Modeling the Effectiveness of High Occupancy Vehicle (HOV) Lanes at Improving Air Quality

FINAL REPORT

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Bourns College of Engineering
Center for Environmental Research and Technology
University of California
Riverside, CA 92521

Executive Summary

In the past decade, there has been a growing concern nationwide regarding the effectiveness of high-occupancy vehicle (HOV) systems in meeting their intended goals and objectives. As a result, many states have improved their performance monitoring programs and periodically conduct performance evaluations of their HOV facilities (see, e.g., [Caltrans, 2005a; Caltrans, 2005b; Nee et al., 2004; Perrin et al., 2004; Zilliacus et al., 2005]). In California, the effectiveness of HOV lanes was reviewed and discussed in a report by the Legislative Analyst Office in 2000 [California LAO, 2000]. One of the key comments from the report was that the benefits of HOV lanes concerning air quality were unclear and needed further investigation. Following this legislative report, two HOV lane performance evaluation studies were conducted in Southern California [PB study team, 2002; SCAG, 2004]. Due to the large scope of these two studies (i.e., an evaluation of many aspects of HOV lanes), the benefits and impacts regarding air quality was left unanswered. As a result, Caltrans was facing an increased number of challenges by the general public, environmentalists, and policy makers regarding the justification of building and operating HOV lanes. It was determined to carry out a specific evaluation of HOV lanes that focuses on the air quality aspect together with a scientifically sound modeling toolset that provide reliable estimates of the air quality impacts of HOV lanes. This modeling toolset will then assist Caltrans to better respond to the air quality questions raised about HOV lanes.

In 2005, the University of California, Riverside Center for Environmental Research and Technology (CE-CERT) was contracted to evaluate HOV air quality impacts, which is the subject of this report. The overall goal of the project was to evaluate the air quality benefits of existing HOV lanes in California and develop a public domain modeling toolset that can be used to provide reliable estimates of the air quality impacts of HOV lanes. The development of the modeling toolset consists of two major components: 1) a *mesoscopic* modeling tool that can be used for regional planning-level air quality analyses. This tool is based on a top-down approach that uses existing mobile source emission factor models (i.e. California's EMFAC and U.S. EPA's MOBILE) along with appropriate correction factors derived in this study; and 2) a *microscopic* modeling tool developed using a bottom-up approach that uniquely combines a traffic simulation model with a comprehensive modal emissions model. Overall, the goals of the project has been accomplished and several conclusions were developed, as described below.

HOV Lane Air Quality Evaluation

An evaluation of HOV lane air quality benefits/impacts was performed by comparing the emissions from HOV lanes vis-à-vis their mixed-flow (MF) lane counterparts. Representative driving data samples from both lane types were collected on selected freeways and then used as input to a state-of-the-art modal emissions model to estimate the resultant emissions. The driving was controlled for driver, vehicle, test location, segment length, and environmental conditions so that the differences in emission results were due to only driving and traffic-related factors (i.e. driving speed as well as frequency and magnitude of acceleration/deceleration). The evaluation was conducted separately for HOV lanes in Northern and Southern California because of their different operational characteristics. For Southern California HOV lanes, the emissions comparison was made multiple times at different traffic conditions as designated by four HOV lane operation scenarios—under-utilized, neutral, well-utilized, and over-utilized. For Northern

California HOV lanes, the emissions comparison was made both when HOV lanes were actuated and when they were not actuated.

Key findings from this evaluation study are that: 1) under existing demand conditions, the HOV lanes on the freeways produce less pollutant emissions per lane as compared to the adjacent MF lanes. This is mainly due to the better flow of traffic in the lanes; and 2) considering that the average vehicle occupancy in the HOV lanes is approximately double of the average vehicle occupancy in the MF lanes, the HOV lanes are also found to produce far less emissions per traveler. These findings are applicable to both HOV lanes in Southern California and HOV lanes in Northern California when they are actuated.

Mesoscopic Modeling Improvements

The objective of this task is to make improvements to the emission inventory process for HOV lane facilities. It is well understood that HOV lanes experience higher speeds than MF lanes most of the time, depending on traffic conditions. In order to improve HOV/MF emissions modeling, it is necessary to separately apply speed correction factors for the lane types within the regulatory emissions factor model EMFAC. In addition to speed, there are other factors contributing to emission estimates that need to be examined for differences between HOV and MF lanes. These factors include driving trajectory and fleet composition.

To examine the differences in fleet composition, a sample of more than 3,000 license plate numbers from vehicles running in both lane types were collected from three selected freeways. These anonymous license plates were then matched with a partial Department of Motor Vehicles (DMV) vehicle information table as of December 2005 to extract information of each individual vehicle. The information regarding vehicle model year was used to perform statistical tests for difference between the two fleets. It was found that there was no statistically significant difference between the distributions of vehicle model year in HOV and MF lane on three sampled freeways.

To examine the differences in driving trajectories (i.e., speed versus time profiles), a database of driving trajectory data for both HOV and MF lanes was compiled along with level of service (LOS) congestion information for a variety of freeways. The data were then grouped according to the designated LOS before statistical analyses were performed. According to the statistical analysis results, it was found that traffic dynamics (as described by speed, acceleration, and road load power) in HOV lanes were significantly different from those in MF lanes at every LOS. When calculating the emissions corresponding to these data sets, it was found that the average emission rates in the two lane types could be different by as much as 20% for CO and CO_2. These results warrant the development of lane-specific emission correction factors for HOV lanes.

The development of lane-specific emission correction factors for HOV lanes was based on finding the ratio of HOV lane emissions rates to MF lane emissions rates at the same average vehicle speeds. First, HOV and MF emission rates were plotted as relative to the average speeds associated with each LOS. Then, a parabolic curve was fitted to each data set to represent speed correction factors for each lane type. The goodness of fit of these curves is considered very strong as the coefficients of determination (R^2) of the associated equations are in the range of 0.88-0.98. Using the equations, the ratio of HOV emission rates to MF emission rates at different levels of average speed for each pollutant was computed. These ratio values can be used as HOV lane emission correction factors by multiplying them to freeway emission rates to obtain emission rates specific for HOV lanes. These factors allow modelers to adjust the emission rates for HOV lanes to properly reflect the acceleration/deceleration characteristics of HOV lane operation at different traffic conditions, thus resulting in more accurate emission estimates.

Microscopic Modeling Demonstration

The objective of this task was to demonstrate the deployment of an integrated microscopic traffic simulation and modal emissions modeling tool to evaluate air quality benefits/impacts of HOV lane at corridor-specific levels. A freeway section in Southern California was used as a case study to conduct analyses in response to the question "how should the innermost lane of this freeway section be used effectively?" Three lane configurations were modeled and the resulting pollutant emissions were compared. These lane configurations are: 1) Southern California style HOV lane (limited access), 2) Northern California style HOV lane (continuous access), and 3) a standard MF lane. First, the coded model network, demand, and other model parameters went through an extensive verification and validation process following Caltrans' guidelines to ensure the model appropriately replicated the existing roadway and traffic conditions. Next, the model was used to analyze multiple what-if scenarios and to conduct numerous sensitivity analyses with respect to changes in demand and HOV proportion in the traffic mix. Lastly, an investigation of the modeling results was performed on a case-by-case basis in order to better understand the reasons behind these results. Overall, this integrated microscopic modeling tool was shown to be very powerful for detailed analysis of project-specific, corridor-level implementations of HOV lanes.

One of the key findings is that under the same travel demand and percentage of HOVs in the traffic mix, the limited access HOV lane (Southern California style) produced more pollutant emissions than the continuous access HOV lane (Northern California style). This is a result of highly concentrated lane changing activities over the limited length of the provided ingress/egress sections. With this constraint, the HOVs often have to conduct a variety of driving maneuvers such as slowing down to wait for an acceptable gap in the adjacent lane, accelerating aggressively in order to take the gap ahead of them, or making a forceful merge into the adjacent lane, causing the following and surrounding vehicles to brake unexpectedly. These maneuvers not only affect the driving pattern of those HOVs themselves but also influence the driving pattern of other vehicles in the mainstream traffic in all lanes. As a result, the frequency and magnitude of acceleration/deceleration and thus emissions of vehicles on this section are relatively high.

According to the what-if scenarios tested, it was found that for the existing conditions on the simulated freeway, the conversion of the limited access HOV lane to another MF lane will provide an emission benefit (emissions/total demand) if it induces vehicle travel demand of less than 5% onto the freeway. Similarly, the conversion of the continuous access HOV lane to another MF lane will provide emission benefit if it induces vehicle travel demand for less than 2% onto the freeway. These are minimum criteria considering all pollutants analyzed (CO, HC, NO_x, and CO_2). However, if HOV lanes are converted to MF lanes, it is highly likely that vehicle travel demand will increase, due to former carpoolers splitting and generating additional vehicle trips to meet the travel needs. As a result, emissions will certainly increase.

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Contents

1. Introduction

Historically, there has been continual expansion of the number of freeways and freeway lanes in response to ever increasing travel demand. This has required considerable financial resources and has had significant impact on the environment in terms of land use, air quality, and noise. In many urban areas it is no longer realistic to continue building more freeways and adding more lanes. Instead, a variety of efforts are being made towards improving the overall efficiency of the current infrastructure. One of the major efforts to improve this efficiency is the implementation of High Occupancy Vehicle (HOV) lanes.

The primary concept behind an HOV lane is to give a travel time advantage and to provide trip time reliability to high occupancy vehicles, and in doing so, induce more people to shift from traveling alone (i.e., Single-Occupant Vehicles or SOVs) to carpooling, vanpooling, or using express bus services that operate on the HOV facilities. As a result, it is expected that the implementation of HOV lanes will increase the average number of persons per vehicles, preserve the person-movement capacity of the roadway, reduce congestion, enhance bus operations, and improve air quality [NCHRP, 1998; PB Study, 2002]. With regard to air quality, current federal policies encourage construction of HOV lanes and restrict funding for mixed-flow (MF) lanes in areas that have not attained air quality standards [FHWA, 2002a].

There is a very large body of literature on HOV and specialty-use lanes. Most of this has been documented in [USDOT, 2004]. A historical perspective of HOV lane evolution is provided in [Fuhs and Obenberger, 2002]. Further, there is a tremendous amount of data available at the U.S. DOT web site (http://ops.fhwa.dot.gov/Travel/traffic/hov/index.htm). An HOV systems manual has also been developed as part of NCHRP Project [NCHRP, 1998]. In addition, there is a very active Transportation Research Board (TRB) committee on high-occupancy vehicle systems (TRB Committee AHB35, formerly A3A06) that maintains an up-to-date web site (www.hovworld.com). This committee is concerned with designing, operating, and evaluating HOV priority facilities and the development, validation, and dissemination of theoretical, experimental and applied research related to HOV priority facilities. The objectives of the committee include assisting in enhancing the performance, safety, and efficiency of the priority HOV facilities and establishing preferential HOV improvements as an integral element of the urban transportation system.

There have been several specialty HOV conferences and workshops in the past few years (e.g., [FHWA, 2002b] and [TRB, 2002]). The most recent one is the California HOV lane summit that was held in Irvine California in July 2006. The summit was attended by Caltrans managers and staff, members of the California Highway Patrol, Federal Highway Administration, Federal Transit Administration, regional transportation agencies, and California's University Transportation Centers, as well as academic researchers and the private sector. It was a very fruitful workshop with presentations and discussions on topics that are important to future HOV lane policies in California.

Most of the HOV literature focuses on various aspects of HOV lanes, such as the design and operations (e.g., maximum flow operations, travel time benefits, overall capacity analysis, optimal occupancy rates, and travel demand mode shifts [TRB, 2001], [FHWA, 2002b], [TRB, 2002], [NCHRP, 1998]). In terms of operations, it is often pointed out that HOV lanes have significantly different characteristics and that it is difficult to evaluate HOV lane performance as a "lump sum". Key characteristics that affect overall operations include: (a) whether it is part time versus full time operation, (b) occupancy requirement (i.e., 2+ or 3+ occupancy), (c) HOV lane enforcement, (d) ingress and egress issues (i.e., limited access or open access), and (e) lane separation (i.e., whether lanes have a buffered separator or not).

Many theoretical papers have also been written on HOV lanes, often comparing real-world data with theoretical formulations of flow rate. These often focus on what the density ratios should be between the HOV and MF lanes (e.g., [Prassas et al, 2004]). Other research papers have focused on performing predictive modeling of HOV lanes. Much of this has occurred at a regional macroscopic-level of analysis. Recently, there have been more and more research studies that employs microscopic modeling tools for specific project implementations (e.g., [Basak and Abdulhai, 2004]; [Gomes et al., 2004]; [Cherry et al., 2005]; and [Breiland et al., 2006]).

1.1. HOV SYSTEM PERFORMANCE EVALUATION

In the past decade, there has been a growing concern nationwide regarding the effectiveness of HOV systems in meeting its goals and objectives. As a result, many areas have improved their performance monitoring program and periodically conducted a performance evaluation of their HOV facilities [Caltrans, 2005a; Caltrans, 2005b; Nee et al., 2004; Perrin et al., 2004; Zilliacus et al., 2005]. Although varying among areas, common performance measures widely used are vehicle volume, average vehicle occupancy, speed, and travel time [Henderson, 2003]. In California, the effectiveness of HOV lanes was reviewed and discussed earlier in the report by the Legislative Analyst Office [California LAO, 2000]. The report suggested that although HOV lanes in California appeared to have a positive impact on carpooling (in terms of increasing person-moving capacity), they were operating at only two-third of their vehicle-carrying capacity. In addition, the benefits concerning air quality were unclear and needed further investigation. Recommendations were made that relevant agencies: (a) develop a statewide plan to promote carpool lane usage; (b) compile a set of performance measures and most cost-effective practices to increase carpool lane usage; and (c) consider converting under-utilized HOV lanes to MF lanes where congestion is not present in MF lanes. Following this legislative report were two HOV lane performance evaluation studies conducted in Southern California [PB Study, 2002; SCAG, 2004]. Some of the concurrent findings in favor of HOV lanes from these two studies are: 1) the general public understands and supports HOV lanes; 2) In general, HOV lanes provide travel time savings; 3) HOV lanes do indeed encourage ridesharing; 4) HOV lanes are well-utilized, with many operating at near capacity during peak periods; and 5) Violation rates are well below the threshold for concern. Key findings from each study are listed in Table 1.1.

However, other HOV lane studies have been carried out with contrasting results. For example, [Kwon & Varaiya, 2006] have shown that HOV lanes: 1) can contribute to increased congestion; 2) do not significantly increase person throughput; and 3) do not provide significant travel-time savings.

Table 1.1. Key findings from HOV lane performance evaluation studies in Southern California

Los Angeles County [PB Study, 2002]	San Bernardino, Riverside, and Orange Counties [SCAG, 2004]
• Nearly everyone (88%) supports HOV lanes, and 64% agree that HOV lanes reduce congestion. • All HOV lanes save time. Although the travel time savings varies by route, they can add up. • HOV lanes are effective. All but one of the existing freeway HOV routes exceed the minimum operating threshold of 800 veh/hr/ln. • HOV lanes are used all day, everyday. On many routes, off-peak demand represents 30-50% of peak hour demand. • HOV lanes encourage people to switch from driving alone. Over 50% of carpoolers previously drove alone. • HOV lanes are a good public investment. Most residents (82%) support the use of a portion of sales tax revenues for transit-related highway improvements like HOV lanes. • Many HOV lanes are full and have no capacity to sell. They are carrying between 1,200 and 1,600 veh/hr/ln during peak periods. • HOV lanes are important to bus transit. One-third of transit riders surveyed would most likely discontinue riding the buses if they were no longer able to travel in the HOV lanes. • Violation rates are 0-1% on most routes. The maximum rate found is only 3% • HOV lanes can help air quality. They generate about half the emissions per person-mile than the other MF lanes on a freeway. • A majority of carpoolers (82%) uses HOV lanes to save travel time rather than other reasons.	• General public (76%) understands and strongly supports HOV lanes. • Introduction of HOV lanes on freeways has been followed by a gradual growth of ridesharing and an increase in the life span of carpooling and vanpooling arrangements. • Existing HOV lanes are well utilized, with most operating near full capacity during the peak periods. • With the exception of a few instances, HOV lanes provide time savings ranging from 1 to 15 minutes to rideshare vehicles per trip. • There is no evidence that HOV Lanes are subject to a greater accident rate than other freeway lanes. The installation of direct HOV-to-HOV connectors almost universally reduced accident rates in the vicinity of the affected intersections. • Violation rates average 1.2%, well below the 10% level identified as a threshold for concern. • Transit operations currently contribute relatively little to person movement on the HOV lanes. • Current occupancy requirement are adequate at this time. Based on modeling results, regional VMT, VHT, and average speed are all optimized with a 2+ occupancy requirement. • Continued 24/7 operation of HOV lanes is supported and warranted as congestion and peak spreading continue to grow. • Public surveys express a preference for HOV lane separations from MF lanes.

1.2. AIR QUALITY BENEFITS/IMPACTS OF HOV LANES

Most of the research concerning HOV system to date has focused on various aspects including operations, flow rates, travel time benefits, and travel demand mode shifts. However, a limited amount of research has been done to fully understand the air quality impacts of HOV lanes. A recent study in the metropolitan Washington, D.C. area measured and compared vehicle emissions in HOV and MF lanes using a portable emissions monitoring system (PEMS) [Krimmer & Venigalla, 2006]. The major finding was that higher speeds in HOV lanes resulted in higher emissions in many cases. However, this finding was applicable to only a specific vehicle model used in the experiment, and was limited to the traffic conditions the experimental vehicles experienced.

Conceptually, HOV lanes may lower vehicle emissions by reducing running emissions and trip-end emissions. Running emissions may be reduced due to the increased ridesharing, which results in fewer vehicle-miles traveled (VMT), and as a result of better flow in HOV lanes. HOV lanes may also reduce trip-end emissions if they do not cause additional trips to be taken. In terms of estimating running emission impacts, the traditional methodology consists of acquiring link average speeds and VMT (either from travel demand models or field data collection), followed by the application of conventional emissions factors (e.g., from regional emission factor models EMFAC or MOBILE). The emission results are then compared between the two lane types. However, this methodology ignores the operational effects such as differences in traffic dynamics between HOV and MF lanes. With the advancement in vehicle emissions modeling in the past decade, a more sophisticated microscopic model evaluation and analysis can take place, improving the accuracy of the overall emission estimates leading to a better evaluation of HOV lane air quality impacts.

1.3. PROJECT MOTIVATION, SCOPE, AND OBJECTIVES

California has some of the most severe air quality issues in the country, which has put considerable emphasis on the reduction of emissions from all sources. In the state, a number of local air districts are in non-attainment of the Federal and State ozone and PM-10 air quality standards. One strategy being pursued is the implementation of HOV lanes. As stated previously, the primary purpose of HOV lanes is to reduce the number single-occupancy vehicle (SOV) trips through carpooling, vanpooling, and express bus use. The common belief is that fewer vehicles will be required to meet the travel demand and total vehicle emissions will be reduced and air quality should improve. However, there are questions on whether creating an HOV lane would induce additional trips through a perceived capacity increase. Further, if HOV lanes are not fully utilized, then existing traffic would be squeezed into the remaining general-purpose lanes, creating higher congestion and possibly higher emissions. It is critical to better understand the complicated relationship between HOV lanes and vehicle emissions and develop a comprehensive HOV lane set of models that can aid in determining HOV lane impacts on air quality.

The objective of this project is to evaluate the air quality benefits of existing HOV lanes in California and develop a public domain modeling toolset that can be used to provide reliable estimates of the air quality impacts of HOV lanes. This modeling toolset consists of two major components:

1) a *macroscopic* modeling tool that can be used for regional planning-level air quality analyses. This tool is based on a top-down approach that uses California's existing mobile source emission factor model EMFAC along with appropriate correction factors derived in this study.

2) a *microscopic* modeling tool that combines traffic simulation modeling tools with a comprehensive modal emissions model. This tool serves multiple purposes including: a) allowing for the detailed analysis of project-specific, corridor-level implementations; and b) developing supporting data and factors that can be integrated into the macroscopic modeling tool described above.

Both modeling tools are able to provide emission inventories of carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NOx), and carbon dioxide (CO_2), as well as fuel consumption. The microscopic modeling tool is also able to predict the traditional freeway performance measures such as travel-time savings, traffic flow, and speed. The modeling toolset can be used by program staff at Caltrans and governmental and other institutions in developing estimates of emissions from HOV projects. The modeling tools are designed such that emissions estimates are based on readily available data, such as roadway geometry, vehicle and passenger volumes, average vehicle occupancy, compliance rate, and local fleet composition.

Several tasks were carried out in the project:

Task 1: A literature review was conducted of all aspects of HOV lanes, especially that pertaining to air quality. At the same time, existing available data on HOV lanes were also gathered;

Task 2: Based on the results of Task 1, data gaps were identified and additional data collection was taken place. These data included freeway lane operation data, probe vehicle data, and fleet composition data;

Task 3: Using the data from Tasks 1 and 2, an empirical evaluation of air quality benefits/impacts of existing HOV lanes in California was performed;

Task 4: A series of analyses was conducted to examine differences between MF and HOV lanes in terms of speed, driving trajectory, fleet composition, and emissions. Based on the results of these analyses, improvements to the current modeling practice were made where the focus was on the development of correction factors for estimating HOV lane emission factors;

Task 5: An integrated traffic simulation and modal emissions modeling tool for HOV lane evaluation was developed. After being carefully calibrated, the tool was applied to assess air quality benefits/impacts of different types of HOV lane configuration and operation. Sensitivity analyses of numerous what-if scenarios were also conducted.

These tasks were carried and are described in the following chapters. In Chapter 2, the methodologies developed and applied are described, as well as the data collection process. In Chapter 3, a variety of HOV lane analyses are described along with their results. Chapter 4 focuses on the macroscopic modeling improvements that were made as part of this project. Similarly, Chapter 5 describes the developed microscopic modeling tools that can be applied for detailed HOV lane analysis. Conclusions and recommendations are given in Chapter 6.

2. Methodology

2.1. OVERVIEW

Vehicle emissions modeling and inventorying can be done at different levels of resolution depending on the type of transportation models/data sets and the interfacing emission models used. As shown in Figure 2.1, the transportation models/data sets vary in terms of their inherent temporal resolution. For example, at the lowest level, microscopic transportation models typically produce second-by-second vehicle trajectories (location, speed, acceleration). Driving cycles used for vehicle testing are also specified on a second-by-second basis (speed vs. time). In addition, there are other types of transportation models/data sets that aggregate with respect to time, producing traffic statistics such as average speed on a roadway facility type basis. Similar acceleration statistics may also be produced by these models. At the highest level, total vehicle volume and average speed over an entire regional network may be all that is provided.

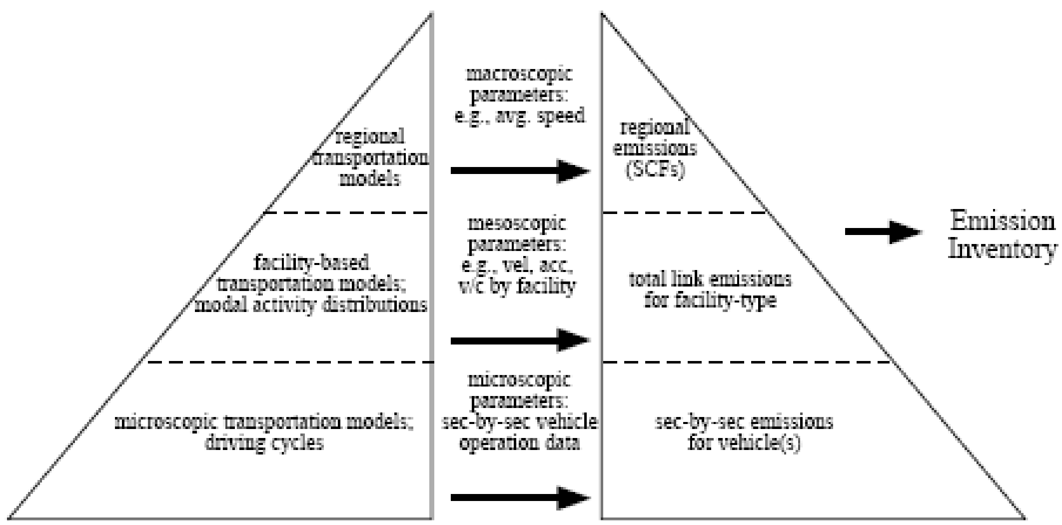


Figure 2.1. Interfaces between transportation and emission models.

For freeways with HOV facilities, there are generally three modeling approaches that can be employed, described below. One approach may be preferred over the others depending on the purpose and the required level of detail of analysis.

1) *Use the same emissions and fuel factors for all freeway lanes*: This is the coarsest approach. This approach does not differentiate between HOV and MF lanes. It takes the average speed across all freeway lanes to determine link emission factors from emission factor models (e.g. EMFAC). Link VMT is the sum of VMT in HOV and MF lanes.

2) *Use separate emission factors for HOV and MF lanes*: This approach takes into account the difference in vehicle speed between HOV and MF lanes. It applies separate average speeds for HOV and MF lanes to standard emission factor models (e.g. EMFAC [CARB, 2006]) in determining lane-specific emission factors. Link VMT and emissions are also calculated separately for each lane type. Finally, the calculated emissions for each lane type are combined to produce total link emissions.

3) *Use second-by-second modal emission estimates for vehicles in HOV and MF lanes*: This approach is similar to the second approach but with much higher resolution of data and analysis. In addition to the difference in speed, it takes into consideration differences in traffic dynamics of vehicles between the two lane types. These differences are captured in second-by-second driving trajectory, of which associated second-by-second emissions can be estimated using modal emission models (e.g. CMEM [Barth et al., 1999]).

Of all three approaches, only the second and the third approaches allow for the proper evaluation of HOV lanes air quality benefits because they enable the calculation of emissions from each lane type individually.

2.2. HOV LANE AIR QUALITY EVALUATION

In this project, the key effort was devoted to evaluating air quality benefits of HOV lanes. The most effective way is to directly compare emissions from HOV lanes vis-à-vis MF lanes, in terms of operational differences. For the comparison results to be meaningful, differences in emissions should be due to only driving and traffic-related factors such as driving speed as well as frequency and magnitude of acceleration/deceleration. Therefore, the comparison must be controlled for other influential factors including driver, vehicle, test location, segment length, and environmental conditions. On the other hand, the comparison should be made multiple times for different traffic conditions.

Emission factors can be obtained from either measurement (e.g. using PEMS) or from modeling. Although the use of on-board measurement equipment has become popular in recent years, it has a relatively high cost and therefore only allows for a restricted amount of test runs on only a few numbers of vehicles. Therefore, modeling is considered to be a good choice in terms of cost and breadth. However, care must be given to accuracy and reliability of transportation data inputs (e.g. speed) as they are critical to model results. The inputs from field measurement (e.g. loop detectors) are usually preferred to those obtained from travel demand modeling.

In this project, a hybrid modeling approach was adopted. Driving trajectory data, which is easy and inexpensive to collect, were obtained in the field. These data were then applied to a state-of-the-art Comprehensive Modal Emissions Model (CMEM) which can predict second-by-second emissions and fuel use given any driving pattern or vehicle type (for a detailed description of CMEM, see Section 2.4.4). The framework of the emissions estimation used in this evaluation is shown in Figure 2.2. Inputs to CMEM consists of vehicle activity (second-by-second speed profile) and fleet composition (proportion of each vehicle category in CMEM). These data can be collected in the field. Alternatively, the fleet composition can be derived from the county-specific fleet database in the current EMFAC model. The results from CMEM include second-by-second emissions of CO_2, CO, HC, and NO_x as well as fuel consumption. With additional information of distance, volume, and vehicle occupancy rate for each lane type, the second-by-second emissions can be converted to emission rates per vehicle, emission rates per person, and total emissions mass. These results can be used to answer different types of questions from multiple stakeholder groups (e.g. emissions modelers, freeway operators, transportation and environmental planners, and policy makers). As an example, it is interesting to see how driving characteristics in each lane type affect emissions. It is also useful to understand how travel demand can be accommodated with the least impact to environment. Further, it is valuable to better distinguish the contribution of different freeway lanes to the overall emissions inventory.

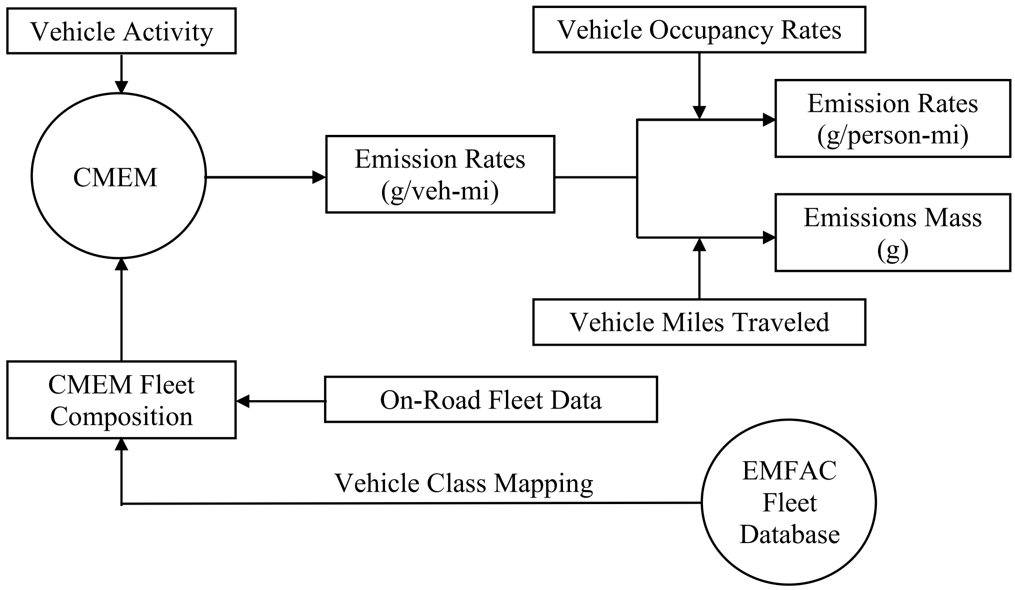


Figure 2.2. Framework of the emissions estimation for the evaluation.

2.3. MESOSCOPIC MODELING IMPROVEMENTS

The current trend in mobile emissions modeling is going toward a further degree of disaggregation in terms of emission factors, vehicle types, and vehicle activity. A good example is the introduction of facility-specific emission factors in MOBILE6 where different emission factors are used for different roadway types (e.g. freeway, ramp, arterial, etc.). In California, an effort has also been made to refine emission factors in EMFAC2002. Facility specific allocation factors were developed to allocate trip-based emissions to specific facilities including freeway, ramp, arterial, collector, local, and private that are composed of the trip [Sebate, 2005].

Despite these efforts, model limitations still exist when conducting certain specialized analyses such as modeling the effectiveness of HOV lanes. As emission factors for freeways are not distinguished between MF and HOV lanes, it is questionable whether freeway emission factors are good representative emission factors for both lane types. A review of the LA92 vehicle activity database already shows that out of over 100,000 seconds of driving activity data collected, only 0.0001% or about 10 seconds are those occurred in HOV lanes [Niemeier et al, 1999]. Since traffic dynamics and operational characteristics of MF and HOV lanes may not be the same, it is imperative to statistically test these differences and evaluate their impact on resulting emission factors. The results showing statistically significant differences in vehicle activity and emission factors between the two lane types will indicate the need for improvements in the modeling of air quality benefits of HOV lanes. These improvements could be the development of new lane-specific emission factors or the derivation of correction factors that can be applied to the freeway emission factors to obtain more accurate emission factors for HOV lanes.

One of the goals of this project was to make short-term improvements to the emission inventory process for HOV facilities. It is well understood that HOV lanes often experience higher speeds compared to MF lanes, depending on the traffic conditions. In order to improve on HOV/MF emissions inventories, it is necessary to separately apply speed corrections for the lane types within the EMFAC analysis. Recent studies have shown that vehicles traveling at speeds significantly higher than the speed limit can have a significant emissions contribution. In addition to speed, there are other factors contributing to emission estimates that need to be examined for differences between HOV and MF lanes. The following steps were performed, as illustrated in Figure 2.3:

1) *Examination of driving trajectory differences between HOV and MF lanes*: First it was necessary to understand the differences in how the vehicles accelerate and decelerate at various traffic conditions in each lane type.

2) *Examination of vehicle fleet differences between HOV and MF lanes*: Vehicle fleet mixes in both lane types were compared to determine if it is necessary to use separate sets of fleet data when modeling emissions from MF and HOV lanes.

3) *Examination of emission differences between HOV and MF lanes*: Emissions were estimated using inputs from the previous two steps and then compared.

4) *Development of lane-specific correction factors for HOV lanes*: Based on the results from the previous steps, correction factors were created. Further, a quick HOV air quality analysis tool was created in a spreadsheet format with embedded HOV correction factors.

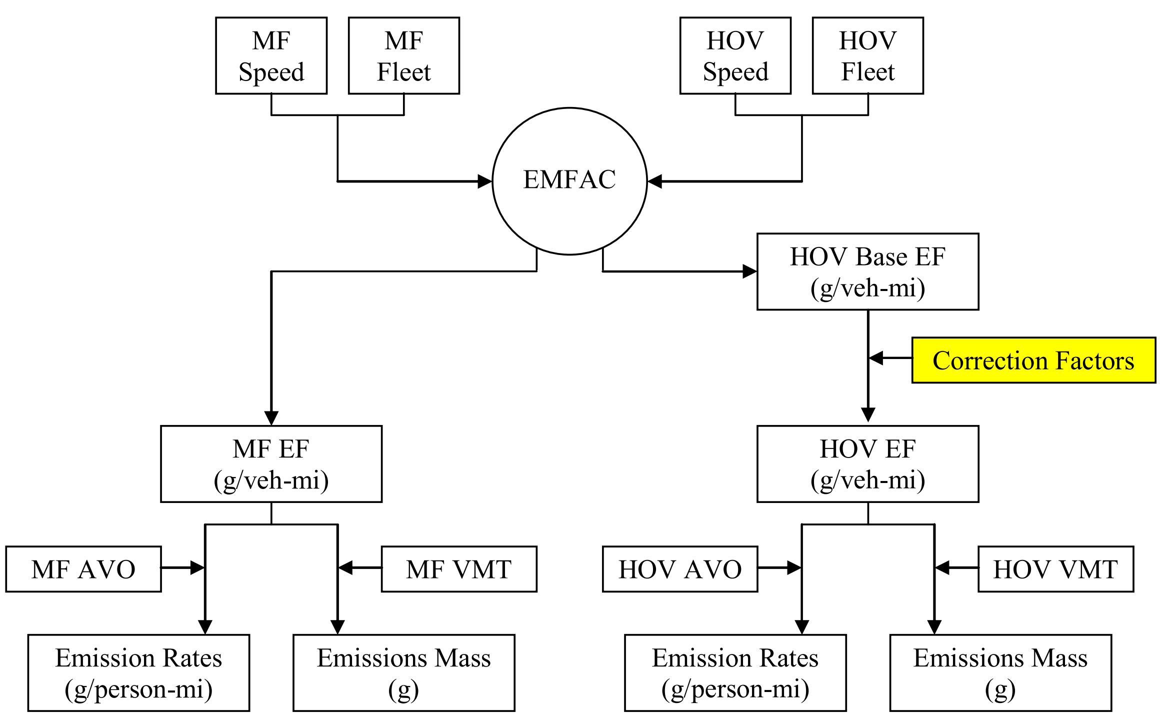


Figure 2.3. Flowchart of the improved mesoscopic emissions modeling process.

2.4. MICROSCOPIC MODELING DEMONSTRATION

2.4.1. Transportation/Emissions Modeling Interfaces

The transportation/emission modeling process involves several interfaces between travel demand models, traffic simulation models, and emissions models at different levels of details. As shown in Figure 2.4, the regional travel demand model estimates the number of zone-to-zone trips in the area based on land use and socioeconomic factors. After determining the mode split, it assigns zonal vehicle trips onto the roadway network based on the minimization of trip distance or travel time between pairs of zones. The output is applied to the roadway network, which is loaded by a certain amount of vehicles traveling on each link. This loaded network can be used to extract a sub-area network of interest and its corresponding travel demand for conducting microscopic traffic simulations. In addition to the network and travel demand, the traffic simulation model also takes the inputs of vehicle fleet composition and model configuration parameters. After being properly calibrated for existing conditions, the model can be used to simulate other what-if scenarios. The simulated results include traffic performance measures and relevant statistics. The simulation model also produces an animation of vehicle movement in the network. Finally, the emissions model that interfaces with the traffic simulation model calculates pollutant emissions of each individual vehicle being simulated. The emissions results are then aggregated and reported. The following sections describe each model used in the process in greater detail.

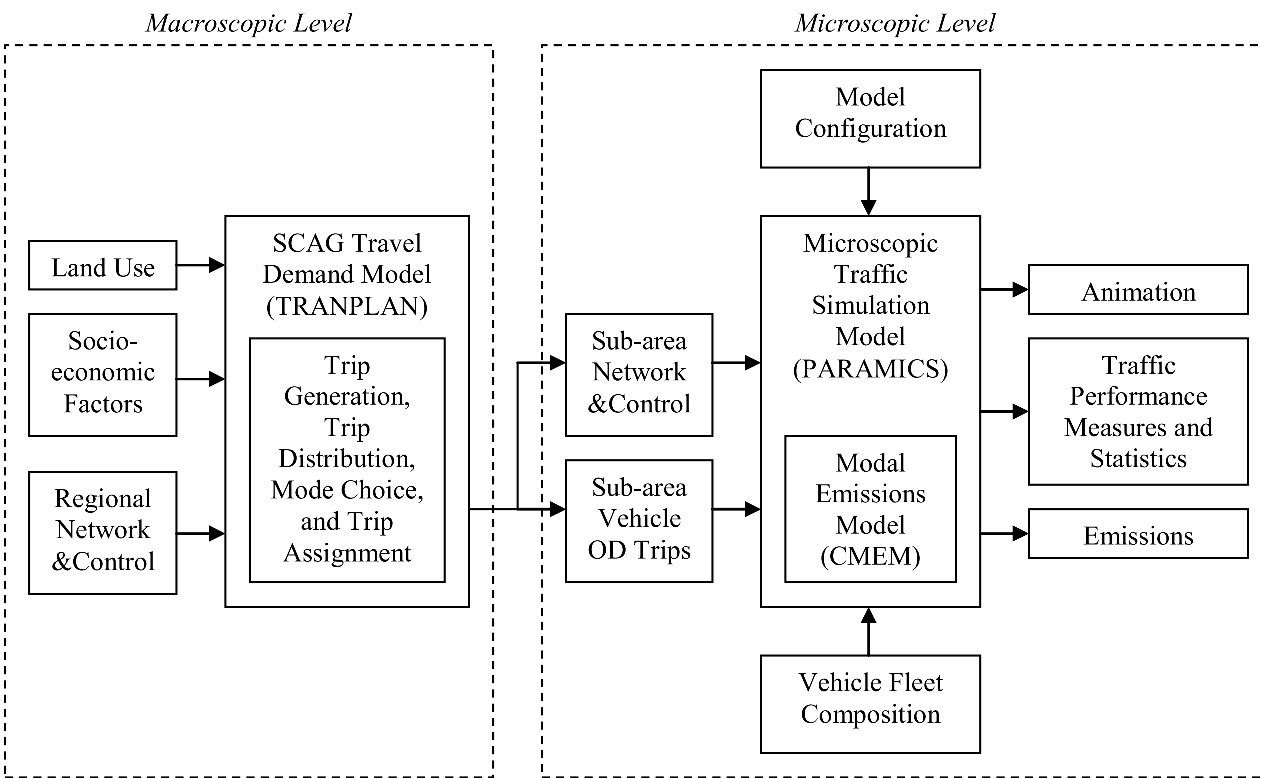


Figure 2.4. Transportation/emissions modeling process used in this study.

2.4.2. SCAG Regional Travel Demand Model

The Southern California Association of Governments (SCAG) is the regional planning agency that maintains and updates a travel demand model of six counties (Los Angeles, Orange, Ventura, Riverside, San Bernardino, and Imperial) in Southern California. Its model has been updated periodically with the latest model update conducted for the base year of 2000 and the forecast year of 2030. The model contains more than 3,000 transportation analysis zones and 26 external zones. Its transportation networks include both highway network and transit network [SCAG, 2003]. In the highway network, HOV lanes are coded as separate links in the network, which allow only eligible vehicles to access. Virtual links are provided at HOV egress/ingress locations so that HOVs can merge in and out HOV lanes. In addition, special network coding allows heavy-duty trucks to be converted into passenger car equivalents, which enables the model to account for the effects of trucks on facility capacity in the traffic stream. The embedded heavy-duty truck model categorizes trucks by weight into three categories: 1) Light-heavy (8,500 to 14,000 lbs gross vehicle weight (GVW)), 2) Medium-heavy (14,000 to 33,000 lbs GVW), and 3) Heavy-heavy (over 33,000 lbs GVW).

The model consists of four modeling time periods: 1) A.M. peak period (6 a.m. to 9 a.m.), 2) Midday period (9 a.m. to 3 p.m.), 3) P.M. peak period (3 p.m. to 7 p.m.), and 4) Night (7 p.m. to 6 a.m.). In the mode choice module, auto travel modes are split into auto passenger, drive alone (SOV), 2 person carpool (HOV2+), and 3+ person carpool (HOV3+). The summary results show that in year 2000 the HOV2+ and HOV3+ modes account for 4.25 and 1.64% of total vehicle trips in the region, and the average vehicle occupancy is 1.10 [SCAG, 2003; SCAG, 2004].

The travel data produced by the SCAG travel demand model was used in part to calculate a regional on-road mobile emissions inventory of total organic gases (TOG), CO, NO_x, and particulate matter (PM) using emission factors from EMFAC. The types of emissions calculated include running exhausted emissions, trip end emissions (e.g. cold starts), and diurnal evaporative emissions. The results show that the daily pollutant emissions are highest in Los Angeles County, as expected.

2.4.3. PARAMICS Microscopic Traffic Simulation Model

PARAMICS (Parallel Microscopic Simulator) is a suite of software tools for performing time-stepping, microscopic and stochastic traffic simulation. Individual vehicles are modeled in fine detail for the duration of their entire trip, providing traffic flow, travel time, and congestion information. The internal structure of PARAMICS includes the following software modules:

- *Modeler*: the core simulation and visualization tool;
- *Processor*: the batch assignment tool;
- *Analyzer*: the post simulation data analyzer tool;
- *Programmer*: the application programming interface (API);
- *Monitor*: the pollution modeling interface; and

- *Estimator*: the origin-destination (OD) matrix estimation tool.

PARAMICS *Modeler* and *Analyzer* are the basic components required to run simulations and analyze the output. Network build-up, simulation control, and demand information are carried out using the *Modeler*. Simulation output from *Modeler* is then loaded into *Analyzer* for detailed analysis. The PARAMICS *Processor* is a batch assignment tool and is useful for running the simulation in a batch mode. This allows running of predefined scenarios which may included simulation runs with different random numbers and other control parameters, varying flow levels and analysis for various time periods. The PARAMICS *Programmer* is an API which provides *Modeler* with an opportunity to simulate additional features and user defined algorithms and functionality such lane change models and car following rules. In addition, it allows for development of plug-ins to interface PARAMICS with third party software or real word systems such as network control systems. The PARAMICS *Monitor* is an emission calculating tool that allows inputting of emissions data based on speed and acceleration of different engine categories. It is primarily based on emissions inventories of the United Kingdom.

General model inputs to PARAMICS include:

- *Network and control characteristics*: e.g. network geometry, link speed limits, lane restrictions, signposting distance, traffic signals, stop signs, etc.

- *Vehicles characteristics*: e.g. vehicle type, dimensions, top speed, crawl speed, power, bus rapid transit, etc.

- *Demand*: e.g. OD zone areas, level of OD demand broken down by time period, vehicle type, and vehicle proportion;

- *Model configuration*: e.g. time step duration, speed memory, mean target headway, mean reaction time.

Typical model outputs include statistics at the network level (overall travel time, total travel distance, average speed), on a link-by-link basis (with *Analyzer* which reports statistics such as traffic flow, queue lengths, delays, speeds, and densities) or at specific locations (instantaneous detector type of information). PARAMICS *Modeler* also produces simultaneous time-step animation during a model run, which allows the analyst to visualize simulated traffic conditions in a network in order to identify problem areas and their potential causes. In addition, the analyst may obtain second-by-second speed and acceleration data of vehicles in a network. For more information about PARAMICS, see [PARAMICS, 2006].

2.4.4. The Comprehensive Modal Emissions Model (CMEM)

In 1996, a comprehensive modal fuel consumption and emissions model (CMEM) was developed, sponsored by the National Cooperative Highway Research Program (NCHRP, Project 25-11, see [Barth et al., 1999]). The overall objective of this research project was to develop and verify a modal model that accurately estimates fuel consumption and emissions as a function of the vehicle's operating mode. The model is comprehensive in the sense that it is able to predict for a wide variety of vehicles in various states of condition (e.g., properly functioning, deteriorated, malfunctioning). The model is capable of predicting second-by-second tailpipe (and engine-out) emissions and fuel consumption for a wide range of vehicle/technology categories. The need for this type of microscale model that can predict second-by-second fuel consumption and emissions based on different traffic operations was and remains critical for developing and evaluating transportation policy. In the past, large regional emissions inventory models were being applied for these types of microscale evaluations with little success. The majority of the modeling effort was completed in 2000 and the model has been updated and maintained since then under sponsorship from the U.S. EPA, with the addition of new vehicle/technology categories for heavy-duty vehicles. CMEM is a public-domain model and has several hundred registered users worldwide.

One of the most important features of CMEM is that it uses a physical, power-demand approach based on a parameterized analytical representation of fuel consumption and emissions production. In this type of model, the entire fuel consumption and emissions process is broken down into components that correspond to physical phenomena associated with vehicle operation and emissions production. Each component is modeled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary according to the vehicle type, engine, emission after-treatment technology, and level of deterioration. One distinct advantage of this physical approach is that it is possible to adjust many of these physical parameters to predict energy consumption and emissions of future vehicle models and applications of new technology (e.g., aftertreatment devices) and road grade effects. The fuel consumption/emission models were designed so that they can interface with a wide variety of transportation models and/or transportation data sets in order to perform detailed fuel consumption analyses and to produce a localized emissions inventory. For further information on this modeling effort, please refer to [Barth et al., 1996; Barth et al., 1997; Barth et al., 1999; Barth et al., 2001; and Barth et al., 2004].

2.4.5. Integrated Traffic Simulation and Modal Emissions Modeling Tool

With advancement in microscopic traffic simulation and modal emissions modeling, it is of great advantage to integrate these two analytical models together. The integrated tool allows a comprehensive evaluation of vehicle emissions impacts due to various transportation/traffic-related aspects in the finest level of analysis. For example, it can be applied to evaluate emissions benefits of project-level or corridor-specific transportation control measures (e.g. HOV lanes), ITS implementations (e.g. electronic toll collection), and traffic flow improvements (e.g. traffic signal coordination).

It should be noted that CMEM was designed so that it can interface with a wide variety of transportation models and/or transportation data sets in order to perform detailed fuel consumption analyses and to produce a localized emissions inventory. CMEM has been developed primarily for microscopic traffic simulation models that typically produce second-by-second vehicle trajectories (location, speed, and acceleration). These vehicle trajectories can be applied directly to the model, resulting in both individual and aggregate energy/emissions estimates. Over the past several years, CMEM has been integrated into various traffic simulation models (e.g., CORSIM, TRANSIMS, etc.), with a focus on corridor-level analysis and ITS implementations. One of the more powerful and useful efforts was the integration of CMEM with PARAMICS. As described earlier, PARAMICS has an opened architecture for integrating plug-in modules to perform specific simulation functions. Integrating CMEM within PARAMICS was accomplished by creating a plug-in through the use of PARAMICS *Programmer*, which allows the user to access many of PARAMICS' features and variables as the simulation takes place. The CMEM plug-in for PARAMICS was written in C language and revolves around two elements: 1) control functions and 2) callback functions. Control functions are functions that PARAMICS uses as part of its standard simulation. These control functions allow the user to override or add additional code to the simulation run. Callback functions allow the user to retrieve specific information from the simulation such as vehicle and network attributes.

The CMEM plug-in for PARAMICS was tested extensively to ensure that the modeling results are error-free. Effort has also been made to keep it updated and compatible with new versions of PARAMICS as they were released. Using this integrated PARAMICS/CMEM tool, various projects have been successfully evaluated, for example, the study of high-occupancy toll lane extension on SR-91 and the 215/60/91 interchange reconstruction project in Riverside, CA [Barth et al., 2001a].

The last task in this HOV project was to develop and demonstrate an integrated traffic simulation and emissions modeling tool for HOV lane evaluation. This state-of-the-art tool has several unique capabilities. It allows for driving trajectory of individual vehicles to be modeled, thus enabling the calculation of their second-by-second emissions. Once the tool is fully developed and calibrated, it can be used to carry out detailed vehicle emissions analysis of existing or proposed HOV facilities. In addition, a variety of generic HOV facility scenarios can be set up in the model and iterated over a wide variety of variables such as lane separation and entrance/egress methods, HOV/SOV ratios, different traffic volumes, etc. A large number of simulation runs can be made as an overall sensitivity analysis. At the same time, freeway performance measures (e.g., travel-time, flow, speed) can also be evaluated.

2.5. DATA COLLECTION

Many data collection activities were carried out in the project to ensure that there are sufficient data to make robust analyses. These data are necessary for several different tasks of the project. These data collection efforts are described below.

2.5.1. Traffic Data

A very useful tool in this project is the Freeway Performance Measurement System (PeMS) project, developed as a joint effort between UC Berkeley and Caltrans. PeMS is an interactive system that allows users to investigate various performance measures of the freeway system historically and in real time. The system collects flow and occupancy data from 23,237 loops covering 2,812 out of 30,726 miles of interstate and state highways in California [Varaiya, 2004]. The system filters, processes, aggregates, and examines the data before making them available for transportation management, research, and commercial use. The system provides real-time five-minute, per-loop averages of flow, speed, occupancy, and other congestion measures. All the data is currently available over the Internet through PeMS website [PeMS5.4, 2005]. The advantages of PeMS are enormous. Examples of PeMS application include freeway operational analyses, bottleneck identification, level of service (LOS) determination, assessment of incident impacts, and evaluation of intelligent transportation systems (ITS) deployment, as shown by Choe et al.

[2002]. In this study, PeMS was extensively used as a source of many useful freeway data, such as volume, speed, and LOS, as well as their statistics. Much of this data is important to determine the variety of congestion levels that occur in both MF and HOV lanes at different times of the day.

2.5.2. Driving Trajectory Data

To perform the comparative analyses, it was necessary to have second-by-second trajectory data of vehicles traveling both in HOV and MF lanes. Driving trajectory data were collected using a Global Positioning Satellite (GPS)-equipped probe vehicle. The probe vehicle collects information about the location (latitude, longitude, and altitude), time, and speed of the vehicle on a second-by-second basis. Numerous experiment runs were made on designated freeways at different times of the day to capture the true traffic dynamics in different lanes. This data collection effort was carried out in conjunction with PeMS data collection so that the two data sets could be correlated.

2.5.3. Fleet Composition Data

Fleet composition data is not readily available, in particular for HOV lanes compared to MF lanes. In fact, the most disaggregated fleet data available is county specific. It has been shown that small differences in fleet data can cause tremendous differences in emissions [Malcolm et al., 2002]. Vehicle fleet data can be categorized using information extracted from license plate surveys. Therefore, a small-scale license plate survey of vehicles on local freeways that have both HOV and MF lanes was carried out. Two video cameras were set up on overpass bridges across the freeways. One captured traffic stream information in an HOV lane while the other captured traffic stream in the adjacent MF lane. Several hours of videos were recorded. They were played back to extract license plate numbers of vehicles. The license plate data was then used to index the California vehicle registration database, which in turn provided detailed information on each vehicle, such as the model year, vehicle make and model, and engine/emissions technology.

3. HOV Lane Air Quality Evaluation

Sections 3.1 to 3.4 of this chapter describe the data collection and analysis efforts, as well as the results from the analysis of HOV lanes in Southern California. Next, Section 3.5 presents similar efforts and analysis results for a selected Northern California HOV lane. Finally, findings and concluding remarks are given in Section 3.6.

3.1. ANALYSIS SCENARIOS – SOUTHERN CALIFORNIA

The setup of our analysis scenarios is based on the idea that they should encompass a variety of operational performance of HOV lanes as compared to MF lanes. The performance measure of freeway lane operation used in this analysis is Level Of Service (LOS), which is a function of vehicle density, and thus speed and flow [TRB, 2000]. LOS is a measure that can be rationally related to emissions, since: 1) emission rates are highly dependent on speed; 2) flow is a surrogate for VMT; and 3) both emission rates and VMT are two major factors contributing to emissions.

Figure 3.1 presents a freeway lane performance matrix of HOV and MF lanes. Conceptually, the upper right elements of the matrix are cases in which one might expect emissions benefits from HOV lanes over MF lanes due to having better LOS. The diagonal elements indicate no or little difference in operational performance between both lane types. Consequently, there might be no or little difference in emissions. Finally, the lower left elements represent situations in which the LOS in HOV lanes is worse than the LOS in MF lanes. In these situations, an emissions burden of HOV lanes might be expected. Of particular interest are the upper right elements of the matrix since they serve the operational purpose of HOV lanes. Therefore, these elements are divided into subgroups that form four analysis scenarios as described below.

		LOS of Mixed-Flow (MF) Lane					
	%	**A**	**B**	**C**	**D**	**E**	**F**
	A	0	1	1	1	3	3
LOS	**B**	X	0	2	2	3	3
of	**C**	X	X	0	2	3	3
HOV	**D**	X	X	X	0	4	4
Lane	**E**	X	X	X	X	0	4
	F	X	X	X	X	X	0

Figure 3.1. Freeway lane performance matrix. The numbers in the matrix correspond to the scenario numbers.

- ***Scenario 1 (under-utilized)***: This is the case in which an HOV lane is under-utilized. The average vehicle volume is below 800 veh/hr/ln, which is the minimum criterion of operating HOV lanes set by California Department of Transportation (Caltrans). Vehicles traveling in the HOV lane, therefore, enjoy free-flow speeds (LOS A) for most of the time. Meanwhile, vehicles in adjacent MF lanes travel at near free-flow or moderate speeds (LOS B-D) under uncongested conditions.

- ***Scenario 2 (neutral)*****:** In this scenario, an HOV lane meets the minimum vehicle volume criterion. Both lane types are not congested and operate at near free-flow or moderate speeds (LOS B-C for the HOV lane and LOS C-D for the MF lanes).

- ***Scenario 3 (well-utilized)*****:** This scenario represents a very congested freeway where vehicles in the MF lanes experience LOS E and F for most of the time. On the other hand, carpoolers do not encounter congested traffic and that allows them to travel at better speed and flow (LOS A-C).

- ***Scenario 4 (over-utilized)*****:** This scenario is similar to Scenario 3 except that carpoolers also suffer congestion and delay (LOS D-E). This is the only case in which the demand for an HOV lane exceeds the capacity.

The first two scenarios are cases in which a driver's decision to use HOV lanes is not driven by the level of congestion in MF lanes. In these cases, carpoolers may choose to use either HOV lanes or MF lanes depending on personal preference and other factors. On the other hand, Scenarios 3 and 4 represent cases in which the congestion in MF lanes does have influence on carpoolers' lane choice. They will be likely to take advantages of HOV lanes and the HOV lane utilization will depend on the proportion of HOVs in traffic mix.

3.1.1. Study Sites and Data Acquisition

A preliminary analysis was conducted to identify freeway segments as well as days and time periods that the operational performance of HOV and MF lanes would fall in each scenario. This preliminary analysis was based on six-week historical freeway performance data in July and August 2005, which are presented in Appendix A. These freeway performance data were obtained from the California PeMS. Note that the data used for this purpose are for Tuesday, Wednesday, and Thursday only. This is to eliminate weekend effects on travel behavior and lane usage as well as to capture only the regular commuting patterns on weekdays.

The sites for the study were carefully selected based on two criteria. First, they should well represent spatial variability of driving behavior within the study area [Malcolm et al., 2002]. Second, the selected sites should have reasonable amount of PeMS vehicle detector stations (VDS). Further, each loop detector at these VDS should function properly so that data extracted from PeMS are reliable and useful. Therefore, the information of detector health as reported by PeMS was examined as part of the site selection process. Table 3.1. illustrates the health summary of detectors on three freeway segments that were initially evaluated. According to this table, the number of loop detectors on SR-91E, SR-60E, and I-10W that were in good condition was more than 80% at the time of study (August 2005). In addition, they make up a complete VDS for more than 60% of the total number of VDS in the segment. Figure 3.2 shows the locations of the three specific freeway segments (SR-91E, SR-60E, and I-10W) that were chosen based on the set criteria. A description of these locations is given in Table 3.2.

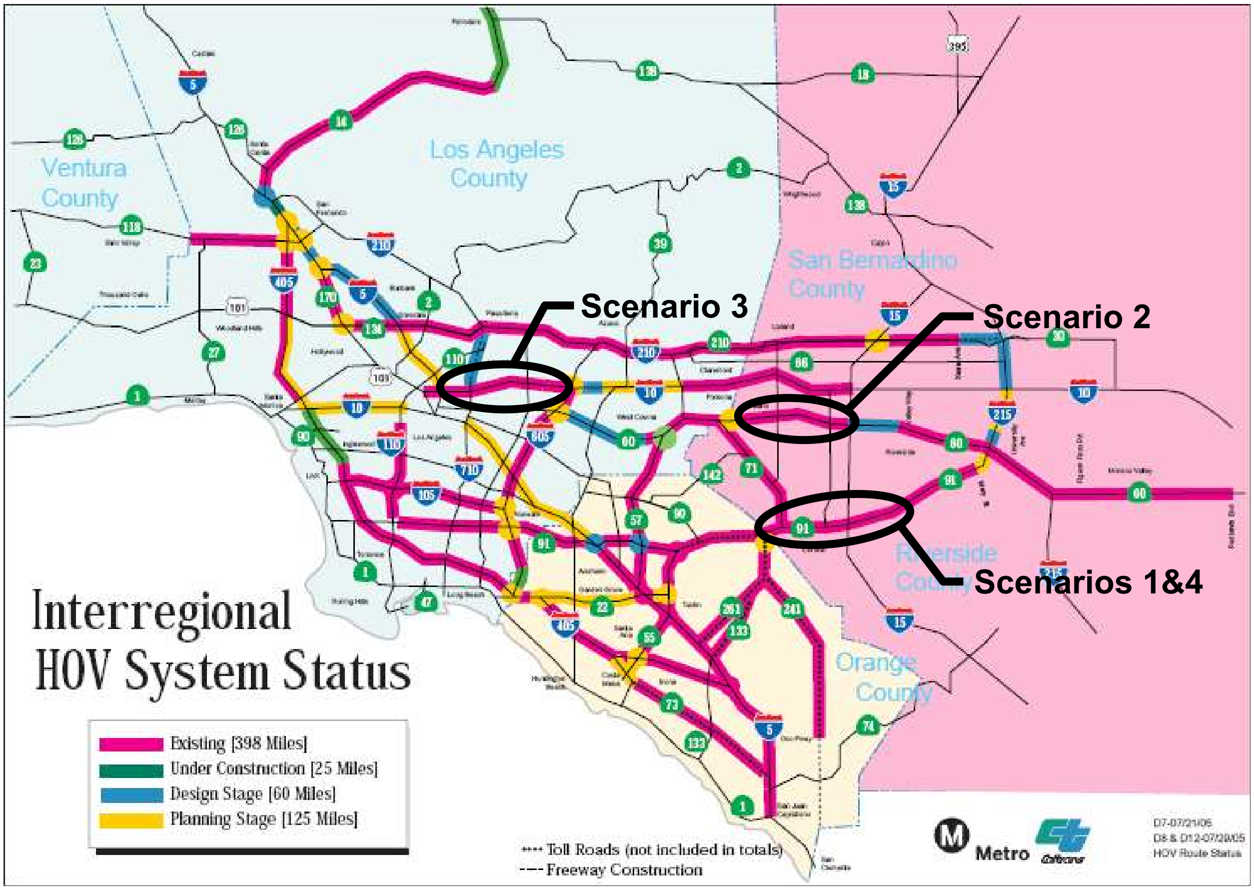


Figure 3.2. Sites of probe vehicle runs in Southern California.

3.1.2. Driving Trajectory Data Collection and Analysis

Driving trajectory data were collected in September 2005 using a Global Positioning Satellite (GPS)-equipped probe vehicle. This probe vehicle collects information about the location (latitude, longitude, and altitude), and speed of the vehicle on a second-by-second basis while the vehicle is running on the roadways. It also records precise time that can be correlated with the on-road PeMS sensor data.

For each scenario, two sets of runs were made: one in HOV lanes and one in MF lanes. The driver was instructed to drive a vehicle in a manner that represents the traffic in a particular lane type. For example, when running in an HOV lane, the driver would maintain a consistent gap distance from the vehicle in front. For the runs in MF lanes, lane changing was allowed. A voice recorder and a stopwatch synchronized to the computer clock time were given to the driver. During the HOV runs, the driver recorded the time that the vehicle entered and exited an HOV lane. During the MF runs, the driver recorded the time that the vehicle passed the HOV lane entrance and exit. The time that lane changes were made from one MF lane to another adjacent MF lane and the lane number the vehicle moved into were also recorded.

Table 3.1. Condition of PeMS loop detectors in August 2005. [1] Between CA-71 and I-15; [2] Between CA-71 and CA-60; [3] Between I-110 and I-605; * means that every detector in a station is in good condition.

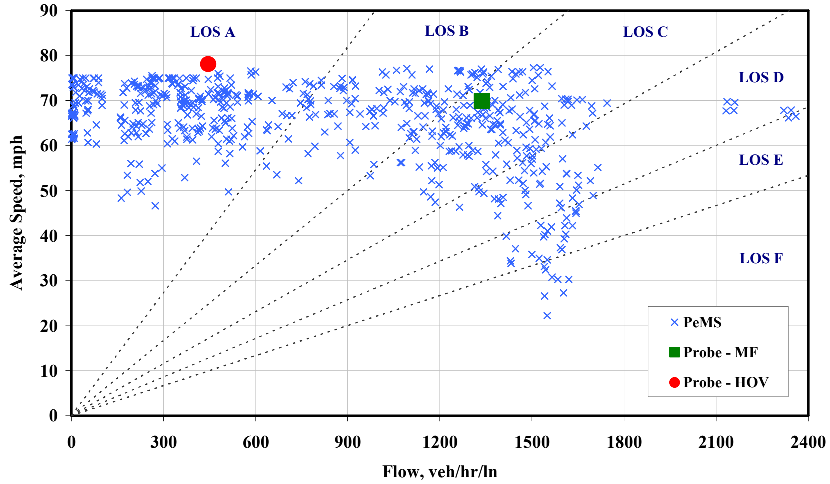
	SR-60[1]		SR-91[2]		I-10[3]	
	EB	WB	EB	WB	EB	WB
Start post mile	32.06	31.78	37.65	37.73	16.76	16.76
End post mile	40.78	40.37	54.10	54.02	29.19	29.19
Length (mi)	8.72	8.59	16.45	16.29	12.43	12.43
# of detectors	45	45	81	89	125	130
Good	40	36	67	47	96	105
Bad	5	9	14	42	29	25
% of detectors	100%	100%	100%	100%	100%	100%
Good	89%	80%	83%	53%	77%	81%
Bad	11%	20%	17%	47%	23%	19%
# of VDS	9	9	17	19	23	25
Complete*	6	4	12	9	12	16
Incomplete	3	5	5	10	11	9
% of VDS	100%	100%	100%	100%	100%	100%
Complete	67%	44%	71%	47%	52%	64%
Incomplete	33%	56%	29%	53%	48%	36%

The driving trajectory data collected in the field were filtered into a database, followed by the calculations of second-by-second acceleration/deceleration rates, distance traveled, and road grade. After that, the information concerning the time the vehicle entered and exited HOV lanes were used to match the driving data between HOV and MF lanes. This allows for consistent comparison of the driving data over the same section of freeway.

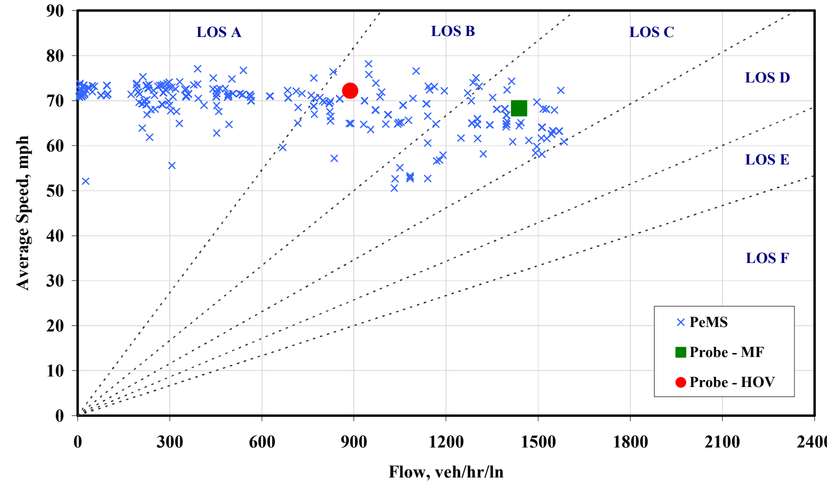
In order to verify that the collected driving data corresponds to the definition of each scenario, an investigation of PeMS loop detector data was performed. Figure 3.3 shows the speed-flow relationship of each scenario plotted using hourly average data from every good vehicle detector station on the freeway segments in the data collection date. The relationships between flow data from PeMS and average speed data collected by the probe vehicle are also plotted. It is shown that the probe data points meet the LOS designation of each scenario. In addition, it is observed that the probe vehicle is a reasonable representative of the population of traffic at each site as the probe data points are located in the ranges of PeMS data points. The only minor exception is the probe vehicle running in HOV lanes under Scenario 1, as it seems to run at a slightly faster speed than average traffic.

Table 3.2. Summary results of freeway performance, driving trajectory, and emissions estimates. [a] Data extracted from PeMS website (PeMS5.4, 2005) [b] Weighted to average fleet in Riverside County, 2005

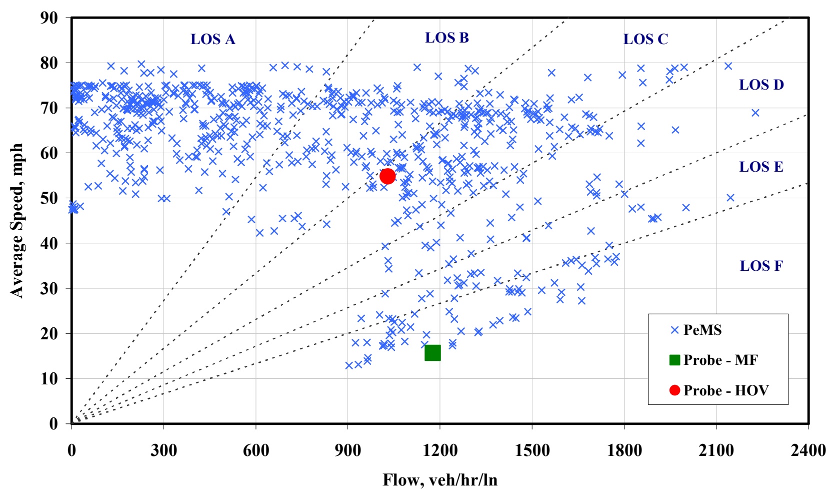
Scenario	1		2		3		4	
Description	Under-utilized		Neutral		Well-utilized		Over-utilized	
Freeway	SR-91 E		SR-60 E		I-10 W		SR-91 E	
From	SR-241		SR-71		I-605		SR-241	
To	La Sierra exit		I-15		SR-101		La Sierra exit	
Time	8-10 a.m.		4-6 p.m.		7-9 a.m.		4-6 p.m.	
Lane type	MF	HOV	MF	HOV	MF	HOV	MF	HOV
Freeway performance [a]								
% LOS A	0	78	0	19	0	0	0	0
% LOS B	5	22	10	81	0	16	0	10
% LOS C	88	0	76	0	3	24	12	0
% LOS D	8	0	14	0	0	25	0	48
% LOS E	0	0	0	0	14	11	0	18
% LOS F	0	0	0	0	83	24	88	24
VMT (mi/hr/ln)	15,810	5,266	13,173	8,135	8,449	7,395	13,332	14,915
Statistics of driving trajectory								
Travel time (sec)	605	542	482	457	1,650	471	2,665	1,188
Travel distance (mi)	11.7	11.7	9.1	9.1	7.2	7.2	11.8	11.8
Avg. speed (mph)	69.9	78.1	68.4	72.2	15.6	54.8	16.0	35.8
Max speed (mph)	81.6	87.5	78.8	83.9	59.8	63.6	68.0	67.6
Max acc. rate (mph/s)	2.2	1.9	2.1	2.0	7.2	3.6	5.0	3.8
Emissions rate estimates (g/vehicle/mi) [b]								
CO	13.64	24.21	13.82	11.04	4.06	6.43	4.34	4.34
HC	0.53	0.59	0.53	0.45	0.37	0.34	0.40	0.34
NO_x	0.82	0.98	0.80	0.78	0.66	0.61	0.70	0.60
CO_2	385.70	428.41	468.63	374.47	541.59	335.62	557.21	370.33
Fuel	128.90	147.67	155.14	123.99	173.12	109.34	178.23	119.25
Emissions rate estimates (g/person/mi) [b]								
CO	12.40	11.05	12.56	5.04	3.69	2.94	3.94	1.98
HC	0.48	0.27	0.48	0.21	0.33	0.15	0.37	0.16
NO_x	0.75	0.45	0.73	0.35	0.60	0.28	0.63	0.27
CO_2	350.64	195.62	426.02	170.99	492.35	153.25	506.56	169.10
Fuel	117.19	67.43	141.03	56.62	157.38	49.93	162.02	54.45
Emissions mass estimates (metric tons/hr/ln) [b]								
CO	0.216	0.127	0.182	0.090	0.034	0.048	0.058	0.065
HC	0.008	0.003	0.007	0.004	0.003	0.002	0.005	0.005
NO_x	0.013	0.005	0.011	0.006	0.006	0.004	0.009	0.009
CO_2	6.098	2.256	6.173	3.046	4.576	2.482	7.429	5.524
Fuel	2.038	0.778	2.044	1.009	1.463	0.809	2.376	1.779



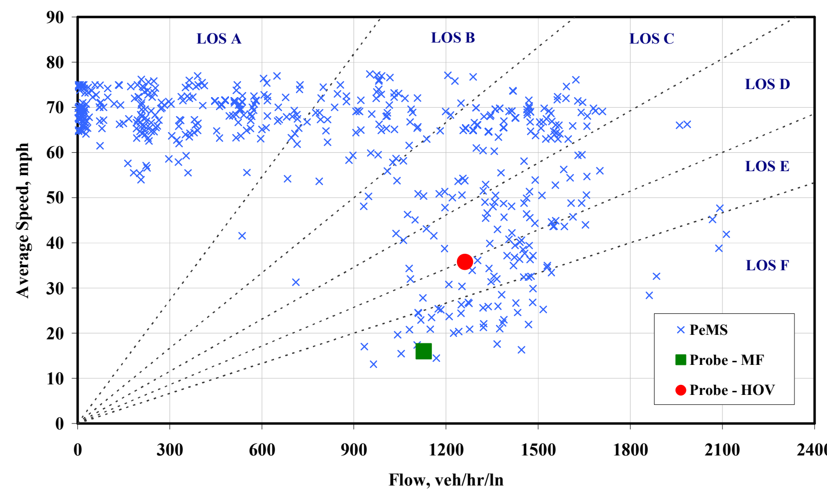
(a) Scenario 1: under-utilized



(b) Scenario 2: neutral



(c) Scenario 3: well-utilized



(d) Scenario 4: over-utilized

Figure 3.3. Speed-flow relationship for each scenario.

3.1.3. Vehicle Emissions Estimation

Vehicle fleet emissions were estimated using the Comprehensive Modal Emissions Model (CMEM). As described in Section 2.4.4, CMEM was initially developed with sponsorship from the National Cooperative Highway Research Program and the U.S. Environmental Protection Agency (EPA) to fulfill the need for microscopic emissions modeling. This type of model is necessary for evaluating emissions benefits of project-level or corridor-specific transportation control measures (e.g. HOV lanes), intelligent transportation systems (ITS) implementations (e.g. electronic toll collection), and traffic flow improvements (e.g. traffic signal coordination).

CMEM is microscopic in the sense that it predicts second-by-second tailpipe emissions and fuel consumption based on different modal operations from in-use vehicle fleet. One of the most important features of CMEM is that it uses a physical, power-demand approach based on a parameterized analytical representation of fuel consumption and emissions production. In this type of model, the entire fuel consumption and emissions process is broken down into components that correspond to physical phenomena associated with vehicle operation and emissions production. Each component is modeled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary according to the vehicle type, engine, emission technology, and level of deterioration. One distinct advantage of this physical approach is that it is possible to adjust many of these physical parameters to predict energy consumption and emissions of future vehicle models and applications of new technology (e.g., after-treatment devices).

The required inputs for CMEM include vehicle activity (second-by-second speed trace, at a minimum) and fleet composition of traffic being modeled. The initial version of CMEM consisted of 23 light-duty gasoline vehicle/technology categories characterized by emission control technology, emission certification standard, mileage, power-to-weight ratio, and high emitting characteristics. With the continued support from the U.S. EPA, CMEM has been maintained and updated by adding new vehicle/technology categories as they emerged. Examples of additional vehicle/technology categories are ultra-low emission vehicles (ULEV), super ultra-low emission vehicles (SULEV), and partial zero emission vehicles (PZEV). In addition, CMEM has been expanded to include the heavy-duty diesel vehicles. The current version of CMEM (version 3.0, 2005) includes 28 light-duty vehicle/technology categories and three heavy-duty vehicle/technology categories, as listed in Table 3.3. CMEM is a public-domain model and has several hundred registered users worldwide. At present, it is claimed to be the most detailed and best tested model for estimating hot-stabilized vehicle exhaust emissions at different speeds and accelerations [Dowling et al., 2005]. For further information on the CMEM efforts, please refer to [Barth et al., 1999; Barth et al., 2001b; Barth et al., 2004].

The HOV/MF driving data (second-by-second data of speed in mph) collected in the field were used as input to CMEM. The resulting second-by-second tailpipe emissions for all vehicle/technology categories were then weighted to the average vehicle fleet of Riverside County, California in September 2005. The proportion of each vehicle/technology category is listed in Table 3.3. All scenarios were evaluated using the same vehicle fleet for a fair comparison. After that, the weighted emissions were aggregated over the entire driving trace and reported as shown in Figure 3.4.

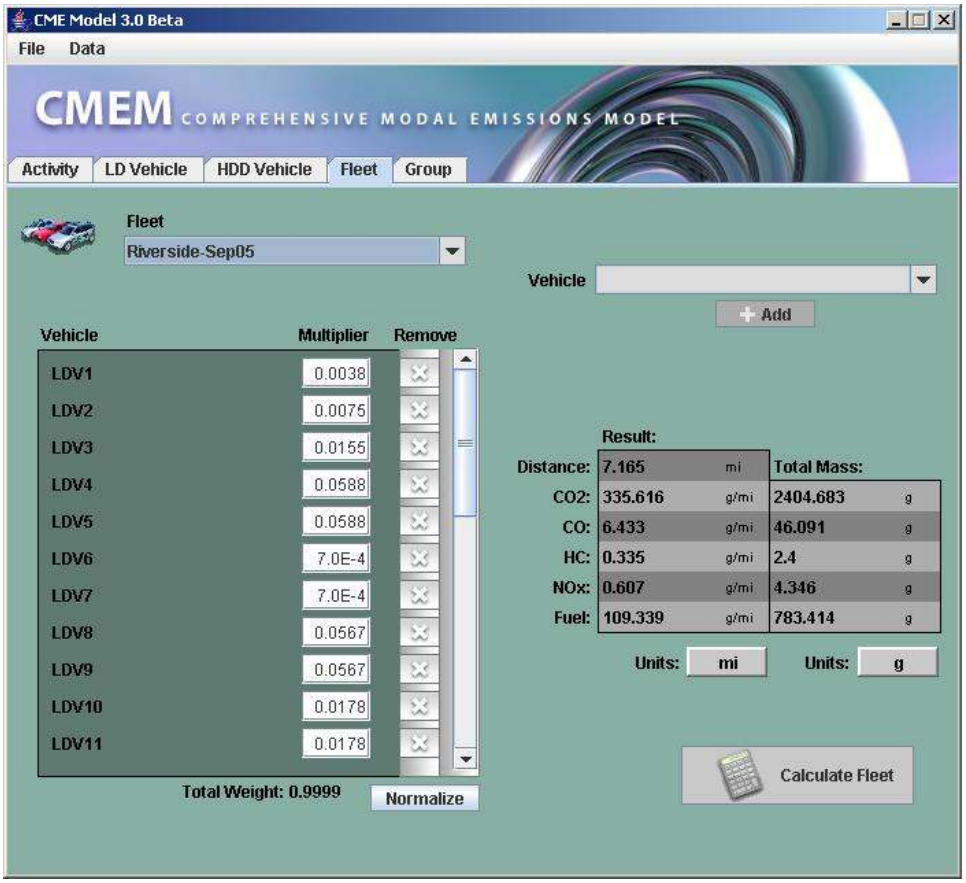


Figure 3.4. Example screen of CMEM version 3.0.

3.1.4. Fleet Composition Estimation

Fleet composition presented in Table 3.3 is estimated from the California vehicle database embedded in the latest version of EMFAC (EMFAC2002). Table 3.4 shows the mapping between EMFAC vehicle classes and CMEM vehicle categories. The VMT data for each EMFAC vehicle class disaggregated to county-specific level can be extracted from EMFAC2002, and the fraction can be derived. Some EMFAC vehicle classes (line-haul vehicles, urban buses, motorcycles, school buses, and motor homes) are excluded because they do not have a matched CMEM vehicle category. However, the effect of omitting these vehicle classes is negligible since their VMT contribution to the overall VMT is less than 1.5%. It can be seen in Table 3.4 that some CMEM vehicle categories fall into the same EMFAC2002 vehicle class. For example, LDVs 2-11, 19-24, and 26-27 in CMEM are all analogous to gasoline-catalytic passenger cars in EMFAC2002. Also, the high emitting vehicle categories in CMEM (LDVs 19-23) may include some from each relevant EMFAC2002 vehicle class (LDA, LDT1, LDT2, and MDV). In these circumstances, the EMFAC2002-CMEM vehicle class mapping methodology is refined to appropriately distribute the VMT fraction between the two vehicle class systems. The refinement of EMFAC2002-CMEM vehicle class mapping methodology was done using the categorization technique described in [Barth et al, 1999]. The technique assigns vehicles to CMEM categories using information regarding model year, fuel type, weight, emitting condition, accumulated mileage, and power-to-weight ratio. The assignment technique was fine-tuned for specific county and month based on the mileage accrual data available in EMFAC2002. Some assumptions were made to reflect the phase-in of Tier I standard in 1990's and the ending of Tier I and TLEV emission standards after 2003 [DieselNet, 2001].

Table 3.3. CMEM vehicle/technology categories.

Category	Description	Riverside, Sep 2005		Alameda, Feb 2006	
		Raw Fraction	Adjusted %	Raw Fraction	Adjusted %
Normal Emitting Cars					
LDV 1	No Catalyst	0.0036	0.38	0.0046	0.49
LDV 2	2-way Catalyst	0.0071	0.75	0.0101	1.07
LDV 3	3-way Catalyst, Carbureted	0.0147	1.55	0.0186	1.98
LDV 4	3-way Catalyst, FI, >50K miles, low power/weight	0.0557	5.88	0.0642	6.83
LDV 5	3-way Catalyst, FI, >50K miles, high power/weight	0.0557	5.88	0.0642	6.83
LDV 6	3-way Catalyst, FI, <50K miles, low power/weight	0.0007	0.07	0.0010	0.10
LDV 7	3-way Catalyst, FI, <50K miles, high power/weight	0.0007	0.07	0.0010	0.10
LDV 8	Tier 1, >50K miles, low power/weight	0.0536	5.67	0.0573	6.09
LDV 9	Tier 1, >50K miles, high power/weight	0.0536	5.67	0.0573	6.09
LDV 10	Tier 1, <50K miles, low power/weight	0.0169	1.78	0.0151	1.60
LDV 11	Tier 1, <50K miles, high power/weight	0.0169	1.78	0.0151	1.60
LDV 24	Tier 1, >100K miles	0.1393	14.72	0.1350	14.35
LDV 26	Ultra-Low Emission Vehicle (ULEV)	0.0724	7.66	0.0885	9.41
LDV 27	Super Ultra-Low Emission Vehicle (SULEV) and Partial Zero Emission Vehicle (PZEV)	0.0081	0.86	0.0233	2.48
Normal Emitting Trucks					
LDV 12	Pre-1979 (<=8500 GVW)	0.0050	0.53	0.0039	0.41
LDV 13	1979 to 1983 (<=8500 GVW)	0.0078	0.82	0.0089	0.95
LDV 14	1984 to 1987 (<=8500 GVW)	0.0228	2.41	0.0230	2.45
LDV 15	1988 to 1993 (<=3750 LVW)	0.0308	3.26	0.0263	2.79
LDV 16	1988 to 1993 (>3750 LVW)	0.0664	7.01	0.0562	5.97
LDV 17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	0.1660	17.54	0.1263	13.44
LDV 18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	0.0681	7.20	0.0522	5.55
LDV 25	Gasoline-powered, LDT (>8500 GVW)	0.0187	1.97	0.0173	1.84
LDV 40	Diesel-powered, LDT (>8500 GVW)	0.0157	1.66	0.0213	2.27
High Emitting Vehicles					
LDV 19	Runs lean	0.0071	0.75	0.0076	0.81
LDV 20	Runs rich	0.0152	1.61	0.0157	1.67
LDV 21	Misfire	0.0145	1.54	0.0160	1.70
LDV 22	Bad catalyst	0.0051	0.54	0.0056	0.59
LDV 23	Runs very rich	0.0040	0.43	0.0048	0.51
	Subtotal	*0.9460*	*100.00*	*0.9401*	*100.00*
Heavy-Duty Diesel Vehicles					
HDDV 5	1994 to 1997, 4 stroke, electronic FI	0.0097	32.3	0.0111	30.0
HDDV 6	1998, 4 stroke, electronic FI	0.0018	6.2	0.0023	6.1
HDDV 7	1999 to 2002, 4 stroke, electronic FI	0.0185	61.5	0.0236	63.9
	Subtotal	*0.0300*	*100.0*	*0.0370*	*100.0*

Notes: Tier 1 phased in 40% in 1994 and 80% in 1995 for cars and LDT1 (50% in 1996 and 100% in 1997 for LDT2/3 and LDT4). After 2003, Tier 1 and TLEV standards were eliminated as available emission categories [DieselNet, 2001].

Table 3.4. Vehicle class/category mapping between EMFAC and CMEM models

EMFAC2002					% VMT from EMFAC		Corresponding CMEM3.0 Vehicle Category
Class	Abbr.	Description	Weight	Fuel	Riverside, Sep 2005	Alameda, Feb 2006	
1	LDA	Passenger Cars	All	gas-non-catalytic	0.4	0.5	LDV 1
				gas-catalytic	52.0	58.0	LDVs 2-11, 19-24, 26-27
				diesel	0.1	0.2	-
2	LDT1	Light-Duty Trucks	0-3750	gas-non-catalytic	0.3	0.2	LDV 12
				gas-catalytic	17.7	10.9	LDVs 13-15 & 19-23
				diesel	0.4	0.2	-
3	LDT2	Light-Duty Trucks	3751-5750	gas-non-catalytic	0.2	0.1	LDV 12
				gas-catalytic	15.4	13.8	LDVs 16-17 & 19-23
				diesel	0.2	0.1	-
4	MDV	Medium-Duty Trucks	5751-8500	gas-non-catalytic	0.1	0.1	LDV 12
				gas-catalytic	5.3	6.7	LDVs 16, 18 & 19-23
				diesel	0.2	0.2	-
5	LHDT1	Light-Heavy-Duty Trucks	8501-10000	gas-non-catalytic	0.0	0.0	LDV 25
				gas-catalytic	1.3	1.1	LDV 25
				diesel	0.3	0.3	LDV 40
6	LHDT2	Light-Heavy-Duty Trucks	10001-14000	gas-non-catalytic	0.0	0.0	LDV 25
				gas-catalytic	0.3	0.3	LDV 25
				diesel	0.3	0.2	LDV 40
7	MHDT	Medium-Heavy-Duty Trucks	14001-33000	gas-non-catalytic	0.0	0.0	LDV 25
				gas-catalytic	0.3	0.3	LDV 25
				diesel	1.0	1.7	LDV 40
8	HHDT	Heavy-Heavy-Duty-Trucks	33001-60000	gas-non-catalytic	0.0	0.0	-
				gas-catalytic	0.2	0.2	-
				diesel	3.0	3.7	HDDVs 5-7
				Total	*98.7*	*98.6*	

Notes: EMFAC vehicle classes 9-13 (line-haul vehicles, urban buses, motorcycles, school buses, and motor homes) are excluded because they do not have a matched CMEM vehicle category.

3.2. DIFFERENCES IN VEHICLE ACTIVITY

3.2.1. Driving Trajectory

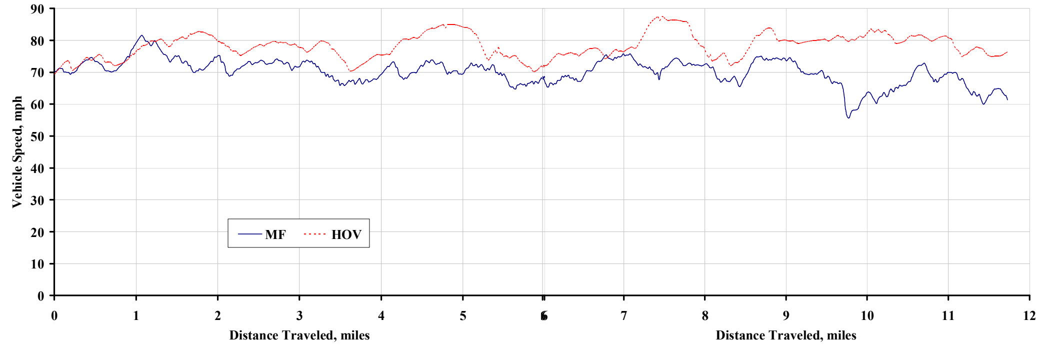
Figure 3.5 shows an example speed trajectory of the driving in HOV lanes and MF lanes over the same segment of freeways. Under Scenario 1, the speeds in HOV lanes are slightly higher than in MF lanes constantly over the entire segment. Under Scenario 2, the speed in both lane types are comparable except for at the beginning and at the end of the section. The speed profiles under Scenarios 3 and 4 provide the evidence of congested conditions in MF lanes as well as the proof that the flow in HOV lanes outperformed the flow in MF lanes. In essence, these speed profiles agree with the designation of each scenario.

Table 3.5 contains statistics of the driving trajectory data. Under every scenario, the driving in HOV lanes has higher average speeds than the driving in MF lanes. This translates to the less travel time required to complete the trip. The amount of travel time savings depends on the relative difference between the average speeds in each lane type. In the first two scenarios, the differences in average speeds are relatively small (less than 10 mph). Hence, the travel time savings are also small (5 and 3 seconds/mile for Scenarios 1 and 2, respectively). Most probably, these amounts of travel time saving would not be realized by carpoolers. On the other hand, the relative differences in average speeds of the last two scenarios are large enough that the resultant travel time savings (165 and 125 seconds/mile for Scenarios 3 and 4, respectively) surpass the minimum threshold of 96 seconds per mile identified by [NCHRP, 1998].

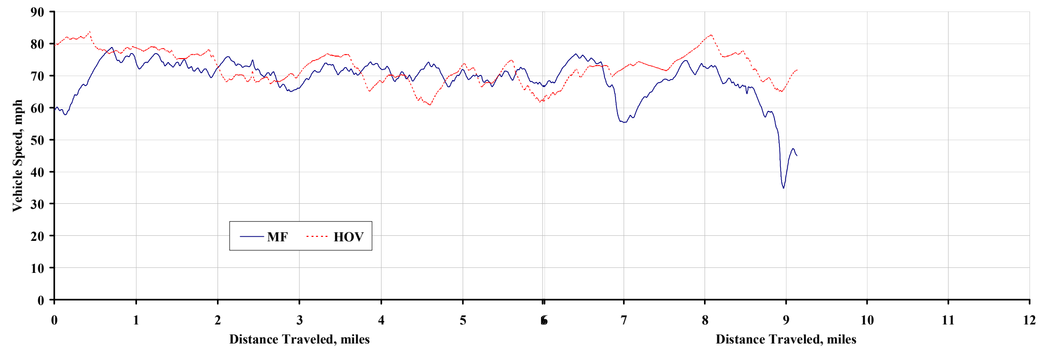
Under every scenario, the maximum acceleration rates of the driving in HOV lanes are less than the rates of the driving in MF lanes. It is well understood that the amount of tailpipe emissions depends not only on average speed, but also on speed fluctuations (acceleration and deceleration). For instance, acceleration/deceleration events are likely to occur more frequently at low speeds and that gives rise to higher emissions. At high speeds, even small accelerations can cause power enrichment events that result in significantly higher emissions than a steady-state cruise.

3.2.2. Joint Speed-Acceleration Frequency Distribution

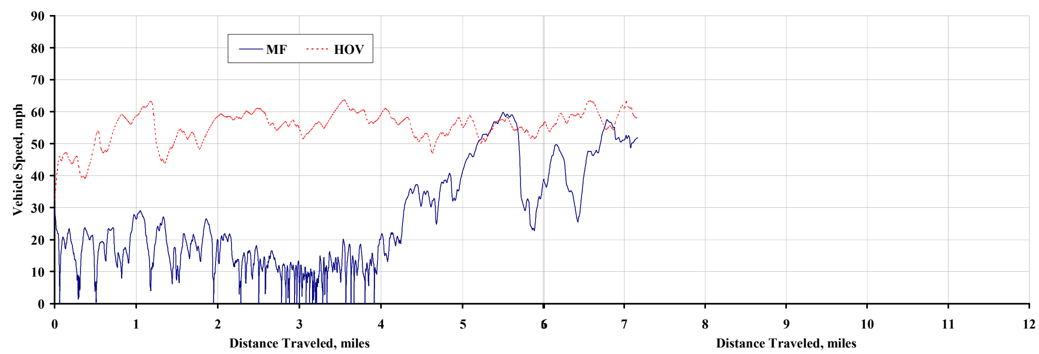
In this study, the investigation of speed and acceleration/deceleration differences between the two data sets was conducted by plotting the contours of joint speed-acceleration frequency distribution (SAFD), as shown in Figure 3.6. The SAFDs of uncongested freeway operations (Scenarios 1 and 2) are centralized around a narrow range of speed. For MF lanes, this range is 65-75 mph. For HOV lanes, this range is as high as 70-85 mph when it is under-utilized. In both lane types, the acceleration rates at near free-flow or better operations are unlikely to be more than 1 mph/s while the deceleration rates are unlikely to drop below -2 mph/s. The concentric SAFDs of these two scenarios affirm the stable conditions of traffic flow. As freeways become congested, the flow becomes unstable as indicated by how the SAFDs are more spread out for the MF lanes under Scenarios 3 and 4. Under congested conditions, vehicles experience wider ranges of speed and more aggressive acceleration/deceleration events, especially at low speeds, due to stop-and-go movements. Note that Caltrans defines congested freeway locations as those where average speeds are 35 mph or less during peak commute periods on a typical incident-free weekday [PB study team, 2002]. Under Scenario 3, although the speed range of the HOV lane operation is only 50-60 mph, it still maintains the shape of stable flow. As the average speed approaches the threshold level, as in HOV lanes of Scenario 4 (the average speed of 35.8 mph), the operation is at the edge of congested conditions and the SAFD starts to lose its stable flow pattern.



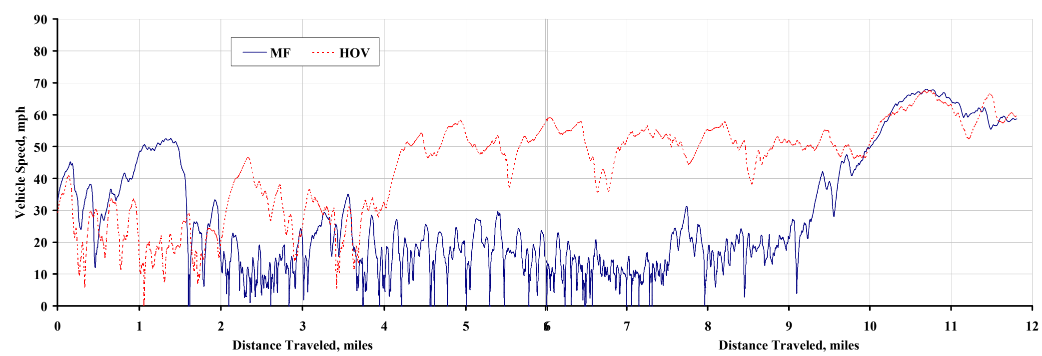
(a) Scenario 1: under-utilized



(b) Scenario 2: neutral

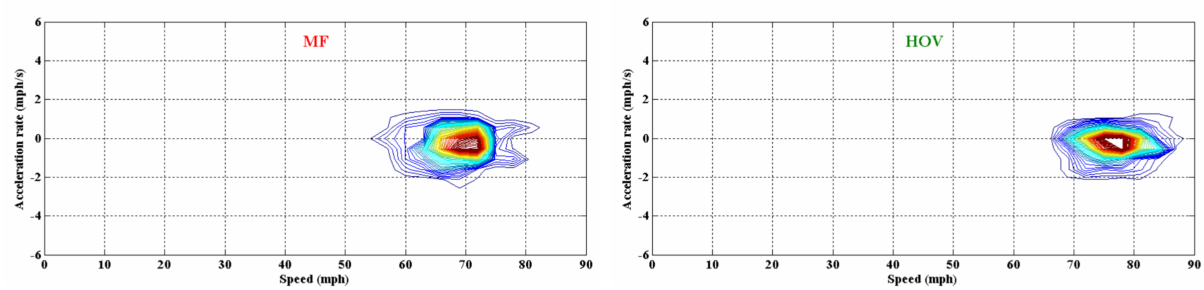


(c) Scenario 3: well-utilized

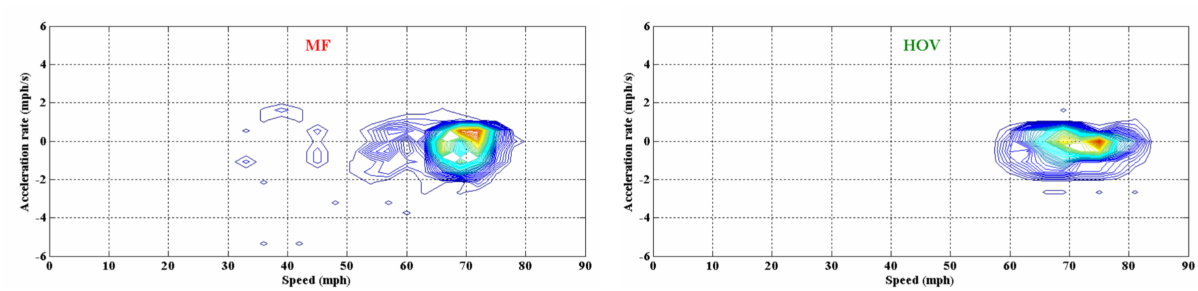


(d) Scenario 4: over-utilized

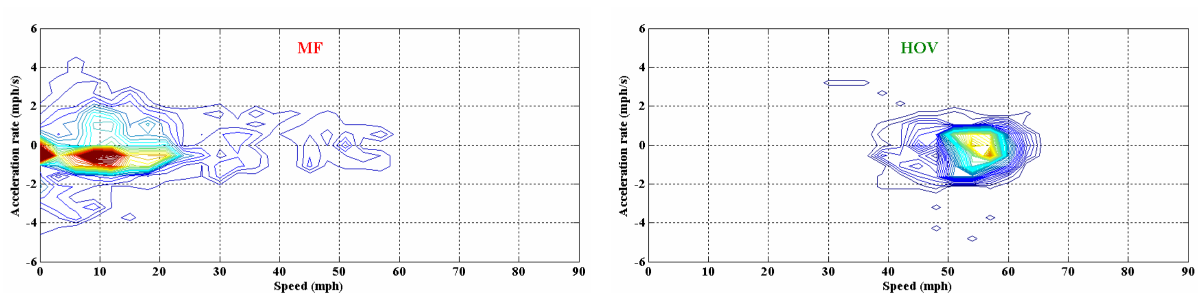
Figure 3.5. Example speed trajectories of probe vehicle runs.



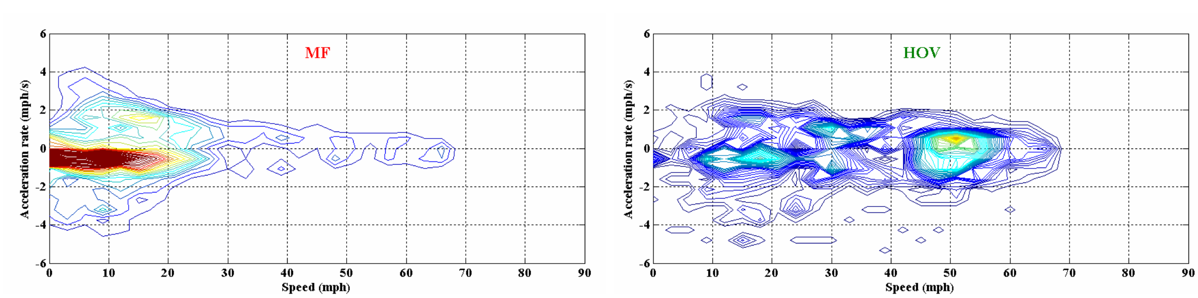
(a) Scenario 1: under-utilized



(b) Scenario 2: neutral



(c) Scenario 3: well-utilized



(d) Scenario 4: over-utilized

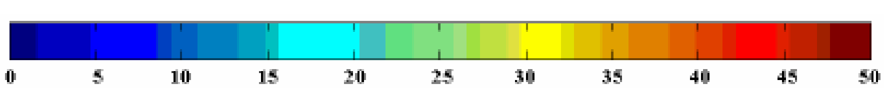


Figure 3.6. Joint speed-acceleration frequency distribution.

3.3. DIFFERENCES IN EMISSIONS

The estimated emission rates per vehicle per mile from CMEM are summarized in Table 3.2. The percentage differences in emission rates between the two lane types were calculated and plotted in Figure 3.7. In the plot, negative values mean emissions and fuel consumption rates in HOV lanes are lower. The results are discussed below:

- ***Scenario 1*****:** At comparatively high speeds, the speeds in the HOV lane are moderately higher than in the MF lanes. While the gained travel time saving is not significant, a vehicle running at very high speeds (above 70 mph) in the HOV lane has almost 80% higher CO emission rate and about 20% higher NO_x emission rate, as compared to running in the MF lanes.

- ***Scenario 2*****:** The average speeds in both lane types are marginally different, so the travel time saving is minimal. The relatively smaller magnitude of acceleration/deceleration events in the HOV lane results in about 20% lower CO emission, CO_2 emission, and fuel consumption rates compared to the MF lanes.

- ***Scenario 3*****:** The approximately 40 mph difference in average speeds allows carpoolers to enjoy the travel time saving as high as 2.75 minutes per mile. The better flow in the HOV lane results in about 10% less HC and NO_x emission rates, and 35% less CO_2 emission and fuel consumption rates. It is interesting to see that under this scenario the CO emission rate in the HOV lane is about 60% higher. This may be due to a few power enrichment events that give rise to the CO emission rate.

- ***Scenario 4*****:** Although the traffic in both lane types is congested, carpoolers travel at double the speeds of solo-drivers and gain the travel time saving of about 2 minutes per mile. Although the traffic flow in the HOV lane starts to enter an unstable condition, the relatively better flow in the lane brings about 15% less HC and NO_x emission rates and about 35% less CO_2 emission and fuel consumption rates than in the MF lanes.

The CMEM-estimated emission rates per vehicle were also normalized by the average vehicle occupancy for each lane type, resulting in estimated emission rates per person. The average vehicle occupancy of HOV and MF lanes calculated from data collected on SR-60E and SR-91E are 2.19 and 1.10, respectively [Caltrans, 2005b]. Figure 3.8 shows the percentage difference in emission rates per person between the two lane types. It is obvious from the figure that HOV lanes produce much lower emission rates per the same amount of travel demand. The magnitude of differences ranges from 10% up to almost 70%.

Different conditions of traffic operation in the two lane types lead to different results of emission rates. They also result in different amounts of VMT on the freeway segments. Figure 3.9 compares the VMT per hour per lane between HOV and MF lanes. The numeric values are given in Table 3.2. Because the HOV lane is under-utilized under Scenario 1, its VMT is 67% less than VMT in the MF lanes. On the other hand, under congested conditions the better flow in the HOV lane under Scenario 4 brings approximately 12% higher per-lane VMT than in its counterpart. These VMT values were multiplied by the previously calculated emission rates to obtain the total emissions mass, as shown in Table 3.2. Again, the percentage differences between the two lane types were computed and plotted in Figure 3.10. Negative values mean emissions and fuel consumption in HOV lanes are lower. The results are interesting. Although the HOV lane under Scenario 1 produces higher emission rates than in the MF lanes, the lower VMT in the lane brings the total emissions mass down to 40-60% of those generated in the adjacent MF lanes. In almost every case, HOV lanes produce less emissions mass than MF lanes.

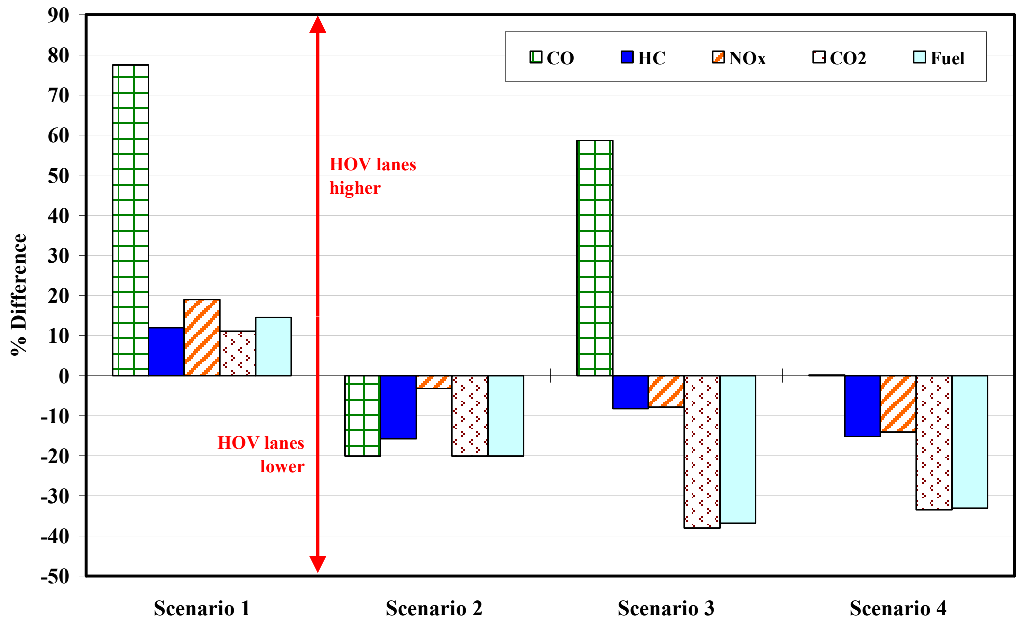


Figure 3.7. Differences in emission rates per vehicle between HOV and MF lanes

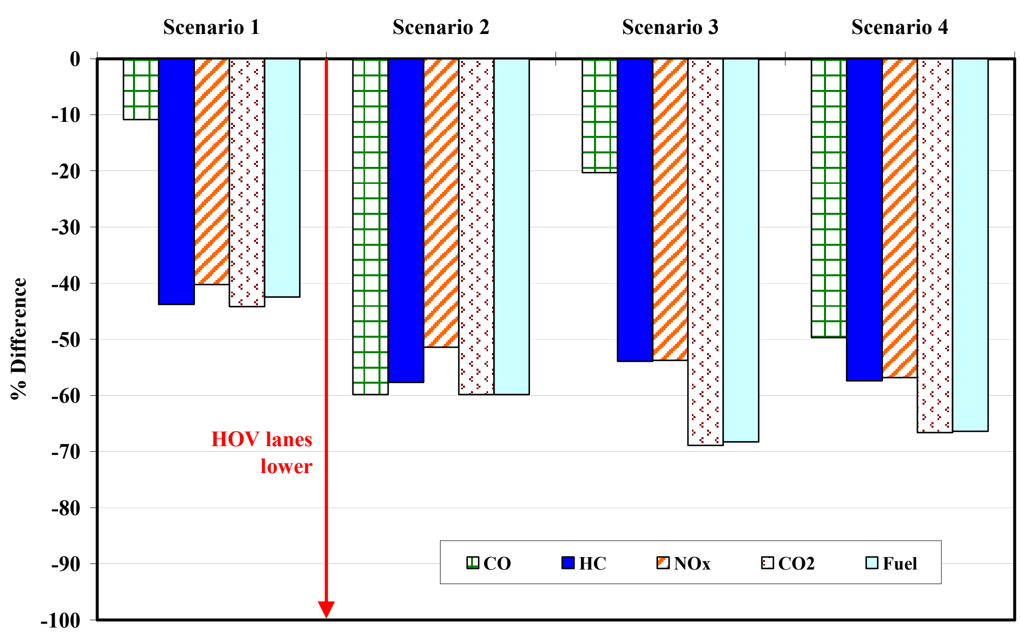


Figure 3.8. Differences in emission rates per person between HOV and MF lanes

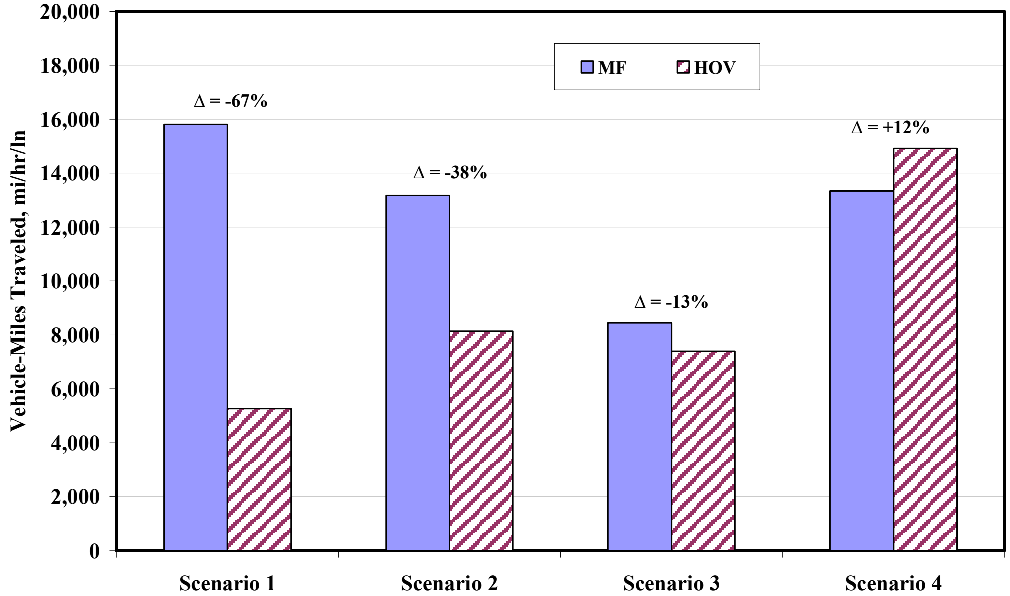


Figure 3.9. Vehicle-miles traveled per lane in both lane types

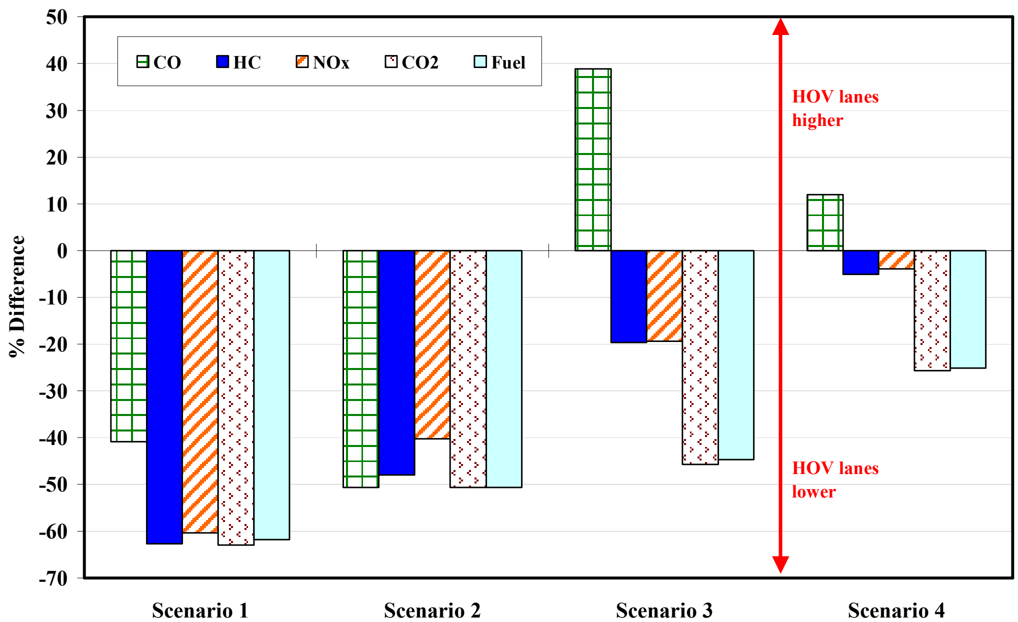


Figure 3.10. Differences in resulting emissions mass between HOV and MF lanes.

3.4. FREEWAY LANE PERFORMANCE MATRIX

According to the previous results, the following question then is raised: in a typical day, what is the occurrence probability of the performance of actual freeway operations falling into each scenario? To answer this question, a Bayesian analysis [Calin & Louis, 2000] of freeway lane

LOS was performed using LOS data for HOV and MF lanes extracted from PeMS. The ultimate goal is to find:

$$p(HOV_i \mid MF_j) = \frac{p(HOV_i) \cdot p(MF_j \mid HOV_i)}{\sum_i \left[p(HOV_i) \cdot p(MF_j \mid HOV_i) \right]} = \frac{p(HOV_i) \cdot p(MF_j \mid HOV_i)}{p(MF_j)} \quad (3.1)$$

where:

$p(HOV_i \mid MF_j)$ is the posterior probability of HOV lane having LOS i given that MF lane is known to have LOS j;

$p(MF_j \mid HOV_i)$ is the conditional probability of MF lane having LOS j given that HOV lane is known to have LOS i;

$p(HOV_i)$ is the prior probability of HOV lane having LOS i;

$p(MF_j)$ is the marginal probability of MF lane having LOS j; and

i, j = {A, B, C, D, E, F}.

The PeMS data are available in the form of the percentage breakdown of each LOS (discrete probability distribution) for each lane type. These data can be used to calculate $p(HOV_i)$ and $p(MF_j)$. However, the *priori* knowledge regarding the probability distribution of LOS in MF lanes conditional on the LOS in HOV lanes, $p(MF_j \mid HOV_i)$, is not readily available. To simplify the analysis, we rewrite Equation 1 and rearrange the equation as:

$$p(HOV_i \mid MF_j) = \frac{p(HOV_i \cdot MF_j)}{p(MF_j)} \quad (3.2)$$

$$p(HOV_i \cdot MF_j) = p(HOV_i \mid MF_j) \cdot p(MF_j)$$

Further, we assume that HOV_i and MF_j are independent events, thus:

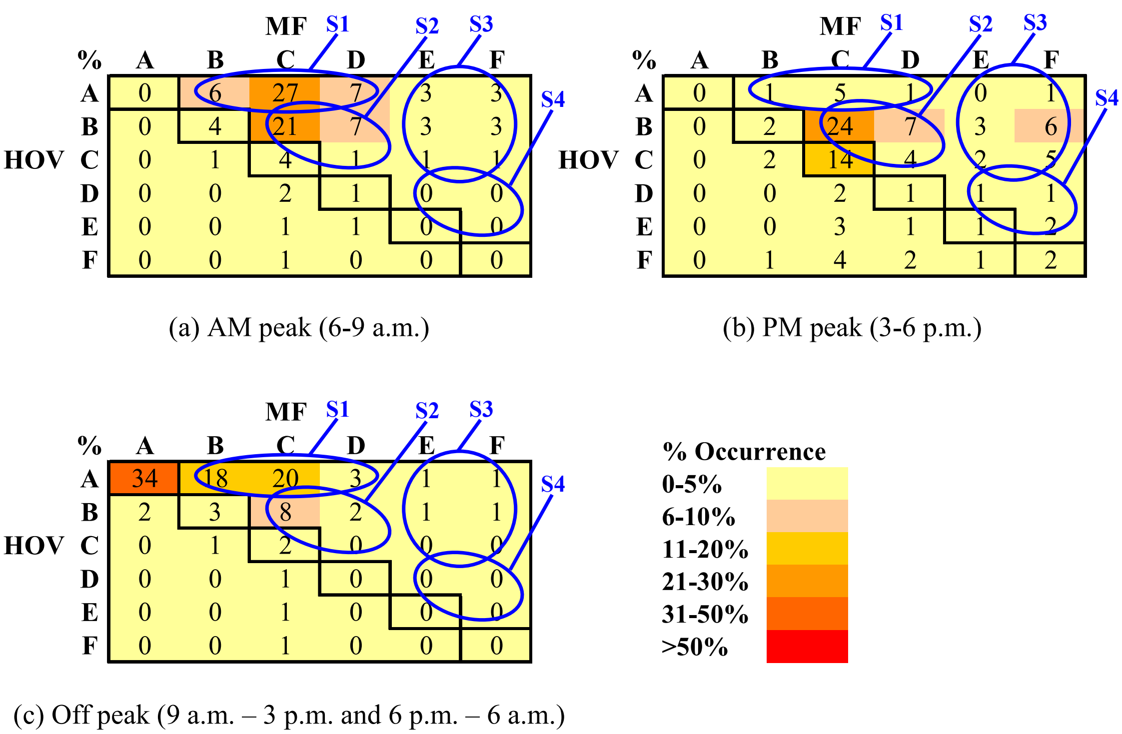
$$p(HOV_i \cdot MF_j) = p(HOV_i) \cdot p(MF_j) \quad (3.3)$$

The PeMS LOS data can be queried for a specified period (e.g. 3 months). In the specified period, the data are aggregated for each hour, t, of a day. Therefore, the probability of freeway lane performance in a typical day during the specified period can be calculated as:

$$p(HOV_i \cdot MF_j) = \frac{1}{24} \sum_{t=1}^{24} \left[p_t(HOV_i) \cdot p_t(MF_j) \right] \quad (3.4)$$

Examples of the analysis results for the entire SR-91 corridor (both eastbound and westbound) from July to September 2005 are presented in Figures 3.11 and 3.12. The illustration of each of the four scenarios is also provided. It is observed that in a typical weekday, HOV lanes in the SR-91 corridor operated mostly under Scenarios 1 and 2 during peak periods. This is also true for weekends with a caution that the peak period during weekends is defined differently. Overall, they were well-utilized about 14-17% of the time during weekday and only 6% of the time during weekend. According to the emissions comparison previously discussed, the HOV lanes on SR-91 are considered effective in reducing vehicle emissions.

It is observed that there are a few percentages in lower left elements of the matrices. Although such circumstances are intuitively rare especially during the off-peak period, they may be possible due to one or a combination of the following reasons: (a) errors in loop detector data, (b) the assumptions regarding the *priori* probability and the independency made in the Bayesian analysis, and (c) actual congestion and events occurred in HOV lanes. An example of the actual events that will result in poorer LOS in HOV lanes is when there is a capacity drop in HOV lanes such as those caused by incidents or geometric changes. Since HOV lanes in Southern California are separated from the adjacent MF lane by intermittent buffers or barriers, any event occurring in a lane will considerably influence the operational performance of the lane. For instance, when there is a drop in capacity that forces a vehicle in front to decrease speed, vehicles that follow cannot change their lane and also are forced to decrease the speed. This speed reduction will possibly propagate and build up a queue in the lane.



% (HOV \ MF)	A	B	C	D	E	F
A	0	6	27	7	3	3
B	0	4	21	7	3	3
C	0	1	4	1	1	1
D	0	0	2	1	0	0
E	0	0	1	1	0	0
F	0	0	1	0	0	0

(a) AM peak (6-9 a.m.)

% (HOV \ MF)	A	B	C	D	E	F
A	0	1	5	1	0	1
B	0	2	24	7	3	6
C	0	2	14	4	2	5
D	0	0	2	1	1	1
E	0	0	3	1	1	2
F	0	1	4	2	1	2

(b) PM peak (3-6 p.m.)

% (HOV \ MF)	A	B	C	D	E	F
A	34	18	20	3	1	1
B	2	3	8	2	1	1
C	0	1	2	0	0	0
D	0	0	1	0	0	0
E	0	0	1	0	0	0
F	0	0	1	0	0	0

(c) Off peak (9 a.m. – 3 p.m. and 6 p.m. – 6 a.m.)

% Occurrence
0-5%
6-10%
11-20%
21-30%
31-50%
>50%

Figure 3.11. Probabilistic performance matrix of SR-91 corridor (weekday, Jul-Sep, 2005)

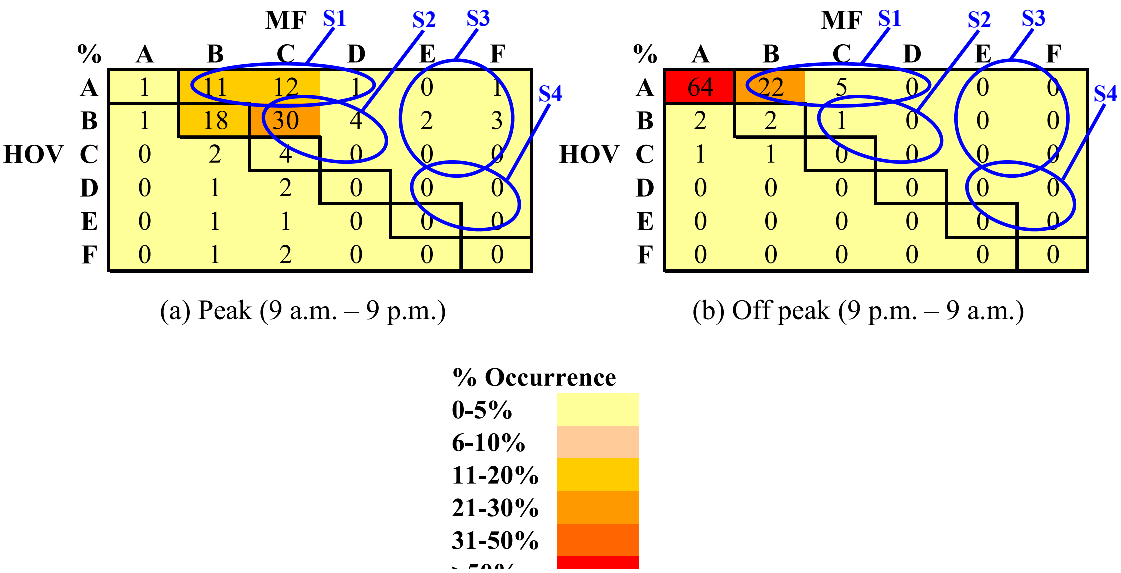
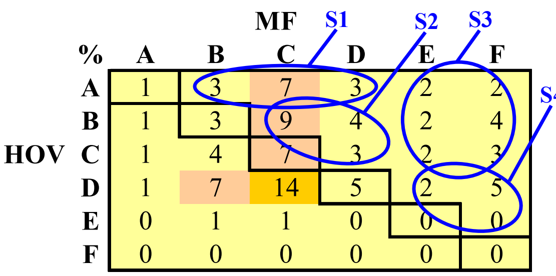
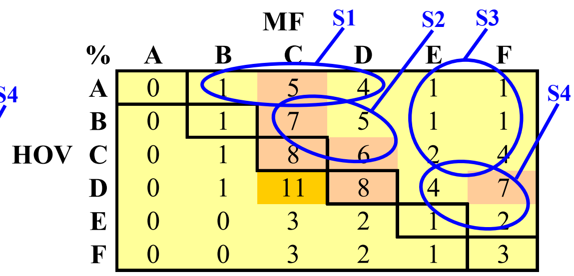


Figure 3.12. Probabilistic performance matrix of SR-91 corridor (weekend, Jul-Sep, 2005)

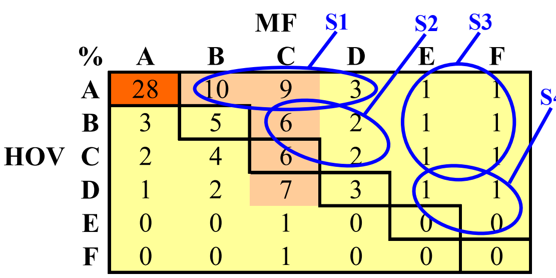
Figures 3.13 and 3.14 display the probabilistic performance matrices of I-10 and SR-60 corridors, respectively. Table 3.5 summarizes the total percentage occurrence of each freeway operation scenario in the probabilistic performance matrix for I-10, SR-60, and SR-91 freeway corridors on a typical weekday from July to September of 2005. The total percentage occurrence of the lower left elements of the matrix, where emissions burden of HOV lanes might be expected, and the diagonal elements, where there might be no or little difference in emissions, is also reported. According to the results, the performance of HOV lanes on SR-60 and SR-91 is comparable to each other. They operate mostly under Scenarios 1 and 2 (under-utilized and neutral) even during peak periods, which imply that they may still have some capacity left for additional traffic. Overall, the HOV lanes on these two corridors are providing air quality benefits. Comparatively, the performance of HOV lanes on I-10 is worse than those on the other two corridors. There is at least 20% of the time throughout a day that HOV lanes on I-10 have poorer LOS than MF lanes. On the other hand, it is only for 50% or less of the time that HOV lanes on I-10 operate at better LOS and provide air quality benefits.

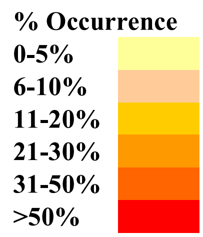


(a) AM peak (6-9 a.m.)



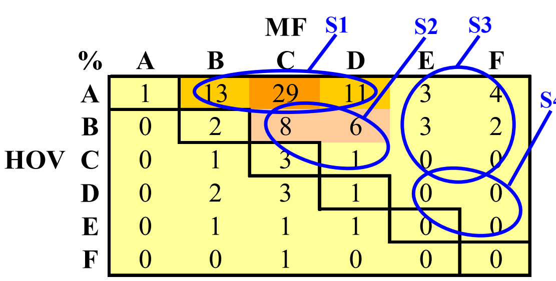
(b) PM peak (3-6 p.m.)



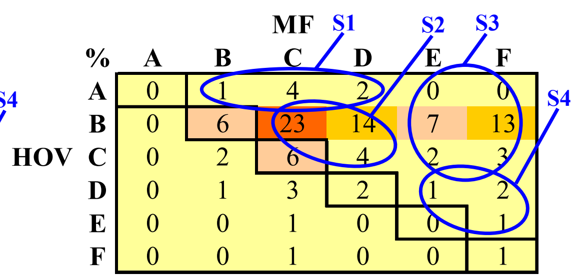


(c) Off peak (9 a.m. – 3 p.m. and 6 p.m. – 6 a.m.)

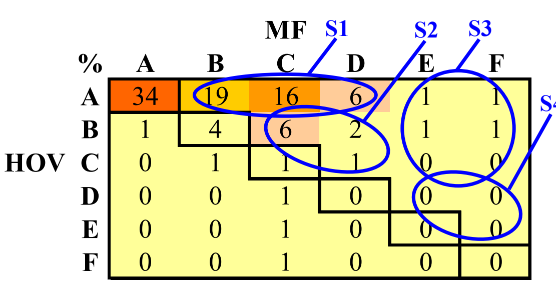
Figure 3.13. Probabilistic performance matrix of I-10 corridor (weekday, Jul-Sep, 2005)

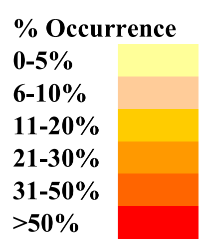


(a) AM peak (6-9 a.m.)



(b) PM peak (3-6 p.m.)





(c) Off peak (9 a.m. – 3 p.m. and 6 p.m. – 6 a.m.)

Figure 3.14. Probabilistic performance matrix of SR-60 corridor (weekday, Jul-Sep, 2005)

Table 3.5. Summary of the probabilistic freeway lane performance on weekdays (Jul-Sep, 2005)

Jul-Sep, 2005	Freeway Corridor	Total Percentage Occurrence						
		X	O	S1	S2	S3	S4	Total
AM peak (6-9 a.m.)	I-10	30.0	16.7	13.6	16.4	15.7	7.5	100.0
	SR-60	10.7	6.6	53.3	15.2	13.5	0.7	100.0
	SR-91	7.2	9.7	40.6	29.3	12.1	1.0	100.0
PM peak (3-6 p.m.)	I-10	26.9	22.1	10.4	17.6	10.3	12.7	100.0
	SR-60	8.1	15.1	7.0	41.2	25.0	3.6	100.0
	SR-91	17.0	19.8	7.1	35.2	17.3	3.6	100.0
Off peak (9 a.m.-3 p.m. & 6 p.m.-6 a.m.)	I-10	21.0	41.5	21.7	9.7	4.2	1.9	100.0
	SR-60	6.3	39.7	40.6	8.8	4.3	0.3	100.0
	SR-91	6.5	38.8	41.4	9.9	3.1	0.3	100.0

Notes: X = the lower left elements of the performance matrix; O = the diagonal elements of the performance matrix

3.5. ANALYSIS FOR NORTHERN CALIFORNIA

The types of HOV facilities are different from state to state. In California, they are also different by region. In Southern California, HOV lanes provide concurrent flow but are separated from the adjacent MF lane by either physical barriers or double yellow lane markings. They provide limited access/egress at designated locations. HOV lanes in Southern California are operational 24 hours a day, seven days a week, because traffic peak periods are long, expanding from morning hours to evening hours. An occupancy requirement is two or more persons (2+) for every freeway except for the famous El Monte busway that enforces a 3+ occupancy requirement during peak periods (5-9 a.m. and 4-7 p.m.) and a 2+ occupancy requirement for the rest of the day in order to maximize its operation performance [Turnbull, 2002]. In Northern California, HOV lanes have concurrent flow with continuous access; they are separated from the adjacent MF lane by broken lane markings. These HOV lanes are enforced only during peak periods, which vary slightly from one freeway to another. During off-peak periods, they are used as MF lanes.

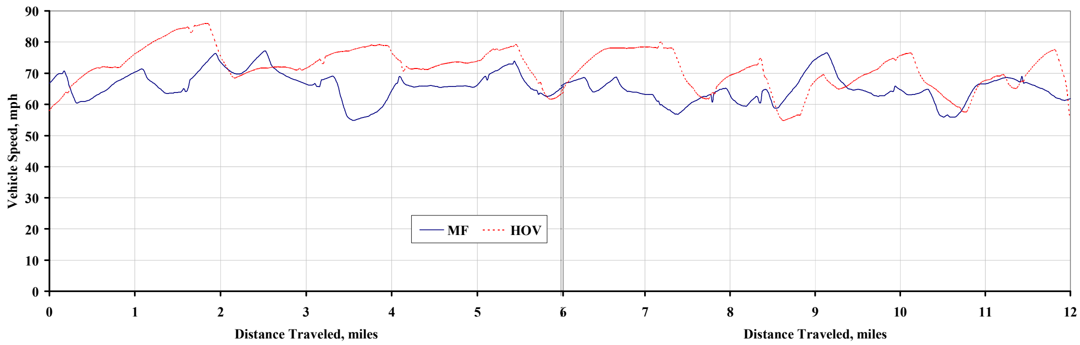
Due to the differences in characteristic between HOV lanes in Southern and Northern California, another set of the empirical analysis was performed for Northern California-style HOV lanes. Additional vehicle activity data was collected on the I-880 N freeway section between SR-262 interchange and SR-61 interchange, as shown in Figure 3.15. On this freeway, the innermost lane next to the median is designated as an HOV lane. Only vehicles that have two or more passengers can use the lane during actuation periods, which are from 5 a.m. to 9 a.m. in the morning and from 3 p.m. to 7 p.m. in the afternoon. During other periods, the lane is used as an MF lane. Driving trajectory data was collected in the HOV lane and the adjacent MF lane during HOV actuation and non-actuation periods. The data collection was performed both in the morning and in the afternoon of 2/9/2006. The collected driving data was processed into a database, and the driving trajectories in the HOV lane and the adjacent MF lane were compared (Figure 3.16). The SAFD of each driving was plotted (Figure 3.17). Some statistics of the driving trajectory are given in Table 3.6.

According to Figure 3.16, the speed trajectories of driving in the HOV lane and the adjacent MF lane during off-peak (non HOV-actuation) periods look similar to each other for both AM and PM. They fluctuated between 55 mph and 85 mph throughout the section. The statistics in Table 3.6 suggest that the average speed in the HOV lane is approximately 5 mph higher. During peak

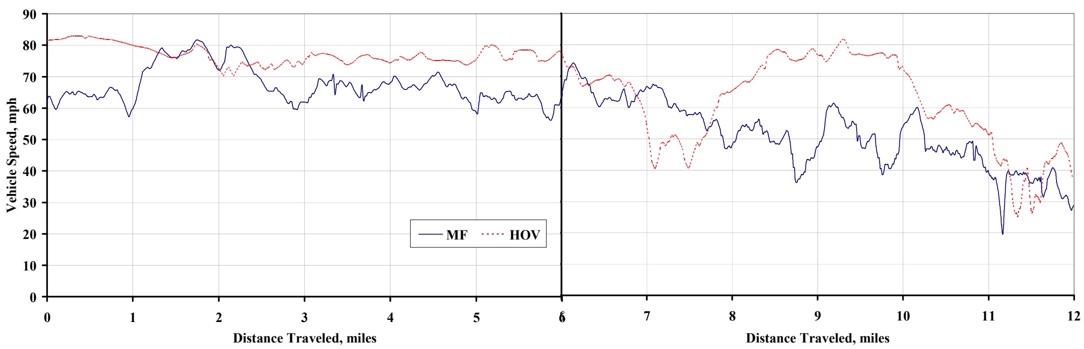
(HOV-actuation) periods, driving in both lanes experienced some degree of congestion in the second half of the freeway section, as noticed by speed drops and more frequent acceleration/deceleration events. As a result, the average speeds in both lanes dropped below the ones during the off-peak. The drops were more pronounced for the PM peak. Between the two lane types, the drop was larger for the MF lane so that the difference in average speed between the two lanes became approximately 10 mph, greater than that during the off-peak.

The SAFDs in Figure 3.17 exhibit patterns relevant to the trajectories. The SAFDs of the non HOV-actuation periods are centralized around a speed range of 55-85 mph. The acceleration and deceleration are mostly mild as indicated by the values of the acceleration rate not greater than 1 mph/s and the values of the deceleration rates not less than -2 mph/s. On the other hand, during the HOV-actuation periods the SAFDs show the evidence of unstable flow as they are more spread out across a wide range of speed. The speed range is wider for the MF lane since it experienced relatively more congestion. More aggressive acceleration and deceleration are also observed, especially in the MF lane during the AM peak.

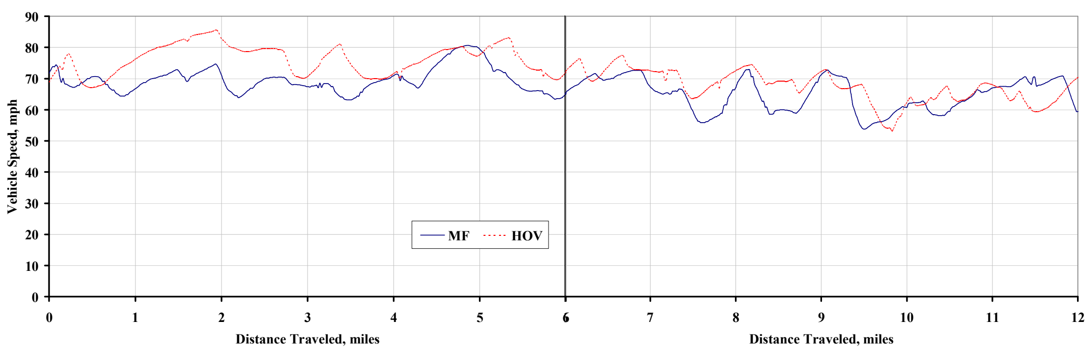
Figure 3.15. Sites of probe vehicle runs in Northern California.



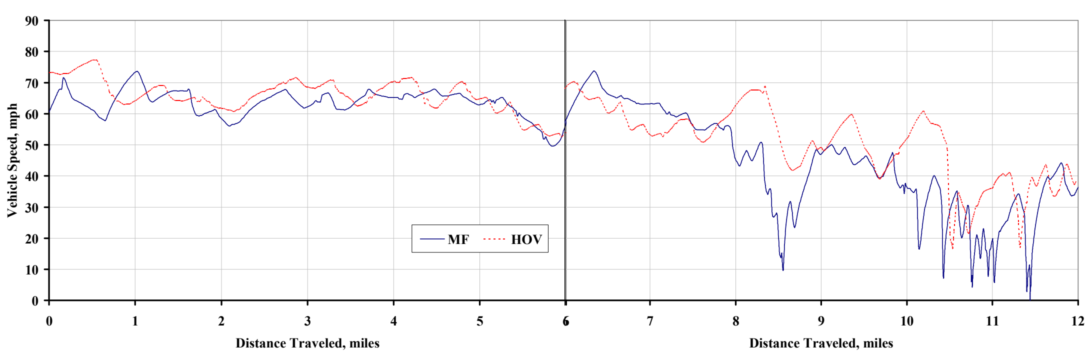
(a) AM non HOV-actuation period (9:30 – 10:30 a.m.)



(b) AM HOV-actuation period (8 – 9 a.m.)



(c) PM non HOV-actuation period (1:30 – 2:30 p.m.)



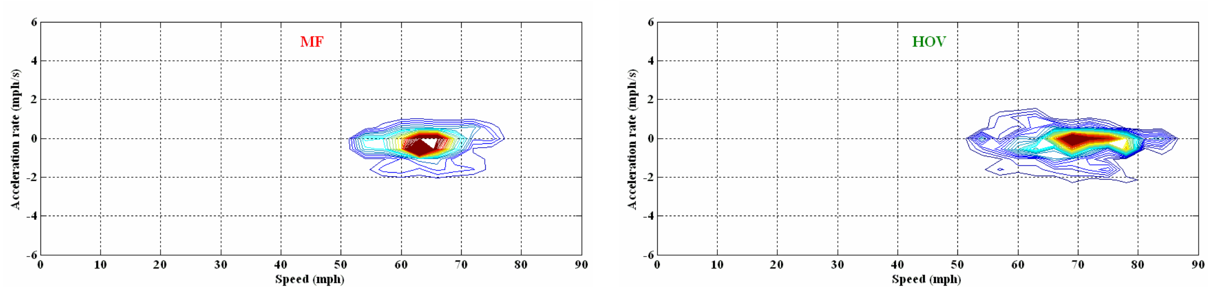
(d) PM HOV-actuation period (4 – 5 p.m.)

Figure 3.16. Speed trajectories of probe vehicle runs

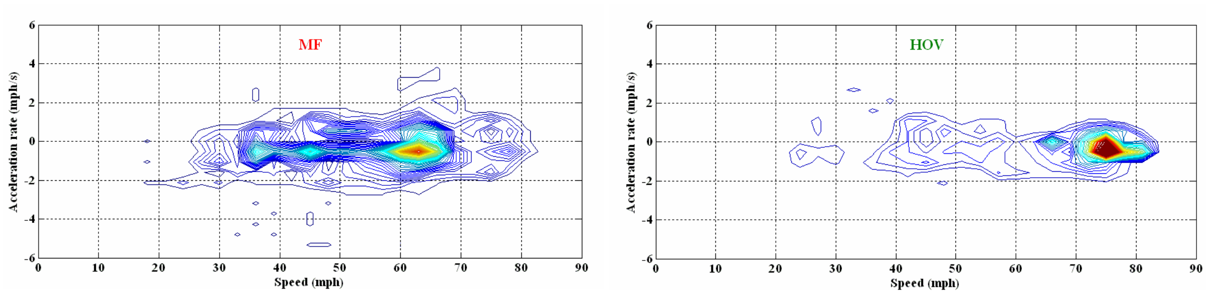
Table 3.6. Summary results of freeway performance, driving trajectory, and emissions estimates.

Period	AM off-peak		AM peak		PM off-peak		PM peak	
HOV actuation	No		Yes		No		Yes	
Time	9:30-10:30 a.m.		8-9 a.m.		1:30-2:30 a.m.		4-5 p.m.	
Lane type	MF	HOV	MF	HOV	MF	HOV	MF	HOV
Freeway data [a]								
VMT (mi/hr/ln)	11,576	9,136	18,605	8,708	16,683	15,347	21,925	14,471
Statistics of driving trajectory								
Travel time (sec)	664	609	768	658	648	608	979	774
Travel distance (mi)	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Avg. speed (mph)	65.2	71.0	54.7	63.4	66.8	71.2	44.2	55.9
Max speed (mph)	77.1	85.9	81.7	81.8	80.6	85.6	73.8	81.3
Max acc. rate (mph/s)	3.6	2.2	5.0	3.5	2.2	3.2	3.6	3.2
Emissions rate estimates (g/vehicle/mi) [b]								
CO	8.30	11.04	21.59	13.62	8.26	11.93	5.45	7.47
HC	0.33	0.40	0.50	0.45	0.33	0.41	0.30	0.33
NO_x	0.63	0.77	0.77	0.77	0.66	0.78	0.55	0.61
CO_2	367.42	411.06	329.52	353.35	335.31	375.97	329.31	362.21
Fuel	120.28	135.47	115.10	118.61	110.14	124.86	106.83	118.23
Emissions rate estimates (g/person/mi) [b]								
CO	6.38	8.50	19.63	5.24	6.88	9.94	4.95	3.56
HC	0.25	0.31	0.46	0.17	0.27	0.34	0.27	0.16
NO_x	0.48	0.59	0.70	0.30	0.55	0.65	0.50	0.29
CO_2	282.63	316.20	299.56	135.90	279.42	313.31	299.37	172.48
Fuel	92.52	104.21	104.64	45.62	91.78	104.05	97.12	56.30
Emissions mass estimates (metric tons/hr/ln) [b]								
CO	0.096	0.101	0.402	0.119	0.138	0.183	0.119	0.108
HC	0.004	0.004	0.009	0.004	0.005	0.006	0.007	0.005
NO_x	0.007	0.007	0.014	0.007	0.011	0.012	0.012	0.009
CO_2	4.253	3.755	6.131	3.077	5.594	5.770	7.220	5.242
Fuel	1.392	1.238	2.142	1.033	1.837	1.916	2.342	1.711

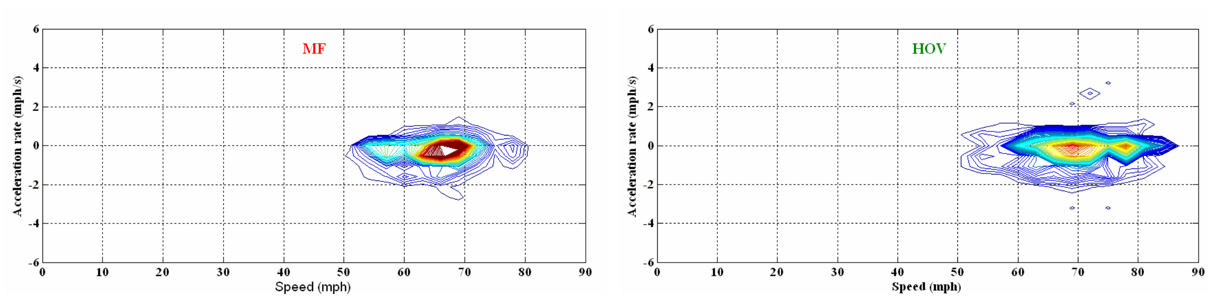
[a] **Data extracted from PeMS website (PeMS6.0, 2006)** [b] **Weighted to average fleet in Alameda County, 2006**



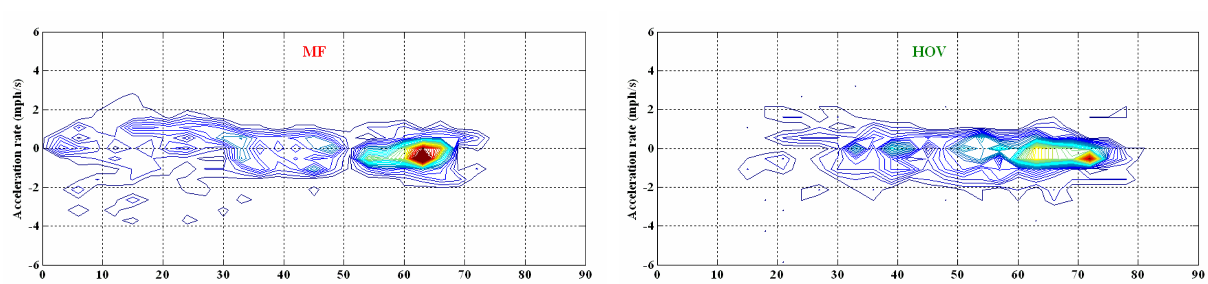
(a) AM non HOV-actuation period (9:30 – 10:30 a.m.)



(b) AM HOV-actuation period (8 – 9 a.m.)



(c) PM non HOV-actuation period (1:30 – 2:30 p.m.)



(d) PM HOV-actuation period (4 – 5 p.m.)

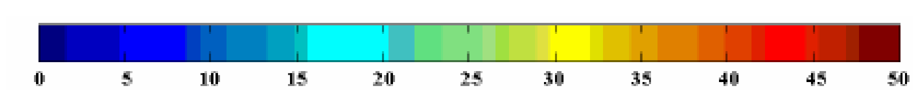


Figure 3.17. Joint speed-acceleration frequency distribution

Again, the HOV/MF driving data (second-by-second data of speed in mph) collected in the field were used as input to CMEM. The resulting second-by-second tailpipe emissions for all vehicle/technology categories were then weighted to the average fleet of Alameda County, California in February 2006. The proportion of each vehicle/technology category is listed in Table 3.6. The weighted emissions for every of the four cases were computed using the same vehicle fleet for a fair comparison. Next, the weighted emissions were aggregated over the entire driving trace and divided by the distance to result in the emission rates per vehicle per mile, as presented in Table 3.6. The percentage differences in emission rates between the two lane types were calculated and plotted in Figure 3.18. In the plot, negative values mean emissions and fuel consumption rates in HOV lanes are lower. The results are discussed below:

- ***Non HOV-actuation periods*****:** Comparatively, the average speed in the HOV lane is about 5 mph higher than in the MF lanes. A vehicle running at very high speeds (above 70 mph) in the HOV lane produces roughly 35% higher CO emission rate, 20% higher HC and NO_x emission rates, and 10% higher CO_2 emission rate and fuel consumption rate, as compared to running in the MF lanes. These trends are similar to Scenario 1 (under-utilized HOV lanes) in the analysis for Southern California HOV lanes.

- ***HOV-actuation periods*****:** The trends of emission rates during AM peak and PM peak are different. During the AM peak, the HOV lane has lower emission rates of CO and HC while having higher rates of CO_2 emission and fuel consumption. On the other hand, during the PM peak the emissions and fuel consumption rates are all higher in the HOV lane. This paradox may be due to the dissimilarity of speed-acceleration histogram of HOV and MF lanes during the two peak periods. As observed in Figure 3.19, although the speeds in the MF lanes during the AM peak rarely reach a low speed range of 0-30 mph, the acceleration/deceleration at medium to high speeds (30 mph and above) seems to be more aggressive than that of the PM peak. This gives rise to the emission rates of pollutants that are highly sensitive to power enrichment (i.e. CO and HC). Therefore, the emissions rates of these two pollutants for the MF lanes are high and even higher than those for the HOV lane.

After normalized by the average vehicle occupancy, the percentage difference in emission rates per person between the two lane types were computed and plotted in Figure 3.20. Note that the average vehicle occupancy across all lanes during non HOV-actuation periods is 1.3 for AM and 1.2 for PM. These values turn to 1.1 for MF lanes when the HOV lane is actuated. During that period, the average vehicle occupancy in the HOV lane is 2.6 for AM and 2.1 for PM [Caltrans, 2005a]. According to Figure 3.19, the trends are obvious that the HOV lane produces less emission rates per person during actuation period by at least 30% for CO and at least 40% for other pollutants. During non-actuation period when the HOV lane is used as another MF lane, it brings about 10-40% higher emission rates per person.

When considering the amount of traffic both lanes carry as presented in Figure 3.20, the total emission mass produced in the HOV lane during actuation period is less than that produced in MF lanes on a per lane basis for every pollutant. As shown in Figure 3.21, the differences are 50-70% for the AM peak and by 10-30% for the PM peak. Overall, the results for Northern California have provided evidence that the HOV lane analyzed helps reduce emissions when it is actuated.

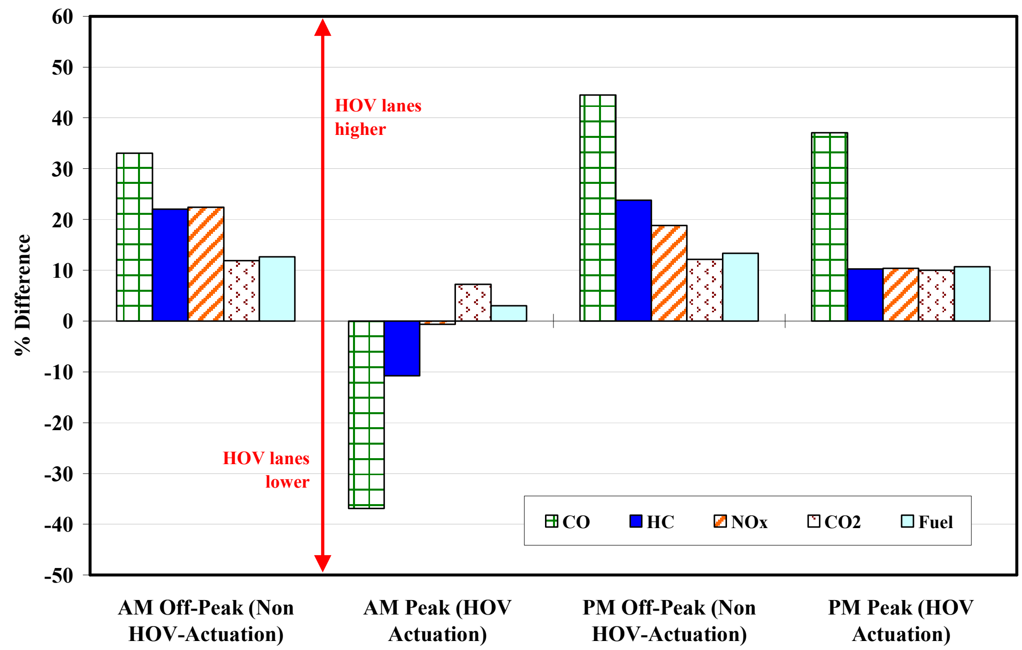


Figure 3.18. Differences in emission rates per vehicle between HOV and MF lanes

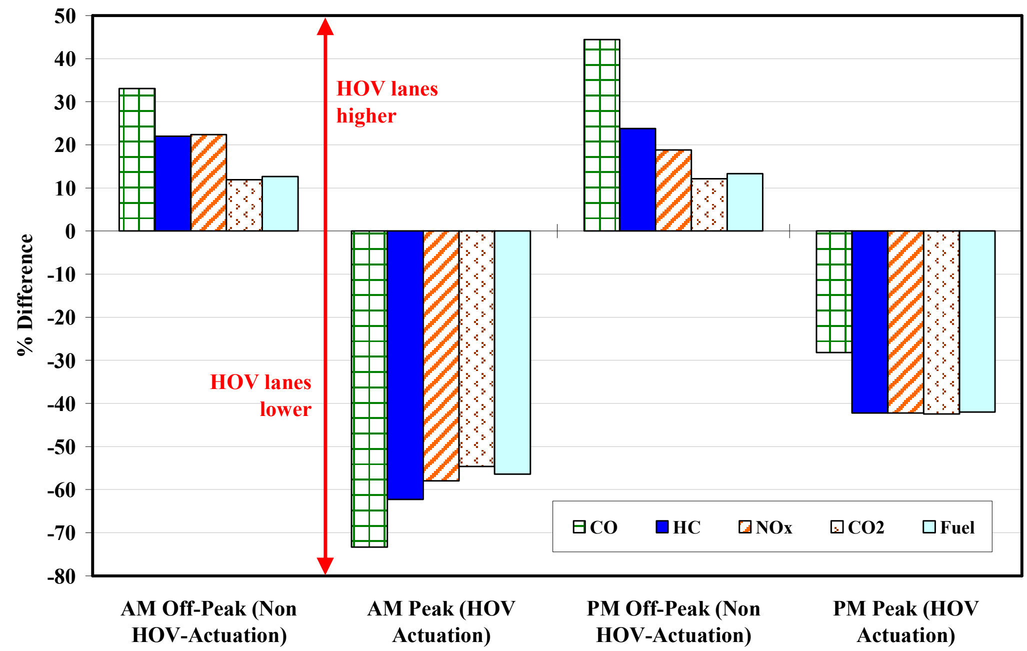


Figure 3.19. Differences in emission rates per person between HOV and MF lanes.

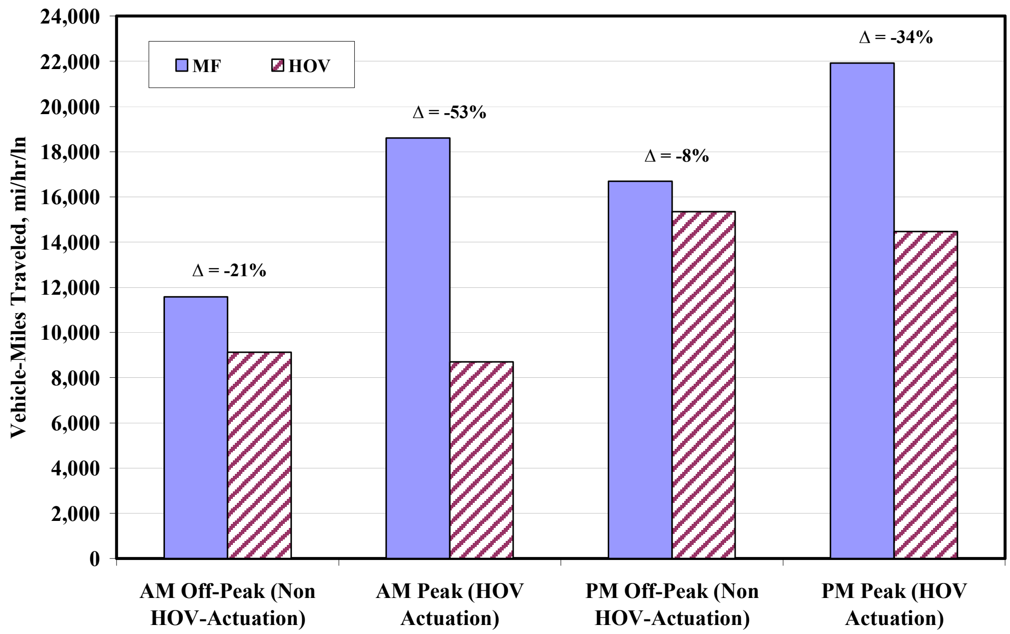


Figure 3.20. Vehicle-miles traveled per lane in both lane types.

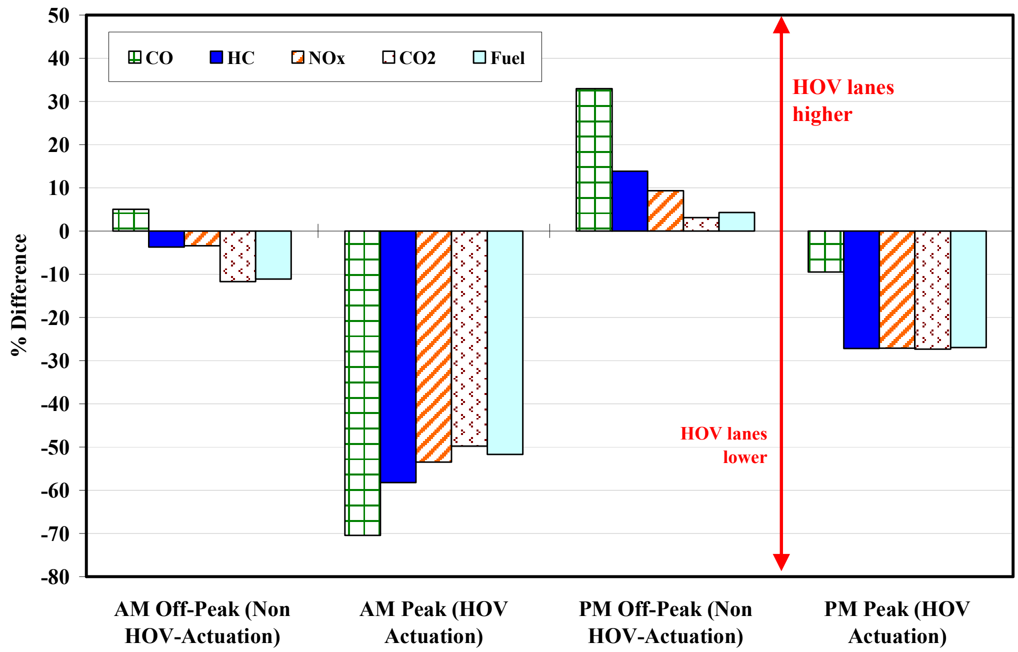


Figure 3.21. Differences in resulting emissions mass between HOV and MF lanes.

3.6. CHAPTER CONCLUDING REMARKS

In the empirical analyses, the differences in traffic dynamics between HOV lanes and adjacent MF lanes on selected freeway segments in both Southern and Northern California were compared, and their impacts on vehicle emissions were evaluated. Several findings are summarized below:

Southern California

- The differences in traffic dynamics between HOV lanes and MF lanes are more pronounced under congested freeway conditions. Drivers in MF lanes experience more aggressive acceleration and deceleration rates than drivers in HOV lanes.

- On congested freeways, HOV lanes provide generous amount of travel time saving of up to 2.75 minutes per mile to carpoolers. Vehicles traveling in HOV lanes produce 10-15% less HC and NO_x emission rates and about 35% less CO_2 emission and fuel consumption rates than those traveling in MF lanes due to a better flow of traffic in the lanes.

- On uncongested freeways, the travel time benefits provided by HOV lanes are negligible. When they are under-utilized, running at very high speeds in HOV lanes results in higher emission and fuel consumption rates, as compared to MF lanes. However, in such a case, VMT in the HOV lanes are much lower, and thus, the resulting emissions mass on a per lane basis is lower.

- Due to higher vehicle occupancy, HOV lanes produce much lower emission rates per the same amount of travel demand. The magnitude of differences ranges from 10% up to almost 70%. In almost every case, HOV lanes produce less emissions mass on a per lane basis than MF lanes.

Northern California

- During non HOV-actuation periods, running at very high speeds in the HOV lane results in higher emission and fuel consumption rates per vehicle. Because the average vehicle occupancy in the HOV lane is approximately the same as that in MF lane, it also has higher emission and fuel consumption rates per person. The differences are roughly 35% for CO, 20% for HC and NO_x, and 10% for CO_2 and fuel consumption.

- During HOV-actuation periods, the HOV lane produces less emission rates per person during actuation period by at least 30% for CO and at least 40% for other pollutants. It also produces less emission mass by 50-70% for the AM peak and by 10-30% for the PM peak. Overall, these results have provided evidence that the HOV lane analyzed helps reduce emissions when it is actuated.

It is imperative to note that the emission results presented in this chapter are only intended to serve as a good example of how the emissions in HOV and MF lanes could be different under generalized freeway operation scenarios. They are not intended to be a solid representative of actual emissions on freeways operating under each scenario. Although it can be anticipated that another set of driving in HOV and MF lanes will result in the same direction of emission differences, the magnitude of the differences will certainly be not the same. This will depend on the differential speed between HOV and MF driving as well as the frequency and magnitude of acceleration/deceleration events. Likewise, the probabilistic freeway performance matrix is only intended for use as a quick screening tool to compare lane performance of different freeways. The numerical results in the matrix are estimated as accurately as the quality of the input data permit under the stated assumptions.

4. Macroscopic Modeling Improvements

As part of this project, it was desired to develop HOV lane emission factors that could be used with existing regulatory emission inventory modeling tools. This chapter addresses the development of such factors. Section 4.1 describes the compilation of a lane-specific driving trajectory database followed by the statistical analysis of difference in driving trajectory between MF and HOV lanes. Section 4.2 describes the fleet composition data collection effort and the results from the comparison of the fleet compositions. Next, Section 4.3 presents differences in emission factors between the two lane types as a result of the differences in driving trajectory in the lanes. The derivation of lane-specific correction factors is then explained in Section 4.4. Finally, Section 4.5 summarizes the findings in this chapter and discusses the limitations of the developed HOV lane-specific correction factors.

4.1. DIFFERENCES IN DRIVING TRAJECTORY

4.1.1. Compiling a Lane-Specific Driving Trajectory Database

Within the limited scope of this study, it is not viable to conduct a large-scale driving data collection and emission testing program. Rather, a study was designed around the rationale that allows a small data set to be utilized effectively. Therefore, the driving data collection was performed by the same driver on the same vehicle across the entire driving program in order to control for these two variables. The driver was a young adult male and the vehicle used was a 2004 Honda Civic instrumented with GPS and data logger units.

The locations of driving are mostly on the same sections of SR-91, SR-60, and I-10 that were used for the evaluation in Chapter 3. Again, these sections were selected because they had a good coverage of vehicle detector stations that were in good condition. With a voice recorder and a stopwatch synchronized to the computer clock time, the driver recorded the time that the vehicle entered and exited an HOV lane. The time that lane changes were made from one MF lane to another adjacent MF lane and the lane number the vehicle moved into were also recorded. The driving trajectory data collected in the field were filtered into a database, followed by the calculations of second-by-second acceleration/deceleration rates. In addition, second-by-second specific power (SP) and road load power (RLP) were calculated using Equations 4.1 and 4.2, respectively. These two variables are known to be associated with emissions [Barth et al, 1999; Jiménez et al., 1999; Stoeckenius et al., 2000].

$$SP = \begin{cases} 2 \cdot v \cdot a & \text{for } a > 0 \\ 0 & \text{for } a \le 0 \end{cases} \qquad (4.1)$$

$$RLP = \begin{cases} 86.3 \cdot v + 0.0459 \cdot v^3 + 317 \cdot v \cdot a & \text{for } a > 0 \\ 86.3 \cdot v + 0.0459 \cdot v^3 & \text{for } a \le 0 \end{cases} \qquad (4.2)$$

where v denotes second-by-second speed (mph); a is second-by-second acceleration/deceleration rate (mph/s); SP is specific power (mph^2/s); and RLP is road load power (watts).

Driving in different traffic conditions can undergo various levels of speed and acceleration/deceleration and result in different levels of emissions. Therefore, driving trajectory for each lane type was grouped into 6 LOS from A-F. In the driving data collection program conducted in early 1990s' by the U.S. EPA, the designation of LOS to driving data was performed visually by a driver and/or an observer. This method has been criticized for a large degree of human errors or unconscious biases [Niemeier et al., 1999]. With the availability of a large-scale loop detector data in the last decade, an extensive data collection program was conducted by Caltrans/CARB to collect chase car speed data in Los Angeles [Choe et al., 2002]. The average density of freeway segments per 15 minutes was computed and used to determine LOS according to the definition in Highway Capacity Manual [TRB, 2000]. This method helps eliminate human biases, and upon the verification of the condition of loop detectors, can provide more reliable LOS data.

Nevertheless, Ko et al. [2006] recently showed that traffic dynamics can vary greatly within the 15-minute time interval and the size of time interval has a significant impact on the LOS determination. Using Atlanta data, they showed that about 25% of 15-minute data that are designated LOS A are designated as LOS B when using 1-minute time interval. Figure 4.1 illustrates the same issue using the data collected in this study. The LOS shown in the figure was designated at 30-second interval, which is the most disaggregated loop data available from PeMS. In the figure, the yellow band represents a 15-minute interval. It is obvious that the speeds of the instrumented vehicle fluctuate dramatically from 0 mph to above 60 mph. Using 15-minute LOS designation, it would have been assigned a single LOS. In contrast, the LOS designation for every 30 seconds gives a better correlation between speed levels and LOS.

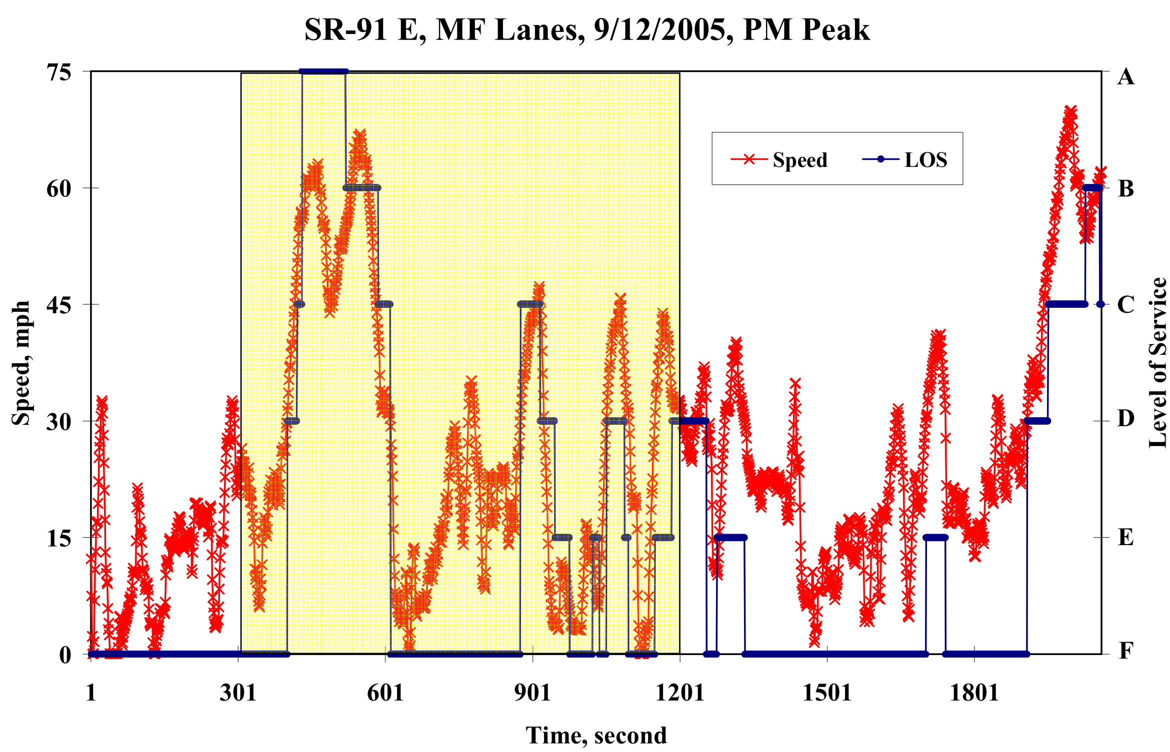


Figure 4.1. Speed profile and associated LOS.

Figure 4.2 illustrates the relationship between spatial and temporal resolution of the LOS designation used in this study. Typically, vehicle detector stations (VDS) are located around 0.6-1.0 miles apart from each other. The spatial coverage of each VDS is between the mid distance between itself and the VDS to its left and the mid distance between itself and the VDS to its right. A vehicle running in lane *l* within the coverage of VDS *i* at time *t* is considered to experience the LOS reported by the loop detector in lane *l* at VDS *i* during period *p*. Note that the lane information was simultaneously collected by the driver when the probe vehicle runs were taken place.

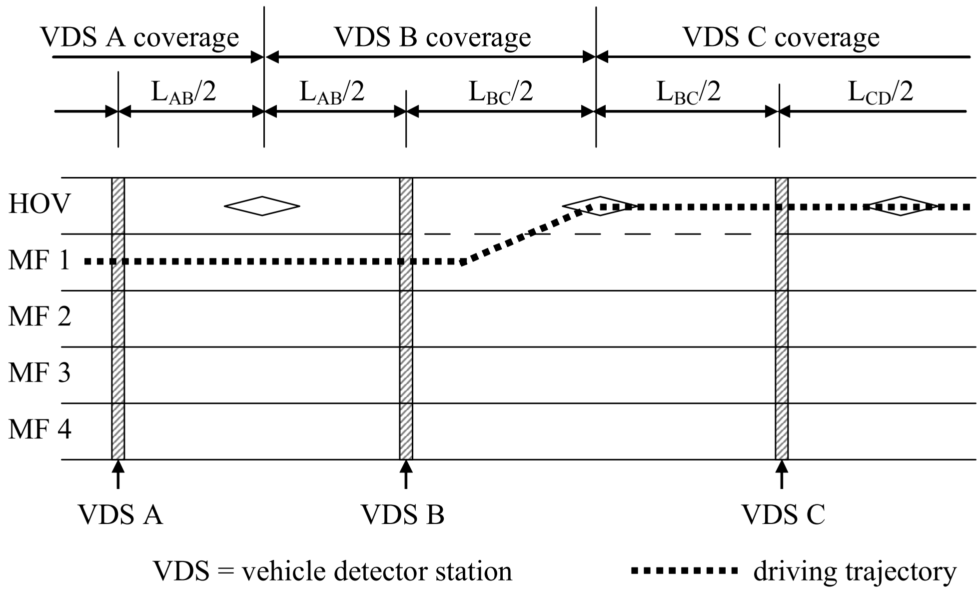


Figure 4.2. Spatial and temporal mapping of PeMS LOS to driving trajectory

LOS for each loop detector at each VDS is updated every 30 seconds. Therefore, for every 30-second period the second-by-second driving trajectory were spatially mapped with the corresponding VDS. The LOS of the lane the driving trajectory is in was then assigned to each second of driving data. This process started at the beginning of the driving trace and was repeated until the end of the driving trace was reached. Again, to assure the quality of the LOS data, only data from loop detectors in good condition were assigned. Portions of driving trace (or “snippets”) that are in coverage of unreliable loop detectors are discarded and excluded from the database.

The final database consists of 12 data tables (2 lane types x 6 LOS). The total number of data records is 28,493. This is equivalent to almost 8 hour worth of driving for a total distance of 371 miles. Table 4.1 summarizes basic statistics of driving trajectory for each data group. The SAFD plots and other statistics of each group are provided in Appendix B. Several trends can be observed from Table 4.1. For example, the average speeds of both lane types are comparable for every LOS except LOS F. The magnitude of the average and maximum acceleration values consistently increases as traffic conditions worsen from LOS A to LOS B to LOS C… to LOS F. This is also true for the magnitude of the average and minimum deceleration values. Between the two lane types, HOV lanes often have higher magnitude of the average acceleration and average deceleration.

Table 4.1. Descriptive statistics of collected lane-specific driving trajectory

Lane Type	Total Time (sec)	Total Dist. (mi)	Avg Speed (mph)	Max Speed (mph)	Avg Acc. (mph/s)	Max Acc. (mph/s)	Avg Dec. (mph/s)	Min Dec. (mph/s)	Avg Non-zero SP (mph^2/s)	Avg RLP (kW)
LOS A										
MF	1,721	36.1	75.6	85.6	0.4	2.2	-0.4	-2.1	54.0	30.9
HOV	2,495	51.9	74.9	87.5	0.4	2.0	-0.6	-3.7	64.9	31.3
LOS B										
MF	1,892	37.2	70.9	86.2	0.4	3.6	-0.5	-4.1	61.1	27.9
HOV	2,002	38.1	68.5	84.8	0.5	2.9	-0.6	-4.1	65.8	26.8
LOS C										
MF	2,414	45.1	67.2	81.0	0.5	2.1	-0.6	-7.2	65.4	25.2
HOV	1,719	31.2	65.3	84.4	0.5	2.9	-0.7	-8.6	67.4	24.8
LOS D										
MF	1,770	27.4	55.8	83.0	0.7	2.8	-0.8	-8.0	71.6	20.6
HOV	1,841	25.1	49.2	82.2	0.8	3.8	-1.1	-9.7	74.4	17.6
LOS E										
MF	1,104	11.2	36.4	79.1	0.9	4.6	-0.8	-9.1	56.2	11.8
HOV	1,568	17.0	39.0	73.1	1.0	5.5	-0.9	-5.5	74.7	13.5
LOS F										
MF	6,195	25.4	14.8	60.8	1.2	7.2	-1.0	-9.3	37.5	4.2
HOV	3,772	25.4	24.2	61.1	1.2	7.4	-1.2	-13.2	56.4	2.9

4.1.2. Data Analysis

Aside from the subjective comparison of observed trends of the descriptive statistics discussed above, the differences in driving trajectory between MF and HOV lanes can be objectively determined by comparing their SAFDs for each LOS. Traditionally, a “DiffSum” statistic has been used to measure the difference between a pair of SAFDs. It is the sum of the absolute value of the differences between the frequencies (in percent) in each cell of the SAFDs. Two identical SAFDs will have a DiffSum statistic equal to zero. One of the drawbacks of this statistic is that it provides no means of making a statistical inference. In other words, an analyst cannot draw a conclusion whether two SAFDs are statistically different or not.

An alternative way of comparing driving trajectory is to treat speed and acceleration of the two data sets as univariate data and compare them separately. For either speed or acceleration, if the probability density functions of MF and HOV lanes are significantly different, then their SAFDs are also significantly different. If that is not the case, then more sophisticated multivariate analysis techniques (e.g. Cramer test) can be employed to test differences between joint probability density functions based on skewness and curtosis [Baringhaus & Franz, 2004]. However, it should be noted that multivariate analyses can be very computational intensive.

The comparison of probability density function of two univariate data sets can be performed using a two-sample Kolmogorov-Smirnov (KS) test [Conover, 1971]. It is a nonparametric test for any differences in probability distribution between two data samples. It tests against a null hypothesis that the probability distributions of the two samples do not differ. In this test, the maximum difference in the cumulative distributions of the two samples (referred to as "KS test statistic") is compared to a KS test value, which is based on the sample size and the alpha level. If the KS test statistic is smaller than the KS test value, then the null hypothesis is accepted. The two-sample KS test is one of the most useful and general nonparametric methods for comparing two samples, as it is sensitive to differences in both location and shape of the cumulative distribution functions of the two samples, as depicted in Figure 4.3. Both location (central tendency) and shape (dispersion) differences in probability distribution of either speed or acceleration/deceleration between MF and HOV lanes can be detected using this test.

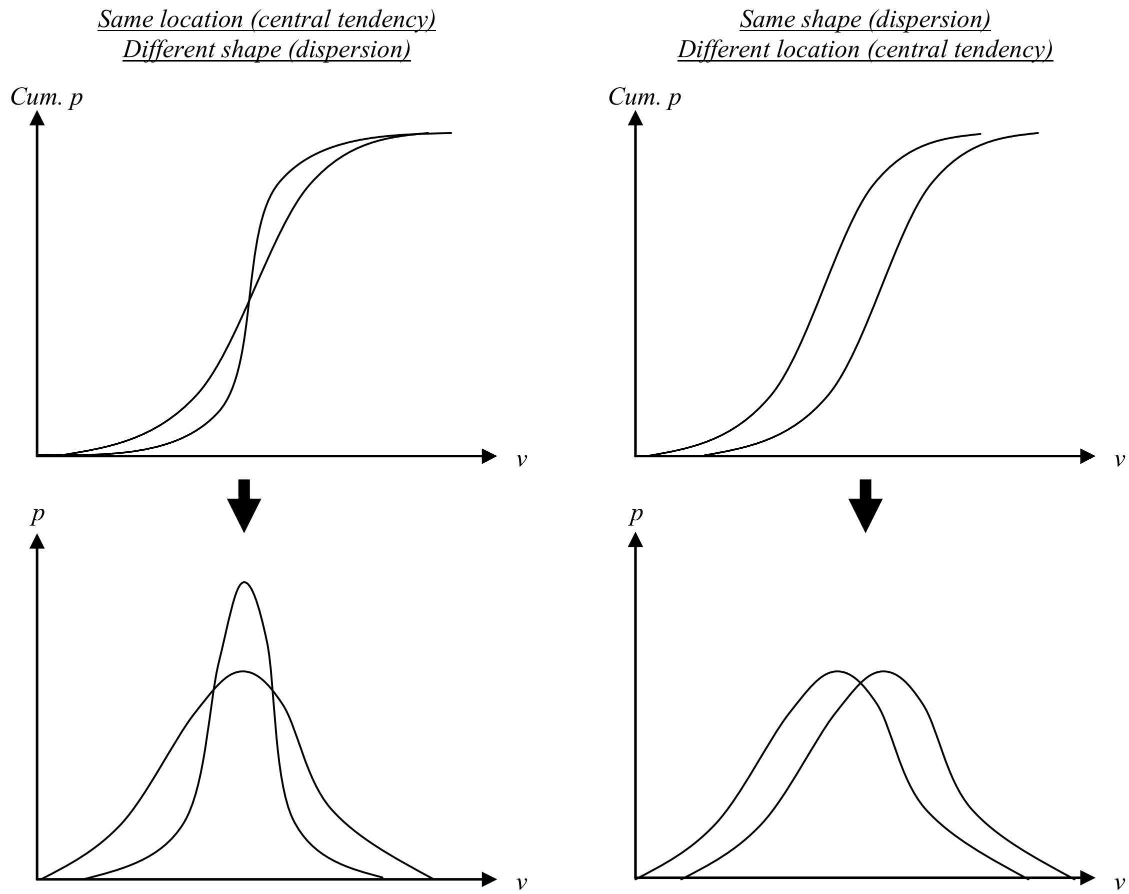


Figure 4.3. Differences in cumulative frequency distribution of two samples.

Table 4.2 summarizes the KS test results of speed and acceleration in MF and HOV lanes. It is found that for every LOS, the probability distribution of speed in MF lanes is significantly different from that in HOV lanes at 5% alpha level. This is also true for acceleration. Therefore, their SAFDs are also significantly different. These results imply that at the same LOS of freeway operation the traffic dynamics in MF and HOV lanes are statistically not the same. To determine the impact of such implication on vehicle emissions, the same analysis method was applied to the road load power variable. The results shown in Table 4.2 affirm that the differences in traffic dynamics between MF and HOV lanes also cause the required road load power of the vehicle, and possibly emissions, to be significantly different.

Table 4.2. Summary of Kolmogorov-Smirnov test results for differences in driving trajectory.

H0: Driving trajectories in HOV and MF lanes have the same distribution

Freeway	KS Test Value*	KS Test Statistic	*p*-value	Conclusion
Speed				
LOS A	0.043	0.111	<0.001	Reject H0
LOS B	0.044	0.138	<0.001	Reject H0
LOS C	0.043	0.188	<0.001	Reject H0
LOS D	0.045	0.286	<0.001	Reject H0
LOS E	0.053	0.236	<0.001	Reject H0
LOS F	0.028	0.350	<0.001	Reject H0
Acceleration				
LOS A	0.043	0.088	<0.001	Reject H0
LOS B	0.044	0.054	0.007	Reject H0
LOS C	0.043	0.050	0.013	Reject H0
LOS D	0.045	0.083	<0.001	Reject H0
LOS E	0.053	0.117	<0.001	Reject H0
LOS F	0.028	0.054	<0.001	Reject H0
Road Load Power				
LOS A	0.043	0.070	<0.001	Reject H0
LOS B	0.044	0.072	<0.001	Reject H0
LOS C	0.043	0.098	<0.001	Reject H0
LOS D	0.045	0.188	<0.001	Reject H0
LOS E	0.053	0.158	<0.001	Reject H0
LOS F	0.028	0.262	<0.001	Reject H0

*** At 5% alpha level**

4.2. DIFFERENCES IN FLEET COMPOSITION

Another important aspect of on-road mobile emissions modeling is fleet composition. Since HOV lanes limit their accessibility to only those vehicles meeting the occupancy requirement, it is unclear whether this will make the vehicle fleet mixes in the lanes be different from those running in MF lanes. Therefore, fleet composition data were collected for both MF and HOV lanes by videotaping traffic in both lane types. The data collection was performed on three freeways in Southern California, which are: 1) I-10W in Los Angeles County, 2) SR-60E in San Bernardino County, and 3) SR-91E in Riverside County. These locations of video shooting correspond to the freeway segments on which driving trajectory data were collected.

More than 3,000 license plate numbers were extracted from videos. Next, these were matched with a partial Department of Motor Vehicles (DMV) vehicle information table as of December 2005. The table contains information regarding vehicle license plate number, vehicle identification number, vehicle model year, DMV registration expiration date, zip code, and California county code. The matching provided the records of 2,656 vehicles (about 80%) that was used for subsequent analyses.

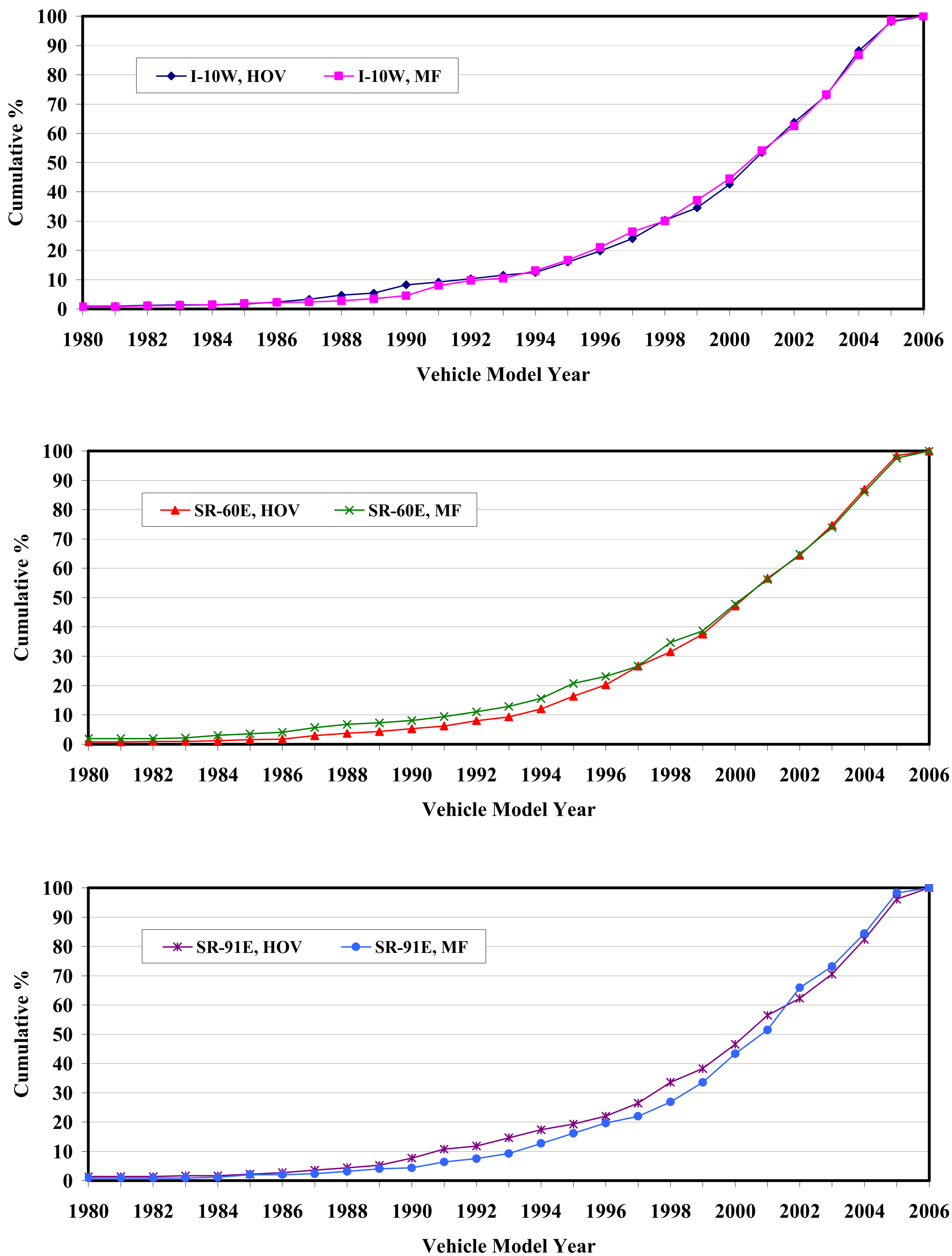


Figure 4.4. Cumulative frequency distribution of vehicle model year by freeways.

Figure 4.4 shows the cumulative distributions of vehicle model year in MF and HOV lanes for each of the three freeways. Since vehicle model year is known to be correlated to vehicle emissions, one of the analyses is to compare between each pair of these distributions. The comparison was made using the two-sample KS test. The summary of KS test results is given in Table 4.3. It is found that there is no significant difference between the distributions of vehicle model year in HOV and MF lane at 5% alpha level on all three freeways.

Table 4.3. Summary of Kolmogorov-Smirnov test results for differences in vehicle model year.

H0: Model years of vehicles in HOV and MF lanes have the same distribution

Freeway	KS Test Value*	KS Test Statistic	*p*-value	Conclusion
I-10W	0.085	0.037	0.881	Accept H0
SR-60E	0.093	0.044	0.807	Accept H0
SR-91E	0.102	0.067	0.399	Accept H0

*** At 5% alpha level**

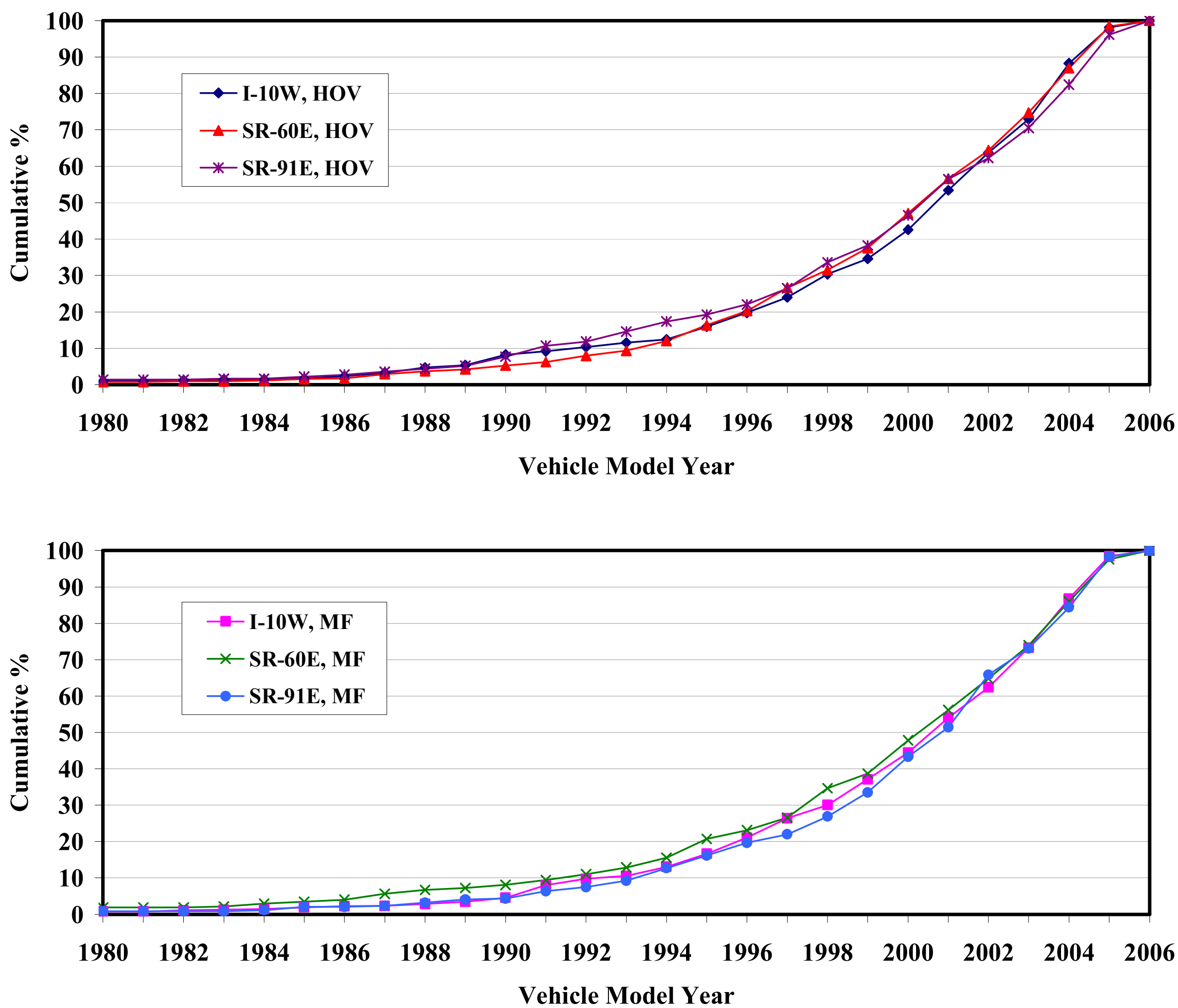


Figure 4.5. Cumulative frequency distribution of vehicle model year by lane type.

Another dimension of the analyses was to compare the distributions of vehicle model year of the same lane types on different freeways, as shown in Figure 4.5. Again, this was done using the two-sample KS test. However, for each lane type the test was repeated three times where each time was the comparison between a pair of freeways, as listed in Table 4.4. According to the test results, it is found that there is no significant difference among the distributions of vehicle model year on the three freeways at 5% alpha level for both lane types.

Table 4.4. Summary of Kolmogorov-Smirnov test results for fleet differences among freeways.

H0: Model years of vehicles on two freeways have the same distribution

Lane	Comparison	KS Test Value*	KS Test Statistic	*p*-value	Conclusion
HOV	10W vs. 60E	0.089	0.045	0.735	Accept H0
	10W vs. 91E	0.097	0.059	0.511	Accept H0
	60E vs. 91E	0.093	0.053	0.590	Accept H0
MF	10W vs. 60E	0.089	0.046	0.692	Accept H0
	10W vs. 91E	0.091	0.044	0.767	Accept H0
	60E vs. 91E	0.102	0.078	0.226	Accept H0

*** At 5% alpha level**

4.3. DIFFERENCES IN EMISSIONS

The results from the previous sections indicate that emissions in MF and HOV lanes are likely to differ as a result of different characteristics of driving trajectory. In this section, this presumption is verified by comparing emissions estimates between the two lane types at each LOS using the same fleet composition. Each of the twelve data sets in the driving trajectory database was used to calculate average emission rates of CO, HC, NO_x, and CO_2. For each data set, the driving data were broken into snippets at points of discontinuity, which refer to those data points of which the adjacent data point is not from the same consecutive driving trace. Then, each snippet was run through CMEM individually to obtain emission estimates. This is to prevent dubious results that may occur at the first and the last seconds of the snippets. Finally, emissions from every snippet were aggregated and divided by the total distance to obtain average emission rates in g/mi for the data set. These emission rates are summarized in Table 4.5 for the statewide fleet in 2005 and 2010.

As expected, the average emission rates in both lane types differ. The differences can be as high as greater than 20% for CO_2 of LOS F and CO of LOS D. The emission rates of HOV lanes at LOS A are higher than those of MF lanes for almost every pollutant. On the other hands, the emission rates of HOV lanes are lower at LOS B and LOS D. For LOS C, E, and F the trends are not consistent. When looking at the differences by pollutant, it is observed that HOV lanes produce less HC emission rates than MF lanes for almost every LOS except LOS A. For other pollutants, HOV lanes could produce either higher or lower emission rates as compared to MF lanes.

The results presented in this section verify that the statistically significant differences in driving trajectory between HOV and MF lanes also cause the corresponding emission rates to be different; thus warranting the development of lane-specific emission correction factors for HOV lanes.

Table 4.5. CMEM-estimated emission rates at different LOS.

LOS	Lane	Statewide - 2005				Statewide - 2010			
		CO	HC	NO_x	CO_2	CO	HC	NO_x	CO_2
A	MF	13.52	0.496	1.161	424.7	8.89	0.313	1.124	427.9
	HOV	14.62	0.526	1.197	424.3	9.60	0.331	1.166	428.7
	%Diff (HOV-MF)	*8.1*	*6.1*	*3.1*	*-0.1*	*8.0*	*5.7*	*3.7*	*0.2*
B	MF	11.67	0.470	1.100	408.5	7.74	0.295	1.067	411.7
	HOV	10.33	0.446	1.058	398.4	6.72	0.279	1.027	401.7
	%Diff (HOV-MF)	*-11.5*	*-5.2*	*-3.8*	*-2.5*	*-13.2*	*-5.4*	*-3.8*	*-2.4*
C	MF	8.86	0.440	0.987	382.6	5.73	0.272	0.955	384.8
	HOV	9.48	0.438	1.011	385.2	6.23	0.272	0.981	388.2
	%Diff (HOV-MF)	*7.0*	*-0.5*	*2.4*	*0.7*	*8.9*	*-0.1*	*2.8*	*0.9*
D	MF	9.34	0.428	1.003	390.2	6.16	0.265	0.975	393.0
	HOV	7.38	0.409	0.948	383.7	4.75	0.251	0.918	386.3
	%Diff (HOV-MF)	*-21.0*	*-4.5*	*-5.5*	*-1.7*	*-22.9*	*-5.5*	*-5.8*	*-1.7*
E	MF	6.83	0.382	0.832	396.5	4.70	0.233	0.800	396.1
	HOV	7.13	0.380	0.926	396.9	4.69	0.233	0.897	399.2
	%Diff (HOV-MF)	*4.4*	*-0.6*	*11.3*	*0.1*	*-0.2*	*-0.2*	*12.2*	*0.8*
F	MF	4.57	0.437	0.920	596.9	2.85	0.260	0.861	590.3
	HOV	5.08	0.401	0.877	458.7	3.33	0.240	0.837	456.8
	%Diff (HOV-MF)	*11.1*	*-8.3*	*-4.7*	*-23.2*	*16.8*	*-7.7*	*-2.8*	*-22.6*

4.4. IMPROVEMENTS TO CURRENT MODELING PRACTICE

4.4.1. Development of HOV Lane Emission Correction Factors

Based on the results from the previous section, HOV and MF emission rates were plotted as relative to the average speeds associated with each LOS. These average speeds range from 15 mph to 76 mph, as shown in Table 4.1. These scattered plots were made for each pollutant and for both fleet years 2005 and 2010. They are shown in Figure 4.6. Next, a parabolic curve in the form of Equation 4.3 was fitted to each data set.

$$\hat{y}_p = b_0 + b_1 \cdot x + b_2 \cdot x^2 \tag{4.3}$$

where x is average vehicle speed (mph) and $\hat{y}_p$ is emission rate (g/mi), p = {CO, HC, NO_x, CO_2}.

These curves represent speed correction factors for each lane type. The goodness of fit of these curves is considered very strong as the coefficients of determination (R^2) of the equations are in the range of 0.88-0.98. The R^2 values are listed in Table 4.6 along with the constant and coefficients of emission curve equations. The constant and coefficient numbers are stored in the equations with 15 significant digits, which is the maximum number of non-zero significant digits that can be obtained from the curve fitting program used. The purpose of keeping all possible significant digits is to maintain the accuracy of the estimated results from the equations.

Table 4.6. Constant and coefficients of emission curve equations.

p	Lane	b_0	b_1	b_2	R^2
Statewide – 2005					
CO	MF	4.483398996075810	0.000055868561931	0.001399691714071	0.90
	HOV	8.152955916710440	- 0.187563303847343	0.003421679780374	0.90
HC	MF	0.505496477288882	- 0.005931276194861	0.000076412771805	0.94
	HOV	0.532627329472315	- 0.007723214453976	0.000098602622539	0.91
NO_x	MF	1.033852744988600	- 0.010529743376577	0.000159489843143	0.88
	HOV	1.014935832417830	- 0.008339815172632	0.000136389809613	0.92
CO_2	MF	787.837148205538000	- 15.362105535782700	0.140532181012751	0.97
	HOV	650.421435639033000	- 10.200996574674700	0.095340363227005	0.98
Statewide - 2010					
CO	MF	2.575702634118130	0.020618084276449	0.000702739922007	0.88
	HOV	5.494581631578320	- 0.130478785981940	0.002317758111271	0.90
HC	MF	0.298933771972414	- 0.003387080269913	0.000046747198310	0.94
	HOV	0.316959550466704	- 0.004552504597235	0.000061036536935	0.92
NO_x	MF	0.946406150580489	- 0.008283494181702	0.000138528781527	0.89
	HOV	0.950856358694003	- 0.007015432547735	0.000124343172345	0.91
CO_2	MF	775.353124189360000	- 14.914029698869400	0.137303010079975	0.97
	HOV	641.592205809846000	- 9.833435125135460	0.092645928975824	0.98

It is noticed in Figure 4.6 that for each pollutant, the shapes of the emission curves for the statewide fleet of 2005 are very much similar to those for the statewide fleet of 2010. However, the magnitude of emissions is lower for the 2010 fleet as it is cleaner. For CO, the fitted curve for HOV lanes estimates lower emission rates than the curve for MF lanes between the average speeds of 30 mph and 65 mph. At both ends of the extreme speeds, the HOV emission rate curve estimates higher CO emission rates. The trend is similar for HC. The HOV emission rate curve for HC estimates lower HC emission rates between the average speeds of 25 mph and 60 mph. In contrast to CO and HC, the HOV emission rate curve for NO_x estimates consistently higher NO_x emission rates than the MF curve. The trend of the HOV emission rate curve for CO_2 is opposite to those for CO and HC. The range of speed of which CO_2 emission rates are higher in HOV lanes is between 40 and 70 mph. For CO_2, it is also noticed that at low speeds the emission rates for HOV lanes are significantly lower than those for MF lanes.

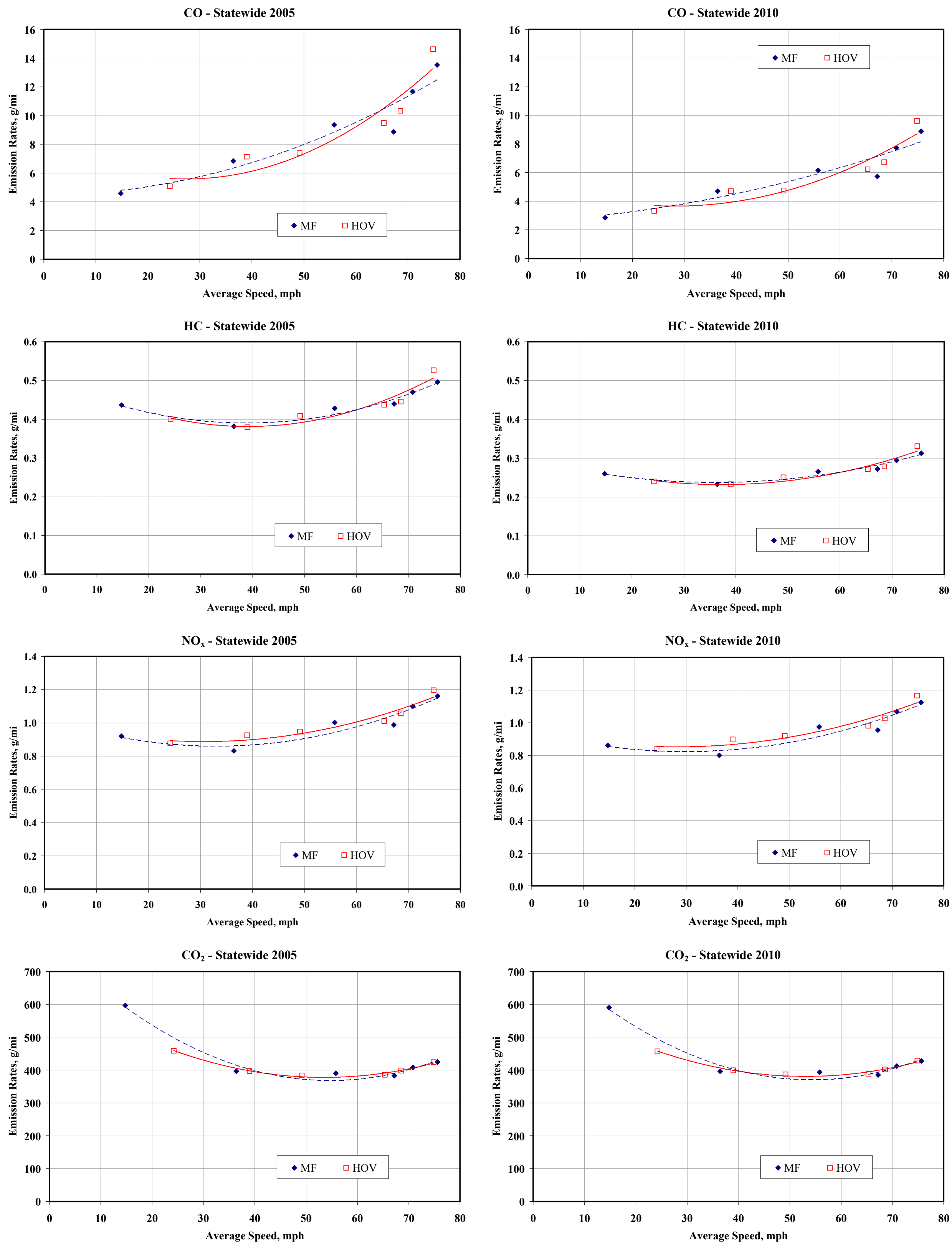


Figure 4.6. Emission rates of MF and HOV lanes at different average speeds.

Based on the curves presented in Figure 4.6 and the corresponding equations in Table 4.6, it is possible to compute the ratio of HOV emission rates to MF emission rates at different levels of average speed for each pollutant. These ratio values can be used as HOV lane emission correction factors by multiplying them to freeway emission rates to obtain emission rates specific for HOV lanes. Figure 4.7 plots the HOV lane emission correction factors for the average speeds from 15 mph to 75 mph. For each pollutant, the factors for both 2005 fleet and 2010 fleet are plotted. It is observed that the correction factors for both fleets are very similar to each other in terms of both direction and magnitude. The only minor difference is for CO.

In terms of the scale of impact, the correction factors have higher impacts on HOV emission rates of CO and CO_2 as compared to HC and NO_x. For CO and CO_2, the impact can be as much as 30% and 10%, respectively, at the lowest speed of 15 mph. For NO_x, the impact is relatively smaller. The difference between NO_x emission rates of HOV and MF lanes is in the order of less than 5%. For HC, the impact is small. HC emission rates for HOV lanes are different from those for MF lanes by merely ± 2%.

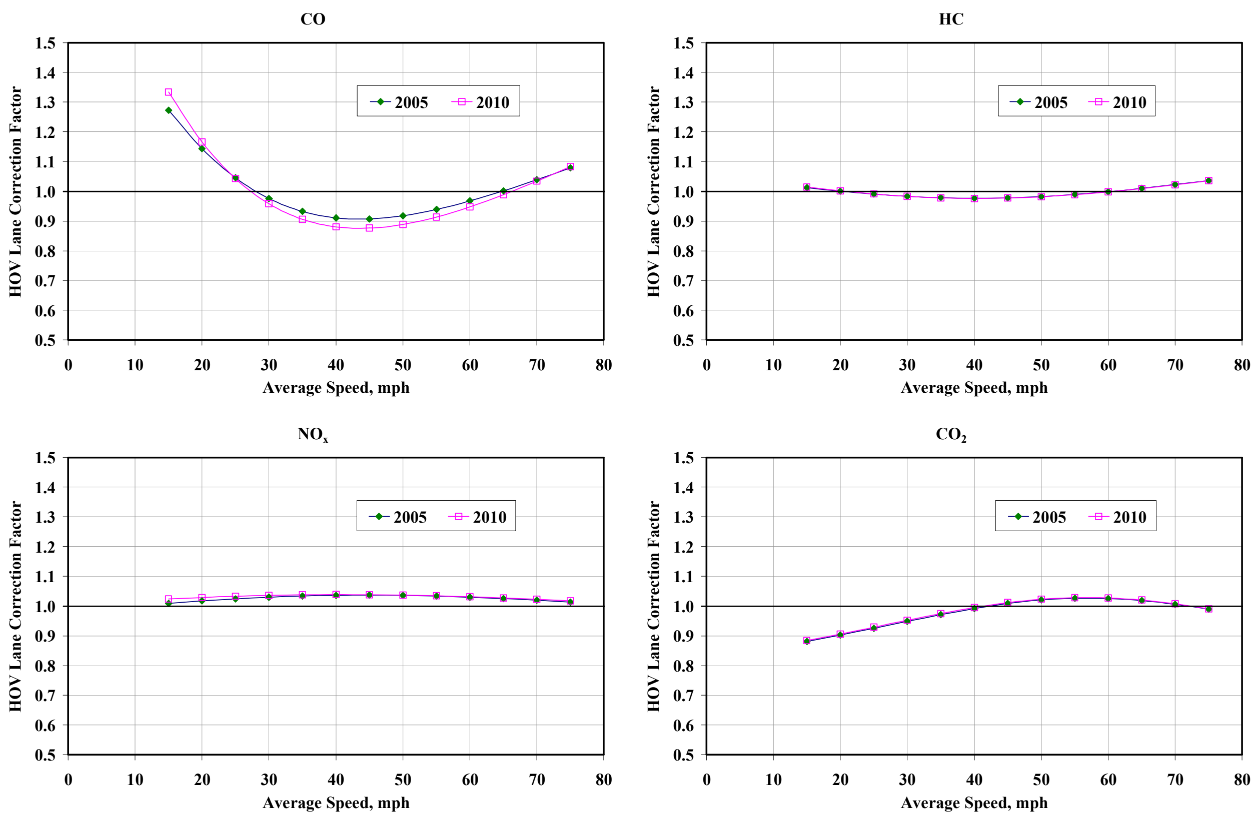


Figure 4.7. HOV lane emission correction factors

It should be noted that the curve fitting of emission rates conducted in this section was based on the emission rate data at average speeds from 15 mph to 76 mph. Therefore, the prediction power of the curve equations (Table 4.6) and thus the validity of the derived HOV lane emission correction factors (Figure 4.7), are limited to only the average speeds within this inference space. Nevertheless, considering a typical freeway operation, this speed range should well cover the majority of VMT occurred. In fact, the speed range of 15-75 mph accounts for more than 95% of total freeway VMT in a typical weekday for freeways in both Northern California (represented by Caltrans District 4) and Southern California (represented by Caltrans District 7). This is shown in Figure 4.8.

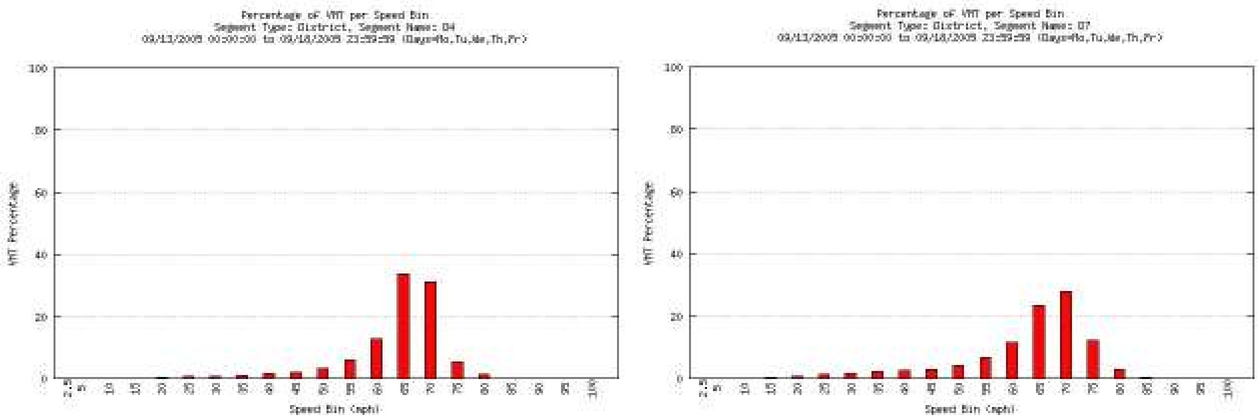


Figure 4.8. Examples of VMT-speed distribution for District 4 (left) and District 7 (right).

4.4.2. Example of Applying HOV Lane Emission Correction Factors

To demonstrate how the developed HOV lane emission correction factors can be applied to calculate emissions inventory of HOV lanes, a section of SR-91E in Riverside County is used as an example. This is essentially the same freeway section used in the HOV lane air quality evaluation in Chapter 3 and shown in Figure 3.2. This freeway section is about 12 mile long with 14 VDS in both MF and HOV lanes. The data regarding number of lanes, hourly average speed, and hourly VMT at each station in both MF and HOV lanes are listed in Table 4.7. These data are for September 13, 2005, which was the date the driving trajectory data was collected on this freeway. Note that the analysis period is for one hour of the PM peak. The steps below were followed in order:

1) For each average speed value, emission rates of CO, HC, NO_x, and CO_2 were estimated in EMFAC for the fleet of Riverside County in September 2005 at the temperature of 75 °F and relative humidity of 40%. These emission rates are given in Table 4.7.

2) Similarly, for each average speed value the HOV lane emission correction factors were calculated using equations in Table 4.6. Then, these correction factors were multiplied by the EMFAC-estimated emission rates to obtain the adjusted emission factors for the HOV lane shown in Table 4.7.

3) The EMFAC-estimated emission rates for the MF lanes and the adjusted emission factors for the HOV lane were multiplied by the corresponding VMT per lane at each station. The resulting emissions in tons per hour per lane are also shown in Table 4.7.

4) The emissions at each station were aggregated to obtain the total emissions per hour per lane produced on this freeway section for each lane type.

At this point the emissions contribution from the two lane types can be compared. It is found that the HOV lane produced 6% lower CO, 22% lower HC, 6% higher NO_x, and 11% lower CO_2 than the MF lanes did.

4.5. CHAPTER CONCLUDING REMARKS

Using data collected in this study, the differences in driving trajectory, fleet composition, and emissions between MF and HOV lanes were examined. Findings are summarized below:

- For every LOS, the probability distributions of both speed and acceleration/deceleration in MF lanes are significantly different from those in HOV lanes at 5% alpha level. This implies that their SAFDs are also significantly different. Such differences in traffic dynamics between MF and HOV lanes also cause the required power of the vehicle to be significantly different.

- Fleet compositions in HOV and MF lanes on the three freeways studied are not found to be significantly different at 5% alpha level in terms of vehicle model year distribution. However, modelers may consider using separate fleets for each lane type when modeling certain HOV lanes that carry a high percentage of buses.

- The estimated emission rates in MF and HOV lanes at each LOS are different where the differences can be as high as greater than 20%. This verifies that the differences in driving trajectory between the two lane types cause the corresponding emission results to be different.

- HOV lane emission correction factors were developed for the prevailing speed range of 15 to 75 mph. They show higher impacts on emission rates of CO and CO_2 as compared to HC and NO_x. These correction factors can be used to multiply freeway emission rates to obtain emission rates specific for HOV lanes.

It is recommended that the developed HOV lane emission correction factors be used when modeling the air quality benefits/impacts of HOV lanes. These factors allow modelers to adjust the emission rates for HOV lanes to properly reflect the acceleration/deceleration characteristics of HOV lane operation at different traffic conditions, thus resulting in more accurate emission results.

It should be noted that a limitation exists when modeling the air quality benefits/impacts of HOV lanes using emission factors from EMFAC. The mismatch between link-based VMT-speed distribution derived from travel demand model and trip-based emission factors obtained from EMFAC has been widely discussed [Nanzetta et al., 2000; Ito et al., 2001]. This issue will also affect the results of the HOV modeling. Although facility specific allocation factors were developed to allocate the calculated trip-based daily emissions to specific facilities including freeway, ramp, arterial, collector, local, and private that are composed of the trip [Sebate, 2005], these factors are not capable of deriving facility-specific emission factors. Until this issue is resolved in a new version of EMFAC, it is recommended that other emission models such as MOBILE6 or CMEM be used in the evaluation of air quality benefits/impacts of HOV lanes.

Table 4.7. Estimation of emissions inventory of the selected section of SR-91 E during PM peak

VDS Number	Station Name	Lane Type	No. of Lanes	Speed (mph)	VMT (mi)	VMT/ Lane	EMFAC EF (g/mi)				HOV Correction Factors				Adjusted EF (g/mi)				Emissions (tons/hr/ln)			
							CO	HC	NOx	CO2		HC	NOx	CO2	CO	HC	NOx	CO2	CO	HC	NOx	CO2
801415	2180' E/O CO LINE	MF	4	46	2,115	529	4.22	0.353	1.073	425.3	-	-	-	-	-	-	-	-	0.002	0.000	0.001	0.225
801422	GREEN RIVER	MF	4	31	2,698	675	5.01	0.467	1.028	476.7	-	-	-	-	-	-	-	-	0.003	0.000	0.001	0.322
801428	2400' W/O RTE 71	MF	4	16	2,946	737	7.14	0.923	1.263	720.9	-	-	-	-	-	-	-	-	0.005	0.001	0.001	0.531
801435	RTE 71	MF	4	16	3,036	759	7.14	0.923	1.263	720.9	-	-	-	-	-	-	-	-	0.005	0.001	0.001	0.547
801442	3500' W/O SERFAS CL	MF	4	38	2,490	623	4.52	0.390	1.018	436.8	-	-	-	-	-	-	-	-	0.003	0.000	0.001	0.272
801449	SERFAS CLUB	MF	4	20	2,884	721	6.37	0.739	1.166	624.7	-	-	-	-	-	-	-	-	0.005	0.001	0.001	0.450
801457	MAPLE	MF	4	13	2,004	501	7.86	1.111	1.358	816.4	-	-	-	-	-	-	-	-	0.004	0.001	0.001	0.409
801464	100' E/O SMITH	MF	4	14	2,728	682	7.60	1.042	1.324	781.9	-	-	-	-	-	-	-	-	0.005	0.001	0.001	0.533
801473	LINCOLN	MF	4	17	3,631	908	6.93	0.870	1.236	693.9	-	-	-	-	-	-	-	-	0.006	0.001	0.001	0.630
801485	MAIN	MF	4	17	2,756	689	6.93	0.870	1.236	693.9	-	-	-	-	-	-	-	-	0.005	0.001	0.001	0.478
801488	500'E/O EAST GRAND	MF	4	17	4,961	1,240	6.93	0.870	1.236	693.9	-	-	-	-	-	-	-	-	0.009	0.001	0.002	0.861
806674	MCKINLEY LOOP ON	MF	3	18	4,745	1,582	6.73	0.823	1.210	669.0	-	-	-	-	-	-	-	-	0.011	0.001	0.002	1.058
801493	MCKINLEY	MF	4	23	4,875	1,219	5.90	0.638	1.112	570.3	-	-	-	-	-	-	-	-	0.007	0.001	0.001	0.695
801502	MAGNOLIA	MF	3	68	6,303	2,101	5.07	0.459	1.809	542.6	-	-	-	-	-	-	-	-	0.011	0.001	0.004	1.140
																		Total	*0.081*	*0.009*	*0.017*	*8.151*

VDS Number	Station Name	Lane Type	No. of Lanes	Speed (mph)	VMT (mi)	VMT/ Lane	EMFAC EF (g/mi)				HOV Correction Factors				Adjusted EF (g/mi)				Emissions (tons/hr/ln)			
							CO	HC	NOx	CO2	CO	HC	NOx	CO2	CO	HC	NOx	CO2	CO	HC	NOx	CO2
801416	2180' E/O CO LINE	HOV	1	61	728	728	4.50	0.403	1.447	494.8	0.97	1.00	1.03	1.02	4.21	0.398	1.469	510.3	0.003	0.000	0.001	0.371
801423	GREEN RIVER	HOV	1	10	867	867	8.76	1.360	1.476	938.9	1.43	1.03	1.00	0.86	11.32	1.265	1.424	699.2	0.010	0.001	0.001	0.606
801429	2400' W/O RTE 71	HOV	1	14	562	562	7.60	1.042	1.324	781.9	1.30	1.01	1.01	0.88	9.04	0.970	1.293	604.1	0.005	0.001	0.001	0.340
801436	RTE 71	HOV	1	27	963	963	5.40	0.538	1.060	515.6	1.01	0.99	1.03	0.93	5.18	0.504	1.068	450.5	0.005	0.000	0.001	0.434
801443	3500' W/O SERFAS CL	HOV	1	27	885	885	5.40	0.538	1.060	515.6	1.01	0.99	1.03	0.93	5.18	0.504	1.068	450.5	0.005	0.000	0.001	0.398
801450	SERFAS CLUB	HOV	1	29	876	876	5.20	0.499	1.042	494.4	0.99	0.98	1.03	0.94	4.87	0.469	1.054	440.0	0.004	0.000	0.001	0.385
801458	MAPLE	HOV	1	37	731	731	4.58	0.398	1.016	440.6	0.92	0.98	1.04	0.98	4.05	0.377	1.038	419.6	0.003	0.000	0.001	0.307
801465	100' E/O SMITH	HOV	1	34	883	883	4.77	0.428	1.017	455.7	0.94	0.98	1.03	0.97	4.29	0.404	1.036	423.6	0.004	0.000	0.001	0.374
801474	LINCOLN	HOV	1	34	1,115	1,115	4.77	0.428	1.017	455.7	0.94	0.98	1.03	0.97	4.29	0.404	1.036	423.6	0.005	0.000	0.001	0.472
801486	MAIN	HOV	1	28	744	744	5.30	0.518	1.050	504.6	1.00	0.99	1.03	0.94	5.02	0.486	1.060	444.9	0.004	0.000	0.001	0.331
801489	500'E/O EAST GRAND	HOV	1	37	1,540	1,540	4.58	0.398	1.016	440.6	0.92	0.98	1.04	0.98	4.05	0.377	1.038	419.6	0.006	0.001	0.002	0.646
806676	MCKINLEY LOOP ON	HOV	1	57	1,269	1,269	4.29	0.374	1.301	463.0	0.95	0.99	1.03	1.03	3.92	0.366	1.327	479.2	0.005	0.000	0.002	0.608
807246	MCKINLEY	HOV	1	53	1,438	1,438	4.19	0.357	1.193	441.6	0.93	0.99	1.03	1.02	3.75	0.347	1.221	455.4	0.005	0.000	0.002	0.655
801503	MAGNOLIA	HOV	1	59	2,044	2,044	4.38	0.387	1.368	477.5	0.96	1.00	1.03	1.03	4.04	0.381	1.392	493.7	0.008	0.001	0.003	1.009
																		Total	*0.072*	*0.007*	*0.017*	*6.937*

5. Microscopic Modeling Demonstration

This chapter describes the microscopic modeling tool that has been developed and introduced in Section 2.4 of this report. Further, this chapter describes how this integrated traffic simulation/modal emissions modeling tool can be implemented to evaluate the air quality benefits/impacts of HOV lanes. Note that this demonstration focuses on running emissions only. A freeway section in Southern California was used as a case study to conduct analyses in response to the question "how should the innermost lane of this freeway section be used effectively?" Three lane configurations were modeled and the resulting pollutant emissions were compared. These lane configurations are:

1) *Southern California style HOV lane (SoCal network)*: This is the existing configuration on the freeway section. The lane has concurrent flow and is separated from the adjacent MF lane by double yellow lane markings. It has limited access and provides ingress/egress at designated locations. It enforces the 2+ occupancy requirement.

2) *Northern California style HOV lane (NoCal network)*: This lane configuration has concurrent flow with continuous access; they are separated from the adjacent MF lane by broken lane markings. It enforces the 2+ occupancy requirement.

3) *Mixed-flow lane (MF network)*: This is a regular MF lane.

Section 5.1 of this chapter describes in more details the study site and network configuration of the case study. Section 5.2 explains how the model was set up in terms of zone system, travel demand, and vehicle types. Next, the model verification and calibration processes are discussed in Section 5.3. Then, Section 5.4 presents modeling results and sensitivity analyses. Finally, Section 5.5 summarizes the findings in this chapter and discusses the implications of the results.

5.1. STUDY SITE AND NETWORK CODING

The site selected for conducting the micro-simulation analyses is the 12-mile stretch of SR-91E from the end of toll lanes after the SR-241 interchange to Magnolia Ave exit to the east of I-15 interchange, as shown in Figure 5.1. It has 11 off ramps and 11 on ramps of which two have an HOV bypass lane. HOV lanes on this freeway are Southern California style—intermittent barrier, 2+ occupancy requirement, and full-time enforcement. Along the selected freeway section, there are seven HOV ingress/egress locations. The freeway section is well covered by PeMS VDS—14 stations in MF lanes and 14 stations in the HOV lane. This section of SR-91E is essentially the same section on which probe vehicle runs were conducted earlier. Thus, the data from probe vehicle runs can be derived to result in travel time data for use in the model calibration process.

The high resolution satellite imagery of the area acquired from the Google Map website was used to guide a coding of the roadway network for traffic simulation in PARAMICS. It was imported into PARAMICS as background image such as that shown in Figure 5.2. The image was then used to guide a coding of the detailed geometry of each node and link; for example, degree of curvature of curves, locations of ramp diverge and ramp merge, etc. However, the resolution of the image does not allow for the proper determination of number of lanes as well as the exact location of HOV lane ingress/egress sections. Therefore, this information were obtained from several site visits. The accuracy of these detailed geometric features is very important to the simulation results as they control how vehicles interact with the roadway and with each other. It is always recommended that the geometry of roadway network be coded as nearly as possible to the real world. Figure 5.3 shows the number of lanes of the freeway mainline at each section of the freeway. It also shows the location of the HOV lane ingress/egress sections.

Figure 5.1. Study site for micro-simulation case-study.

Figure 5.2. Detailed network geometry coded in PARAMICS.

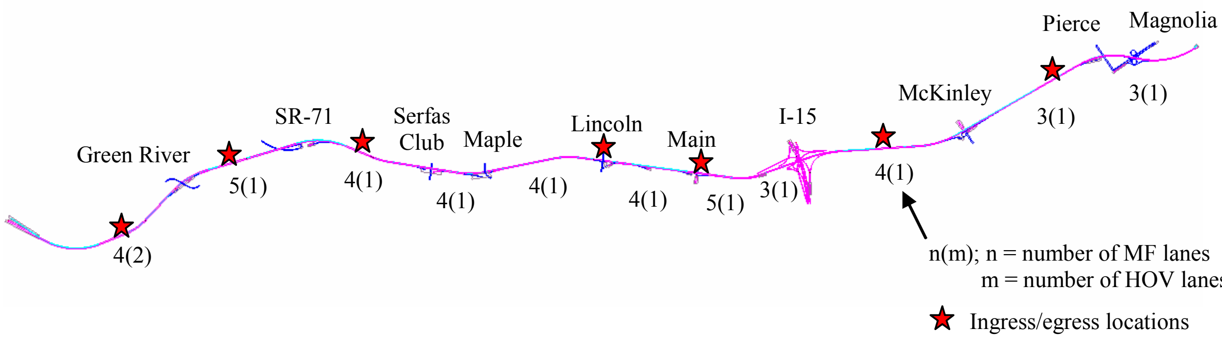


Figure 5.3. Number of lanes and HOV lane ingress/egress locations

In the SoCal network, HOV lanes and MF lanes were coded as two separate links at points where there is a barrier between HOV and MF lanes and as the same link between ingress and egress points. For those sections with two separate links, the MF lanes were coded to have a median that is as wide as the HOV lane. Then, the HOV lane was coded into the provided median space. This is to prevent it from having unrealistically longer distance than its MF counterpart, which may affect travel time calculation and route choice selection of vehicles. While coding this network, particular attention was paid to the location and length of HOV lane ingress/egress points as it was felt that there would be a lot of weaving in these areas. The HOV lane enforcement was coded using the "restriction" feature in PARAMICS. With this feature, certain vehicle types can be barred from using designated links or lanes. In our application, the HOV lane restriction was created that allows only HOVs to use the lanes. In the NoCal network, both HOV and MF lanes were coded on the same link. The HOV lane restriction was assigned to the innermost lane along the freeway section. No ingress/egress locations were provided as HOVs can weave in and out the HOV lane anywhere. In the MF network, the HOV lane restriction was removed and the innermost lane was open to any vehicle types.

As part of the network coding, virtual loop detectors were also coded. These loop detectors represent the PeMS loop detectors in the real world. It is important that loop detectors are coded in the model network at the same locations they are in the real network. Since data collected by loop detectors are point data, the data at different points, although being on the same link, could differ dramatically. This is especially important for weaving sections such as HOV lane ingress/egress sections.

5.2. MODEL SETUP

5.2.1. Zone System and Demands

In addition to nodes and links of the roadways, it is necessary to code origin-destination (OD) zones in the model network. These zones are where vehicles enter and exit the network. Since the study network is a freeway-only network, these zones are located at the two ends of the mainline and at every freeway on-ramp and off-ramp. At some locations, an on-ramp and an off-ramp were coded into a single zone following the zone system generated by the sub-area extraction module of the travel demand model. Note that the upstream end of the mainline is essentially the ending of the SR-91E toll lanes. Therefore, the origin zones at that end were coded separately for vehicles entering the network from regular lanes and from the toll lanes. For the SoCal network, the destination zones at the downstream end were also coded separately for vehicles exiting the network via MF lanes and via the HOV lane. At the end, the SoCal network had a total of 23 zones while the NoCal and MF networks had a total of 22 zones.

Travel demand entering and exiting the network at each designated zone were extracted from the SCAG regional OD trip tables for year 2006 obtained from the SCAG staff. They consist of six OD tables, each table for each mode of highway travel. These six OD tables are for SOV (65.7%), HOV2+ (22.2%), HOV3+ (6.3%), LDT (1.9%), MDT (1.6%), and HDT (2.3%). The percentage in parentheses after the mode name is the percentage of that travel model in the total travel demand. In the SCAG travel demand model, the trip assignment is based on equilibrium, iterative, capacity-restrained assignment process, which also takes into account passenger car equivalent unit (PCU) in the calculation of volume. Therefore, the distribution of each of the six travel mode is unlikely to be biased. For convenience in a demand calibration process, the OD tables for HOV2+ and HOV3+ were combined into one because they represent the similar mode of carpooling. Also, the OD tables for LDT and MDT were combined. Both modes contribute to only a few percentage of the total travel demand and their vehicle characteristics are also comparable. Finally, there were four OD tables for SOV (65.7%), HOV (28.5%), MDT (3.5%), and HDT (2.3%).

The simulation period was chosen to be an A.M. peak hour (7-8 a.m.). According to the analysis conducted earlier, HOV lane operation during this hour is under-utilized. Therefore, it is well suited for answering the question "should an under-utilized HOV lane be converted to an MF lane?" In addition, it can be used as a base scenario under which the level of demand and the percentage of HOVs can be adjusted to evaluate other what-if scenarios.

The extracted demands for A.M. peak period (6 a.m. to 9 a.m.) are for three hours. These 3-hour demands were factored into 1-hour demands using the time-of-day distribution factors shown in Figure 5.4. These factors were derived from PeMS loop data for a typical weekday (including only Tuesday, Wednesday, and Thursday). To obtain the data that represent a typical weekday, first, loop detector health was examined to identify a 3-week period within one year from the time of study that the loop detectors on this section of SR-91 E were healthiest. This turned out to be from April 3 to April 21, 2006. Then, the data of the identified period for the total of 9 days (3 weeks x 3 days per week) were extracted and the average values were used. The data of the same period were used when determining the typical mainline volumes for a calibration purpose.

Once the initial hourly OD tables were obtained, they were adjusted based on the count data from PeMS loop detectors at ramp locations using the Furness process [Dowling et al., 2002]. In each iteration of the process, the four OD tables were adjusted simultaneously. This was aimed at maintaining the same proportion of each travel mode in the network.

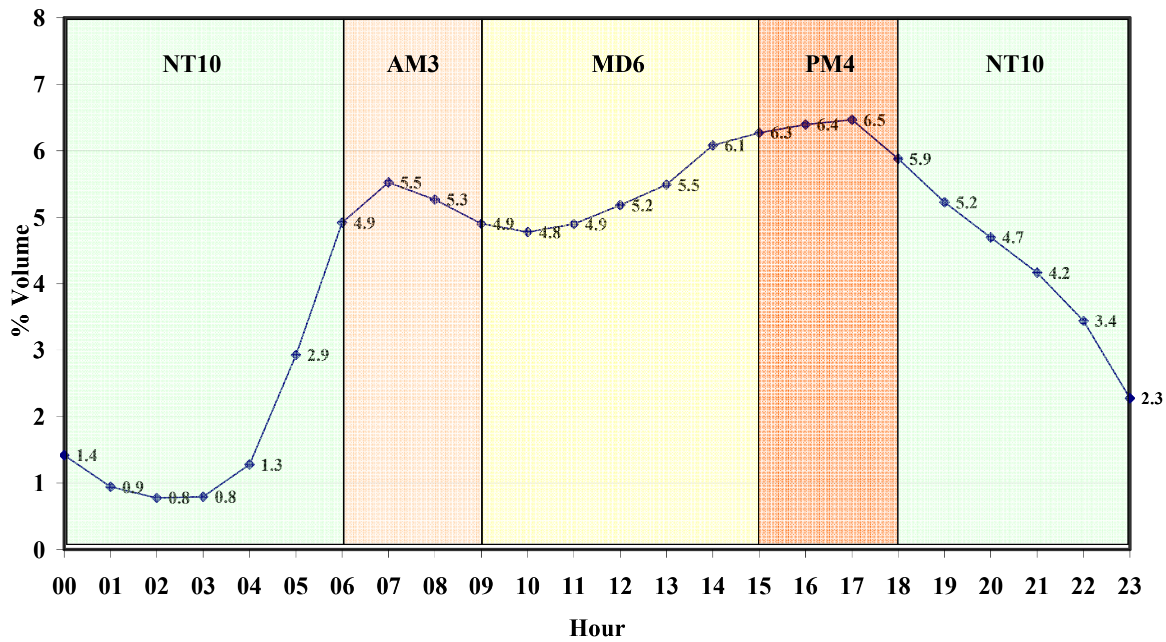


Figure 5.4. Diurnal profile of demands entering the simulated freeway in a typical weekday.

5.2.2. Vehicle Types

As the microscopic traffic simulation models the movement of vehicles and the interaction among them individually, input data relating to vehicle performance and characteristics will have significant effect on modeling results; and thus should represent the real-world fleet as much as possible. PARAMICS supplies default values for these inputs. However, these default values are for a fleet in the United Kingdom (U.K.) and not recommended for applications in the U.S. Therefore, these data for a typical U.S. fleet are adopted from [Dowling et al., 2002] for four vehicle types. These data are provided in Table 5.1. Next, each vehicle type was divided into several vehicle categories to match up with their corresponding CMEM vehicle categories. After that, they were grouped into four groups associated with the four demand tables that had been derived, as shown in Table 5.2. Each vehicle category accounts for a certain percentage of the total fleet within a group. For example, SOV demands were stored in demand matrix 1. They are composed of cars and trucks for a total of 31 categories. Vehicle category 13 is ultra-low emission cars, which account for 7.94% of the total SOVs. Likewise, vehicle category 30 is trucks with bad catalyst, which account for 0.26% of the total SOVs. Note that the demand percentages shown in Table 5.2 are for the fleet of Riverside in September 2005.

Table 5.1. Vehicle performance and characteristics (adopted from [Dowling et al., 2002])

Type	Length (m)	Width (m)	Height (m)	Weight (metric ton)	Top Speed (km/h)	Maximum Acceleration (m/s^2)	Maximum Deceleration (m/s^2)	PCU
Car	4.4	1.7	1.4	1.1	169	2.3	-4.1	1.0
Truck	5.3	2.0	1.8	1.8	171	2.3	-3.7	1.2
MDT	7.8	2.4	3.6	15.0	105	1.7	-4.1	1.5
HDT	12.2	2.6	4.1	32.6	100	1.7	-3.7	2.0

Table 5.2. CMEM vehicle categories and corresponding PARAMICS vehicle types

PARAMICS		CMEM		Demand Matrix	Demand Percentage
Category	Type	Category	Description		
1, 32	car	LDV 1	No Catalyst	1, 2	0.39
2, 33	car	LDV 2	2-way Catalyst	1, 2	0.78
3, 34	car	LDV 3	3-way Catalyst, Carbureted	1, 2	1.61
4, 35	car	LDV 4	3-way Catalyst, FI, >50K miles, low power/weight	1, 2	6.11
5, 36	car	LDV 5	3-way Catalyst, FI, >50K miles, high power/weight	1, 2	6.11
6, 37	car	LDV 6	3-way Catalyst, FI, <50K miles, low power/weight	1, 2	0.07
7, 38	car	LDV 7	3-way Catalyst, FI, <50K miles, high power/weight	1, 2	0.07
8, 39	car	LDV 8	Tier 1, >50K miles, low power/weight	1, 2	5.88
9, 40	car	LDV 9	Tier 1, >50K miles, high power/weight	1, 2	5.88
10, 41	car	LDV 10	Tier 1, <50K miles, low power/weight	1, 2	1.85
11, 42	car	LDV 11	Tier 1, <50K miles, high power/weight	1, 2	1.85
12, 43	car	LDV 24	Tier 1, >100K miles	1, 2	15.28
13, 44	car	LDV 26	Ultra-Low Emission Vehicle (ULEV)	1, 2	7.94
14, 45	car	LDV 27	Super Ultra-Low Emission Vehicle (SULEV) and Partial Zero Emission Vehicle (PZEV)	1, 2	0.89
15, 46	car	LDV 19	Runs lean	1, 2	0.42
16, 47	car	LDV 20	Runs rich	1, 2	0.95
17, 48	car	LDV 21	Misfire	1, 2	0.84
18, 49	car	LDV 22	Bad catalyst	1, 2	0.30
19, 50	car	LDV 23	Runs very rich	1, 2	0.21
20, 51	Truck	LDV 12	Pre-1979 (<=8500 GVW)	1, 2	0.55
21, 52	Truck	LDV 13	1979 to 1983 (<=8500 GVW)	1, 2	0.85
22, 53	Truck	LDV 14	1984 to 1987 (<=8500 GVW)	1, 2	2.50
23, 54	Truck	LDV 15	1988 to 1993 (<=3750 LVW)	1, 2	3.38
24, 55	Truck	LDV 16	1988 to 1993 (>3750 LVW)	1, 2	7.28
25, 56	Truck	LDV 17	Tier 1 LDT2/3 (3751-5750 LVW or Alt. LVW)	1, 2	18.21
26, 57	Truck	LDV 18	Tier 1 LDT4 (6001-8500 GVW, >5750 Alt. LVW)	1, 2	7.47
27, 58	Truck	LDV 19	Runs lean	1, 2	0.36
28, 59	Truck	LDV 20	Runs rich	1, 2	0.72
29, 60	Truck	LDV 21	Misfire	1, 2	0.76
30, 61	Truck	LDV 22	Bad catalyst	1, 2	0.26
31, 62	Truck	LDV 23	Runs very rich	1, 2	0.23
				Total	*100.00*
63	MDT	LDV 25	Gasoline-powered, LDT (>8500 GVW)	3	54.28
64	MDT	LDV 40	Diesel-powered, LDT (>8500 GVW)	3	45.72
				Total	*100.00*
65	HDT	HDDV 5	1994 to 1997, 4 stroke, electronic FI	4	32.30
66	HDT	HDDV 6	1998, 4 stroke, electronic FI	4	6.16
67	HDT	HDDV 7	1999 to 2002, 4 stroke, electronic FI	4	61.54
				Total	*100.00*

5.3. MODEL VERIFICATION AND CALIBRATION

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

5.3.1. Network Verification

Before proceeding to calibration it is necessary to ensure that the model input data has been entered correctly. Error checking involves various tests of the coded network, for example, checking link attributes (e.g. number of lanes, free-flow speed, etc.), checking lane restrictions (i.e. HOV lane), checking traffic zones, and reviewing demand inputs. In addition, partial demands were loaded onto the network and vehicle behaviors were observed as the simulated vehicles moved through the network. This was to check for improper network connectivity, unrealistic congestion that might show up at low demand levels, hidden bottlenecks, as well as unexpected braking and lane changing of the vehicles.

After the network coding had been verified, the capacity of the network was calibrated. This stage involves calibrating global parameters and fine-tuning link specific parameters in order to best reproduce observed traffic capacities in the field. Global parameters include mean target headway and mean driver's reaction time. Local parameters include signposting and sign range distances as well as headway and reaction time factors of a link. At ramp locations, certain specific parameters were also calibrated. These parameters include slip lane length, ramp aware distance, and minimum ramp time. The capacity calibration started from the link at the upstream end of the freeway section and moved downstream to the link at the other end.

5.3.2. Demand Calibration

In this step, the model was run using the adjusted demands from the earlier step. During the model run, the coded loop detectors collect data of count, occupancy, and speed of simulated vehicles. The collected data can be aggregated across multiple lanes for any specified time period using the "loop data aggregator" plug-in supplied with PARAMICS. In this study, the "loop data aggregator" plug-in was used to aggregate count data on an hourly basis for MF and HOV lanes separately. Then, the aggregated data for the two lane types were summed together later to obtain the total hourly flows. These hourly flows were compared with those collected in the field by PeMS. The criteria and acceptable targets for the comparison used in this study follow the guidelines by Caltrans [Dowling et al., 2002]. For hourly flow, the set criteria are based on the link flow value and the *GEH* statistic. The *GEH* statistic is computed as:

$$GEH = \sqrt{\frac{(q_m - q_o)^2}{(q_m + q_o)/2}} \tag{5.1}$$

where q_m is modeled hourly volume at a location and q_o is observed hourly volume at a location.

Based on the simulated link flow and the computed *GEH* statistic, the adjusted OD tables were fine-tuned and the model was rerun with the new OD tables. This process was repeated until the calibration targets were met. The final demands consisted of SOV, HOV, MDT, and HDT for 65.8%, 25.5%, 4.8%, and 4.0%, respectively. Table 5.3 shows the demand calibration results of the final OD tables. Note that although the network is covered by 14 VDS in both HOV and MF lanes, three of them were excluded from being used for the calibration because the observed data at these locations were below 85%. According to Table 5.3, the errors of individual link flows and their corresponding GEH statistic were well below the threshold. In addition, the error of the total link flow was as low as -0.5%. These calibration results implied that the overall demands entering and exiting the network had been well calibrated.

Table 5.3. Demand calibration results of hourly flow

VDS Number	Station Name	Lane Type	No. of Lanes	Observed Flow	Modeled Flow	Modeled - Observed	*GEH* Statistic
801415	2180' E/O CO LINE	All	5	6954	6891	-63	0.8
801435	RTE 71	All	5	6441	6416	-25	0.3
801442	3500' W/O SERFAS CL	All	5	7227	7304	77	0.9
801449	SERFAS CLUB	All	5	7158	7197	39	0.5
801457	MAPLE	All	5	7009	7005	-4	0.0
801464	100' E/O SMITH	All	5	7261	7217	-44	0.5
801473	LINCOLN	All	5	6869	6806	-63	0.8
801485	MAIN	All	5	6964	7029	65	0.8
801488	500'E/O EAST GRAND	All	5	6286	5987	-299	3.8
806674	MCKINLEY LOOP ON	All	4	5664	5700	36	0.5
801502	MAGNOLIA	All	4	5855	5777	-78	1.0
			Total	*73688*	*73329*	*-359*	*1.3*

5.3.3. HOV Lane Choice Calibration

After the overall demands were well calibrated, the next step was to calibrate flows in the HOV and MF lanes separately. This is concerned with how many HOVs choose to use the HOV lane for all or part of their trips. The decision is likely to depend on the traffic condition in the MF lanes, the traffic condition in the HOV lane, and some other casual factors. This complex behavior is usually modeled as a route choice (or, in the context of this network, lane choice) behavior in the traffic assignment process. For the traffic assignment process in PARAMICS, first the travel cost for each vehicle to reach its destination is calculated. Then, the costs of all alternative routes are compared and the best route is taken as the route with lowest cost. The travel cost can be defined as travel time, travel distance, a combination of both, etc. In this study, the travel cost is referred to as the travel time. There are many route choice parameters that can play a role in the travel cost calculation, for example, category cost factor, link cost factor, and cost perturbation factor. For the modeling of HOV lanes, these parameters need to be calibrated so that the simulated HOVs replicate the actual HOVs in their route choice decision.

SoCal Network

In the SoCal network, the stochastic route choice model with dynamic feedback traffic assignment technique was employed. This route choice model applies only to HOVs as they may use either the HOV lane or the MF lanes to travel between two nodes on the freeway. It does not affect other types of vehicles as they do not have alternative routes. The stochastic route choice model in PARAMICS assumes that different drivers perceive different costs from a decision node to the destination. The different perception of costs by different drivers is triggered by the cost perturbation factor, which needs to be calibrated. The dynamic feedback assignment component allows the travel costs to be recalculated periodically based on the most recent traffic condition. Then, these updated travel costs are fed back to the route choice model in determining the best route for each vehicle traveling to its destination.

Note that by default the dynamic feedback assignment affects only "familiar" drivers as it is assumed that only these drivers know the road network and potential alternative routes. The proportion of familiar drivers in the driver population can be set as an input to the model. It was observed in the field during site visits that not every HOV used the HOV lane and there were always certain percentages of HOVs that used the MF lanes even when the MF lanes were very congested. It was felt that this information is useful for the calibration of route choice behavior and should be incorporated into the model. Since there was no observed data available, this information was estimated from the percentage of HOVs in the fleet for each hour derived from the travel demand model and the percentage of hourly traffic in the network that used the HOV lane. It was found that the percentage of HOVs not using the HOV lane was lowest at 10% during the most congested hour of the day (5-6 p.m.). These HOVs are equivalent to unfamiliar drivers in the context of PARAMICS route choice model. Therefore, the percentage of unfamiliar drivers was set to 10% in the model.

Table 5.4. Route choice calibration results of hourly flow

VDS Number	Station Name	Lane Type	No. of Lanes	Observed Flow	Modeled Flow	Modeled - Observed	*GEH* Statistic
801415	2180' E/O CO LINE	MF	4	6011	5976	-35	0.5
801435	RTE 71	MF	4	5752	5683	-69	0.9
801442	3500' W/O SERFAS CL	MF	4	6528	6567	39	0.5
801449	SERFAS CLUB	MF	4	6384	6397	13	0.2
801457	MAPLE	MF	4	6229	6202	-27	0.3
801464	100' E/O SMITH	MF	4	6482	6425	-57	0.7
801473	LINCOLN	MF	4	6190	6088	-102	1.3
801485	MAIN	MF	4	6362	6365	3	0.0
801488	500'E/O EAST GRAND	MF	4	5709	5359	-350	4.7
806674	MCKINLEY LOOP ON	MF	3	4884	4915	31	0.4
801502	MAGNOLIA	MF	3	5044	4988	-56	0.8
			Total	*65575*	*64965*	*-610*	*2.4*
801416	2180' E/O CO LINE	HOV	1	943	915	-28	0.9
801436	RTE 71	HOV	1	690	733	43	1.6
801443	3500' W/O SERFAS CL	HOV	1	699	737	38	1.4
801450	SERFAS CLUB	HOV	1	774	800	26	0.9
801458	MAPLE	HOV	1	779	803	24	0.8
801465	100' E/O SMITH	HOV	1	779	792	13	0.5
801474	LINCOLN	HOV	1	679	718	39	1.5
801486	MAIN	HOV	1	602	664	62	2.5
801489	500'E/O EAST GRAND	HOV	1	578	628	50	2.1
806676	MCKINLEY LOOP ON	HOV	1	780	785	5	0.2
801503	MAGNOLIA	HOV	1	811	789	-22	0.8
			Total	*8113*	*8364*	*251*	*2.8*

In the implementation of this assignment technique, the link speed and link cost factor of the HOV lane were set to be equal to those of the MF lanes. That means at the beginning of the simulation the two competing routes (HOV lane and MF lanes) have the same travel cost (i.e. travel time). With the cost feedback set to be one minute, the travel times on both lanes were recalculated and the lane choice of HOVs was updated every minute. In addition, the route choice of HOVs was also influenced by the cost perturbation factor. This factor was calibrated so that the route choice decision in the modeled network replicated the real world as determined by the split of link flows between the HOV and MF lanes. After several trial and error repetitions, the cost perturbation factor of 8 was considered to produce the best results. The simulated link flows as compared to the observed link flow in both HOV and MF lanes are provided in Table 5.4. These calibration results meet the hourly flow criteria set by Caltrans.

In addition to the hourly flow, the calibration criteria also include travel time and other visual audits. The observed travel time data were obtained from probe vehicle runs during the data collection program earlier in the project. They were obtained both for running in the HOV lane and running in the MF lanes. Each of them was compared to the simulated travel time in each lane type. Table 5.5 summarizes all the calibration results of the SoCal network. It shows that the simulated network has been well calibrated to the existing traffic condition in the real world.

Table 5.5. Summary of calibration targets and results

Criteria & Measures	Acceptability Targets	Calibration Results
Hourly Flows: Modeled versus Observed		
Individual link flows Within 100 vph, for flow < 700 vph Within 15%, for 700 vph < flow < 2700 vph Within 400 vph, for flow > 2700 vph	 > 85% of all cases > 85% of all cases > 85% of all cases	 100% of 5 cases 100% of 6 cases 100% of 11 cases
Total link flows Within 5%	 All accepting links	 Yes, error for MF = -0.9% HOV = 3.1%
GEH statistic – individual link flows *GEH* < 5	 > 85% of all cases	 100% of 22 cases
GEH statistic – total link flows *GEH* < 4	 All accepting links	 Yes, GEH for MF = 2.4 HOV = 2.8
Travel Time: Modeled versus Observed		
Point-to-point travel times Within 15% or one minute, whichever is higher	 > 85% of all cases	 Yes, for both MF and HOV
Visual Audits		
Individual link speeds Visually acceptable speed-flow relationship Bottlenecks Visually acceptable queuing	 To analyst's satisfaction To analyst's satisfaction	 Satisfied Satisfied

NoCal Network

In the NoCal network, both HOV and MF lanes were coded on the same link as HOVs can weave in and out the HOV lane anywhere. The HOV lane was implemented by imposing the HOV lane restriction on the innermost lane of each link. Unlike the SoCal network, there is no route choice for HOVs in this network. The behavior of HOVs in this setting can be modeled using the "HOV behavior" plug-in supplied with PARAMICS. This plug-in was found to provide satisfactory basis for modeling unlimited access HOV lanes in an earlier study [Gardes et al., 2003]. However, it was shown by [Oh and Chu, 2004] that this plug-in: 1) is not sensitive to MF lane speed and 2) underestimate HOV lane volume in the application that they tested.

There are several behavioral parameters associated with this plug-in, for instance, lane change accept time, lane change reset time, patients, overtake time, etc. These parameters are mostly concerned with how soon and how often HOVs will weave in and out the HOV lane. Because there is no observed data available for this type of HOV lane setting on the study network, it was assumed that the HOV link flows in the NoCal network would be comparable to those in the SoCal network. Thus, an effort was made to calibrate the HOV behavior parameters to the target set by the assumption. Table 5.6 presents the calibration results. It can be seen that without the plug-in the HOV lane usage was underestimated. On the other hand, the plug-in overestimated the HOV link flows. When the plug-in was activated, the HOV link flows were not sensitive to the lane change accept time and lane change reset time parameter. However, they were influenced by the patients and overtake time parameters. The final parameter values, which produced the lowest sum squared error, were shown in the last column of Table 5.6.

Table 5.6. Calibration results of HOV behavior parameters

VDS Number	Observed	No Plug-in	5 & 30[a] 3 & 5[b]	5 & 30[a] 5 & 10[b]	5 & 10[a] 3 & 5[b]	10 & 30[a] 3 & 5[b]	10 & 15[a] 3 & 5[b]	10 & 15[a] 5 & 10[b]
801416	943	951	922	922	955	956	956	956
801436	690	334	766	766	804	853	846	846
801443	699	507	958	958	1002	1009	963	963
801450	774	491	1061	1061	1023	1113	1062	1062
801458	779	536	1108	1108	1092	1122	1083	1083
801465	779	555	1125	1125	1114	1154	1074	1074
801474	679	472	997	997	987	1000	942	942
801486	602	442	947	947	937	937	916	916
801489	578	466	958	958	955	948	906	906
806676	780	329	879	879	872	857	874	874
801503	811	461	967	967	970	975	978	978
SSE[c]	*0*	*759872*	*782310*	*782310*	*760107*	*881024*	*668660*	*668660*

[a] patients & overtake time (seconds); [b] lane change accept time & lane change reset time (seconds); [c] sum squared error

It should be noted that the HOV behavior plug-in currently allows up to 8 HOV vehicle types to be modeled. Therefore, the 8 HOV categories that have the highest proportion in the HOV fleet, according to Table 5.2, were included in this plug-in. These vehicles account for more than 70% of the total HOVs.

5.4. EMISSIONS RESULTS

The final calibrated version for each of the three networks (i.e. SoCal, NoCal, and MF) was further equipped with the "CMEM" plug-in. The plug-in calculated second-by-second tailpipe emissions of CO, HC, NO_x, and CO_2 from the simulated vehicles. Then, it aggregated the calculated emissions over space (for each link in the network) and time (for a specified time period) before reporting the results to a text file. In all three networks, the aggregation time period was set to one hour. For a fair comparison, the result text file was post-processed to include only emissions from mainline links. Emissions from ramp links and zone centroid connectors were not included.

For each run, the simulation period was set to two hours (6 a.m. to 8 a.m.) but only the results of the second hour were used. The first hour is considered a warm-up period that allows traffic to build up in the network. Because of the stochastic nature of the microscopic simulation, for each network multiple runs were made using different seed numbers to produce statically meaningful results. Equation 5.2 was use to determine number of runs required.

$$N = (t_{\alpha/2} \cdot \frac{\delta}{\mu \cdot \varepsilon})^2 \tag{5.2}$$

where μ and δ are the mean and standard deviation of the estimated emissions based on the already conducted simulation runs; ε is the allowable error specified as a fraction of the mean μ; $t_{\alpha/2}$ is the critical value of the *t* distribution at the significance level α. This calculation needs to be done for every pollutant. The highest value is the required number of runs. If the current number of runs is larger than the required number of runs, the simulation of this network is ended. Otherwise, one additional run is performed and then the required number of runs needs to be recalculated. For this study, the significance level was set to 0.05. The allowable error was chosen to be 10%. Based on these values, four runs were made for each network to meet the statistical requirement. It was found that, in many cases, four runs actually resulted in the allowable error of less than 5%.

5.4.1. Existing Traffic Condition

The estimated emissions for the three networks are presented in Table 5.7. These are the average values of four simulation runs. These emissions are for the demand calibrated earlier. For that demand, the percentage of HOVs in the traffic is 25%. Three network performance measures are also reported including vehicle miles traveled (VMT), vehicle hours traveled (VHT), and Q. Q is the ratio of VMT to VHT. It is usually thought of as the ratio of the output of the freeway system, VMT, to the input of the freeway system, VHT. Drivers put in hours of travel time, and get out miles of travel. If this number is high, then the freeway is considered to perform well. For a single link, Q is simply the speed on the link. But for multiple links, Q is the ratio of the sum of the VMT to the sum of the VHT on each link. Note that VMT, VHT, and Q reported here are for the entire network system, which includes ramp links and zone centroid connectors. According to these performance measures, all three networks perform as good as each other in terms of mobility.

Table 5.7. Estimated emissions for existing conditions.

Network	Emissions (kg)				VMT (mi)	VHT (hr)	Q (mph)
	CO	HC	NO_x	CO_2			
SoCal	3,320	50	191	42,592	87002	1501	58.0
NoCal	2,836	46	184	40,944	87093	1491	58.4
MF	2,528	42	175	38,875	86606	1482	58.4

It is interesting to see how the three networks perform differently from environmental point of view. For a comparison purpose, all emissions were normalized by the emissions of the respective pollutants of the SoCal network and then plotted in Figure 5.5. It is shown that for the existing traffic condition and the NoCal and MF networks produce less emission than the SoCal network for every pollutant. The margins for the NoCal network are at 4 to 15%. The margins for the MF network are even more at 9 to 24%.

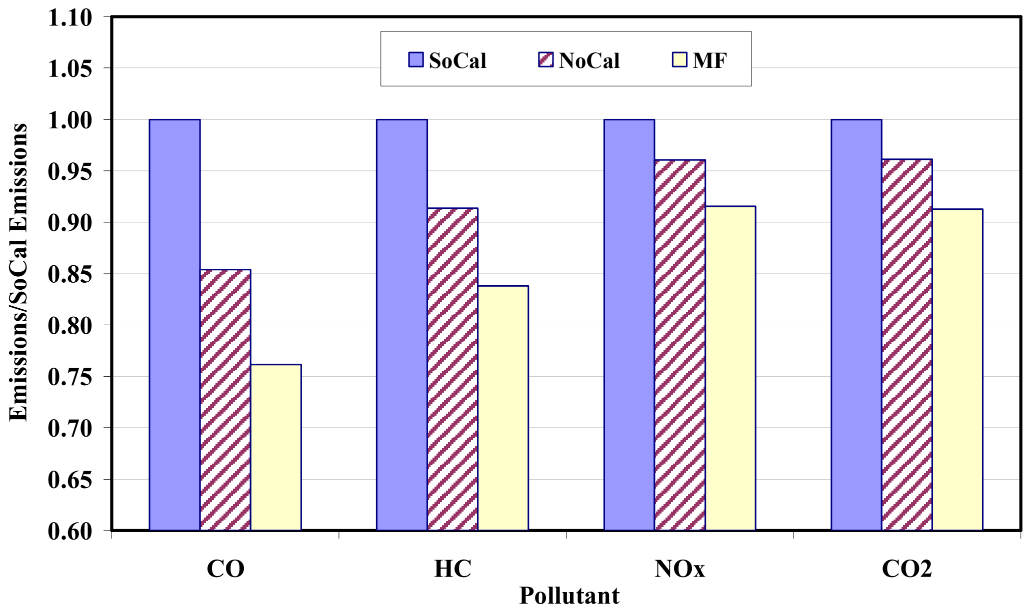


Figure 5.5. Comparison of emissions among three networks for existing traffic conditions.

5.4.2. Sensitivity Analyses

Sensitivity analyses were conducted to investigate how the three networks would perform if the traffic conditions changed. Two major variables were studied—overall demand and the percentage of HOVs in the traffic mix (%HOV). The increase in overall demand for the network will affect the overall operational performance of the network as there are more vehicles using the network. As the demand approaches the network capacity, congestion may occur and the pollutant emissions are likely to increase. The %HOV is important in the sense that it determines how many vehicles are eligible to use the HOV lane. This ratio is also concerned with whether the split between eligible and ineligible vehicles balance with the split between the roadway capacity or not. For example, for a freeway section with three MF lanes and one HOV lane, the HOV lane accounts for 25% of the total capacity. If the %HOV is 20%, the HOV lane will be under-utilized and the remaining 80% of the traffic will be forced to use the 75% capacity of the MF lanes. Nevertheless, the impact may not be significant if the overall demand is well below the total capacity. In essence, both variables and the interaction between them are important factors in determining how a freeway with HOV lane would operate.

Two additional demand values were 5% and 10% growth in demand. Two additional %HOV values were 18% and 32%. Including the existing condition, they formed up a total of 9 scenarios, which were simulated by all three networks. The results of all scenarios are summarized in Table

5.8. Again, for a comparison purpose, the emissions were normalized by the emissions of the respective pollutants of the SoCal network and then plotted in Figure 5.6 for each scenario.

Table 5.8. Sensitivity analysis results.

Scenario	Demand Growth	%HOV	Emissions (kg)				VMT (mi)	VHT (hr)	Q (mph)
			CO	HC	NO_x	CO_2			
SoCal Network									
1	0%	18%	3,432	52	194	43,957	87853	1549	56.7
2*	0%	25%	3,320	50	191	42,592	87002	1501	58.0
3	0%	32%	3,332	51	187	41,719	86932	1491	58.3
4	5%	18%	3,856	57	207	47,638	91118	1744	52.3
5	5%	25%	3,747	56	206	46,596	90404	1703	53.2
6	5%	32%	3,665	55	201	45,213	90322	1629	55.5
7	10%	18%	4,469	65	229	53,956	94849	2184	43.4
8	10%	25%	4,190	61	217	50,255	94122	1879	50.1
9	10%	32%	4,248	62	222	50,620	94744	1867	50.8
NoCal Network									
1	0%	18%	2,932	47	183	41,600	87750	1523	57.6
2*	0%	25%	2,836	46	184	40,944	87093	1491	58.4
3	0%	32%	2,764	44	180	40,029	86533	1462	59.2
4	5%	18%	3,416	53	201	46,162	92264	1665	55.5
5	5%	25%	3,145	50	189	43,351	91270	1580	57.8
6	5%	32%	3,103	49	193	43,467	91055	1552	58.7
7	10%	18%	3,949	61	216	51,540	94401	1919	49.3
8	10%	25%	3,586	56	205	47,542	95037	1703	55.8
9	10%	32%	3,527	55	209	47,485	95563	1669	57.2
MF Network									
1	0%	18%	2,593	43	180	40,100	87840	1518	57.9
2*	0%	25%	2,528	42	175	38,875	86606	1482	58.4
3	0%	32%	2,577	43	174	38,774	86594	1481	58.5
4	5%	18%	2,874	47	187	42,628	91840	1623	56.6
5	5%	25%	2,859	47	191	42,680	91322	1600	57.1
6	5%	32%	2,829	46	184	41,615	90306	1578	57.2
7	10%	18%	3,228	52	210	47,704	95134	1810	52.6
8	10%	25%	3,301	53	206	47,205	95654	1782	53.7
9	10%	32%	3,251	52	208	46,800	94963	1754	54.2

*** Existing condition**

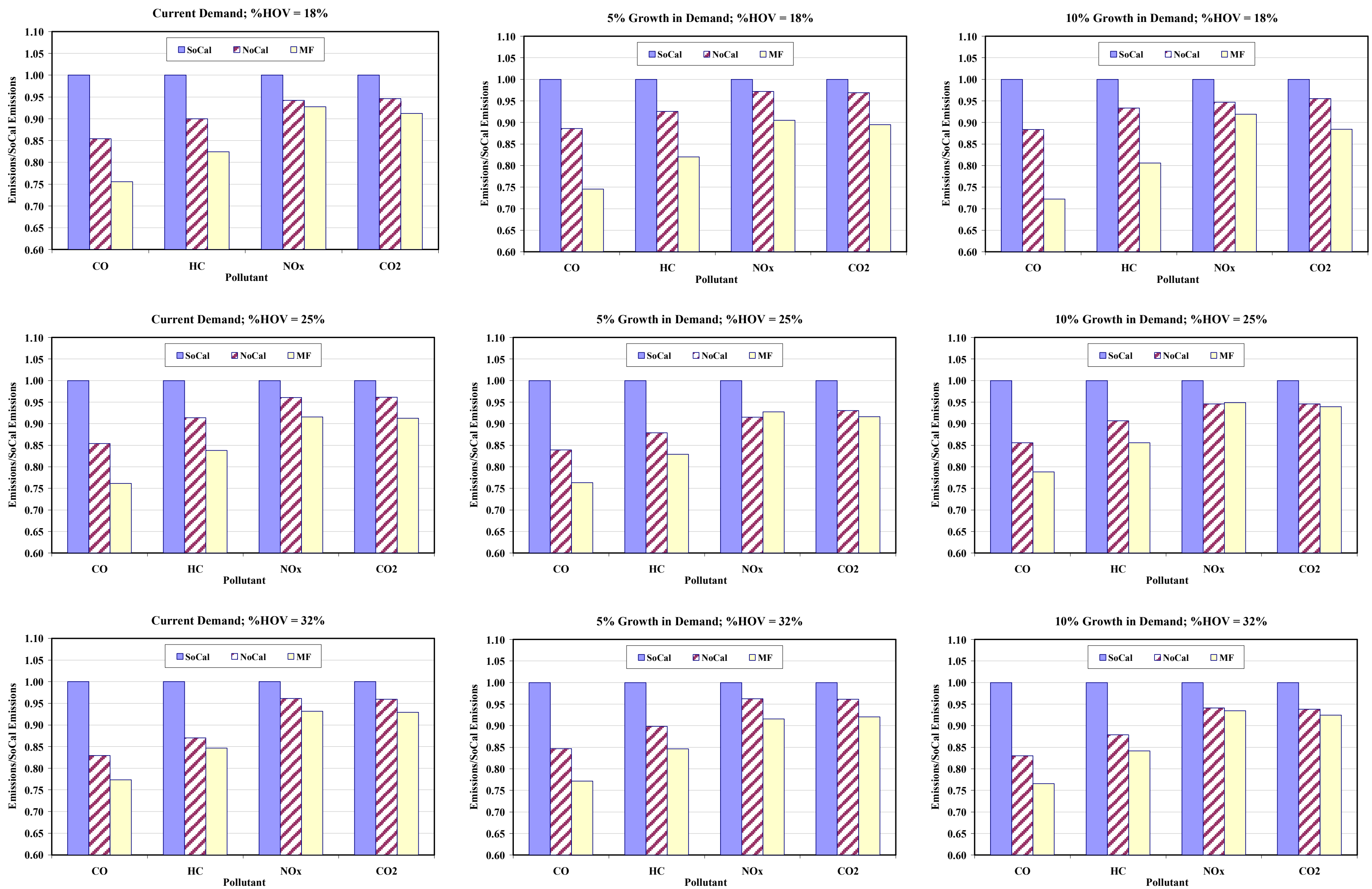


Figure 5.6. Comparison of emissions among three networks for different traffic conditions.

According to Table 5.8 and Figure 5.6, several findings are:

- Under the same traffic conditions, the NoCal and MF networks produce less emission than the SoCal network for every pollutant. Between the NoCal and the MF networks, the MF networks produce less emission except for a few cases.

- The largest emission differences are for CO, followed by HC. The MF network produces about 20-25% less CO and 15-20% less HC than the SoCal network. The NoCal network produces about 10-15% less CO and 5-15% less HC than the SoCal network.

- For NO_x and CO_2, the differences are comparatively lower than CO and HC. Both NoCal and MF networks produce less NO_x and CO_2 than the SoCal network in the order of less than 10%.

- The trends of emissions differences among the three networks do not change significantly as the demand increases. In other words, the absolute emissions increase consistently among the three networks as the demand increases.

5.5. DISCUSSION

Based on the sensitivity analysis results and the relevant findings, several questions related to HOV lane operations may be answered from an environmental point of view. Examples of these questions include:

- Should HOV lanes be limited access or continuous access?

- What would be emission impacts of HOV lane conversion?

- Should HOV lanes be enforced full-time or part-time?

The analyses to answer these questions are presented and discussed in the following sections.

5.5.1. Limited Access vs. Continuous Access

According to Table 5.8 and Figure 5.6, it is shown that the continuous access HOV lane produces less emission than the limited access HOV lane for every pollutant. This is true for every scenario tested. Under the same demand and traffic mix, the continuous access HOV lane produces about 10-15% less CO and 5-15% less HC than the limited access HOV lane. It also produces about 5-10% less NO_x and CO_2. In order to find reasons to support this trend, the emission results from the simulation runs were investigated on a link-by-link basis. It was found that for the SoCal network (limited access HOV lane), the emissions were relatively higher in weaving sections—ingress/egress sections that allow HOVs to weave in and out the lane—than other sections. This is true for every SoCal scenario tested. On the other hand, this trend was not found in the NoCal network (continuous access HOV lane). Figure 5.7 shows the percentage of pollutant emissions from the weaving sections in total mainline emissions. For the SoCal network, these percentage values range from 17% to 23% whereas the total length of these weaving sections accounts for only 16% of the total mainline length. On the other hand, for the NoCal and the MF networks, the contribution of emissions from the same sections to the total mainline emissions is about 15-17%, which is equivalent to the contribution of their length to the total mainline length. In addition, it is shown in Figure 5.7 that as there are more vehicles on the freeway, the impact of weaving sections in the SoCal network on vehicle emissions is more pronounced.

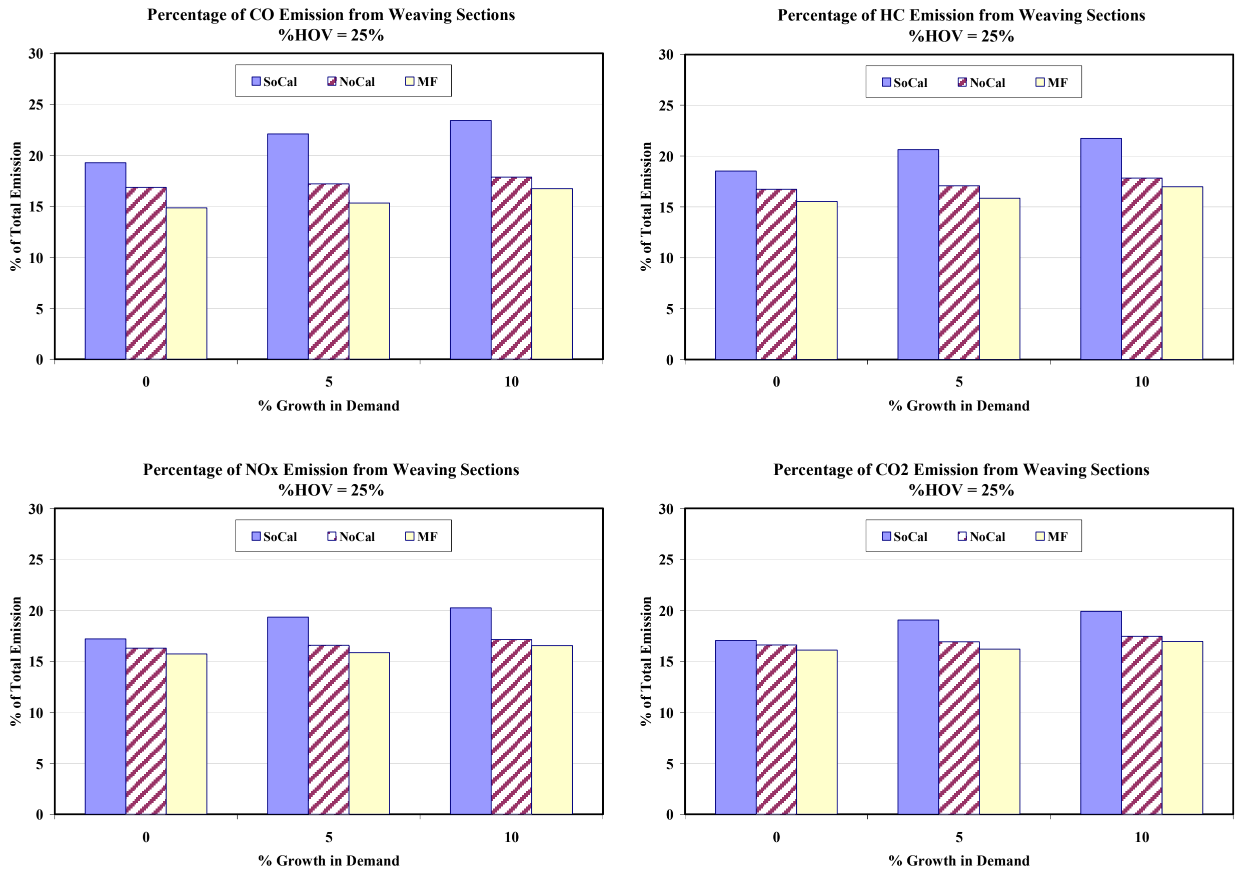
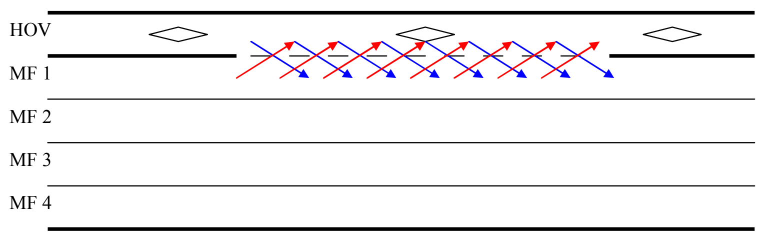


Figure 5.7. Contribution of emissions from weaving sections to the total emissions.

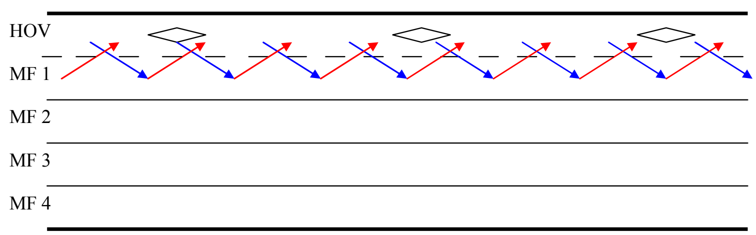
Figure 5.8 shows a simple illustration of generic weaving behavior in the three networks. In the SoCal network, HOVs are limited to change lane between HOV and MF lanes only at designated ingress/egress locations. Both the HOVs that just enter the freeway and want to use the HOV lane and the HOVs that are in the HOV lane and ready to take the next freeway exit need to carry out their lane changing activity at the provided weaving section. Therefore, the lane changing activities are highly concentrated over the limited length of the weaving section. With this constraint, the HOVs often have to conduct unnatural driving behaviors such as slowing down to wait for an acceptable gap in the adjacent lane, accelerating aggressively in order to take the gap ahead of them, or making a forceful merge into the adjacent lane, causing following and surrounding vehicles to brake unexpectedly. These behaviors not only affect the driving pattern of those HOVs themselves but also influence the driving pattern of other vehicles in the mainstream traffic in all lanes. As a result, the frequency and magnitude of acceleration/deceleration and thus emissions of vehicles on this section are relatively high.

Unlike the SoCal network, the HOVs in NoCal network have higher degree of freedom in their driving. In other word, they have an opportunity to weave in and out the HOV lane anywhere anytime. The lane changing activities are distributed over a longer distance and the unexpected driving behaviors are less likely to occur. Therefore, the levels of acceleration/deceleration and the resulting emissions are lower.

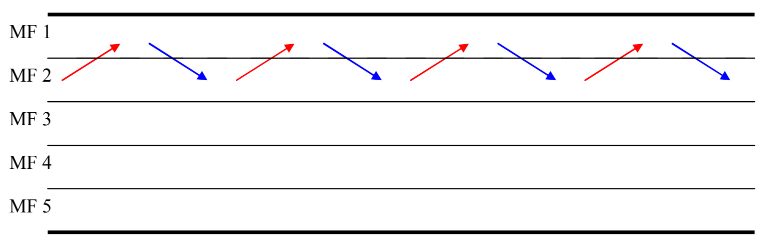
The MF network is similar to the NoCal network in that the lane changing activities can occur anywhere anytime on the freeway. However, vehicles in the MF network have higher degree of freedom in their driving than vehicles in the NoCal network. Non-HOVs in the NoCal network are eligible to use four lanes of the freeway while non-HOVs in the MF network can use all five lanes. In addition, the HOVs in the MF network do not necessarily try to move themselves to the innermost lane, as there is no incentive for them to do so. With these reasons, the MF network tends to have fewer unnatural lane changing activities than the NoCal network.



(a) SoCal network



(b) NoCal network



(c) MF network

Figure 5.8. Illustration of weaving behavior in different lane use schemes.

5.5.2. HOV Lane vs. MF Lane

In the previous discussion, it has been shown that the continuous access HOV lane produce less emissions than the limited access HOV lane. If the limited access HOV lane was converted to a continuous access HOV lane, it would be unlikely that the travel demand and %HOV on the freeway network change as a result of the conversion. On the other hand, if the lane was converted to another MF lane, the conversion would cause the traffic to change as illustrated by

Figure 5.9. Due to an increased capacity for non-HOVs, there might be an increase in demand on this freeway network as a result of induced demand. For example, vehicles from other routes might divert their travel route to use this freeway. Also, some HOVs might no longer carpool and turn to drive alone. Consequently, the %HOV would also change in the decreasing direction. Therefore, the evaluation of emission impacts of HOV lane conversion should not be done on the basis of the same demand and %HOV.

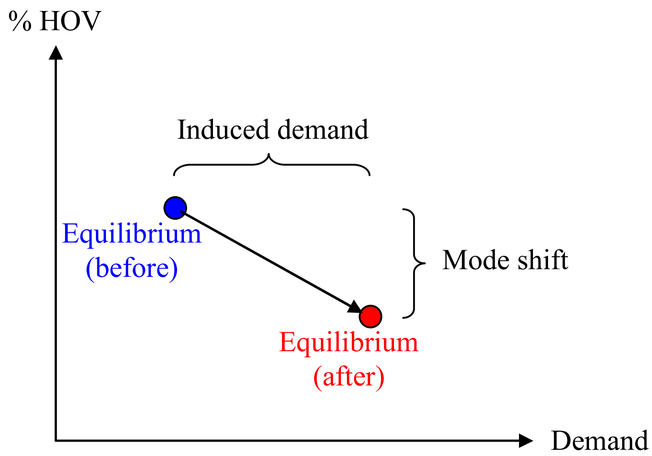


Figure 5.9. Likely impact of HOV lane conversion

It is interesting to determine how much induced demand the freeway can take before the HOV lane conversion will have adverse impacts on air quality. Based on the sensitivity analysis results in Table 5.8, the estimated emissions of the MF network were normalized by the estimated emissions of the SoCal and NoCal networks for the "existing conditions". If the normalized values are less than 1, then the lane conversion is considered to have positive impact because it reduces emissions. If the normalized values are greater than 1, then the lane conversion is considered to have negative impact because it increases emissions. The normalized values were plotted in Figure 5.10 for each level of %HOV. The plots in the left column are for the SoCal HOV lane conversion and the plots in the right column are for the NoCal HOV lane conversion.

In Figure 5.10, the % growth in demand at which the normalized value is equal to 1 is the "even emission point". That means the lane conversion which induces this percentage of demand will result in an equal emission between before and after the conversion. According to the figure, findings are:

- The percentage of even emission point is pollutant dependent. CO_2 is the pollutant with the lowest percentage of even emission point while CO is the pollutant with the highest percentage of even emission point.
- The range of percentages of even emission point for SoCal conversion is 5-11%, which is wider than that for NoCal conversion (2-5%).
- The minimum percentages of even emission point for SoCal conversion are 5%, 5%, and 6% for %HOV of 18%, 25%, and 32% respectively.

- The minimum percentages of even emission point for NoCal conversion are 2%, 3%, and 4% for %HOV of 18%, 25%, and 32% respectively.

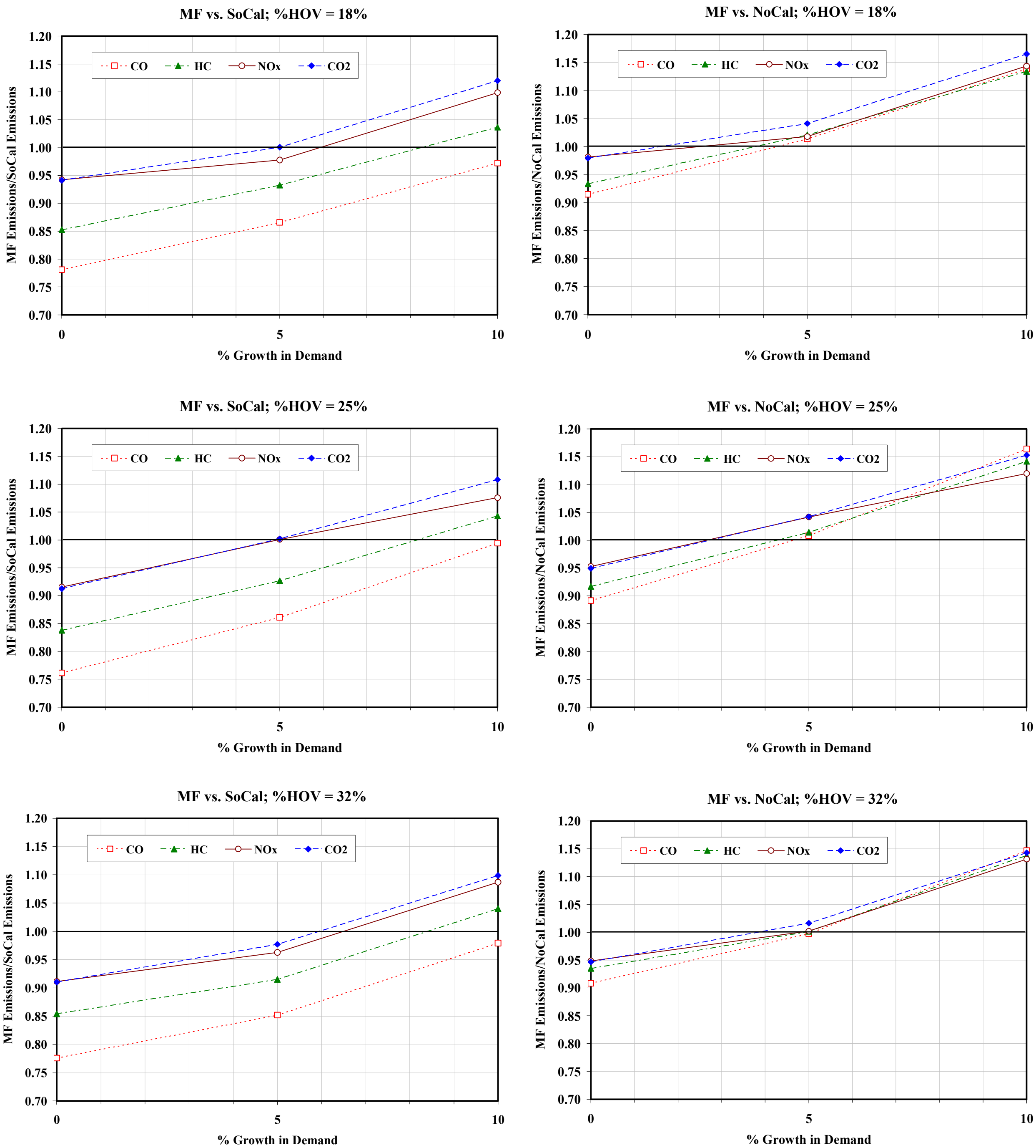


Figure 5.10. Emissions impact of lane conversion for SoCal (left) and NoCal (right)

5.5.3. Full-Time Enforcement vs. Part-Time Enforcement

The even emission point concept from the previous discussion can also be used to determine if an HOV lane should be enforced full-time or part-time. The same analysis can be repeated for other hours of the day and the conclusion regarding the type of lane use which will produce the lowest emissions can be drawn hour-by-hour. It is expected that during off-peak periods the amount of induced demand might not be high and that the lane could be used as an MF lane. On the other hand, during peak periods the induced demand from lane conversion might be more than the even emission point so that the HOV lane could be enforced. In this case, the HOV lane should be enforced part-time. However, for a freeway that the induced demand is expected to be high throughout the day, the HOV lane on that freeway should be enforced full-time.

6. Conclusions, Recommendations, and Future Work

The overall goal of this project was to evaluate the air quality benefits of existing HOV lanes in California and develop a public domain modeling toolset that can be used to provide reliable estimates of the air quality impacts of HOV lanes. The goal has been accomplished and several conclusions and recommendations can be made as follows:

HOV Lane Air Quality Evaluation

- The HOV lane air quality evaluation was conducted on selected freeways in both Northern and Southern California. It was found that under the existing demand, the HOV lanes on these freeways produce less pollutant emissions per lane as compared to the adjacent MF lanes. This was mainly due to the better flow of traffic in the lanes.

- Considering that the average vehicle occupancy in the HOV lanes was approximately double of the average vehicle occupancy in the MF lanes, the HOV lanes was also found to produce significantly less emissions per the same amount of people they carry.

Macroscopic Modeling Improvements

- Based on the data collected in this project, it was found that traffic dynamics as described by speed, acceleration, and road load power in HOV lanes were significantly different from those in MF lanes. This caused the corresponding emission rates in the two lane types to be different, especially for CO and CO_2.

- HOV lane emission correction factors were developed, which can be used to multiply freeway emission rates to obtain specific emission rates for HOV lanes. It is recommended that the developed HOV lane emission correction factors be used when modeling the air quality benefits/impacts of HOV lanes. These factors allow modelers to adjust the emission rates for HOV lanes to properly reflect the acceleration/deceleration characteristics of HOV lane operation at different traffic conditions, thus resulting in more accurate emission results.

- Because emission factors produced by EMFAC are trip-based, they are not a true representative of freeway emission rates. This will affect the results of the emissions modeling of HOV lanes. Until this issue is resolved in a new version of EMFAC, it is recommended that other emission models such as MOBILE6 or CMEM be used in the evaluation of air quality benefits/impacts of HOV lanes.

- Fleet compositions in HOV and MF lanes on the freeways studied were not found to be significantly different in terms of model year distribution. Modelers may use the same fleet input for both lane types when modeling the air quality benefits/impacts of HOV lanes. However, modelers may consider using separate fleets for each lane type if there is resource available for the data collection effort.

Microscopic Modeling Demonstration

- The deployment of the integrated traffic simulation and modal emission modeling tool for HOV lane air quality modeling was demonstrated. The tool was shown to be powerful for detailed analysis of project-specific, corridor-level implementations of HOV lanes.

- Under the same demand and percentage of HOVs in the traffic mix, the limited access HOV lane produced more pollutant emissions than the continuous access HOV lane. This was because the lane changing activities were highly concentrated over the limited length of the provided ingress/egress sections. Thus, the frequency and magnitude of acceleration/deceleration and resultant emissions of vehicles on these sections of the freeway were relatively high.

- Under the scenarios test, the conversion of the limited access HOV lane to another MF lane will provide emission benefit if it induces demand for less than 5% onto the freeway. The conversion of the continuous access HOV lane to another MF lane will provide emission benefit if it induces demand for less than 2% onto the freeway.

In terms of future work, several relevant research projects can be pursued based on the results of this project:

- As demonstrated, the integrated traffic simulation and modal emission modeling tool was powerful for detailed analysis of project-specific, corridor-level implementations of HOV lanes. It can be used more to determine the best operating strategy for HOV lanes on a corridor-by-corridor basis.

- In addition, the tool can be used for other types of evaluation, for example, emissions impact of clean vehicles (e.g. hybrid vehicles and compressed natural gas buses) in HOV lanes, emissions impact of high-occupancy toll (HOT) lanes, etc.

- In this project, the lane choice decision of HOVs in the SoCal network was modeled by the dynamic feedback assignment technique in PARAMICS. The technique allows drivers to perceive updated travel costs from a decision node to the destination. In reality, the updated travel costs that the drivers perceive may not be the cost for the entire remaining path of their travel. Rather, they often make lane choice decision based on the cost (congestion) they visually observe, which could be only for a couple of links ahead. Therefore, a modified dynamic feedback assignment algorithm could be developed, tested, and implemented for improved modeling of not only HOV lane choice behavior but also general route choice behavior.

- In this project, the lane choice decision of HOVs in the NoCal network was modeled by by the “HOV behavior” plug-in (for the NoCal network). However, this plug in is not able to influence HOV lane choice decision based on lane-level travel costs. Therefore, a modified plug-in could be developed, which takes into account traffic condition in MF lanes when modeling HOV lane choice behavior.

- The integrated traffic simulation and modal emission modeling tool could be further enhanced with the integration of pollutant dispersion calculation components (e.g., those based on CALINE4 algorithm). The enhanced tool can then be used for detailed hot spot analysis by Caltrans staff.

7. References

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