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16. ABSTRACT

The Center for Environmental Research and Technology (CERT) at the University of California, Riverside, successfully completed a previous research on the effectiveness of high-occupancy vehicle (HOV) lanes at improving air quality for the California Department of Transportation (Caltrans). As part of that research, analysis tools were developed to evaluate the air quality benefits of limited access HOV lanes, which are commonly found in Southern California. This project used researcher(s) unique skill sets in vehicle activity data collection, traffic simulation and emission modeling as well as extensive experience in this research area to expand the capability of the developed tools to enable air quality impact evaluation of the other types of managed lanes, including continuous access HOV lanes (commonly found in Northern California) and high-occupancy toll (HOT) lanes. These enhanced analysis tools willallow Caltrans' technical staff to compare emission impacts of projects involving the addition of new lane(s), either general-purposed (GP) or any type of managed lanes, or the conversion of existing lane(s) from one type to another against the no-build and other alternatives. The analysis tools will be compatible with the California's EMFAC model, and will be in a spreadsheet platform which is easy to use by Caltrans' technical staff. In addition, prepared user's guide documentation and conducted user training in order to ensure an effective knowledge and technology transfer to Caltrans.

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FINAL REPORT

Prepared for:

California Department of Transportation

By:

Center for Environmental Research and Technology
University of California at Riverside

May 2014

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List of Abbreviations

AVO	Average vehicle occupancy
Caltrans	California Department of Transportation
CARB	California Air Resources Board
CE-CERT	College of Engineering - Center for Environmental Research and Technology
CMEM	Comprehensive Modal Emissions Model
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EMFAC	Emission Factor (model)
EPA	Environmental Protection Agency
GP	General-purpose
GPL	General-purpose lane
GPS	Global positioning system
HC	Hydrocarbons
HOT	High occupancy toll
HOV	High occupancy vehicle
KS	Kolmogorov-Smirnov
LOS	Level of Service
MF	Mixed-flow
ML	Managed lane
MOVES	Motor Vehicle Emission Simulator
NO_x	Oxides of Nitrogen
opMode	Operating Mode
PeMS	Freeway Performance Measurement System
$PM_{2.5}$	Particulate 2.5 microns in diameter or less
PM_{10}	Particulate 10 microns in diameter or less
ROG	Reactive Organic Gases
SAFD	Speed-Acceleration Frequency Distribution
THC	Total hydrocarbons
TOG	Total Organic Gases
VDS	Vehicle detector station
VMT	Vehicle Miles Traveled
VSP	Vehicle specific power

1. Introduction

California has the most extensive managed lane system in the nation, approximately 40% of the total managed lane miles. Managed lane system in California comprise of high-occupancy vehicle (HOV) lanes, express lanes or high-occupancy toll (HOT) lanes, and park-and-ride facilities. Today, over 1,500 lane miles of HOV and HOT lanes are either in operation or under construction with over 1,200 additional lane miles programmed or proposed by the California Department of Transportation (Caltrans) [California Department of Transportation, 2014]. In essence, managed lanes have been and will continue to be an integral part of the California freeway system. Therefore, it is necessary for Caltrans to ensure that these managed lanes are best operated and meeting their purposes of improving mobility, trip time reliability, and air quality.

A critical component of improving California's air quality is the evaluation of air quality benefits of various transportation projects, including managed lanes, in California. Managed lane is a viable alternative, and in most cases is the only alternative, in meeting federal air quality conformity standards for capacity-increasing improvement projects in metropolitan areas. Implementing HOV or HOT lanes represents one approach that is being used in metropolitan areas throughout the state to respond to growing traffic congestion, declining mobility, as well as air quality and environmental concerns. Therefore, there is a need for more research and evaluation of air quality benefits of managed lanes in California, especially in the area of developing analysis tools.

The College of Engineering - Center for Environmental Research and Technology (CE-CERT) at the University of California, Riverside, previously completed a research project for Caltrans on the effectiveness of HOV lanes at improving air quality [Boriboonsomsin and Barth, 2006]. As part of that research project, analysis tools were developed to evaluate the air quality benefits of limited access HOV lanes, which are commonly found in Southern California.

In this research project, we expand the capability of the analysis tools to enable air quality benefit evaluation of other types of managed lanes, including continuous access HOV lanes (commonly found in Northern California) and HOT lanes. These enhanced analysis tools allow users to compare emission impacts of projects involving the addition of new lane(s)—either general-purpose (GP)[1] or any type of managed lanes—and the conversion of existing lane(s) from one type to another against the no-build and other alternatives. The analysis tools are purposefully designed to work in conjunction with the California Air Resources Board (CARB)'s EMFAC model, which is the regulatory emission model for California. The analysis tools are in a spreadsheet platform, which is easy to use, and are accompanied by user's guide to ensure an effective and convenient deployment by Caltrans staff.

[1] Also called mixed-flow (MF)

1.1. Managed Lanes in California

Managed lanes are an operational practice utilized to address congestion by controlling traffic movement on the highway. Two common approaches to lane management are: 1) restricted use based on vehicle eligibility and 2) control of access through limited ingress/egress. Vehicle eligibility can be based on occupancy or vehicle type. HOV lane is the most common type of managed lanes in California. According to California state law, the goals of HOV lane are to reduce congestion and improve air quality on the State Highway System. The law states that HOV lane is used "to stimulate and encourage the development of ways and means of relieving traffic congestion on California highways and, at the same time, to encourage individual citizens to pool their vehicular resources and thereby conserve fuel and lessen emission of air pollutants."

Caltrans' Division of Traffic Operations has developed guidelines for planning, design, and operations of HOV facilities [California Department of Transportation, 2003]. The guidelines indicate that the operation of an HOV facility is closely linked to the design of the facility, the traffic demand in the freeway corridor, and the geographic distribution development as well as the associated travel patterns in the region. In areas that experience regular periods of congestion for many hours of the day, full-time HOV operations with restricted access is favored to maximize opportunities for HOV utilization and travel time savings, thereby providing incentives to rideshare and relieve the rate of congestion.

Conversely, in areas where commute patterns generally consist of short definable peak periods and clear directional flows, part-time, peak period HOV operations are preferred. With part-time operations, the HOV lanes ideally should look like general purpose lanes to minimize the potential for motorist confusion when they are open to general-purpose traffic. Accordingly, it is preferred that access into and out of HOV lanes that operate part time not be restricted. Figure 1-1 shows the two configurations of HOV lanes in California. The limited access HOV lane is commonly found in Southern California while the continuous access HOV lane is dominant in Northern California.

In addition to HOV lanes, there are several express lanes in California. The most well-known one is probably the State Route 91 (SR-91) express lanes in Orange County, which are owned and operated by the Orange County Transportation Authority. The SR-91 express lanes have been a critical component of the Orange-Riverside Counties transportation corridor. The lanes are now operated as HOT lanes with variable toll schedules depending on time of day and day of week. Examples of other express lanes in California include the Interstate 15 (I-15) express lanes in San Diego County, the Interstate 680 (I-680) express lanes in Alameda County, and the Interstate 110 (I-110) HOT lane in Los Angeles County.

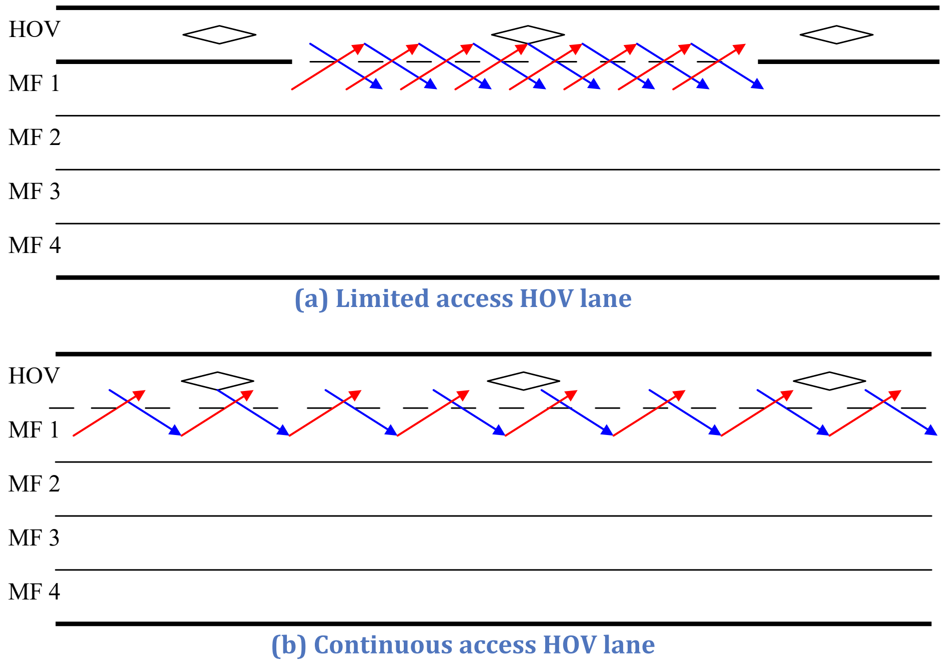


Figure 1-1. Configurations of HOV lanes in California

1.2. Previous Related Research

CE-CERT at the University of California, Riverside, previously completed a research project for Caltrans to evaluate air quality benefits of existing HOV lanes in California and develop analysis tools that can be used to provide reliable estimates of the air quality impacts of HOV lanes [Boriboonsomsin and Barth, 2006]. The summary of research activities and findings from this project is given below.

1.2.1. HOV Lane Air Quality Impact Evaluation

An evaluation of air quality benefits of HOV lanes was performed by comparing the emissions from HOV lanes versus their GP 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 resulting 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 and 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 under 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 during the hours HOV lanes were in operation and when they were not.

Key findings from this evaluation study are that: 1) under the existing vehicle demand, the HOV lanes on the study freeways produce less pollutant emissions per lane as compared to the adjacent GP 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 GP lanes, the HOV lanes are also found to produce far less emissions per person. These findings are applicable to both HOV lanes in Southern California and HOV lanes in Northern California when they are in operation [Boriboonsomsin and Barth, 2007].

1.2.2. Improvements to HOV Emission Modeling Process

The objective of this part of the research is to make improvements to the emission calculation process for HOV lanes. It is well understood that HOV lanes experience higher traffic speed than GP lanes for most of the time, depending on traffic conditions. Therefore, in order to improve emission estimates of freeways with both HOV and GP lanes, it is necessary to separately apply emission factors to the two lane types based on the traffic speed in each lane type. In addition to speed, there are other factors contributing to emission estimates that need to be examined for differences between HOV and GP 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 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 lane and GP lane on the three study freeways.

To examine the differences in driving trajectories (i.e., speed versus time profiles), a database of driving trajectory data for both HOV and GP lanes was compiled along with level of service (LOS) congestion information from a number of freeways. The data were then grouped according to the designated LOS before statistical analyses were performed on it. According to the statistical analysis results, traffic dynamics (as described by speed, acceleration, and road load power) in HOV lanes were significantly different from those in GP lanes under every LOS. When calculating the emissions corresponding to these datasets, 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 type emission adjustment factors for HOV lanes.

The development of lane type emission adjustment factors for HOV lanes was based on finding the ratio of HOV lane emissions rates to GP lane emissions rates at the same average vehicle speeds. First, HOV and GP emission rates were plotted in 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 [Boriboonsomsin et al., 2009]. Using the equations, the ratio of HOV emission rates to GP emission rates at different levels of average speed for each pollutant was computed. These ratio values can be used as HOV lane emission adjustment factors by multiplying them to freeway emission rates to obtain emission rates specific to 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 under different traffic conditions, thus resulting in more accurate emission estimates.

1.2.3. Demonstration of Microscopic Modeling Tools

The objective of this part of the research is to demonstrate the deployment of an integrated microscopic traffic simulation and modal emissions modeling tool to evaluate air quality impacts of HOV lane at a corridor level. A freeway corridor 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 corridor be used effectively?” Three lane configurations were modeled and the resulting pollutant emissions were compared. These lane configurations are: 1) limited access HOV lane (Southern California style), 2) continuous access HOV lane (Northern California style), and 3) standard GP lane. First, the coded model network, demand, and other model parameters were extensively verified and validated following Caltrans’ guidelines to ensure that the model appropriately replicated the existing roadway and traffic conditions. Next, the model network was used to analyze multiple what-if scenarios and to conduct numerous sensitivity analyses with respect to changes in vehicle 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 from the modeling is that under the same vehicle 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 designated ingress/egress sections. With this constraint, 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 mainline traffic in all lanes. As a result, the frequency and magnitude of acceleration/deceleration, and thus emissions, of vehicles on ingress/egress sections are relatively higher [Boriboonsomsin and Barth, 2008a].

According to the what-if scenarios tested, for the existing conditions on the simulated freeway, the conversion of the limited access HOV lane to a GP 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 a GP 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, including carbon monoxide (CO), hydrocarbon (HC), oxides of nitrogen (NO_x), and carbon dioxides (CO_2) [Boriboonsomsin and Barth, 2008b]. However, if HOV lanes are converted to GP lanes, it is possible that vehicle travel demand will increase, due to former carpoolers splitting and generating additional vehicle trips to meet their travel needs. As a result, emissions would likely increase.

1.3. Objectives and Scope of the Project

In the previous HOV air quality research, lane type emission adjustment factors were developed for limited access HOV lanes only. Thus, the objectives of this research project are to:

1. Expand the lane type emission adjustment factors to include emission adjustment factors for continuous access HOV lanes and HOT lanes

2. Develop EMFAC-compatible spreadsheet tools for analyzing the emission impacts of HOV and HOT lanes

3. Support deployment of spreadsheet tools through user's guide documentation and user training.

In terms of scope, the research is aimed at developing spreadsheet analysis tools that can be used to analyze the emission impacts of the following project types and lane types:

- Project types
  - Addition of new lane(s)
  - Conversion of existing lane(s)
  - Change in hours of operation of HOV/HOT lanes
  - Change in eligibility requirement for using HOV/HOT lanes
- Lane types
  - GP lane
  - Limited access HOV lane
  - Continuous access HOV lane
  - HOT lane

Because the lane type emission adjustment factors are to be used in conjunction with EMFAC, they are developed for the following emissions:

- Carbon dioxide (CO_2)
- Carbon monoxide (CO)
- Total hydrocarbon (THC)
- Oxides of nitrogen (NO_x)
- Coarse particulate matter (PM_{10})
- Fine particulate matter ($PM_{2.5}$)

2. Modeling Emission Impacts of Managed Lanes

Managed lanes have different operating characteristics from a regular GP lane. However, these differences are not typically accounted for in planning assumptions and analysis tools such as travel demand models. This also means that emission estimates of managed lanes that are based on vehicle activity inputs from planning analysis tools do not reflect those differences in operating characteristics as well. Therefore, in this research we use a hybrid approach where the unique operating characteristics of managed lanes are first captured in real-world. Then, a set of adjustment factors is developed based on the operating characteristics of managed lanes, which can be used to adjust vehicle activity inputs from planning analysis tools to result in more accurate emission estimates of these lanes. The following sections in this chapter describe the underlying concepts and the methodological framework of this hybrid approach.

2.1. Emission Modeling of Freeways with Managed Lanes

There are generally three modeling approaches that may be employed to estimate on-road mobile emissions from freeways with managed lanes. These approaches are:

1. *Using the same emissions factors for all freeway lanes*: This is the coarsest approach. This approach does not differentiate between managed and GP lanes. It uses the average traffic speed across all freeway lanes in determining emission factors (in terms of grams per miles) for each freeway segment, which are then multiplied by vehicle miles traveled (VMT) on the segment to result in total emissions. The VMT on a freeway segment are the sum of VMT in managed and GP lanes.

2. *Using separate emission factors for managed and GP lanes*: This approach takes into account the difference in traffic speed between managed and GP lanes. It applies separate average speed values for managed and GP lanes to emission factor models (e.g., EMFAC) to obtain separate emission factors for each lane type. VMT and emissions are also calculated separately for each lane type before they are combined to produce total emissions for the freeway segment.

3. *Using modal emission estimates for vehicles in managed and GP lanes*: The modeling in this approach is performed at a much higher resolution of data and calculation than the previous two. It is performed on an individual vehicle and operating mode basis. This approach not only accounts for the difference in speed between the two lane types, but also the difference in acceleration. These differences are captured in second-by-second vehicle activity, of which associated second-by-second emissions can be estimated using modal emission models such as Comprehensive Modal Emissions Model (CMEM) [Barth et al., 2000].

Note that only the second and the third approaches allow for a proper evaluation of the emission impacts of managed lanes because they enable the calculation of emissions from each lane type of a freeway. Between the two approaches, one may be preferred over another depending on the purpose and the required level of detail of the analyses. For instance, for the analyses in which emission results could be sensitive to vehicle operations (e.g. comparing emissions resulting from different design configurations), the third approach is more appropriate [Boriboonsomsin and Barth, 2008a]. On the other hand, the second approach is more suitable for constructing regional on-road emissions inventories where the use of the third approach could be time and cost prohibitive. This research is aimed at making improvements to the emission inventorying process of freeways with managed lanes based on the second modeling approach.

2.2. Managed Lane Demand and Supply

For a freeway with managed lane such as an HOV lane, its total capacity is the sum of the capacity of HOV and GP lanes. The operational performance of this freeway is dependent on two factors: 1) overall vehicle demand and 2) proportion of HOV in the traffic mix (%HOV). The increase in overall vehicle demand will affect the operational performance of the freeway as there will be more vehicles using the limited capacity of the freeway. As the demand approaches the total freeway capacity, congestion may occur. The %HOV is important in the sense that it determines how many vehicles are eligible to use the HOV lane. It is also concerned with whether the split between eligible and ineligible vehicles is balanced with the split between the lane capacity or not. For example, for a freeway section with three GP lanes and one HOV lane, the HOV lane accounts for 25% of the total capacity. If the %HOV is 10%, the HOV lane will be under-utilized and the remaining 90% of the traffic will be forced to use the 75% capacity of the freeway. Nevertheless, the impact may not be significant if the overall vehicle demand is well below the total capacity. In essence, both factors and the interaction between them are important in determining how a freeway with HOV lane would perform. This is illustrated in Figure 2-1.

Therefore, in the assessment of HOV lane performance under various operating conditions, it may also be desirable to perform sensitivity analyses of the overall vehicle demand and %HOV. The overall vehicle demand could be varied from the existing off-peak level to the peak level projected in the horizon year. The %HOV could be varied from the low extreme of less than 5% to the other extreme of 50% or more. In addition, the HOV lane violation by ineligible vehicles can also be accounted for in the analysis by associating it with the %HOV. That is, the violating vehicles will artificially increase the %HOV in the traffic stream. Then, the resulting freeway lane performance can correlate back to various levels of the violation rate. Currently, Caltrans' HOV guidelines identify the violation rate of 10% as the maximum acceptable rate [California Department of Transportation, 2003].

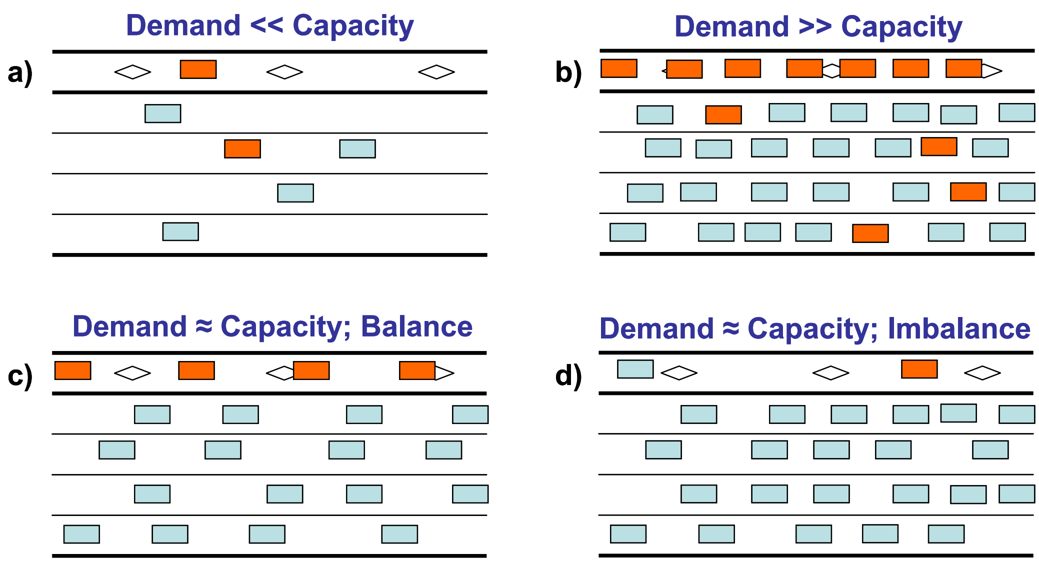


Figure 2-1. Relationship between vehicle demand and freeway capacity for HOV and GP lanes

When there is a change to the capacity of a freeway (e.g., adding a new HOV lane, converting a GP lane to HOV lane, etc.), both the overall vehicle demand and %HOV would also change. For example, in the case of converting a GP lane to HOV lane, some solo drivers may switch to carpooling in order to take advantage of the travel time savings offered by the HOV lane. This mode shift phenomenon will increase the %HOV in the traffic mix and also decrease the overall vehicle demand on the freeway. In addition, some solo drivers may divert to use other alternative routes that provide better travel time for them. Over time, the changes in the overall vehicle demand and %HOV will reach a new equilibrium point, as shown in Figure 2-2. This effect can be captured by current planning analysis tools (i.e., travel demand models).

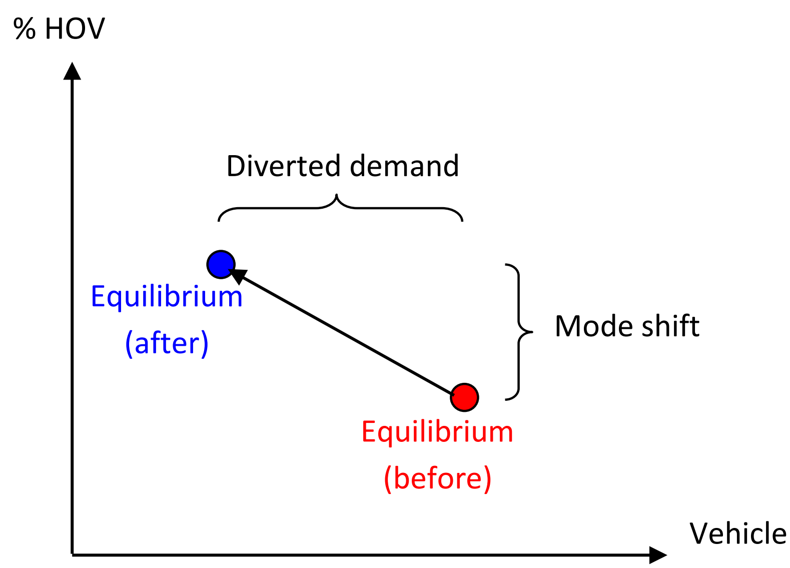


Figure 2-2. Changes in vehicle demand and %HOV due to HOV lane implementation

2.3. Freeway Weaving Induced by Managed Lanes

From a freeway operation perspective, the presence of managed lane such as an HOV lane on a freeway can induce more weaving (or lane changing) activities on that freeway. This is because HOVs that enter the freeway will have to change lane multiple times before they can enter the HOV lane. They will have to do so again when they wish to exit the freeway. These weaving activities and their effects are not accounted for in planning analysis tools such as travel demand models, but they can be captured by operational analysis tools such as traffic simulation models.

The increased weaving activities could interrupt traffic flow, especially when the traffic is near or at capacity. This could cause a decrease in average speed as well as more frequent and sometime more intense acceleration/deceleration events from both HOVs and non-HOVs on the freeway, which may result in higher overall emissions. As an example, it was found in the previous HOV research [Boriboonsomsin and Barth, 2006] that for scenarios where the overall vehicle demand and %HOV are the same, a freeway with HOV lane would have slightly lower average speed and slightly higher total emissions due to having more weaving activities.

2.4. Methodological Framework

Based on the operating characteristics of managed lanes, the methodological framework for analyzing the emission impacts of managed lane projects is shown in Figure 2-3 and described below.

- First, the impact analysis is performed at the planning level (i.e., running travel demand model) to obtain the predicted traffic flow and average traffic speed in both GP and managed lanes for the "build" scenario. Also, the fleet composition data may be obtained from field measurements or based on assumptions. Alternatively, the default fleet composition data in EMFAC may be used.

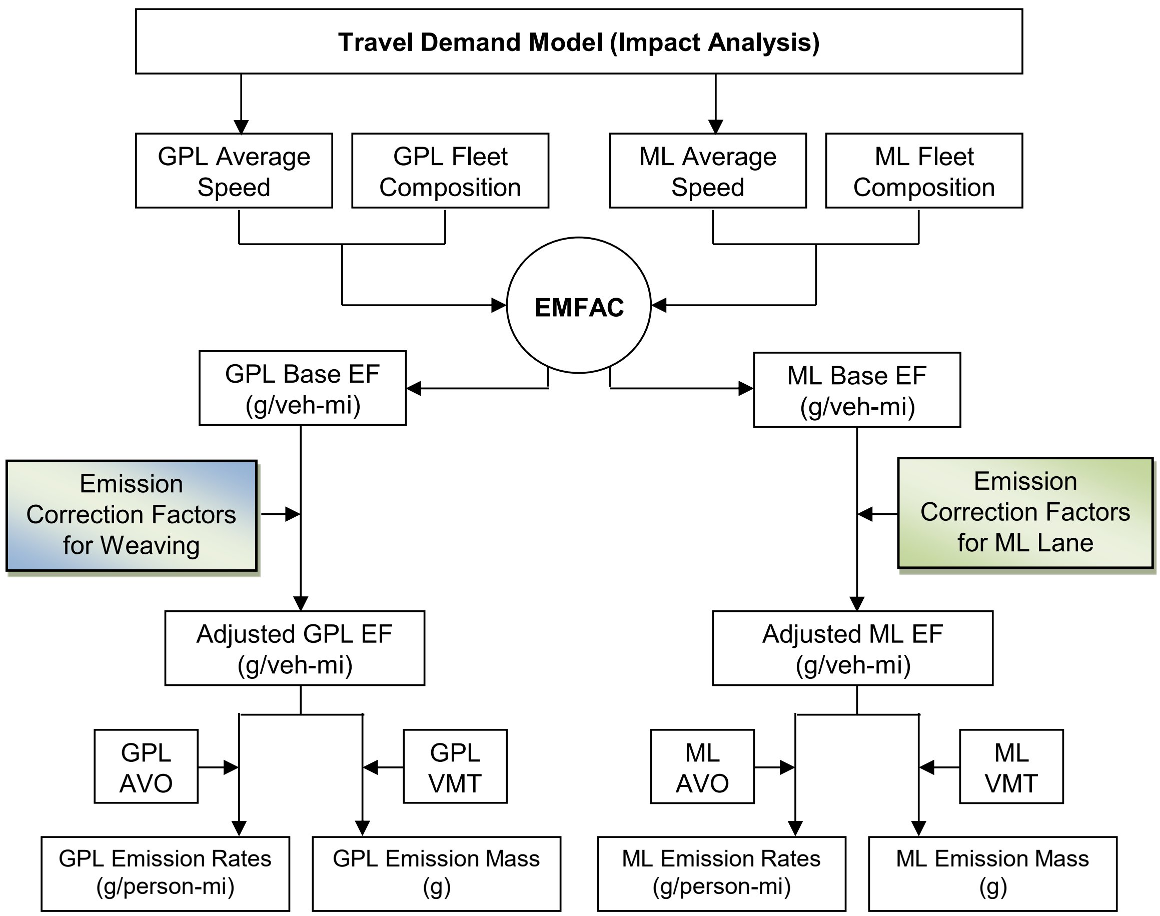
- Next, the average traffic speed and fleet composition data are applied to EMFAC to generate base emission factors in grams per vehicle mile (g/veh-mi) for both GP and managed lanes.

- For the managed lane, the base emission factors are adjusted to account for the differences in driving patterns in managed lane by a set of lane type emission adjustment factors developed in this project. These emission adjustment factors are available for the different types of managed lane (i.e., limited access HOV, continuous access HOV, and HOT lane).

- For the GP lanes, their base emission factors can be adjusted to account for weaving induced by the presence of managed lane. However, the development of this set of emission adjustment factors is out of the scope of this project. In their absence, the base emission factors for the GP lanes can be used in the next step without adjustments.

- Finally, for each lane type the adjusted emission factors are multiplied by the corresponding VMT from travel demand model to obtain emissions mass, which can be aggregated to result in total emissions for the freeway for the "build" scenario. The total emissions can then be compared against the ones for the baseline scenario.

- In addition, for each lane type the adjusted emission factors can be multiplied by the average vehicle occupancy (AVO) values to obtain emission rates per person-mile, which can be compared against each other for both "build" and baseline scenarios.



Notes: GPL = general-purposed lane; ML = managed lanes (including both HOV and HOT lanes); EF = emission factors; AVO = average vehicle occupancy; VMT = vehicle-miles traveled

Figure 2-3. Methodological framework for analyzing emission impacts of freeways with managed lane

3. Data

In this project, a large amount of real-world second-by-second driving data were collected in both GP and managed lanes for use in the development of lane type emission adjustment factors. In the previous HOV research conducted by CE-CERT, we already collected a large amount of driving data with a focus on freeways with limited access HOV lanes. In this research, the data collection effort was therefore focused on freeways with continuous access HOV lanes and HOT lanes. The collected data were processed and then grouped by speed and congestion level for further analysis and modeling. Details of the data collection and processing are provided in the following sections of this chapter.

3.1. Data Collection

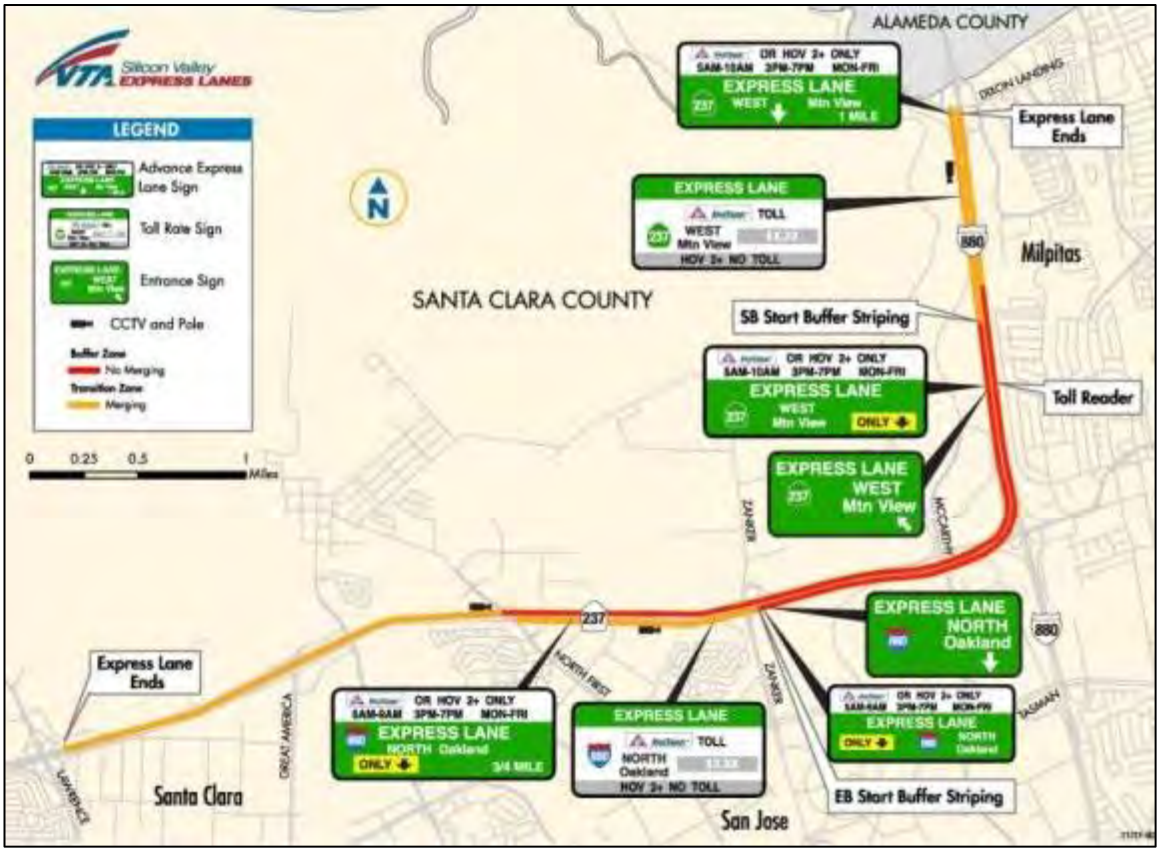
3.1.1. Data Collection Sites

In the past, all HOV lanes in Southern California are limited access. However, in recent years many of them have been converted to continuous access. In addition, some of the new HOV lanes in Southern California, such as the ones on I-215 in Riverside County, were built as continuous access HOV lanes. Therefore, the driving data collection was conducted on freeways in both Northern and Southern California in order to have a representation of data from both regions. The same was true for HOT lanes.

For freeways in Northern California, the driving data were collected only during the periods in which the HOV lanes were operational (i.e., morning and afternoon peaks on weekdays). For freeways in Southern California, the driving data were collected throughout the day. Note that although some HOV lanes in Southern California were continuous access, they were in operation full-time, unlike those in Northern California.

The driving data collection was also conducted in HOT lanes in both Northern and Southern California. These HOT lanes have specific points of entry and exit and some of them have limited operational hours. Therefore, the driving routes and driving times for data collection were carefully designed to capture driving data in these lanes. In this research, driving data were collected from SR-237 express lane (Figure 3-1), I-580 express lane (Figure 3-2), and I-680 express lane (Figure 3-3) in Northern California, as well as SR-91 express lane (Figure 3-4) in Southern California.

The list of all the data collection sites is given in Table 3-1. The data collection sites in Northern California are shown in Figure 3-5 while the data collection sites in Southern California are shown in Figure 3-6.



Source: http://www.vta.org/projects-and-programs/highway/vta-express-lanes-sr-237-express-lanes-project

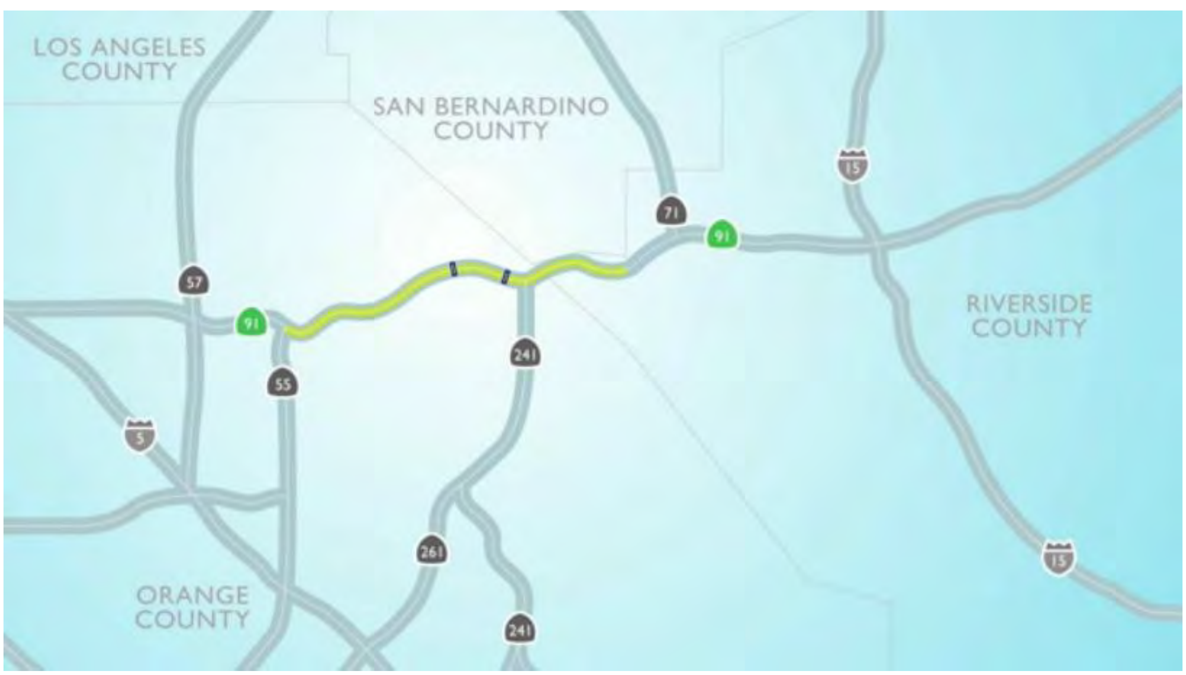
Figure 3-1. SR-237 express lane

Source: http://www.680expresslane.org/I-580_Map.asp

Figure 3-2. I-580 express lane

Source: http://www.680expresslane.org/I-680_Map.asp

Figure 3-3. I-680 express lane



Source: http://www.91expresslanes.com/overview.asp

Figure 3-4. SR-91 express lane

Table 3-1. Summary of data collection sites

Type of Managed Lane	Region	Highway	Direction	From	To	Distance (mi)
Continuous access HOV	NoCal	I-880	N	CA-237	I-580	22.9
			S	I-580	CA-237	22.9
	SoCal	SR-22	E	Palo Verde Ave	Tustin St	16.6
			W	Tustin St	Palo Verde Ave	16.6
		SR-55	N	MacArthur Blvd	Lincoln Ave	10.2
			S	Lincoln Ave	MacArthur Blvd	10.2
		SR-57	N	Orangewood Ave	Tonner Canyon Rd	10.1
			S	Tonner Canyon Rd	Orangewood Ave	10.1
HOT	NoCal	SR-237/ I-880	E	North First Street	Dixon Landing Road	4.3
			W	Dixon Landing Road	Lawrence Expy	6.6
		I-580	E	Hacienda Drive	Greenville Road	10.4
			W	Greenville Road	San Ramon Road	13.0
		I-680	S	SR-84	SR-237	13.8
	SoCal	SR-91	E	SR-55	Green River Road	9.0
			W	Green River Road	SR-55	9.0

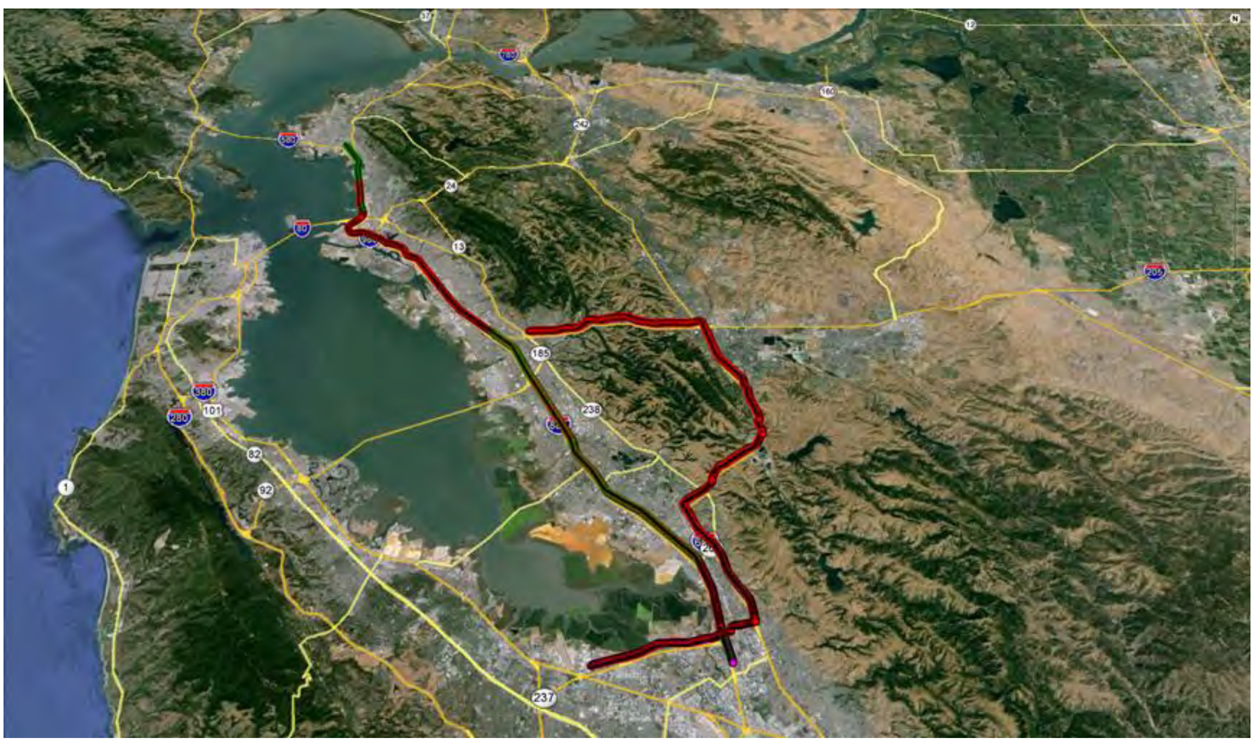


Figure 3-5. Data collection sites in Northern California

Figure 3-6. Data collection sites in Southern California

3.1.2. Data logging Device

The research team collected second-by-second driving data using vehicles instrumented with customized GPS data loggers (Figure 3-7). The E-TEK EB85A GPS engine in the device uses the latest technology to ensure that a signal is received in areas of dense foliage, canyons, and even inside buildings. Power is supplied from a rechargeable 1800 mAh 3.6V lithium ion battery that contains a protection circuit module. The battery can be recharged through any 7-22V external DC sources such as automobile cigarette lighter ports. The data logging device can record up to 30 minutes after external DC power supply is removed (e.g., vehicle ignition switched off).

Data logged by the device are stored on an SD card, which can later be downloaded onto a personal computer. The data can be logged in a couple different formats and settings. In this project, we set the configuration to log the data in a comma separated file (CSV) format with the following data attributes:

- LATITUDE – latitude in decimal degree
- LONGITUDE – longitude in decimal degree
- ALTITUDE – altitude in meter above Mean Sea Level
- HEADING – heading in degree
- SPEED – speed in miles per hour
- SAT – number of satellites available to the GPS
- PDOP – position dilution of precision
- HDOP – horizontal dilution of precision

- VDOP – vertical dilution of precision
- FIX – satellite fix code
    - 0 = no fix
    - 1 = non-differential fix
    - 2 = differential fix
    - 6 = estimated fix
- YEAR – year
- MONTH – month
- DAY – date
- HOUR – hour
- MIN – minute
- SEC – second
- MSEC – millisecond

Figure 3-7. GPS data logger used in this study

Note that the date/time data recorded by the device is coordinated universal time (UTC), which can be converted to Pacific Standard Time by subtracting 8 hours (i.e. UTC-8) during the daylight saving time period. We set the configuration to log the data at one second interval.

3.1.3. Vehicles, Drivers, and Procedures

The vehicles used for the data collection were midsize sedans (i.e., Dodge Avenger for the driving data collection in Northern California and Nissan Altima for the data collection in Southern California). Two personnel were used in each data collection session—one driver and one passenger—so that the vehicle was eligible to use HOV lanes. The driver was a young adult male and was instructed to drive the vehicle in a manner that represents the traffic in a particular lane type. For example, when driving in an HOV lane, the driver would maintain a consistent clearance distance from the vehicle in front. When driving in GP lanes, the driver would drive in the middle lane in order to follow the average flow of the traffic in the GP lanes. However, lane changing and overtaking were still allowed in case the vehicle in front was traveling at a slower speed than the majority of the traffic in other GP lanes.

For each data collection session, the vehicle was driven in both managed lanes and the parallel GP lanes in an alternating fashion. For example, the driver would drive in one lane type for a complete loop (e.g., going on the northbound on the data collection site, getting off the freeway, and coming back on the southbound of the same site), followed by driving in the other lane type in the next loop. During the driving, the passenger recorded the session information (i.e., data collection site and lane type), lane number the vehicle was in, and the timestamp at which lane changes occurred. Two GPS data loggers were used in all data collection sessions to provide back up against data loss.

3.2. Data Processing

The processing of the collected driving data into a database involved multiple steps as described in this section.

First of all, data were filtered out based on poor dilution of precision, having no satellite fix, wrong latitude and longitude, etc. Then, irrelevant data were removed. These included driving data on roadway facilities that were not of interest to this research, such as driving data on ramps and arterials when the driver went from one direction of the data collection site to the other direction, as well as driving data on freeways connecting two data collection sites.

Each second of the relevant data was indexed by freeway, direction, lane type, and lane number. Then, the calculation of second-by-second acceleration was made based on the second-by-second speed values using the central difference method. Subsequently, second-by-second vehicle specific power (VSP) was calculated as:

$$SP = \frac{A}{m} \cdot v + \frac{B}{m} \cdot v^2 + \frac{C}{m} \cdot v^2 + (a + g \cdot \sin\theta) \cdot v \qquad (1)$$

where A, B and C are road load coefficients for rolling resistance ($\mathrm{kW \cdot s/m}$), rotating resistance ($\mathrm{kW \cdot s^2/m^2}$), and aerodynamic drag ($\mathrm{kW \cdot s^3/m^3}$), respectively; v is vehicle speed (m/s); m is fixed mass factor for the vehicle type (metric ton); a is vehicle acceleration (m/s^2); g is acceleration due to gravity (9.8 m/s^2); and sin ? is fractional road grade. For passenger cars such as the ones used in the driving data collection, it was assumed that *A* = 0.156461; *B* = 0.00200193; *C* = 0.000492646; and *m* = 1.4788 [U.S. Environmental Protection Agency, 2010].

At this point, another filter was applied to remove data with unrealistic speed, acceleration, or VSP value. Once the data filtering was complete, the remaining data were spatially and temporally mapped to the congestion level data (represented by freeway level of service or LOS [Transportation Research Board, 2000]) obtained from the Caltrans' Freeway Performance

Measurement System (PeMS) following the methodology shown in Figure 3-8. The coverage of each vehicle detector station (VDS) of PeMS was defined as a segment from the mid distance between itself and the adjacent VDS on one end to the mid distance between itself and the adjacent VDS on the other end. Typically, VDS were located around 0.6-1.0 miles apart from each other. In some cases where VDS were far apart from each other, the maximum coverage for a VDS was set at 5 miles (i.e., 2.5 miles forward and 2.5 miles backward).

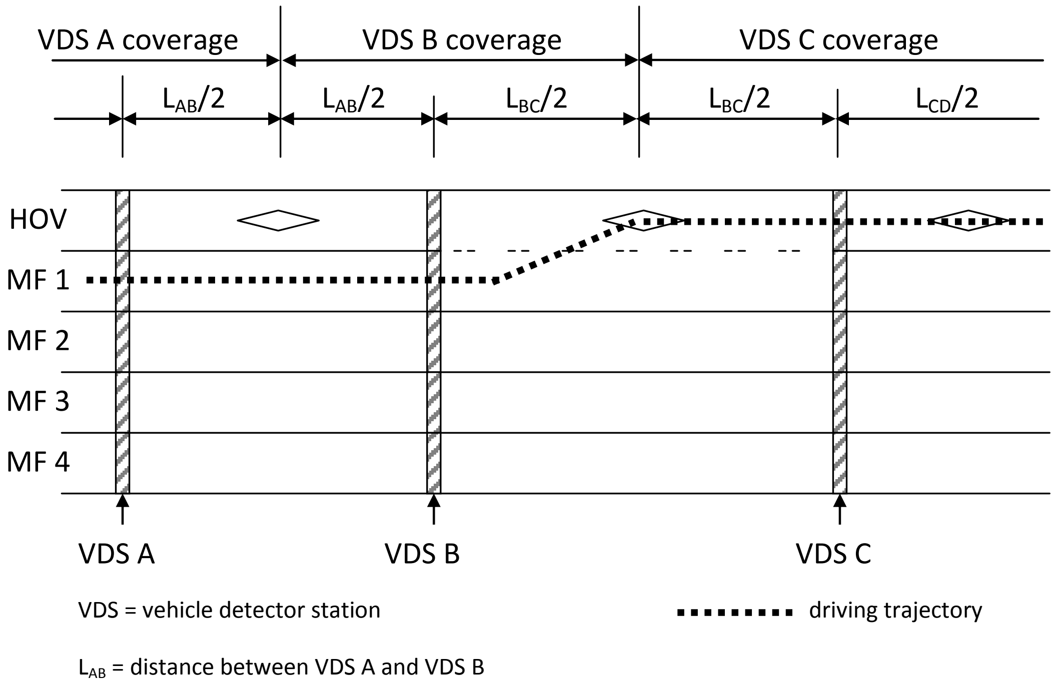


Figure 3-8. Spatial and temporal mapping of PeMS LOS to driving trajectory

Loop sensors at each VDS reported traffic data every 30 second, at which the LOS was updated. Given the followings:

t is time lapse in seconds (t = 1, 2, … , T). For simplicity, we start t = 1 at the first second of the first full minute of time stamp;

p is a 30-second period in which loop sensors collect traffic data, i.e., $p = (t \setminus 30) + 1$;

i is an index for loop sensors, i.e., i = 1, 2, … , n;

j is a lane number (j = 1, 2, … , $m(i)$), where lane 1 is the median lane and lane $m(i)$ is the shoulder lane;

c_i is the spatial coverage of loop sensors i, i.e., $c_i = \left[\frac{l_{i-1}+l_i}{2}, \frac{l_i+l_{i+1}}{2}\right)$;

l_i is a centerline distance from a starting location (at t = 1) to loop sensor i. For simplicity, we assume l_0 = 0 and $l_{n+1} = l_n + 1$.

Then, $v_{c_i,j,t} \in U_{i,j,p}$ where v is second-by-second speed of the vehicles and U is macroscopic traffic parameters (e.g., LOS) from loop sensors. In other words, a vehicle running in lane j within the coverage of VDS i at time t was assumed to experience the LOS determined by the loop sensor in lane j at VDS i during a 30-second period p. Based on this assumption, each second of the collected driving data was assigned a corresponding LOS.

Note that some VDS did not report 30-second raw data during the data collection period due to malfunctioning. However, some of these VDS reported 5-minute aggregate data which were imputed. Therefore, the LOS determined based on 5-minute aggregate data was used if 30-second raw data was not available.

3.3. Data Analysis

3.3.1. Issues with LOS Data

In the previous research, the collected driving data were grouped by LOS for further analysis and modeling. In this research, the collected driving data were also initially grouped by LOS. However, during the data analysis it was found that some of the LOS data were not reasonable. This is illustrated in Figure 3-9, which shows the second-by-second driving speed data in continuous access HOV lanes that are indexed as having LOS F. According to the figure, there is a significant portion of the data with speed higher than 40 mph, which is counterintuitive. Similar issues were found in data in other lane types and for other LOS also.

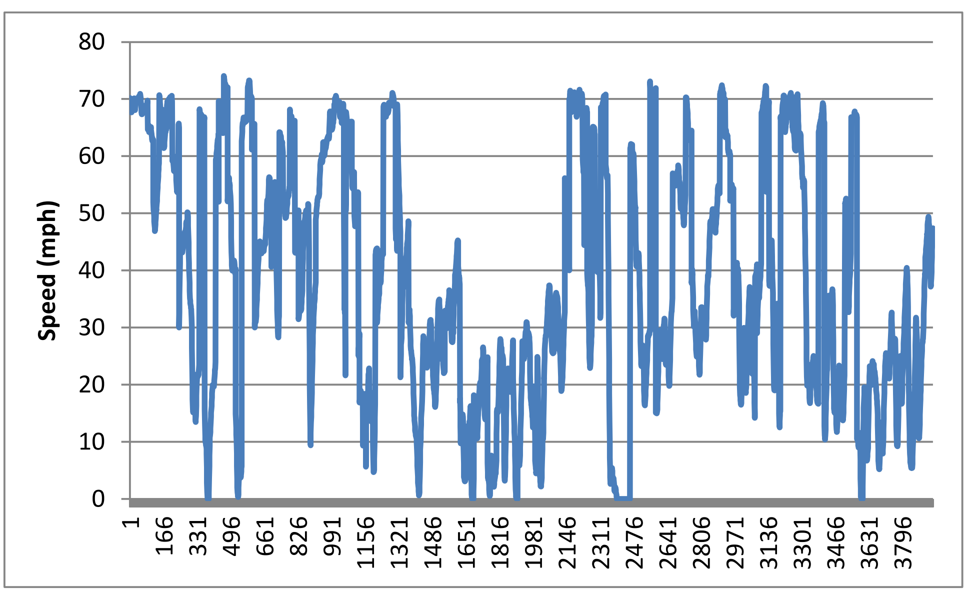


Figure 3-9. Speed data for LOS F in continuous access HOV lanes

Due to the unreliable LOS data, it was decided that the collected driving data would be grouped by speed instead. Speed is a good surrogate for congestion, and thus, provides a reasonable alternative to LOS. In addition, grouping the driving data by speed allows for more number of data groups than grouping by LOS, which has 6 groups (A, B, C, D, E, and F). In fact, grouping the driving data by speed provides so much flexibility that the size of speed groups (or bins) was considered during the modeling part of this project, which is discussed in Chapter 4.

The driving data grouping is one of the important considerations in the emission curve modeling. How driving data are grouped would have a significant impact on the emission curve equations. In order to keep the modeling approach consistent, the driving data collected in the previous research were regrouped by speed in the same way the newly collected driving data were, and then combined with the newly collected driving data. This resulted in a combined dataset that included driving data in all types of managed lane in California. This combined dataset was used in the data analysis, emission modeling, and lane type emission adjustment factor development parts of this project.

3.3.2. Driving Data Statistics

The first part of data analysis was to calculate descriptive statistics of the collected driving data. Table 3-2 presents selected statistics of the data in each lane type by speed bin. The following observations can be made regarding the statistics in this table:

- For all lane types except one, Speed Bin 65 has the most data. For limited access HOV lanes, there are the most data in Speed Bin 75. This implies that under free-flow condition, vehicles in limited access HOV lanes tend to travel at higher speeds than those in other lane types. This lane type also has the highest maximum speed and mean speed among all the lane types.

- The limited access HOV lane type also has the highest mean acceleration and the lowest mean deceleration (arithmetically) for almost all speed bins, implying that the driving in this lane type are generally more transient than in other lane types. On the other hand, the GP lane type has the lowest mean acceleration and the highest mean deceleration (arithmetically) for many of the speed bins.

- In general, the mean and maximum accelerations are higher at low speeds compared to those at high speeds. At highway speeds, vehicles often cruise and do not necessarily have to engage in hard acceleration events. Similarly, the mean and maximum decelerations are generally lower (in arithmetic term) at low speeds as vehicles experience stop-and-go traffic.

- There is only a small amount of driving data in express lanes at speeds below 50 mph. This is expected as these lanes are supposed to maintain an average traffic speed of greater than 45 mph.

Table 3-2. Statistics of collected driving data in different lane type by speed bin

Speed Bin	Speed Range (mph)	No. of Samples (seconds)	Max Speed (mph)	Mean Speed (mph)	Max Accel. (mph/s)	Mean Accel. (mph/s)	Max Decel. (mph/s)	Mean Decel. (mph/s)
General Purposed Lanes								
5	0 – 10	15982	10	5.0	7.2	0.8	-9.5	-0.8
15	10.1 – 20	19605	20	15.1	7.5	0.9	-9.6	-0.8
25	20.1 – 30	15322	30	24.6	5.0	0.8	-9.8	-0.9
35	30.1 – 40	10402	40	34.8	7.4	0.8	-9.0	-0.9
45	40.1 – 50	9874	50	45.1	5.9	0.6	-8.6	-0.8
55	50.1 – 60	21609	60	56.0	4.4	0.4	-6.4	-0.5
65	60.1 – 70	43044	70	64.7	4.9	0.3	-7.2	-0.3
75	>70	6053	86.2	73.9	2.2	0.4	-3.3	-0.4
Limited Access HOV Lanes								
5	0 – 10	580	10	5.3	5.9	1.2	-13.2	-1.6
15	10.1 – 20	1185	20	15.8	7.4	1.4	-10.8	-1.2
25	20.1 – 30	1473	30	24.8	6.5	1.2	-12.0	-1.2
35	30.1 – 40	1423	40	34.9	3.4	1.0	-11.3	-1.2
45	40.1 – 50	1268	50	45.2	3.6	0.9	-9.7	-1.0
55	50.1 – 60	1566	60	55.2	2.9	0.7	-8.6	-0.9
65	60.1 – 70	1925	70	65.4	2.2	0.6	-5.7	-0.8
75	>70	3977	87.5	75.8	2.0	0.4	-3.7	-0.5
Continuous Access HOV Lanes								
5	0 – 10	2510	10	4.3	6.1	0.9	-7.7	-1.0
15	10.1 – 20	2782	20	15.2	6.8	1.1	-8.9	-1.1
25	20.1 – 30	3354	30	25.2	4.1	1.0	-9.0	-1.1
35	30.1 – 40	3864	40	35.2	4.8	0.8	-7.3	-1.0
45	40.1 – 50	5282	50	45.3	4.2	0.6	-7.3	-0.8
55	50.1 – 60	9212	60	55.3	4.5	0.5	-6.4	-0.6
65	60.1 – 70	21758	70	66.0	2.9	0.3	-3.9	-0.3
75	>70	5846	76.8	71.3	2.2	0.3	-2.8	-0.3
Express/HOT Lanes								
5	0 – 10	214	10	4.0	5.7	0.8	-4.8	-1.0
15	10.1 – 20	391	20	15.5	5.1	0.9	-5.4	-1.0
25	20.1 – 30	466	30	24.6	2.5	0.7	-4.0	-0.8
35	30.1 – 40	250	40	34.8	3.0	0.8	-7.4	-1.1
45	40.1 – 50	460	50	46.0	2.5	0.7	-7.4	-1.1
55	50.1 – 60	1515	60	56.1	2.1	0.5	-6.4	-0.6
65	60.1 – 70	8546	70	66.2	2.2	0.3	-3.3	-0.3
75	>70	2350	75.4	71.4	1.7	0.3	-1.5	-0.3

3.3.3. Vehicle Trajectory Comparison

Aside from the subjective comparison of observed trends of the descriptive statistics discussed above, the differences in vehicle trajectory can be objectively determined by comparing their joint speed-acceleration frequency distributions (SAFDs). 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 vehicle trajectory is to treat speed and acceleration as univariate data and compare them separately. For either speed or acceleration, if the probability density functions of two lane types are significantly different, then their SAFDs are also significantly different. The comparison of probability density function of two univariate datasets 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 research, the speed, acceleration, and vehicle specific power data in each type of managed lanes were compared with those in the parallel GP lanes. That is, the data in GP lanes from freeways with limited access HOV lanes were only used for comparison with the data in limited access HOV lanes but not with the data in other managed lane types. This was to avoid any potential biases of data in GP lanes from freeways with different types of managed lanes. The comparison was made for each speed bin, and the null hypothesis (H_0) was that the probability distributions of data samples in managed lanes and the parallel GP lanes do not differ. The results are summarized in Table 3-3. Using the significance level of 5%, the null hypothesis is rejected if the *p*-value is smaller than 0.05.

According to Table 3-3, the probability distributions of speed, acceleration, and VSP of the driving data in limited access HOV lanes are found to be significantly different from those of the driving data in the parallel GP lanes for all but two speed bins. Similarly, the probability distributions of speed, acceleration, and VSP of the driving data in continuous access HOV lanes are found to be significantly different from those of the driving data in the parallel GP lanes for all but one speed bins. On the other hand, the probability distributions of speed, acceleration, and VSP of the driving data in express/HOT lanes are found to be significantly different from those of the driving data in the parallel GP lanes for about half of all the speed bins. Based on these results, it is likely that emission factors (per unit distance) for managed lanes would be different from emission factors for GP lanes.

Table 3-3. KS test results between managed lanes and GP lanes

H_0: The probability distributions of data samples in managed lanes and GP lanes do not differ.

Speed Bin	Speed Range (mph)	Speed		Acceleration		Vehicle Specific Power	
		p-value	Conclusion	*p*-value	Conclusion	*p*-value	Conclusion
Limited Access HOV Lanes							
5	0 – 10	0.833	Accept H0	0.012	Reject H0	0.007	Reject H0
15	10.1 – 20	< 0.001	Reject H0	0.004	Reject H0	< 0.001	Reject H0
25	20.1 – 30	< 0.001	Reject H0	0.045	Reject H0	0.021	Reject H0
35	30.1 – 40	0.049	Reject H0	0.852	Accept H0	0.421	Accept H0
45	40.1 – 50	0.288	Accept H0	0.326	Accept H0	0.239	Accept H0
55	50.1 – 60	< 0.001	Reject H0	0.005	Reject H0	0.028	Reject H0
65	60.1 – 70	< 0.001	Reject H0	0	Reject H0	< 0.001	Reject H0
75	>70	< 0.001	Reject H0	0.002	Reject H0	0.007	Reject H0
Continuous Access HOV Lanes							
5	0 – 10	< 0.001	Reject H0	0.012	Reject H0	< 0.001	Reject H0
15	10.1 – 20	0.947	Accept H0	< 0.001	Reject H0	< 0.001	Reject H0
25	20.1 – 30	< 0.001	Reject H0	< 0.001	Reject H0	< 0.001	Reject H0
35	30.1 – 40	< 0.001	Reject H0	0.001	Reject H0	< 0.001	Reject H0
45	40.1 – 50	0.032	Reject H0	0.501	Accept H0	0.415	Accept H0
55	50.1 – 60	< 0.001	Reject H0	< 0.001	Reject H0	0.003	Reject H0
65	60.1 – 70	< 0.001	Reject H0	0.023	Reject H0	< 0.001	Reject H0
75	>70	0.005	Reject H0	< 0.001	Reject H0	< 0.001	Reject H0
Express/HOT Lanes							
5	0 – 10	0.227	Accept H0	0.058	Accept H0	0.142	Accept H0
15	10.1 – 20	< 0.001	Reject H0	0.015	Reject H0	0.018	Reject H0
25	20.1 – 30	0.238	Accept H0	0.043	Reject H0	0.017	Reject H0
35	30.1 – 40	0.31	Accept H0	0.411	Accept H0	0.502	Accept H0
45	40.1 – 50	< 0.001	Reject H0	0.121	Accept H0	0.019	Reject H0
55	50.1 – 60	0.245	Accept H0	0.100	Accept H0	0.129	Accept H0
65	60.1 – 70	< 0.001	Reject H0	< 0.001	Reject H0	< 0.001	Reject H0
75	>70	0.088	Accept H0	0.030	Reject H0	0.014	Reject H0

4. Lane Type Emission Adjustment Factors

Based on the analysis of the collected driving data, it was found that emission factors (per unit distance) for managed lanes were likely to be different from emission factors for GP lanes due to the differences in speed, acceleration, and VSP distributions between the two lane types. This finding warranted the development of emission adjustment factors for managed lanes. These adjustment factors would be used to adjust base emission factors so that they reflect driving patterns of managed lanes.

The development of lane type emission adjustment factors involved three key steps. First, emissions associated with each second of the collected driving data were estimated. Using these estimated emissions, emission versus speed curves for managed lanes as well as GP lanes were then developed. Finally, lane type emission adjustment factors were derived as the ratio of managed lane emission curve to GP lane emission curve. Each of these key steps was described in more detail in the following sections.

4.1. Estimating Second-by-Second Emissions

In this research, the Motor Vehicle Emission Simulator (MOVES) model was used to estimate emissions associated with each second of the collected driving data. The MOVES model is a state-of-the-art model, developed by the U.S. Environmental Protection Agency (EPA), for the estimation of emissions and energy consumption from all types of on-road vehicles. The MOVES model was chosen for this purpose due to several reasons:

- It is capable of estimating second-by-second emissions from second-by-second speed data, which is the type of data collected in this study. Unlike its predecessors, which can only estimate emissions as a function of average speed, MOVES has been purposefully designed so that it can be used to support emission calculation at multi-scales, from macro (e.g., national emissions inventory development) to meso (e.g., regional transportation conformity analyses) to micro (e.g., project-level conformity and hot spot analyses).

- It is capable of estimating emissions for future vehicle model years and future calendar years. Since the lane type emission adjustment factors will be used to evaluate the emission impacts of managed lanes in future year scenarios, they need to reflect emission characteristics of future vehicles.

- It can estimate emissions of greenhouse gases and criteria pollutants for a variety of conditions (e.g., geographic area, weather, fuel type, etc.) as the lane type emission adjustment factors will be used to evaluate the emission impacts of managed lanes under a variety of conditions.

Using the MOVES model, emission rates (in terms of grams per second) were generated for the conditions presented in Table 4-1. For each condition, a scope was defined for which the lane type emission adjustment factors would be developed. The selection of the scope for each condition was balanced between trying to cover a typical range of condition in which the lane type emission adjustment factors would be used and keeping the scale of the development reasonable. For example:

- The lane type emission adjustment factors would be developed for each calendar year from 2010 to 2035. That means they can be used to evaluate recently implemented managed lane projects as well as future managed lane projects that will be implemented in the next 20 years.

- The adjustment factors would be developed for any air temperature from -20 °F to 120 °F and any relative humidity from 0% to 100%. These are typical ranges for California weather conditions and are consistent with the ranges used in the EMFAC model.

- The adjustment factors would be developed for passenger cars and passenger trucks with gasoline engine. These vehicles are the dominant users of managed lanes.

Table 4-1. Scope of lane type emission adjustment factors development

Condition	Scope	Values for MOVES Model Runs
Calendar year	2010 through 2035	2010, 2011, 2012, 2013, 2014, 2015, 2020, 2025, 2030, and 2035
Geographic area	California statewide	California statewide
Air temperature	-20 °F to 120 °F	-20, 0, 20, 40, 60, 80, 100, and 120 °F
Relative humidity	0% to 100%	0, 20, 40, 60, 80, and 100%
Vehicle type	Passenger car, Passenger truck	Passenger car, Passenger truck
Fuel type	Gasoline	Gasoline
Vehicle age	0 through 25 years	0 through 25 years
Emissions	CO_2, CO, ROG, TOG, NO_x, PM_{10}, $PM_{2.5}$	CO_2, CO, ROG, TOG, NO_x, PM_{10}, $PM_{2.5}$

The defined scopes of lane type emission adjustment factors development would require 740,532 MOVES model runs (26 calendar years x 141 air temperature values x 101 relative humidity values x 2 vehicle types), which would take an enormous amount of time. To limit the amount of MOVES model runs required, only a limited number of values in certain condition ranges were selected for MOVES runs as listed in the last column of Table 4-1. This reduced the number of MOVES model runs to 960 (10 calendar years x 8 air temperature values x 6 relative humidity values x 2 vehicle types).

The MOVES model was run for combined model year emission results for vehicles from 0 to 25 years of age for each calendar year for California statewide. This required vehicle age fraction information for all vehicle ages and for all calendar years by passenger car and by passenger truck. This information was obtained from the latest version of the EMFAC model (i.e., EMFAC2011).

MOVES model runs also required barometric pressure input. The value used for all of the runs was 28.99 inches of mercury which was determined based on the statewide average for all counties in California from the MOVES modeling database.

Emission estimates of CO_2, CO, ROG, TOG, NO_x, PM_{10}, and $PM_{2.5}$ were all requested as output from each MOVES model run. There was no need to make separate runs for each of these emission estimates.

4.1.1. MOVES Project Level Runs

MOVES characterizes running exhaust emission rates by vehicle operating mode (opMode), which are defined by a combination of VSP and speed ranges as shown in Figure 4-1. However, there is no direct mechanism in the MOVES model that outputs emission rates for each opMode directly. In this research, an indirect method had to be developed to obtain emission rates by opMode from MOVES.

To do that, the MOVES model was run at the project level, which is the finest level of modeling in MOVES. It allows the user to model emissions at the roadway link level. For each project level run, a MySQL database was created and populated using Matlab software. Each project level run was set up as a roadway network of 23 links where each link was loaded with vehicle activity that represented a single MOVES opMode. Therefore, the total emission for a link, once normalized by the total vehicle activity time on that link, was essentially the emission rate for the opMode that link represented.

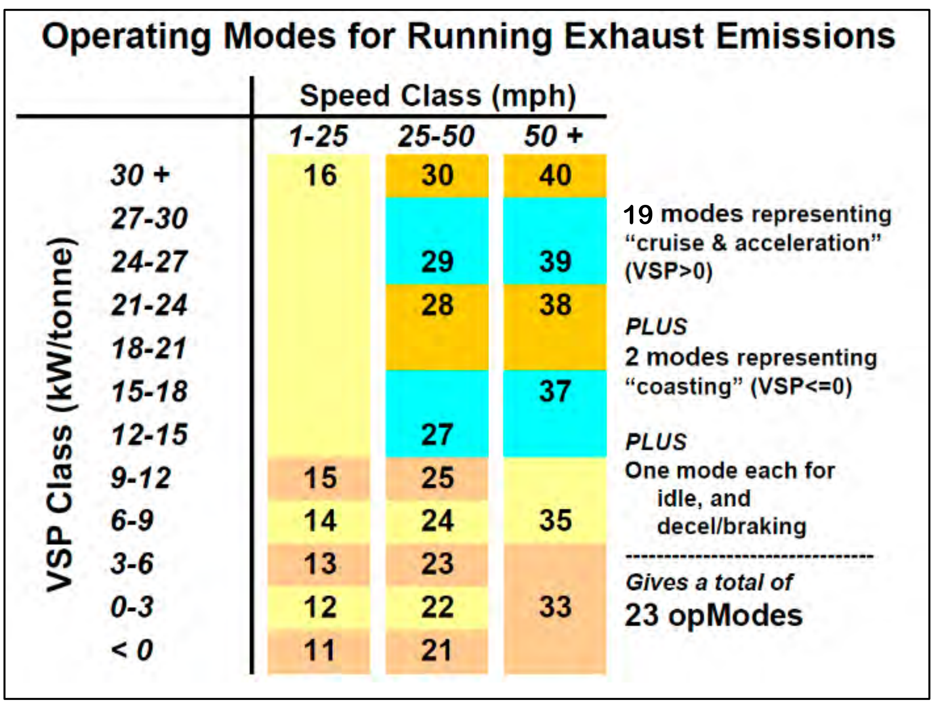


Figure 4-1. MOVES operating mode definition [Warila et al., 2011]

Each project level run database consisted of several tables defining the model run. The tables that were updated for each project level MOVES run included the followings:

- state
- zone
- zoneroadtype
- zonemonthhour
- link
- year
- county
- linksourcetypehour
- sourcetypedistribution
- opmodedistribution

A command-line run specification (runspec) was created for each project level run using Matlab. The runspec file specified run conditions such as the input and output database, pollutant process, geographic area, time span, etc. The runspec name consisted of a code which defined the run conditions of the file. This facilitated queries of the output data in the later stages of the analysis. A batch script was also created in Matlab for each project level run which was used to call the java command to initiate the MOVES model with a given runspec file.

4.1.2. MOVES Distributed Runs

As noted earlier, 960 MOVES runs were required to generate emission rates for the scopes of conditions presented in Table 4-1. Since the MOVES model is computationally intensive, these runs were executed in a distributed process over two computers using design features in the MOVES model for this purpose.

The MOVES model has two components, Master and Worker applications. These two applications communicate through text files written to a shared directory. The Master process creates multiple “to-do” work bundles for each run. Then, one or more Worker processes pick up, process, and return the “to-do” files as “done” files. In this manner, multiple worker processes can process bundles for a MOVES master process as shown in Figure 4-2.

For this project, the shared directory was located on a network and a computer was set up to run the master process and two worker processes. A second computer was set up to run additional worker processes. Finished bundles were combined into completed output for each run by a “pickup” script running in a separate process.

Note that while it took some time and effort to set up the distributed runs, they helped cut down a significant amount of run time. The particular setup used in this research required approximately 48 hours of run time to complete the 960 MOVES model runs.

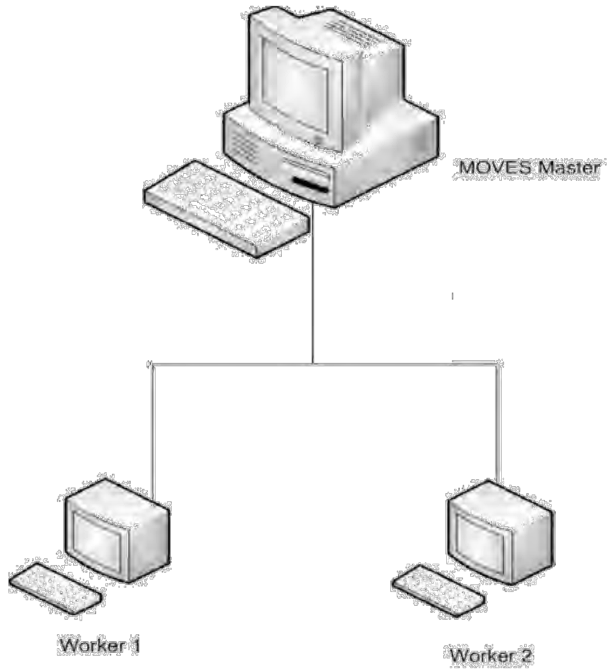


Figure 4-2. Example of MOVES run distributed over multiple processes

4.1.3. Emission Database

Emission results from all the MOVES runs were stored in a single MySQL database. This master database acted as a lookup table and could be queried for emission rates based on run conditions which were specified in the runspec name and link id values which correlated to opModes. The master database consists of a “movesrun” table which defines the run conditions for the model including the runspec filename. The emission results were contained in the “movesoutput” table. Database queries were performed using a Matlab function with input arguments for calendar year, month, model year, source type, pollutant, opMode, air temperature, and relative humidity. This function was designed to query for ranges of input arguments so that repeated calls to the MySql database were kept to a minimum.

The emission database was used to generate emission values associated with the processed driving data based on their opModes. Since the processed driving data consisted of second-by-second speed and VSP, an opMode for each second of the driving data could be determined. Thus, emission rates for a particular combination of conditions (e.g., passenger cars in calendar year 2015 under air temperature of 100 °F and relative humidity of 20%) could be looked up from the emission database and then associated with each second of the driving data based on their opModes. This resulted in a combined database of second-by-second driving data and their corresponding emissions for each of the 960 combinations of conditions, which were used for emission versus speed curve fitting in the next step.

4.2. Fitting Emission versus Speed Curves

For each of the 960 combinations of conditions for which lane type emission adjustment factors would be developed, emission versus speed curves of CO_2, CO, THC, NO_x, PM_{10}, and $PM_{2.5}$ were created for the following 6 cases:

- Limited access HOV lanes
- GP lanes parallel to limited access HOV lanes
- Continuous access HOV lanes
- GP lanes parallel to continuous access HOV lanes
- Express/HOT lanes
- GP lanes parallel to express/HOT lanes

Therefore, a total of 34,560 curves were created (960 combinations x 6 emissions x 6 cases). These curves were created by following these main steps:

1. Emissions for each second of the processed driving data were looked up from the emission database for a combination of conditions (e.g., passenger cars in calendar year 2015 under air temperature of 100 °F and relative humidity of 20%).

2. For each emission (e.g., CO_2) and each case (e.g., limited access HOV lanes), the driving and emission data were grouped by speed into several bins.

3. For each speed bin, the total emission and total distance were calculated from all the second-by-second data in the speed bin. Then, the emission factor (in terms of grams per mile, g/mi) was calculated as total emission divided by total distance. Also, the average speed was calculated.

4. The emission factor (dependent variable) was plotted against the average speed (independent variable). Then, a curve was fitted to the plotted data using ordinary least square regression.

The emission (y) versus speed (x) curves could vary by a number of factors. Some of these factors were examined in this research as discussed below.

- *Speed bin size*: As described above, the driving and emission data were grouped by speed into several bins in order to generate data points for curve fitting. The size of the speed bin directly determined the number of data points. For example, for the speed domain from 0 to 80 mph, using the speed bin size of 2 mph would result in 40 data points while using the speed bin size of 10 mph would result yield 8 data points. In this research, three speed bin sizes were evaluated including 2 mph, 5 mph, and 10 mph. While the speed bin size of 2 mph yielded the most number of data points, these data points were also the nosiest. On the other hand, while the speed bin size of 10 mph yielded only 8 data points, these data points had the highest signal-to-noise ratio.

- *Functional form of the emission factor variable*: In the plot of emission factor (g/mi) versus average speed (mph), the emission factor would theoretically approach infinity when the average speed is close to zero. The logarithmic function is typically used to represent that characteristic. In this research, both the logarithmic form (i.e., ln(*y*)) and the original form (i.e., *y*) of the emission factor variable were evaluated. As expected, the logarithmic form generally provided a better fit to the data points than the original form, especially on the very low speed end. It resulted in the curves having higher R^2 in most cases. Therefore, the logarithmic form was selected.

- *Functional form of the average speed variable*: In emission versus speed curves, the average speed variable is typically represented by a polynomial function. In this research, three forms of polynomial function (second-order, third-order, and fourth-order) were evaluated. While the fourth-order polynomial form provided the best fit to the data points, it resulted in the curves having 3 inflection points. This increased the likelihood of lane type emission adjustment factor curves having multiple inflection points too, which was difficult to interpret. On the other hand, the second-order polynomial form resulted in a reasonable fit to the data points while providing the shape of curves that was easier to interpret. Therefore, the second-order polynomial form was selected.

After the evaluation of these factors, the selected final form of emission versus speed curves was:

$$\ln(\mathrm{y}) = b_0 + b_1 x + b_2 x^2 \qquad (2)$$

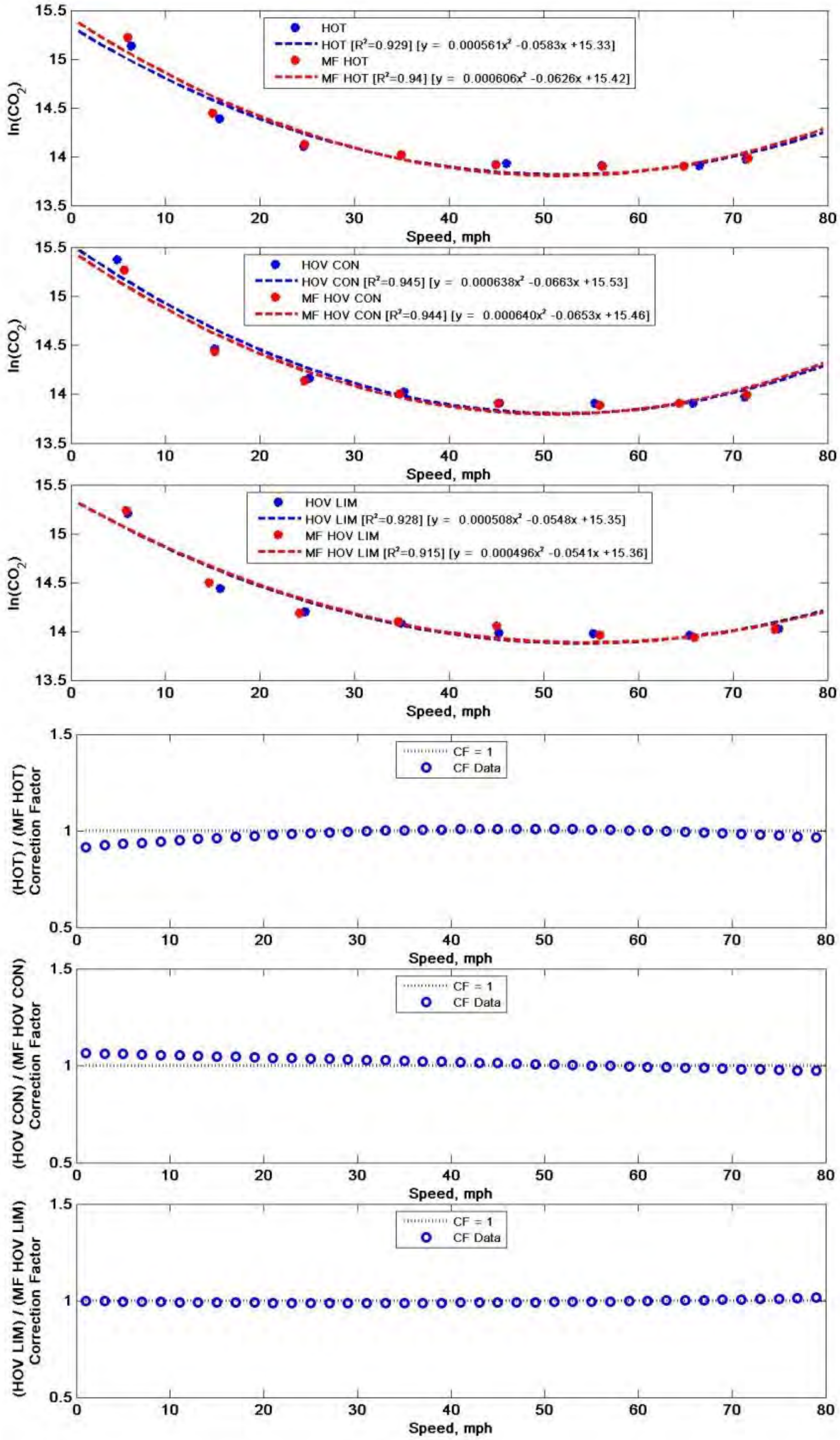
or,

$$\mathrm{y} = e^{(b_0 + b_1 x + b_2 x^2)} \qquad (3)$$

where *y* is emission factor (g/mi); *x* is average speed (mph); and b_0, b_1, and b_2 are regression coefficients.

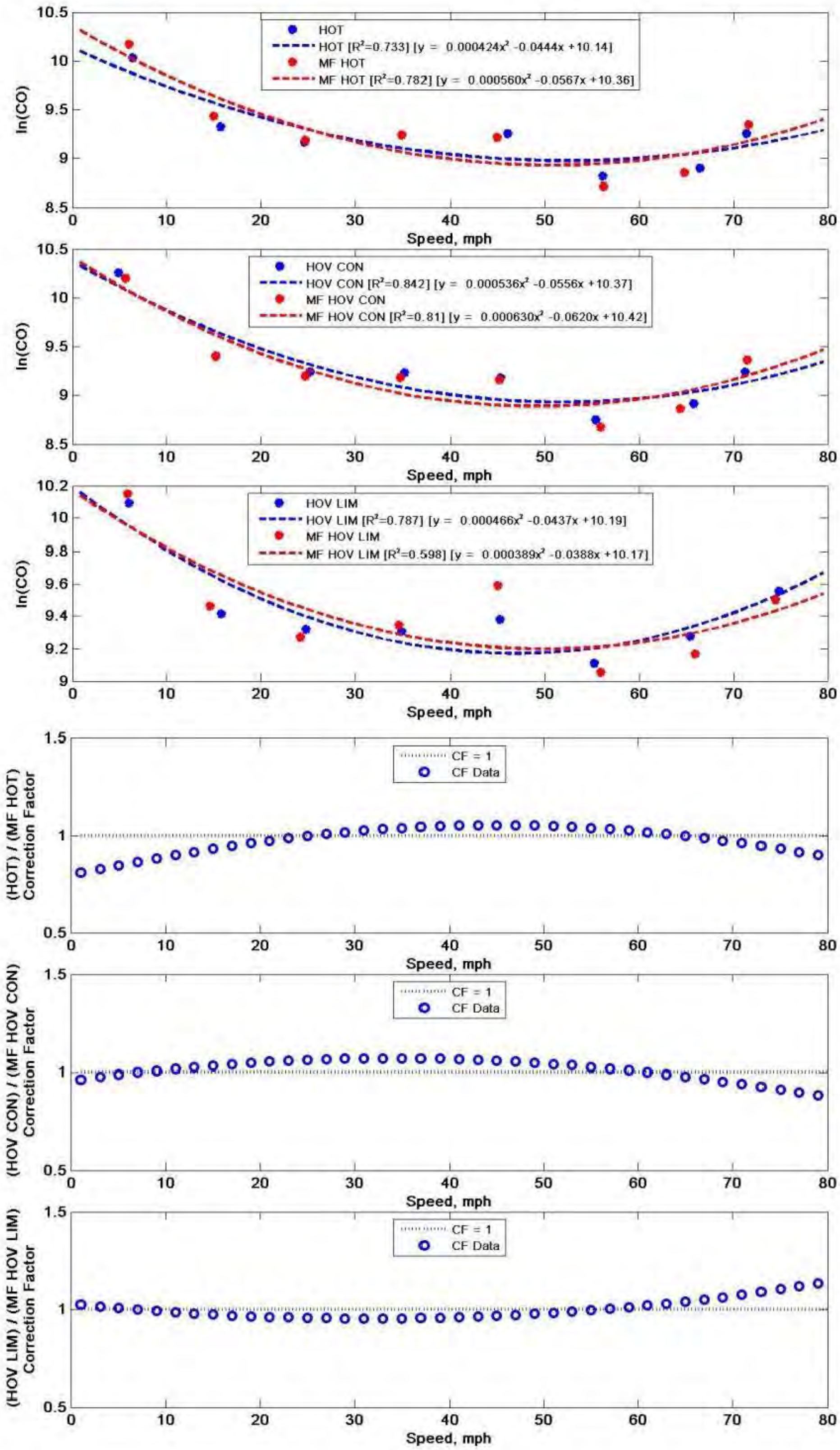
4.3. Deriving Lane Type Emission Adjustment Factors

After all the 34,560 emission versus speed curves were fitted with Equation (2) and the regression coefficients obtained, lane type emission adjustment factors were derived for each of the 6 emissions (CO_2, CO, THC, NO_x, PM_{10}, and $PM_{2.5}$) and each of the 3 managed lane types (limited access HOV lanes, continuous access HOV lanes, and express/HOT lanes) by calculating the ratio of emission factor for managed lanes to that for the parallel GP lanes. Figure 4-3 through Figure 4-8 presents example results of the fitted curves and the derived lane type emission adjustment factors for one of the 960 combinations of conditions. The lane type emission adjustment factor is less than one if the emission factor for managed lanes is lower than the emission factor for the parallel GP lanes, and vice versa.



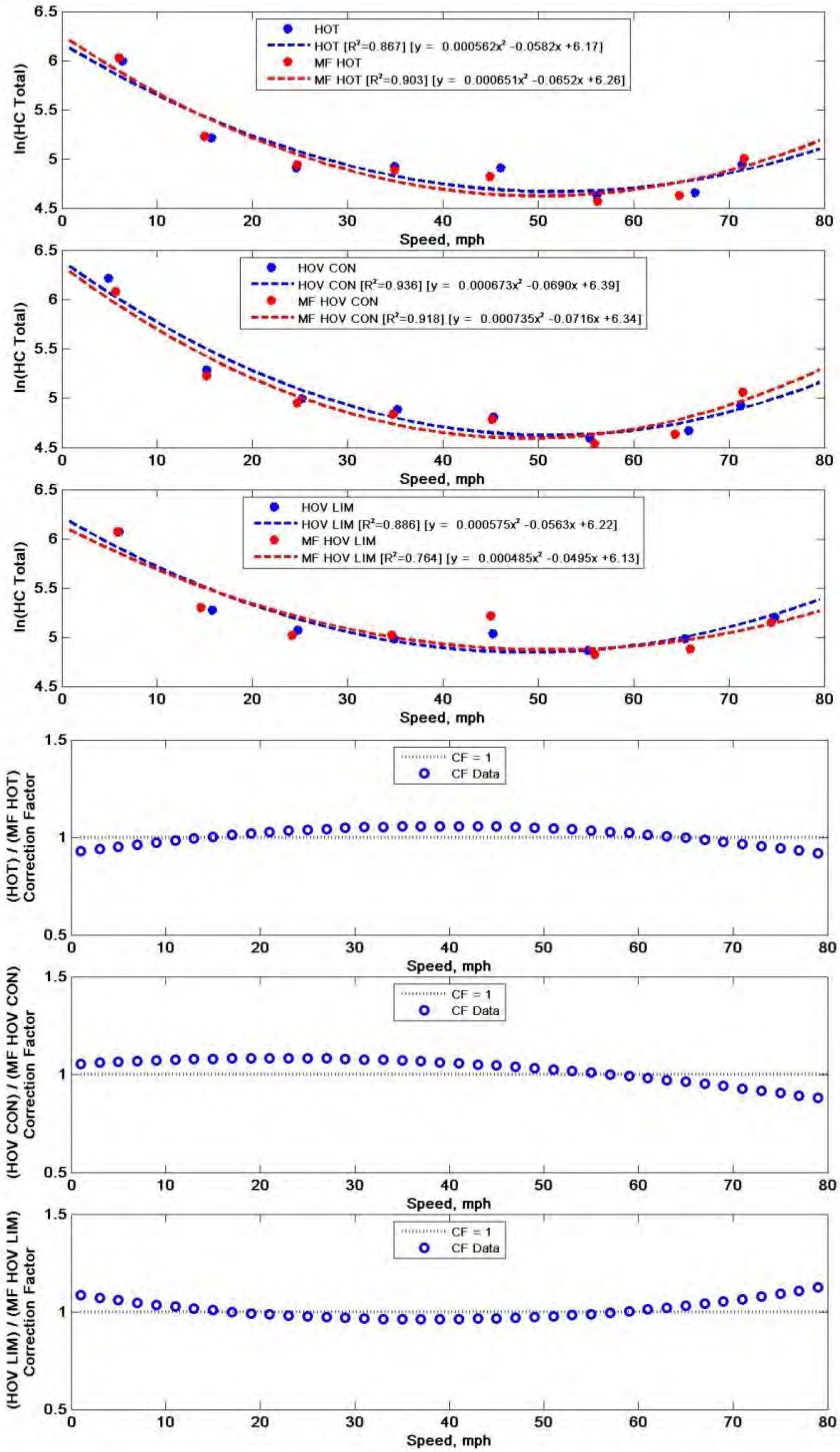
Passenger cars, calendar year 2015, temperature 100 °F, relative humidity 20%

Figure 4-3. Example modeling results for CO_2



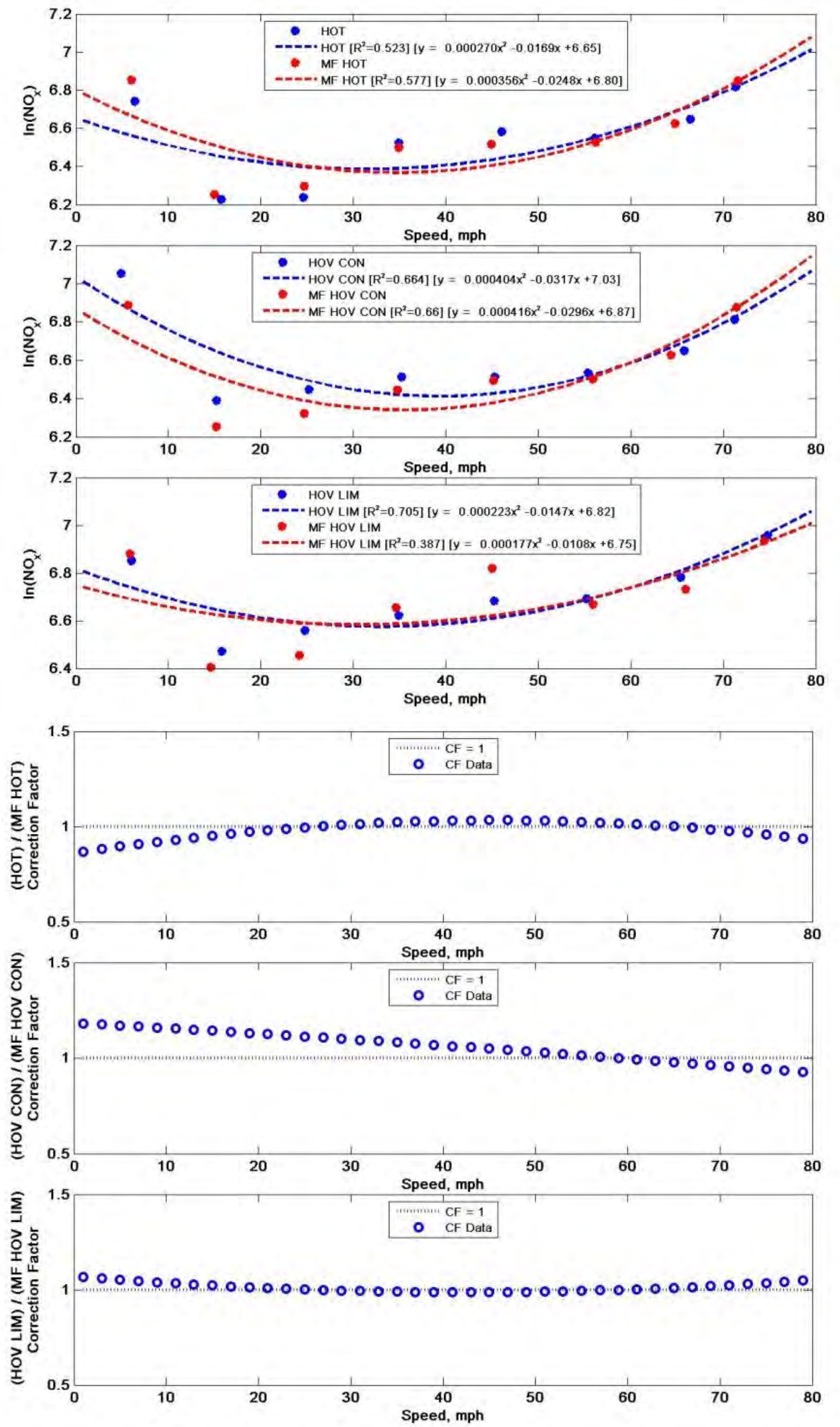
Passenger cars, calendar year 2015, temperature 100 °F, relative humidity 20%

Figure 4-4. Example modeling results for CO



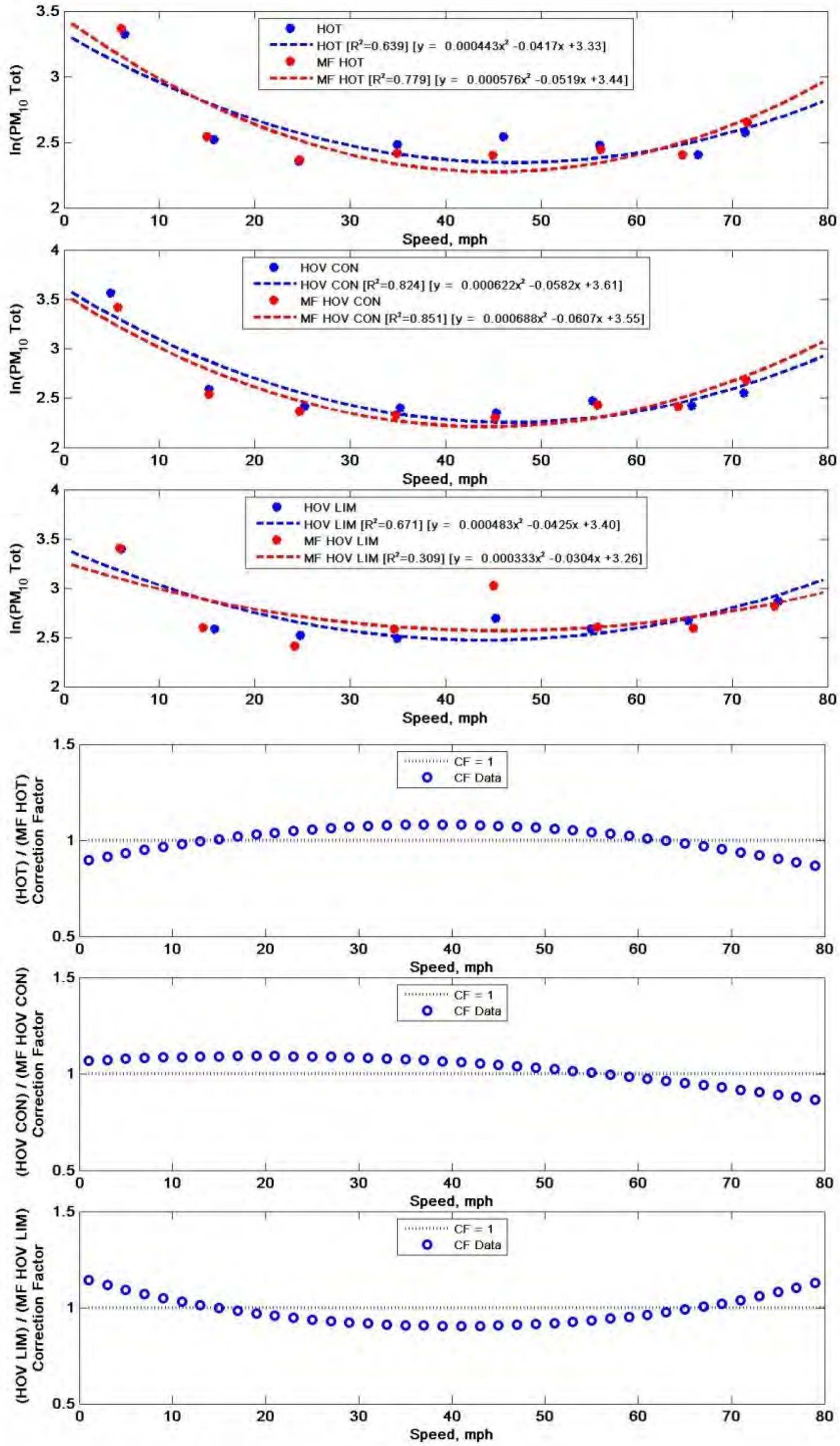
Passenger cars, calendar year 2015, temperature 100 °F, relative humidity 20%

Figure 4-5. Example modeling results for THC



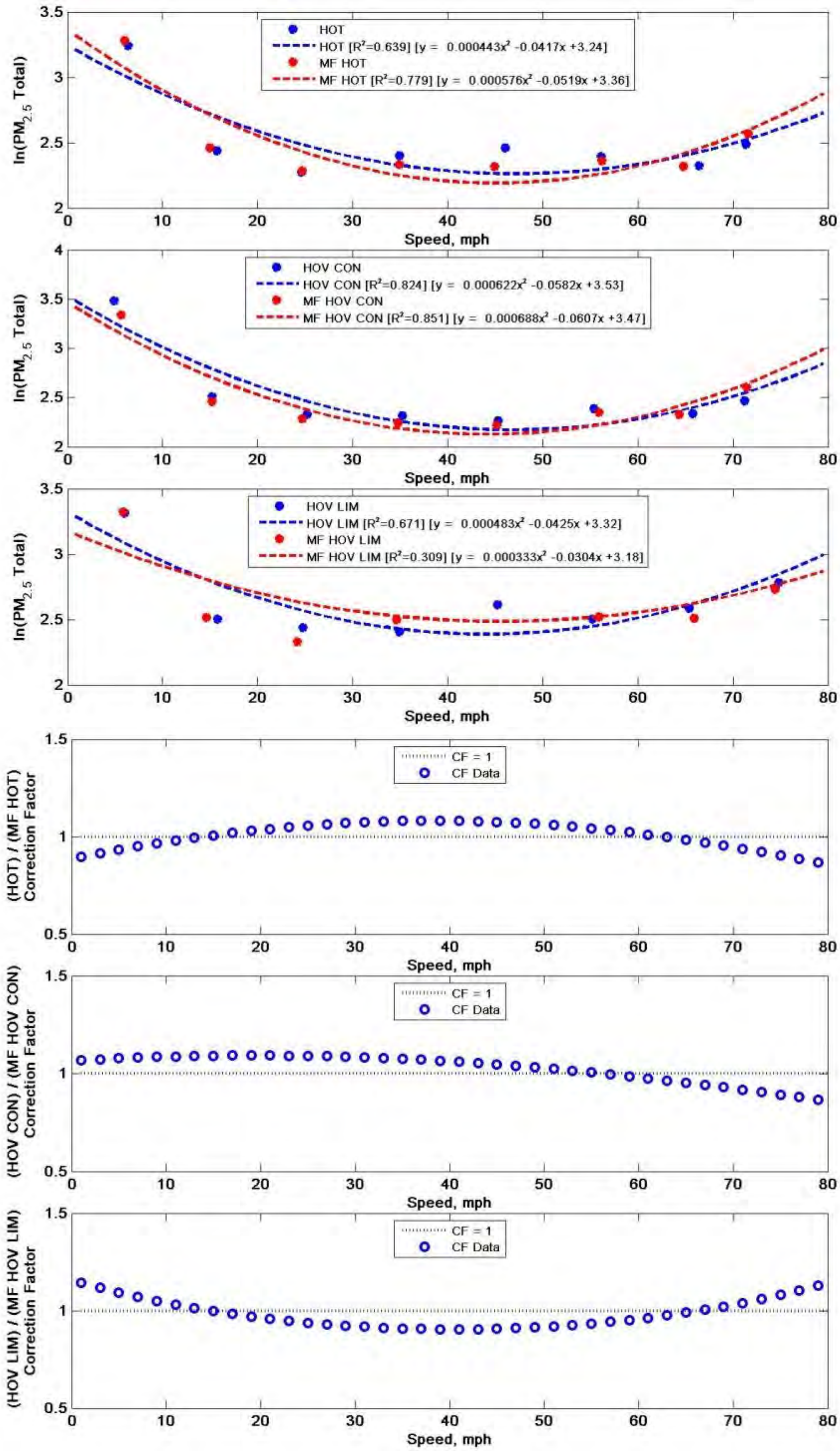
Passenger cars, calendar year 2015, temperature 100 °F, relative humidity 20%

Figure 4-6. Example modeling results for NO_x



Passenger cars, calendar year 2015, temperature 100 °F, relative humidity 20%

Figure 4-7. Example modeling results for PM_{10}



Passenger cars, calendar year 2015, temperature 100 °F, relative humidity 20%

Figure 4-8. Example modeling results for $PM_{2.5}$

As can be observed from Figure 4-3 through Figure 4-8, the lane type emission adjustment factors vary by lane type and emission type. They also vary by the other conditions including vehicle type, calendar year, air temperature, and relative humidity. For the entire scopes of conditions under which the lane type emission adjustment factors were developed in this research, the ranges of lane type emission adjustment factors are summarized in Table 4-2.

Table 4-2. Ranges of lane type emission adjustment factors

Emission	Range of Lane Type Emission Adjustment Factors
CO_2	0.91 – 1.08
CO	0.78 – 1.16
THC	0.80 – 1.22
NO_x	0.81 – 1.20
PM_{10}	0.83 – 1.19
$PM_{2.5}$	0.83 – 1.19

4.4. Developing Spreadsheet Tool

To aid in the deployment of the lane type emission adjustment factors, a spreadsheet tool was developed that can be used in conjunction with the Caltrans version of EMFAC (CT-EMFAC) model to analyze the emission impacts of various managed lane projects. The spreadsheet tool was developed in the Microsoft Excel environment with an extensive use of macros. The lane type emission adjustment factors were stored in the spreadsheet tool in the form of look up table. A user interface was created to facilitate the execution of the tool, as shown in Figure 4-9. The spreadsheet tool had been tested for error checking and quality assurance.

In addition to the spreadsheet tool itself, a user's guide for the tool was also prepared. It describes the components and features of the spreadsheet tool. It also provides step-by-step instructions, with supplementary flow charts and screenshots of the user interface, on how to use the spreadsheet tool to evaluate the emission impacts of the following types of managed lane projects:

1) Adding a new managed lane
2) Converting an existing managed lane
3) Changing managed lane operations

Figure 4-10 presents the flow chart of using the spreadsheet tool with CT-EMFAC. First of all, emission factors will need to be output from CT-EMFAC in an emission factors file. The spreadsheet tool will then take in the emission factors file and apply lane type emission adjustment factors to the base emission factors from CT-EMFAC based on the conditions (lane type, vehicle mix, air temperature, and relative humidity) specified on the user interface. The adjusted emission factors will be saved in the same format as the emission factors file so that they can be imported back into the CT-EMFAC environment for emission mass calculation.

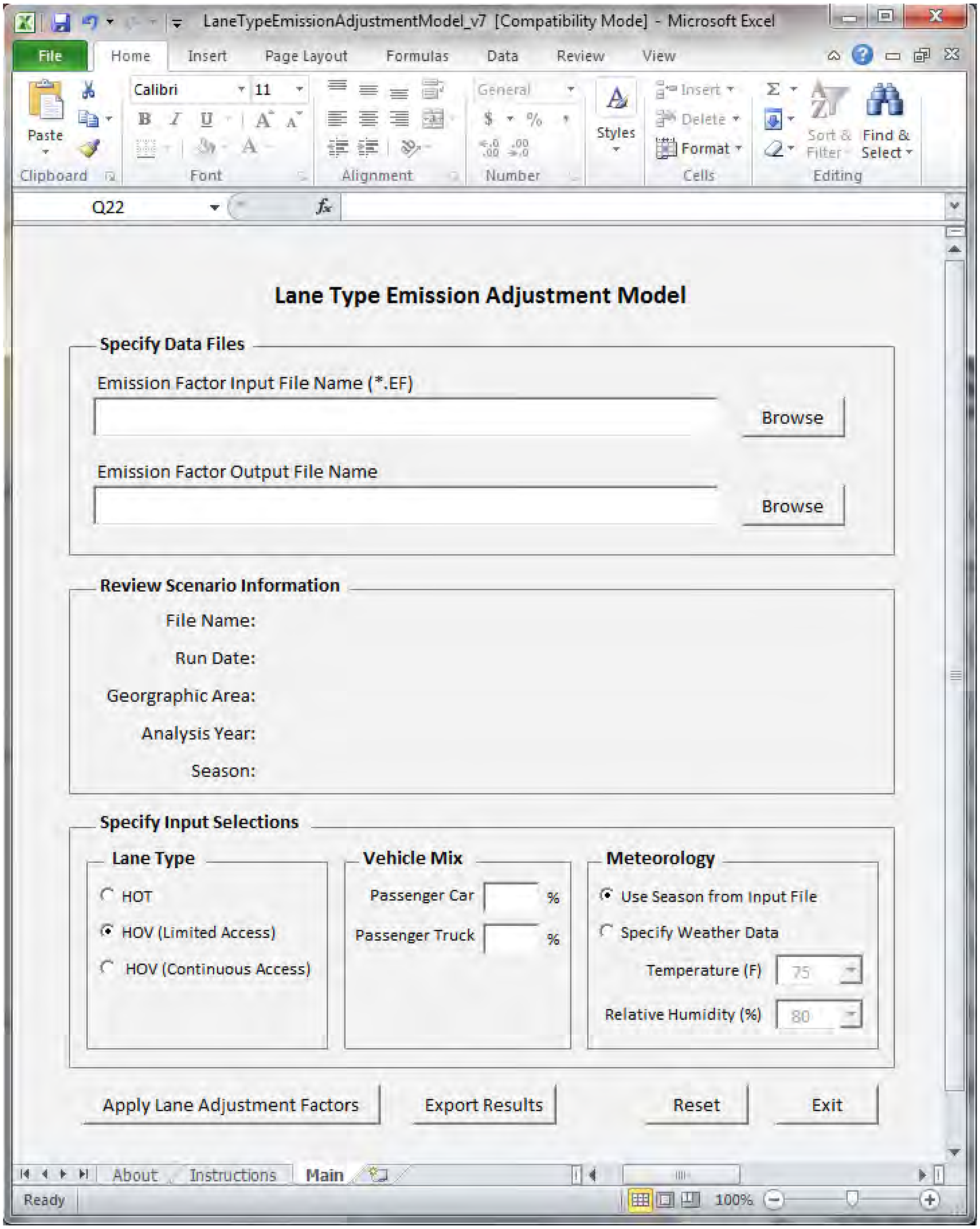


Figure 4-9. Lane Type Emission Adjustment Model tool

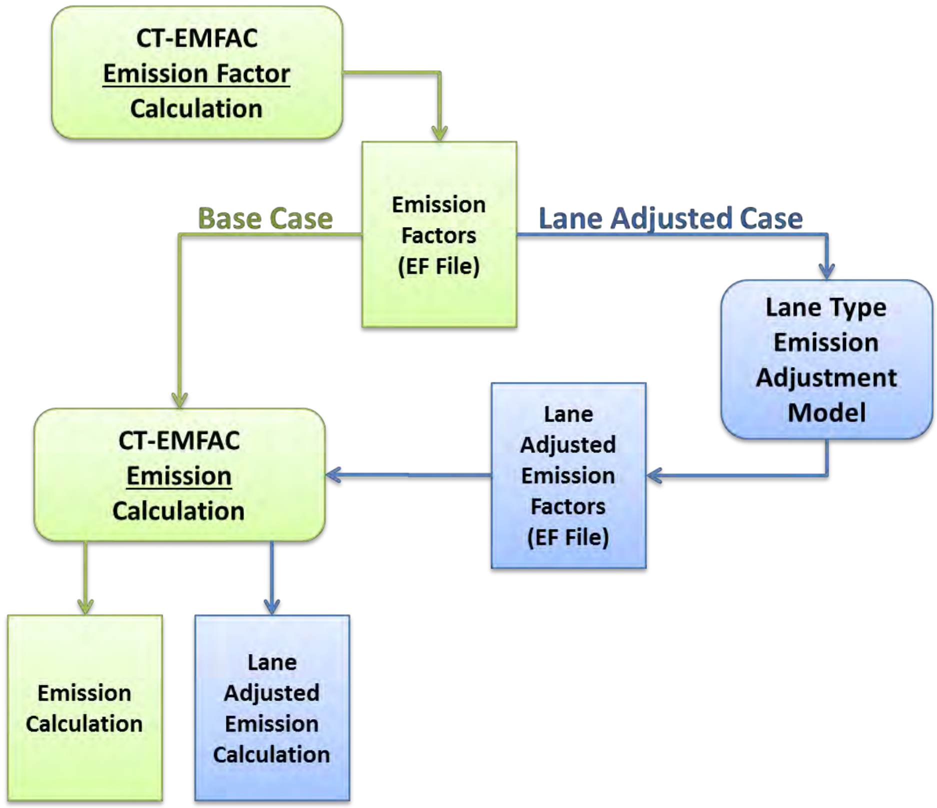


Figure 4-10. Using Lane Type Emission Adjustment Model tool with CT-EMFAC

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