Evaluating Air Quality Benefits of
Freeway High Occupancy Vehicle (HOV) Lanes in Southern California

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ABSTRACT

In the past decade, a variety of questions have been raised concerning the effectiveness of high occupancy vehicle (HOV) lanes. In Southern California, HOV lanes evaluation studies have recently been conducted, justifying the effectiveness of HOV lanes in several ways. However, very little research has been performed in evaluating the *air quality* benefits of HOV lanes. In this paper, a study is described that examines operational differences in traffic dynamics between HOV lanes and mixed-flow (MF) lanes, and evaluates their impacts on vehicle emissions. Four general HOV lane scenarios were identified: under-utilized, neutral, well-utilized, and over-utilized. Extensive driving trajectories in both lane types for each scenario were collected. Their speed profile and joint speed-acceleration frequency distribution were analyzed and compared. Vehicle emissions and fuel consumption were then estimated using a state-of-the-art modal emissions model. The results show that HOV lanes produce lower emission rates per vehicle per mile in most cases, except when they are under-utilized. When normalized by average vehicle occupancy, HOV lanes produce much lower emission rates per the same amount of travel demand on the order of 10-70%. In almost every case, HOV lanes produce less emissions mass on a per lane basis than MF lanes. Southern California freeway lane performance matrices show that on a typical weekday during the summer of 2005, HOV lanes operated mostly under Scenarios 1 and 2 during peak periods. Overall, they were well-utilized about 14-17% of the time. According to the emissions estimates, the HOV lanes are considered effective in reducing vehicle emissions.

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 add 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 *(1, 2)*. 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 *(3)*.

The types of HOV facilities are different from state to state. In California, they are also different by region. 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. In Southern California, HOV lanes are also concurrent flow but 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.

1.1. HOV System Performance Evaluation

In the past decade, there has been a growing concern nationwide regarding the effectiveness of HOV system 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 *(4-8)*. Although varying among areas, common performance measures widely used are vehicle volume, average vehicle occupancy, speed, and travel time *(9)*. In California, the effectiveness of HOV lanes was reviewed and discussed earlier in the report by the Legislative Analyst Office *(10)*. 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 performance evaluation studies conducted in Southern California *(2, 11)*. Some of the 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.

However, other HOV lane studies have been carried out with contrasting results. For example, Kwon and Varaiya 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 *(12)*.

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 portable emissions monitoring systems (PEMS) *(13)*. 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 such as 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.   Objectives and Scope of the Study

The primary goals of this study are to determine the differences in operational characteristics of HOV lanes as compared to MF lanes, and to evaluate their impacts on vehicle emissions. Specific objectives are: (a) to examine and compare driving trajectory in HOV and MF lanes under various traffic conditions and (b) to estimate and compare the resulting emissions from the two lane types. The study focuses on the estimation and comparison of only running emissions produced in HOV lanes and MF lanes under existing demand in both lane types. The geographic area of this study is limited to Southern California.

2. METHODOLOGY

2.1. Analysis Scenarios

The setup of 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 density, and thus speed and flow *(14)*. Since emission rates are highly dependent on speed; flow is a surrogate for VMT; and both emission rates and VMT are two major factors contributing to emissions, LOS is a measure that can be rationally related to emissions.

Figure 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 discussed below.

- *Scenario 1 (under-utilized)*: This is a 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 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 condition.

- *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.

2.2. 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 data in July and August 2005. 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 freeway performance data were obtained from Caltrans' Freeway Performance Measurement System (PeMS) *(15)*. PeMS is an interactive system that allows users to investigate various performance measures of the freeway system historically and in real time. It collects 30-second embedded loop detector data from a large number of sensors covering several thousand miles of interstate and state highways in California. The system filters, processes, aggregates, and examines the data before disseminating the information on the Internet through the PeMS website *(15)*. In this study, PeMS is extensively used as a source of many useful freeway data, such as volume, speed, LOS, as well as their statistics.

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 *(16)*. Second, the selected sites should have reasonable amount of PeMS loop detectors; and these detectors 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. Figure 2 shows the locations of three freeway segments (SR-91 E, SR-60 E, and I-10 W) that were chosen based on these two criteria. A description of these locations is given in Table 1. They mostly have 3+1 (MF+HOV) lanes with the speed limit of 65 mph. The number of good loop detectors at these locations was more than 80% at the time of study.

2.3. 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 freeways. 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 maintained a consistent gap distance from the vehicle in front. For the runs in MF lanes, the driver was instructed to drive in the lane adjacent to an HOV lane in order to minimize the effect of vehicles entering and exiting freeway. However, lane changing was still allowed in case the vehicle in front was running at slower speeds than the majority of traffic in other MF lanes. 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.

The driving trajectory data collected in the field were used to calculate second-by-second acceleration/deceleration rates before they were filtered into a database. 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 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 representation 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 faster speed than average traffic.

2.4. Vehicle Emissions Estimation

Vehicle fleet emissions were estimated using the Comprehensive Modal Emissions Model (CMEM), which was developed mainly for the purpose of microscopic estimation of on-road emissions from light-duty and heavy-duty vehicles. For detailed information regarding CMEM, please see *(17-19)*. To date, CMEM has been applied to a variety of project-specific evaluations of transportation control measures and traffic flow improvements as well as many intelligent transportation systems (ITS) benefit assessments. At present, CMEM is considered to be the most detailed and best tested estimates of vehicle exhaust emissions at different speeds and accelerations *(20)*. 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 Riverside County, California based on year 2005. All scenarios were evaluated using the same vehicle fleet for a fair comparison.

3. RESULTS AND DISCUSSION

3.1. Comparison of Traffic Dynamics

Figure 4 shows the 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 1 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 *(1)*.

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 steady-state cruise.

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 5. 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 turns to be unstable as seen by the more spread out SAFDs of 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. It is shown that zero speed provides some deceleration values. This is because second-by-second acceleration/deceleration rates were calculated as the difference between the speed of a given record and the speed of the previous record. With this calculation method, every first second the vehicle came to stop (i.e. zero speed) was accompanied by a deceleration value. 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 *(2)*. 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.

3.2.   Comparison of Emissions Estimates

The estimated emission rates per vehicle per mile from CMEM are summarized in Table 1. The percentage differences in emission rates between the two lane types were calculated and plotted in Figure 6(a). 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 to result in estimated emission rates per person. The average vehicle occupancy of HOV and MF lanes calculated from data collected on SR-60 E and SR-91 E are 2.19 and 1.10, respectively *(5)*. Figure 6(b) 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, as shown in Table 1. 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 1. Again, the percentage differences between the two lane types were computed and plotted in Figure 6(c). 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.

3.3.   Freeway Lane Performance Matrix

According to the previous results, the 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 of freeway lane LOS was performed using historical LOS data for HOV and MF lanes extracted from PeMS. The data are available in the form of the percentage breakdown of each LOS (discrete probability distribution) in each hour of a day for each lane type. Due to the lack of *priori* knowledge regarding the probability distribution of LOS in MF lanes conditional on the LOS in HOV lanes, it was assumed to be independent. Examples of the analysis results for the entire SR-91 corridor (both eastbound and westbound) from July to September 2005 are presented in Figure 7. 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. Overall, they were well-utilized about 14-17% of the time. 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 assumption regarding the *priori* probability made in the Bayesian analysis, and (c) actual 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.

4.   CONCLUSIONS AND FUTURE WORK

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

- 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 yet 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.

The effectiveness of HOV lanes in Southern California with regard to alleviating congestion, providing travel time savings and trip time reliability, increasing person-moving capacity, and improving system efficiency has been verified by other earlier studies. This paper presents the results that also verify the benefits of HOV lanes in terms of improving air quality under various operation scenarios. The results presented herein are a part of a larger project that looks at several aspects of air quality benefits of HOV lane. A more comprehensive evaluation will take into account the possible difference in fleet composition between HOV and MF lanes when estimating vehicle emissions.

ACKNOWLEDGMENTS

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TABLE 1 Summary Results of Probe Vehicle Trajectory, Freeway Performance, and Emissions Estimates

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_2	385.70	428.41	468.63	374.47	541.59	335.62	557.21	370.33
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
Fuel	128.90	147.67	155.14	123.99	173.12	109.34	178.23	119.25
Emissions rate estimates (g/person/mi)								
CO_2	350.64	195.62	426.02	170.99	492.35	153.25	506.56	169.10
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
Fuel	117.19	67.43	141.03	56.62	157.38	49.93	162.02	54.45
Emissions mass estimates (metric tons/hr/ln)								
CO_2	6.098	2.256	6.173	3.046	4.576	2.482	7.429	5.524
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
Fuel	2.038	0.778	2.044	1.009	1.463	0.809	2.376	1.779

[a] *Data extracted from PeMS website (PeMS5.4, 2005)*   [b] *Weighted to average fleet in Riverside, 2005*

LOS of Mixed-Flow (MF) Lane

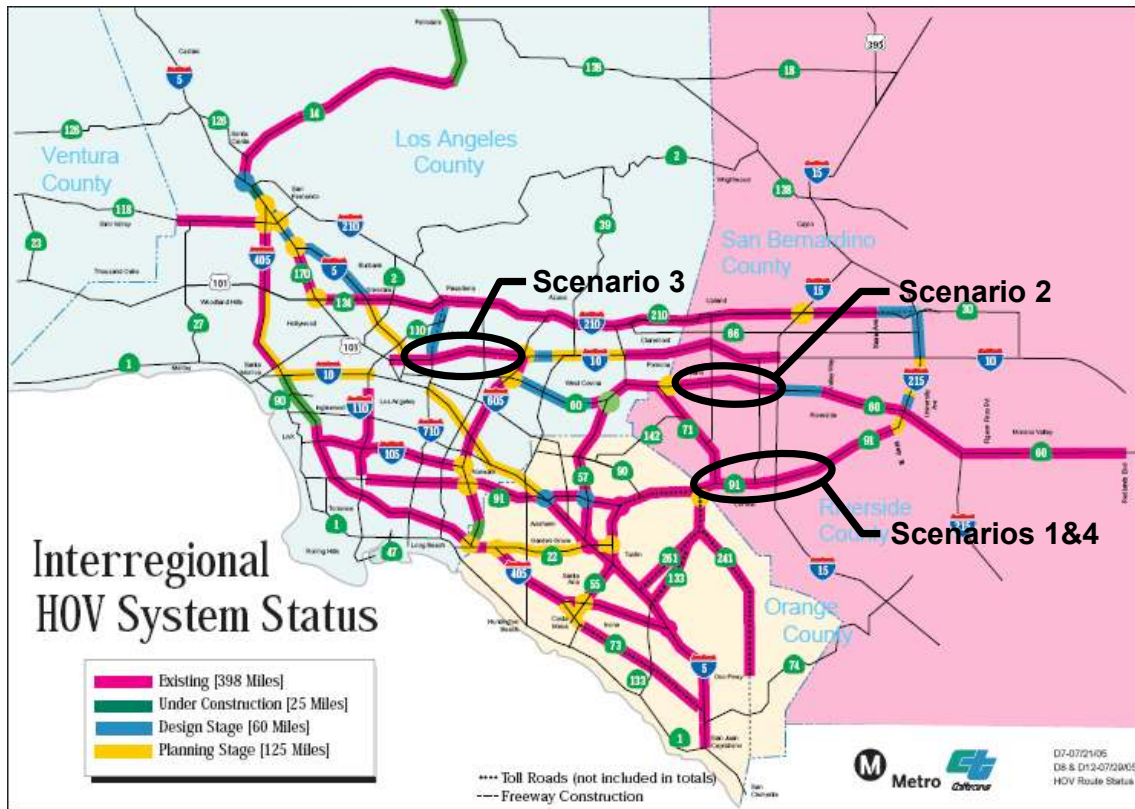|	%	A	B	C	D	E	F
	A	0	1	1	1	3	3
LOS	B	X	0	2	2	3	3
of	C	X	X	0	2	3	3
HOV	D	X	X	X	0	4	4
Lane	E	X	X	X	X	0	4
	F	X	X	X	X	X	0

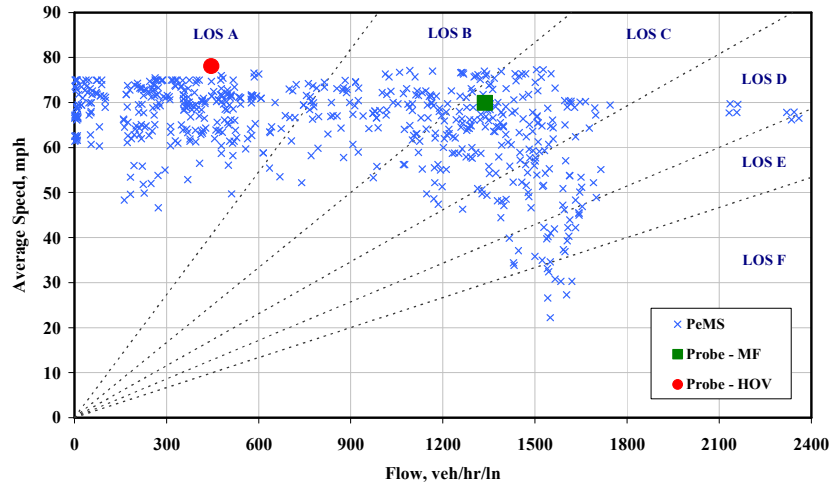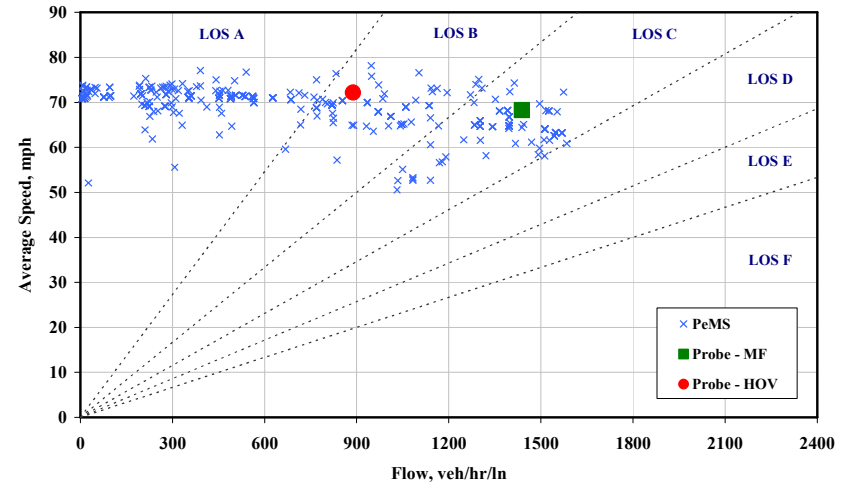**FIGURE 1 Freeway lane performance matrix.**
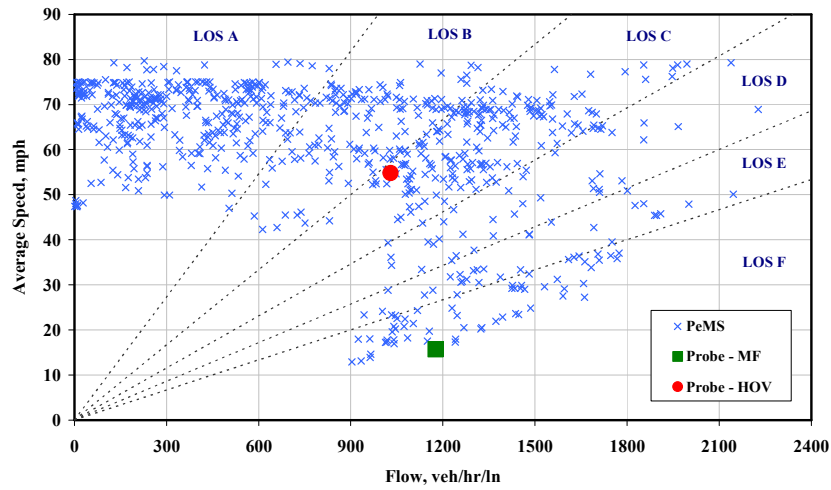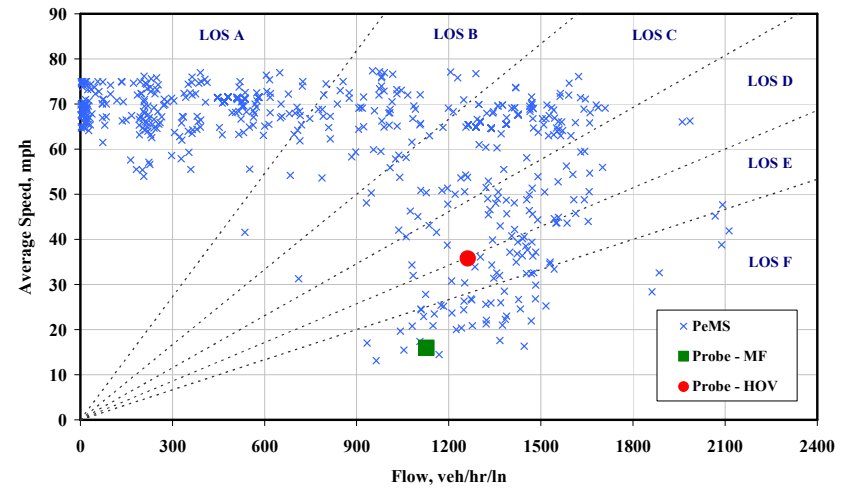
FIGURE 2 Sites of probe vehicle runs.

(a) Scenario 1: under-utilized

(b) Scenario 2: neutral

(c) Scenario 3: well-utilized

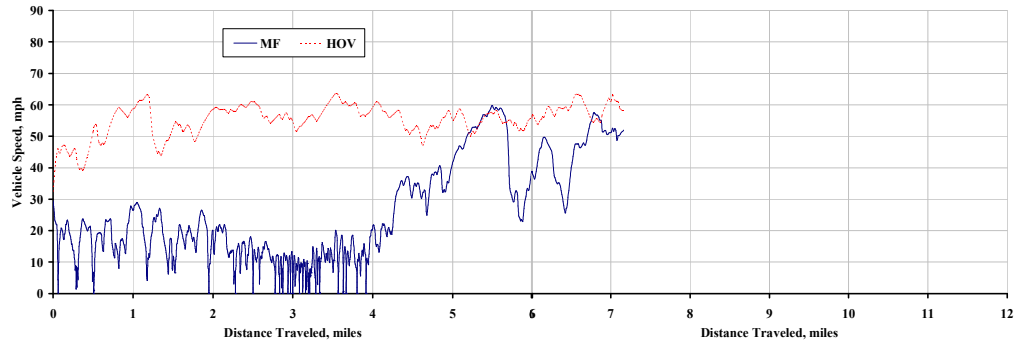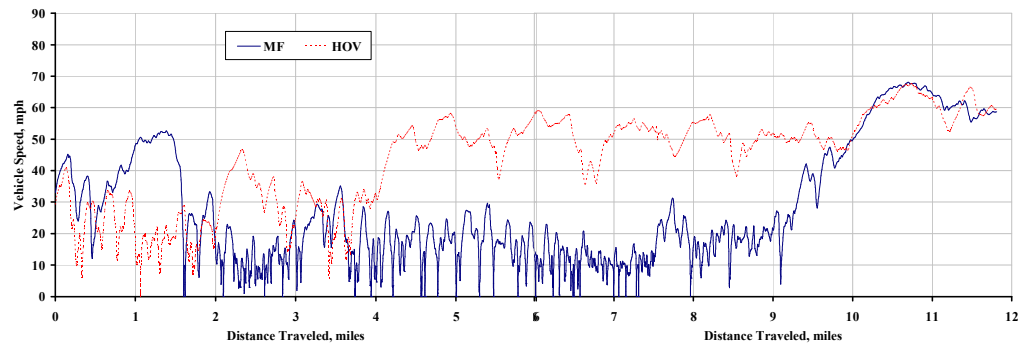(d) Scenario 4: over-utilized

FIGURE 3 Speed-flow relationship for each scenario.
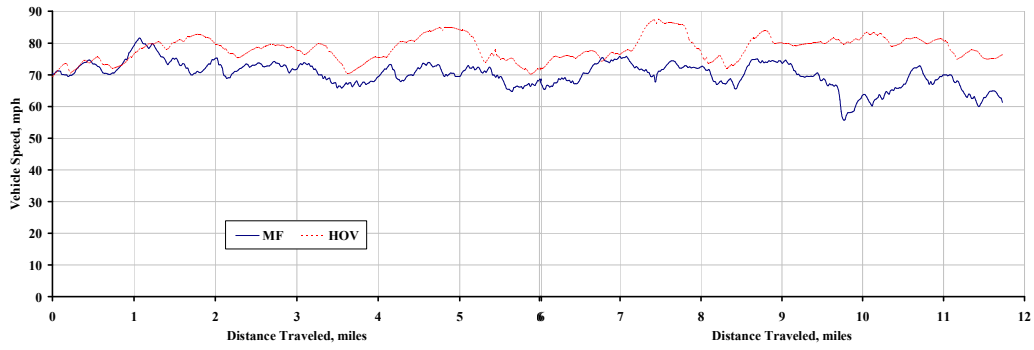
(a) Scenario 1: under-utilized
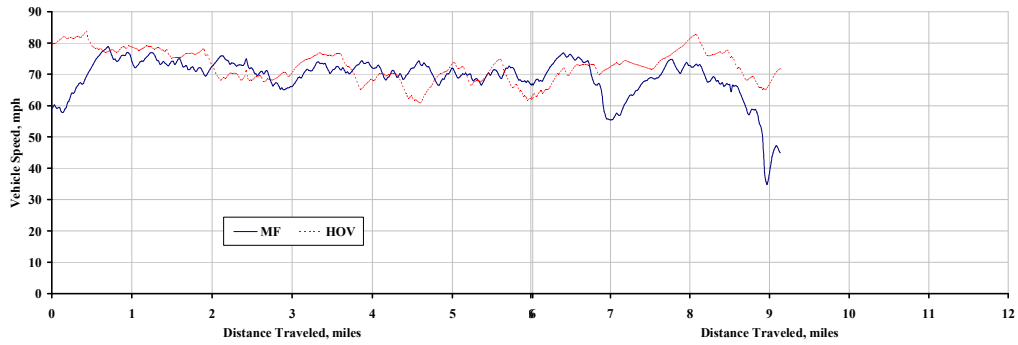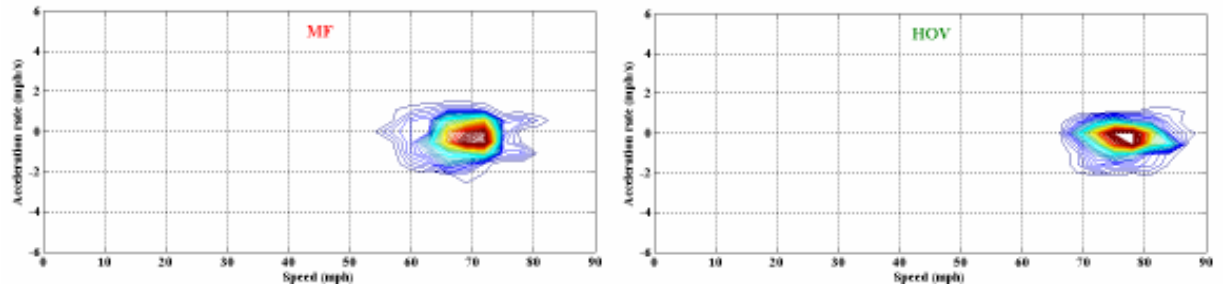

(b) Scenario 2: neutral
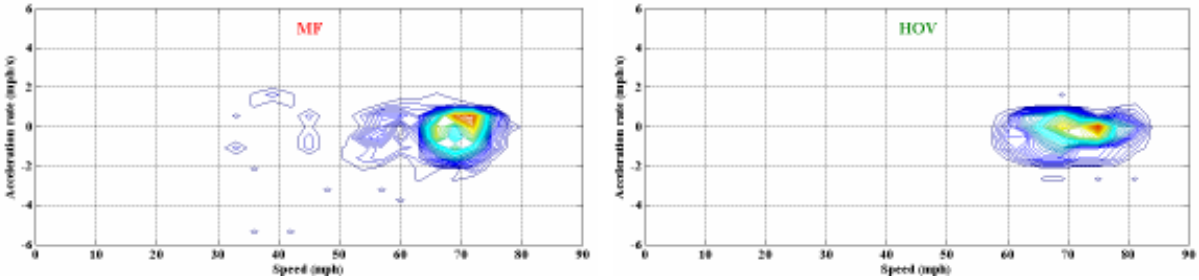

(c) Scenario 3: well-utilized
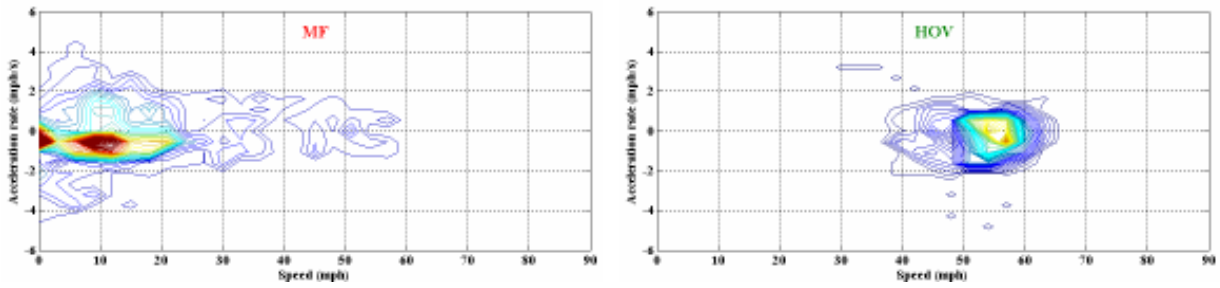

(d) Scenario 4: over-utilized

FIGURE 4 Example speed trajectories of probe vehicle runs.
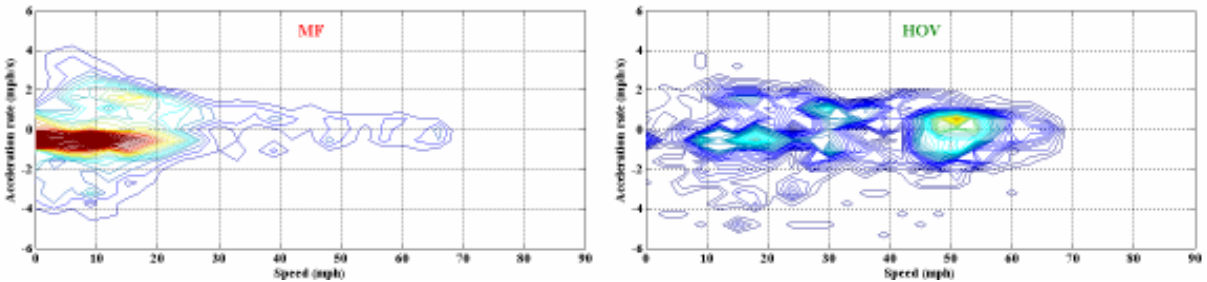
(a) Scenario 1: under-utilized
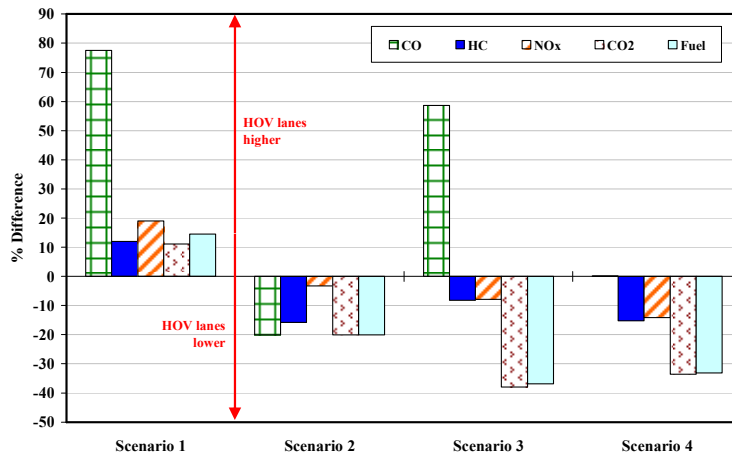
(b) Scenario 2: neutral
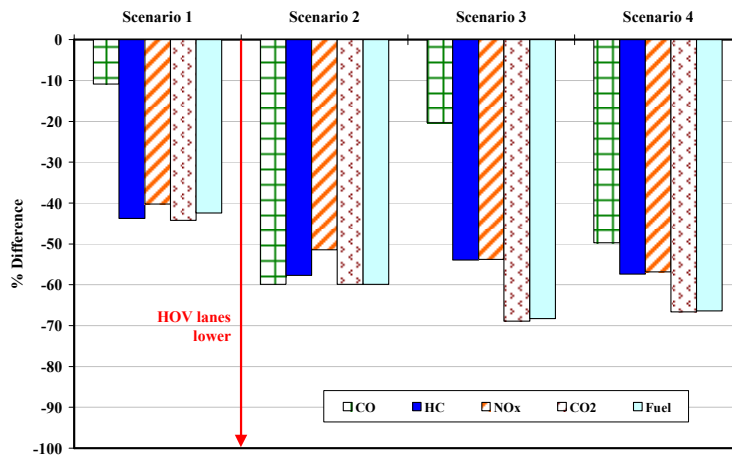
(c) Scenario 3: well-utilized
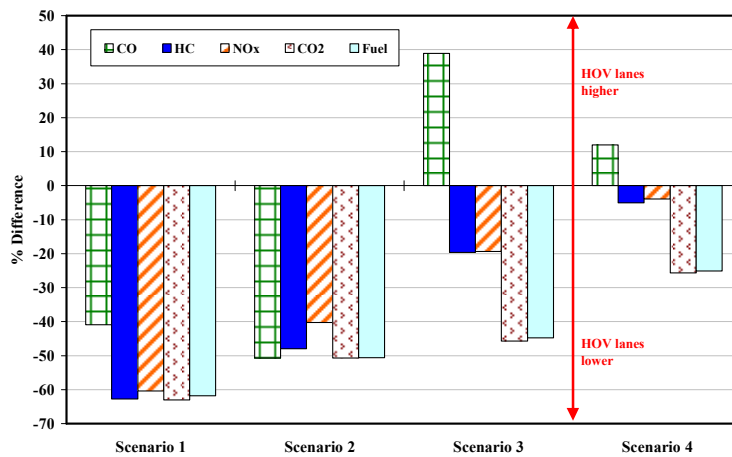
(d) Scenario 4: over-utilized

FIGURE 5 Joint speed-acceleration frequency distribution.

(a) % difference in emission rates per vehicle

(b) % difference in emission rates per person

(c) % difference in resulting emissions mass

FIGURE 6 Differences in emissions between HOV and MF lanes.

(a) AM peak

MF %	A	B	C	D	E	F
A	0	6	27	7	3	3
B	0	4	21	7	3	3
HOV 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.)

(b) PM peak

MF %	A	B	C	D	E	F
A	0	1	5	1	0	1
B	0	2	24	7	3	6
HOV 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.)

(c) Off peak

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

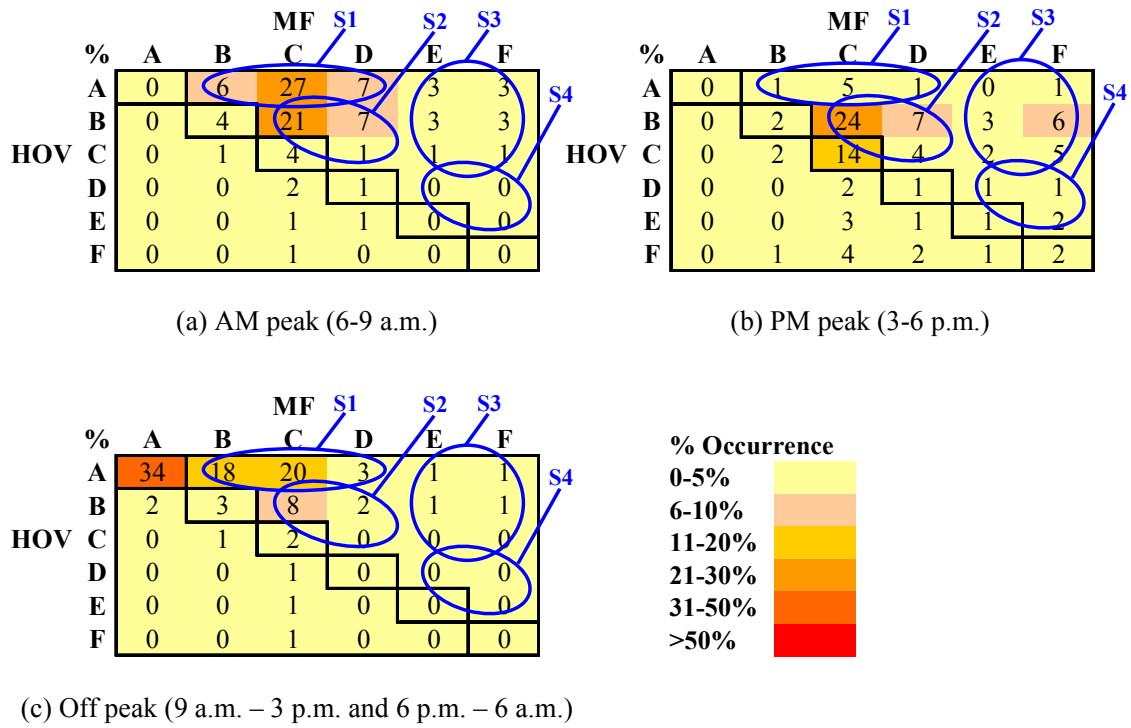- 0-5%
- 6-10%
- 11-20%
- 21-30%
- 31-50%
- >50%

FIGURE 7 Probabilistic performance matrix of SR-91 corridor (weekday, Jul- Sep, 2005).