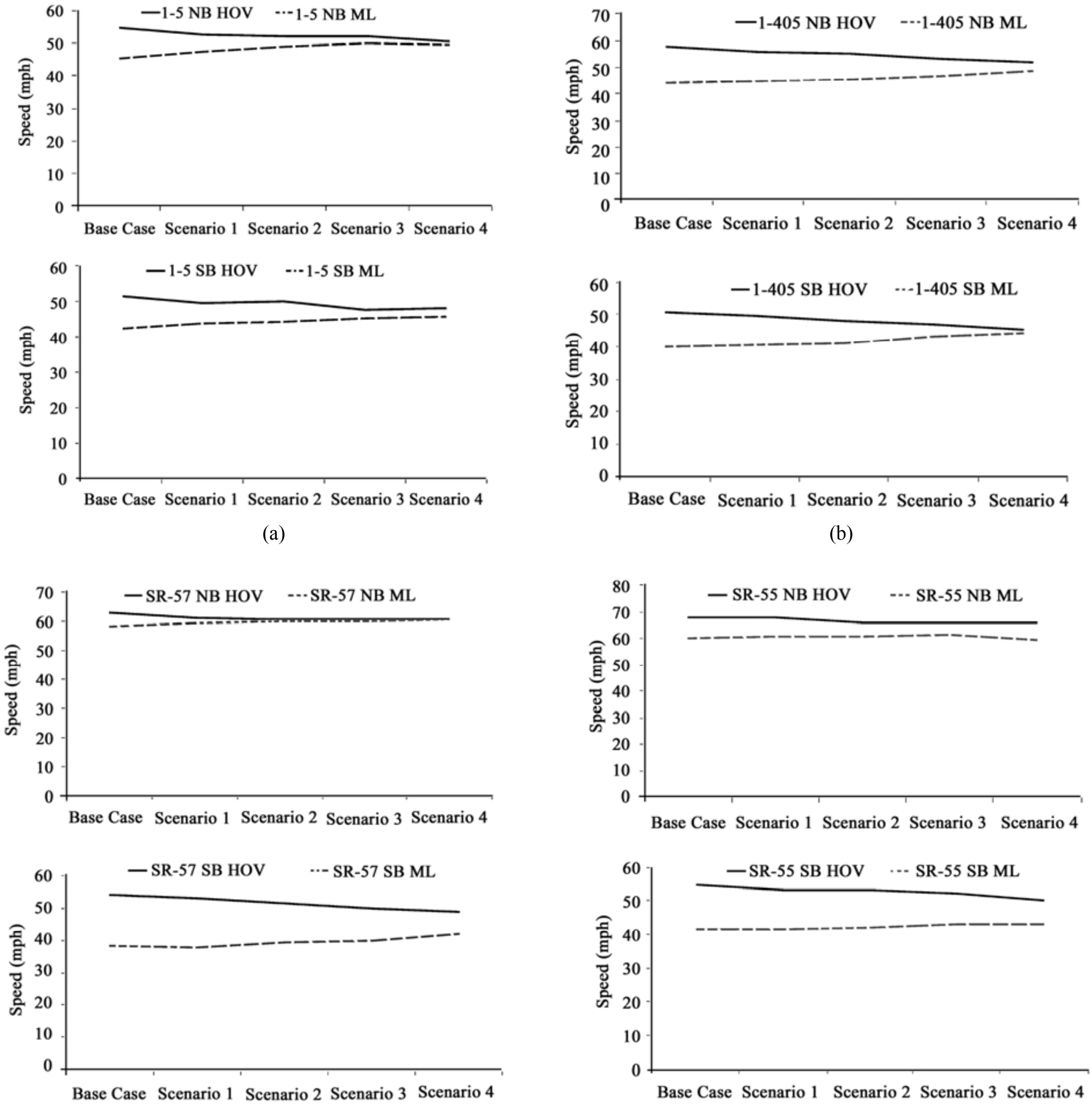

Fig. 4 Comparison of HOV and mixed-flow lane speed (a: Freeway I-5; b: Freeway I-405; c: Freeway SR-55; d: Freeway SR-57)

and HOV freeway-to-freeway interchanges, including I-5 SB at interchanges with SR-22, SR-55, SR-57, and SR-55 SB at the interchange with I-5, and SR-57 SB at interchanges with SR-91 and I-5. An explanation for congestion at freeway-to-freeway interchanges is likely due to a design flaw in the construction of HOV lanes that collect HOV traffic from two freeways but provide only one HOV lane's capacity by the associated lane drop. This situation is at odds with the HOV guideline of Caltrans that requires the HOV facility not be allowed to reach unstable flow (LOS-E), and should not experience congestion on a regular basis.

Corresponding to the hybrid-HOV bill's requirement, the level of service for the HOV lane should ideally be maintained at LOS C. A further analysis was conducted to check the percentage of sections having LOS equal to or better than C (equivalent to 26 vehicles per mile per lane or less) as shown in Fig. 6. It is found that 80% of the sections in the base case meet the criteria. After allowing hybrids into HOV lanes, the percentages of sections from Scenario 1 through 4 are dropped to 70%, 66%, 60%, and 55%, respectively.

Figure 7 shows the temporal and spatial speed distributions of HOV lanes for the various scenarios. Speed is divided into intervals of 10 mph; the x-axis shows the percentage of time spent in different speed ranges. The percentage of sections and time periods with speed greater than 45 mph in HOV lanes were analyzed as illustrated in Fig. 8. In the base case, there are about 77% of HOV lanes having speeds greater than 45 mph. Allowing an increasing number of hybrids into HOV lanes drops the percentages to 75%, 72%, 69%, and 66% for Scenarios 1 through 4, respectively. We note that, because the base scenario's 77% is much lower than the SAFETEA-LU's 90% requirement, the addition of any hybrid vehicles to HOV lanes in Orange County violates the SAFETEA-LU requirement.

The above simulation data was used to investigate the maximum number of hybrid vehicle permits that can be allowed in Orange County to minimize the negative influence of the policy on carpoolers. This is a multi-objective optimization problem. The optimization process aims to reach a tradeoff among all stakeholders by balancing the interests of each party.

(1) The prime objective of the problem is to maximize the benefits obtained from air quality and reducing fuel consumption. Scenario 4 is the best scenario from this perspective.

(2) The second objective is to meet FHWA's SAFETEA-LU's requirement. As mentioned above, the HOV system in Orange County does not meet the 90% requirement and thus needs to be relaxed if any Hybrids are to be allowed access to the HOV lanes. A practical requirement could be to allow another 10% of HOV lanes to be operated less than 45 mph. It was found that scenarios 1-3 meet the requirement.

(3) The final objective is that HOV lanes must continue to provide benefits for existing carpoolers. Caltrans' HOV guideline requires that HOV lanes should maintain the necessary incentive to use the facility. However, Fig. 4 shows that the increase of hybrids gradually decreases the speed difference between HOV lanes and mixed-flow lanes, reducing the benefits that carpoolers obtain from HOV lanes. This is a serious concern since it obfuscates the HOV lane's ability for demand management. To measure this impact, we defined the percentage of average speed difference between HOV lanes and mixed-flow lanes as a performance index.

It was found that the percentage of average speed difference in the base scenario is about 10%–30% (average at 24%) across different freeways. The speed difference percentages in Scenario 1 through 3 are 21%, 16%, and 11%. An intuitive feeling from this is that at least 15% speed difference is required to keep HOV lanes attractive. Under this assumption, Scenario 2 appears likely to satisfy the desires of all stakeholders. This indicates that 50K hybrid vehicle permits throughout the state may be the number of permits that Orange County HOV system and other similar counties can take without much degradation.

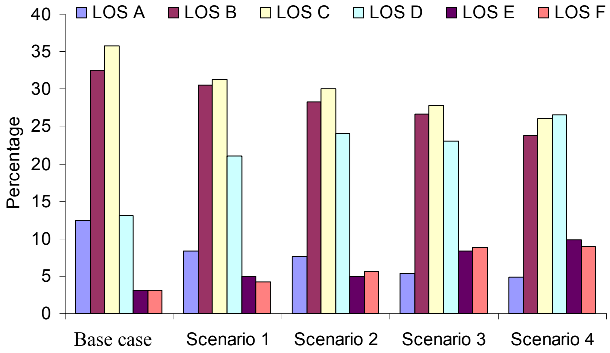

Fig. 5 Level of service distribution in HOV lanes

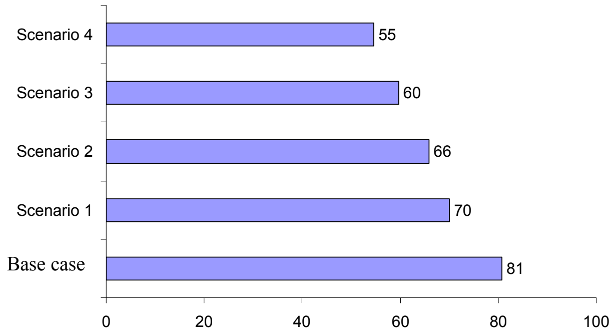

Fig. 6 Percentage of sections and time period spent less than 26 vehicles/mile/lane

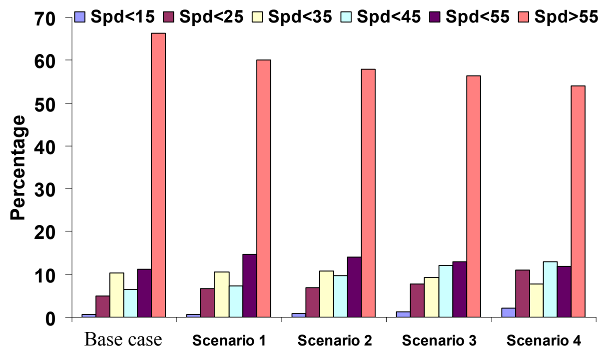

Fig. 7 Speed distributions of HOV lanes

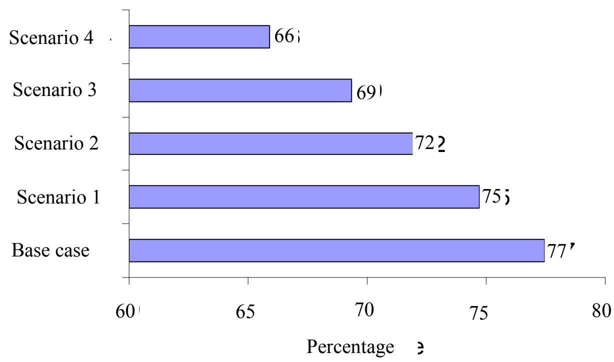

Fig. 8 Percentage of section and time period speed greater than 45 mph

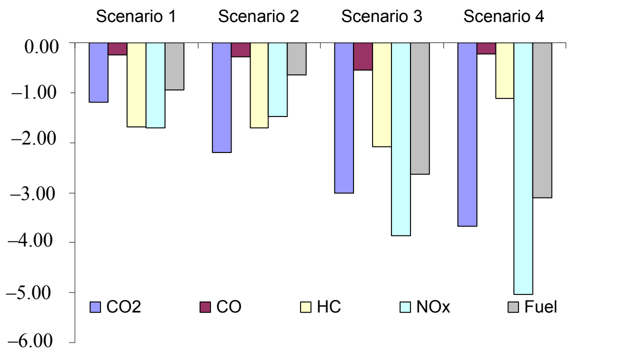

Fig. 9 Comparison of different pollutants with respect to base case

4.4.3 Air quality performance

Figure 9 compares the relative improvement in the emission of different pollutants over the base case. CO and HC are principally emitted by gasoline vehicles and diesel vehicles emit significant share of NOx emissions. CO_2 is directly proportionate to fuel consumption. Overall, scenario 4 performs the best merely because of the high share of hybrid vehicles, indicating that there are air-quality benefits even though 25,000 more hybrid vehicles than the pre-determined maximum, i.e. a statewide 75,000, to be allowed to use HOV lanes. In addition, air quality benefits could be attributed to 5% improvement in speed in general purpose lanes. However, the focus of this paper is not to evaluate the performance of hybrid vehicles.

5 Policy implications

Simulation studies applied to the freeway network in Orange County, California, find that the policy allowing hybrid vehicles to use HOV lanes can be effective in obtaining air quality benefits. From this perspective, the policy is successful, which may also have affected the selling of hybrid vehicles. But, from another perspective, HOV lanes on most freeways in Orange County will become more congested with a significant increase in share of hybrid vehicles. Based on the hybrid-HOV law, Caltrans is required to determine whether HOV lane breakdown has occurred on any of the state's HOV lanes after 50,000 "HOV lane access" permits. Also, Caltrans has the authority to remove "individual HOV lanes or portions of those lanes," if traffic condition exceeds LOS C. The reality is that Caltrans did not stop offering hybrid permits before hitting the original 75,000 cap and also made the decision to extend the maximal permits to be 85,000 (which have been reached in February 2007). The HOV lane operation problem in Orange County was not used as an excuse to stop offering hybrid permits to HOV lanes. The reason could be that the policy is a state-wide policy and thus Caltrans had to synthetically consider the benefits of the policy to the whole state, rather than based on one county, raising an applicability issue for the policy.

A policy like the hybrid-HOV bill has complex influence on the freeway system. Its applicability to an area depends on the current traffic condition, travel pattern, popularity of the public transit of the area. It may be appropriate for those areas (such as the Bay area) that have reserve capacity on HOV lanes. But this may not be appropriate to be applied to the whole of Orange County because most of its HOV lanes are already congested. The policy could have been implemented more strategically to maintain its expected benefits, resulting in the overall corridor speed improved by accommodating some demand from mixed-flow lanes without substantial compromise on HOV performance. It can be applied to selected freeways and/or selected time periods. For example, the policy is viable for the morning peak period of SR-55 NB and SR-57 NB HOV lanes whose HOV lanes are not currently congested and whose mixed-flow lanes are only slightly congested.

Due to the current congestion level on the Orange County freeway system, the hybrid-HOV policy is projected to negatively affect system performance. Improvements in HOV lane configuration and HOV design are needed to accommodate the 85,000 hybrid vehicle permits already issued. As indicated in this study, the current HOV system has design flaws in the HOV lanes at freeway-to-freeway interchanges, which collect HOV traffic from two freeways but there is only one HOV lane's capacity available.

6 Conclusions

This study introduces a method that combines the traditional planning method with microscopic simulation modeling for the investigation of the California hybrid-HOV law that allows single occupant hybrid vehicles into the HOV lanes. According to the policy, four scenarios were constructed, each with a different share of hybrid demand based on the market penetration. A freeway simulation model was used for analyzing these scenarios in terms of a set of operational, performance, and air quality measures. It was found that micro-simulation offer a powerful method to analyze such policies as the hybrid-HOV lane use. The key findings from this study are summarized as follows:

(1) The policy is successful in reducing vehicular emissions by allowing hybrid vehicles into HOV lanes.

(2) The policy is not appropriate to the HOV lanes that don't have reserved capacity.

(3) 50K hybrid vehicle permits throughout the state could be the maximum that the Orange County HOV system can take without much degradation.

(4) The policy could have been implemented more strategically, i.e., applying it to selected freeways and/or selected time periods.

(5) HOV lane configuration and design of the existing HOV

system in Orange County needs to be improved.

The method adopted by this study can be applied to the evaluation of similar policies and traffic management strategies, which may have influence on county-wide traffic network, before their implementation. For example, the evaluation of the impact of alternative HOV lane operation, such as the conversion of HOV lanes to high-occupancy toll (HOT) lanes. Although this study did not provide timely warning and suggestion on implementation of California's hybrid-HOV policy due to the lengthy efforts on the micro-simulation model development, the final simulation based research results were well matched with what have happened in the real world. The evaluation results from this study can be taken into consideration by other states when they plan to implement similar policies. Additionally, the micro-simulation model for the study site can be further used for the evaluation of various policies and strategies that may be potentially applied to the field.

Acknowledgements

The research was supported, in part, by a grant from the California Department of Transportation; their support is gratefully acknowledged. The authors extend appreciation to the whole project team: Prof. David Brownstone and Tom Golob, Albert Chung of University of California Irvine, Prof. Jun Seok Oh of Western Michigan University, and Chris Breiland of Fehr and Peers Associates Inc.

The results and views expressed in this paper are of the authors' alone, and do not necessarily reflect those of the sponsor, the University of California, Irvine or California Center for Innovative Transportation of University of California Berkeley.

References

[1] Poole R W, Orski C K. HOT Networks: A New Plan for congestion Relief and Better, Policy Study 305. www.rppi.org/ps305.pdf, Referred on 2003.

[2] HOV Pool Funded Study. http://hovpfs.ops.fhwa.dot.gov.

[3] Varaiya P. Effectiveness of California's High Occupancy Vehicle (HOV) System, California PATH Research Report, UCB-ITS-PRR-2007-5, 2007.

[4] Legislative Analyst Office. HOV Lanes in California: Are They Achieving Their Goals? 2000.

[5] Chu L, Liu X, Recker W. Using microscopic simulation to evaluate potential intelligent transportation system strategies under nonrecurrent congestion. Transportation Research Record 1886, 2004, 76–84.

[6] Chu L, Kim H K, Liu X, *et al*. Evaluation of traffic delay reduction from automatic workzone information systems using micro-simulation. Transportation Research Board 84th Annual Meeting, Washington DC, 2005.

[7] Nesamani K S, Chu L, McNally M R, *et al*. Estimation of vehicle emissions by capturing dynamic traffic variations. Atmospheric Environment, 2007, 41, 2996–3008.

[8] Ban J X, Chu L, Benouar H. Bottleneck identification and calibration for corridor management planning. Forthcoming in Transportation Research Record, 2007.

[9] Chu L, Liu X, Recker W, *et al*. Performance evaluating of adaptive ramp metering algorithms using microscopic traffic simulation model. Journal of Transportation Engineering, 2004, 130(3): 330–338.

[10] Liu H, Oh J, Recker W. Adaptive signal control with on-line performance measure. Journal of Transportation Research Board, 2002, 1811, 131–138.

[11] Breiland C, Chu L, Benouar H. Operational effect of allowing single occupant hybrid vehicles into high occupancy vehicle lanes. Transportation Research Record 1959, 2006, 151–158.

[12] Gordon D B. Cameron 1, Gordon I D. PARAMICS-Parallel microscopic simulation of road traffic. The Journal of Supercomputing, 1996, 10(1): 25–53.

[13] PeMS Database. http://www. pems.eecs.berkeley.edu.

[14] UK Highways Agency. UK Design Manual for Roads and Bridges, London, UK, 1996.

[15] California Department of Transportation. District 12 HOV Annual HOV Report 2005, 2006.

[16] Dowling R, Skabardonis A, Alexiadis V. Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software, PUBLICATION NO. FHWA-HRT-04-040, 2004.

[17] Brownstone D, Chu L, Golob T, *et al*. Evaluation of Incorporating Hybrid Vehicle Use of HOV Lanes, California PATH Program TO 5315 Final Report, 2007.

[18] Barth M, An F, Younglove T, *et al*. Compherrnshive Modal Emission Model (CMEM): User Guide, National Cooperative Highway Research Program, 2001.

[19] Brownstone D, Recker W, Breiland C. The impacts of allowing hybrid vehicles and solo toll-paying vehicles in existing high-occupancy vehicle lanes. 11th International Conference on Travel Behaviour Research, Kyoto University, Japan, 2006.

[20] Barth M, Scora G, Younglove T. A modal emission model for heavy duty diesel vehicles. Transportation Research Record 1880, 2004, 10–20.