ABSTRACT

Title of Document: EFFECTS OF EXEMPTIONS FOR
LOW- EMITTING VEHICLES
IN MANAGED LANE USE

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A simulation-based study was conducted to investigate the effects of exempting low-emitting vehicles (specifically hybrids and E85 alternative fuel vehicles (AFVs)) from occupancy requirements in high occupancy vehicle (HOV) lane and express toll lane (ETL). Numerical experiments involved various levels of hybrid penetration rates and results were studied. Emission estimates resulting from various AFV penetration levels were compared to those of hybrids at the same penetration levels. It was concluded that exemptions would not significantly degrade the managed lane use at low penetration rates. Performance deterioration was noted at penetration rates of 11.42% and at 26.56% and higher for the HOV lane facility and at penetration levels of 21.89% and higher for the ETL facility. Network-wide emissions and fuel consumption slightly increase while emissions and fuel consumption per vehicle miles traveled generally decrease. Moreover, hybrid vehicle technologies were found to result in greater emissions savings as compared with E85 AFVs.

EFFECTS OF EXEMPTIONS FOR LOW EMITTING VEHICLES IN MANAGED LANE USE

By

Bing Qi

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Dedication

To my dear parents

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List of Acronyms

Acronym	Description
A.B.	Assembly Bill
ADT	Average Daily Traffic
AFV	Alternative Fuel Vehicle
B20	20% Biodiesel, 80% Diesel
CAAA	Clean Air Act Amendments
CALTRANS	California Department of Transportation
CD	Connector-Distributor
CDOT	Colorado Department of Transportation
CH_4	Methane
CMEM	Comprehensive Modal Emission Model
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Equivalent Carbon Dioxide
E85	85% Ethanol, 14% Gasoline
ETL	Express Toll Lane
FC	Fuel Consumption
FHWA	Federal Highway Administration
G.V.W.	Gross Vehicle Weight
GHG	Greenhouse Gas
GP	General Purpose
GVWR	Gross Vehicle Weight Rating
H.B.	House Bill
HEV	Hybrid Electric Vehicle
HHD	Heavy Heavy-Duty Vehicle
HOT	High-Occupancy Toll
HOV	High-Occupancy Vehicle
ILEV	Inherently Low Emission Vehicle
I-TMS	Internet Traffic Monitoring System
KG	Kilogram
LDT	Light-Duty Truck
LDV	Light-Duty Vehicle
LEEV	Low Emission and Energy-Efficient Vehicle
LNG	Liquefied Natural Gas
LOS	Level of Service
LPG	Liquid Propane Gas
MAP-21	Moving Ahead for Progress in the 21st Century Act
MDE	Maryland Department of the Environment

Acronym	**Description**
MHD	Medium Heavy-Duty Vehicle
mm	Micrometer
MOVES	Motor Vehicle Emissions Simulator
MPG	Miles Per Gallon
mph	Mile Per Hour
MVA	Motor Vehicle Administration
MWCOG	Metropolitan Washington Council of Governments
N.R.S.	Nevada Revised Statutes
NJTA	New Jersey Turnpike Authority
NO_x	Nitrogen Oxides
ORSEEM	On -Road Simulation Emission Estimation Model
PHEV	Plug-in Hybrid Electric Vehicle
PM_{10}	Particulate Matter 10 millimeter
$PM_{2.5}$	Particulate Matter 2.5 millimeter
R.T.C.	Referred to Committee
RFS2	Renewable Fuel Standard Program
S.B.	Senate Bill
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
SHA	State Highway Administration
SOV	Single Occupant Vehicles
SO_x	Sulfur Oxides
TEA-21	Transportation Equity Act for the 21st Century
THC	Total Hydrocarbon
U.S	United States
U.S.C.	the United States Code
USDOE	U.S. Department of Energy
USEPA	U.S. Environmental Protection Agency
VBA	Visual Basic for Application
VHT	Vehicle Hours Traveled
VMT	Vehicle Miles Traveled
vpmpl	Vehicle Per Mile Per Lane

Chapter 1: Introduction and Motivation

The transportation sector accounts for 28% of all U.S. greenhouse gas (GHG) emissions (Environmental Protection Agency, 2012). On-road vehicles, including passenger cars, light-duty trucks (LDT), and medium- and heavy- duty trucks, are responsible for 84% of these emissions. State authorities and the U.S. Federal Government have invested in opportunities to support individuals, companies, and organizations (governmental and nongovernmental) in shifting from conventional petroleum powered vehicles to those that can use alternative or mixed fuels. Alternative fuels include: compressed natural gas (CNG), liquefied natural gas (LNG), liquid propane gas (LPG), methanol, ethanol, biodiesel, electricity, hydrogen, and fuels derived from biological materials. Mixed fuels are those that blend alternative fuels with petroleum gasoline or diesel. Examples include E85 (85% ethanol, 14% gasoline) and B20 (20% biodiesel, 80% diesel).

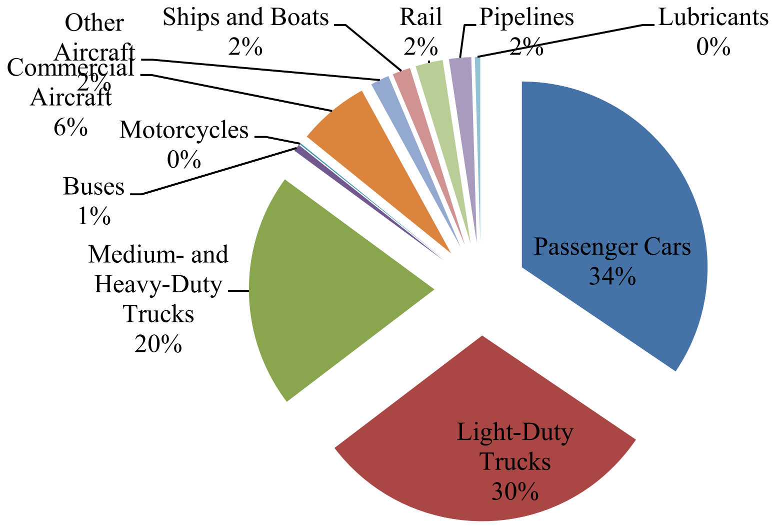


Figure 1-1 Transportation Sector-related 2009 GHG Emission by Source [Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1999-2010, USEPA, 2012]

Alternative fuel vehicles (AFVs) can be categorized into two classes: dedicated AFVs and non-dedicated AFVs. Dedicated AFVs are designed to operate exclusively on one alternative fuel while non-dedicated AFVs are configured to operate on more than one fuel, usually an alternative fuel and gasoline or diesel. Dedicated AFVs are also referred to as inherently low emission vehicles (ILEVs). ILEVs are defined and recognized by the U.S. Environmental Protection Agency (USEPA) for their low level of evaporative emission. Any non-gasoline powered (excluding diesel) vehicle qualifies as an ILEV. Non-dedicated AFVs usually run on mixed fuels, for example, E85 with 85% ethanol blended with gasoline. Non-dedicated AFVs qualify as low emission and energy-efficient vehicles (LEEVs). According to the Section 166 (f)(3) of Title 23 of the United States Code (23 U.S.C.), LEEVs refer to those vehicles that are: 1) certified by the USEPA as meeting the Tier II emission level under Section 202(i) of the Clean Air Act for a particular make and model year and 2) certified by the USEPA as achieving no less than a 50 percent increase in city fuel economy or no less than a 25 percent increase in combined city-highway fuel economy over a comparable internal combustion gasoline fueled vehicle. Hybrids are considered to be a type of LEEVs. AFVs, ILEVs and LEEVs are referred to together as low-emitting vehicles in this study. To encourage the adoption of such low-emitting vehicles, legislation and incentives, including income tax credits, sales tax exemptions, vehicle emissions test exemptions, free or discounted parking fees, AFV rebates, and exemptions for using managed lanes (i.e. high-occupancy vehicle (HOV) /high-occupancy toll (HOT) lanes and express toll lanes (ETLs)), have been introduced.

Through government managed access, vehicles that meet low emission standards are permitted to use HOV lane, HOT lane and ETL facilities without adhering to the minimum occupancy requirements or paying tolls. In some cases, reduced tolls are charged. This preferential treatment is offered to encourage and support individuals and organizations that use low emission vehicles.

Unfortunately, if a large enough number of individuals and organizations purchase reward earning vehicles (i.e. those with low emissions) the performance of the managed lanes will degrade, adversely affecting traffic flow and reducing the intended environmental benefits. Thus, it is imperative that the roadway operators consider the implications of these types of programs.

In compliance with the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU), states monitor, evaluate, and terminate lane-use privileges when degradation in performance is noted. It is critical to understand the extent to which, and under what circumstances, the potential effects of exempting occupancy or toll requirements for low-emitting vehicles on the performance of managed lanes. An understanding of these implications can support policy-makers and traffic management operators in their decisions to introduce, continue, or terminate related programs.

In this thesis, a simulation-based study is conducted to investigate the effects of exempting LEEVs (specifically hybrid vehicles) and AFVs (specifically E85 vehicles) from occupancy requirements in managed lane use. Systematically designed numerical experiments were conducted to assess the operational performance effects of these exemptions. The environmental implications are studied through the use of an advanced emission estimation tool.

Some states, like California, have laws that limit the number of hybrid vehicles that can use the HOV lanes with only a single occupant. In California, this is controlled through a decal or permit-based system. However, it is not clear how the limitations on the number of available decals were determined. A micro-simulation based study described in (Brownstone et al., 2008) evaluated the effects of allowing single occupant hybrid vehicles to use HOV lanes for a network of roadways in California. The study considered three levels of the number of hybrid permits that can be issued in the form of decals. The study found that with more than 50,000 permits issued, it should be expected that the performance of the HOV lane facility in terms of travel speeds and total throughput will degrade very significantly. Despite the fact that AFVs are eligible for lane exemptions, they were not considered in the above mentioned study.

Such traffic simulation tools, as well as emission estimation models and statistical analysis of field data, are typical tools used to assess the operational and environmental effects of existing or potential strategies. The closest study is by Nesamani et al. (2010). Nesamani et al. considered the effects on emissions of increased hybrid use of an HOV lane. Similar to this study, a simulation-based methodology was employed. They concluded that there are significant benefits from exemptions in terms of both emissions (specifically, CO, CO_2, HC and NO_x) and fuel consumption (FC). However, they compared a case of high hybrid penetration rate with exemption for single occupant hybrids to a base case with a lower penetration rate and no exemptions for single occupant hybrids. Consequently, the impacts of increased penetration rate and permitting exemptions are confounded. That is, the benefits may be entirely or almost entirely from increased hybrid penetration levels, rather than due to exemptions. These factors are carefully separated in the experimental design employed herein. Additionally, only one design was considered in the earlier work; whereas, a limited access ETL is studied here. Moreover, implications for AFVs in terms of emissions benefits are derived within this study. More detail on the experimental design used here is given in Section 3.3.

In addition to monetary losses from reduced toll charges, there are other negative effects of allowing qualifying low emission vehicles to use these lanes without paying full-priced tolls. For example, due to the additional facility users, there may be reduced revenue received from toll collections due to reductions in travel time savings for other high-occupancy vehicles or paying customers. Moreover, when more than one class of vehicle is eligible for managed lane access exemption but the excess available capacity of such a facility is limited and, therefore, unable to accommodate all such qualifying vehicles, which class of vehicles should be given preferential treatment must be determined. In this study, the relative benefits in terms of emissions savings when giving access to hybrids versus AFVs (using E85) are explored.

This thesis provides a comprehensive and systematic analysis of the effects of occupancy and toll requirement exemptions in HOV lanes and ETLs. The data is measured quantitatively through the lens of traffic operations in both managed and general purpose (GP) lanes. To accomplish this analysis, a simulation model in a simulation platform, specifically VISSIM (PTV, Inc.), was used. An add-on on-road vehicle emissions model, ORSEEM, developed to quantify the effects on emissions and fuel consumption (Miller-Hooks et al., 2012) is applied. ORSEEM accounts for modal parameters of acceleration, deceleration, vehicle make year, age, mass, vehicle type, fuel usage, and roadway geometry. Moreover, the effects in terms of traffic operations and emissions are studied for different penetration rates of qualifying low-emitting vehicles as a portion of the traffic composition. Based on the assessment results, recommendations are made intending to provide reasonable standards and guidelines when introducing, justifying or contradicting such managed lane access exemption policies.

This thesis contributes to the understanding of the potential effects of managed lane access exemptions. The thesis offers policy-makers a more accurate picture of potential outcomes that can be used when considering on-going or future policy in this area.

The thesis progresses as follows. Chapter 2 presents additional background on incentives and exemptions in the United States (U.S.) aimed at increasing ownership and use of low-emitting vehicles. Chapter 3 reviews related literary works. Chapter 4 describes the experimental environment of the study and gives the overall study structure. The emission tool that is used in estimating emissions is presented in Chapter 4, as well. The modeling and experimental designs in support of simulation experiments used to assess the potential of the exemption policies are discussed in Chapter 5. Chapter 6 presents the experimental results and Chapter 7 summarizes the findings.

Chapter 2: Background

2.1 Overview of Alternative Fuel Vehicles

Reducing GHG emissions would improve air quality and diminish the industrial world's role in global warming and climate change. As such, the adoption of AFVs has accelerated. Additionally, the turn from petroleum products to AFVs could reduce U.S. dependence on imported oil sources, increasing national security. Alternative fuels often provide high energy efficiency and are renewable sources. Consider the example given in Figure 2-1, This figure shows, for example, that switchgrass ethanol reduces GHG emissions by up to 110% when compared to petroleum gasoline and waste grease biodiesel reduces GHG emissions by 86% relative to petroleum diesel.

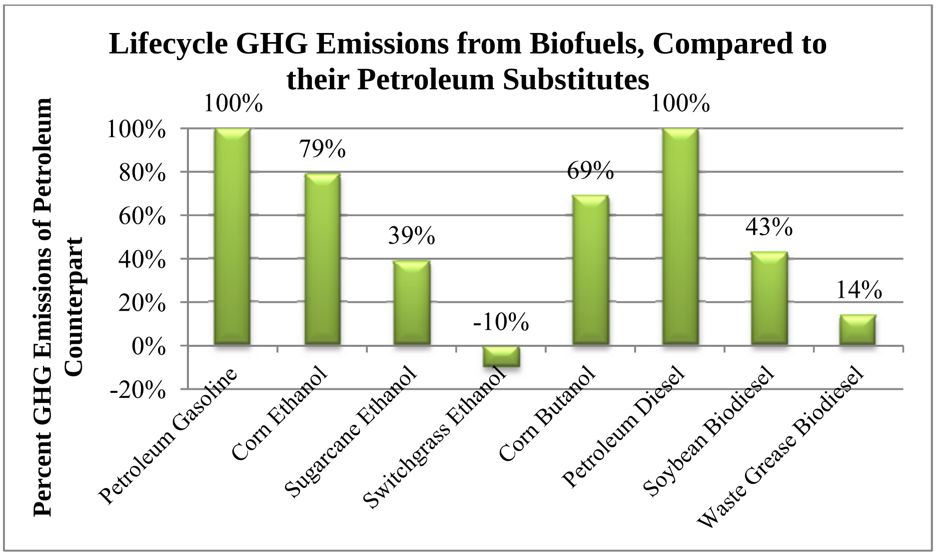


Figure 2-1 GHG Emission Comparisons between Bio-fuels and Petroleum Substitutes [Source: Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis, USEPA, 2010]

As the adoption of AFVs increases, an increasing number of AFVs are manufactured. Figure 2-2 illustrates the trend in number of available on-road AFVs by year.

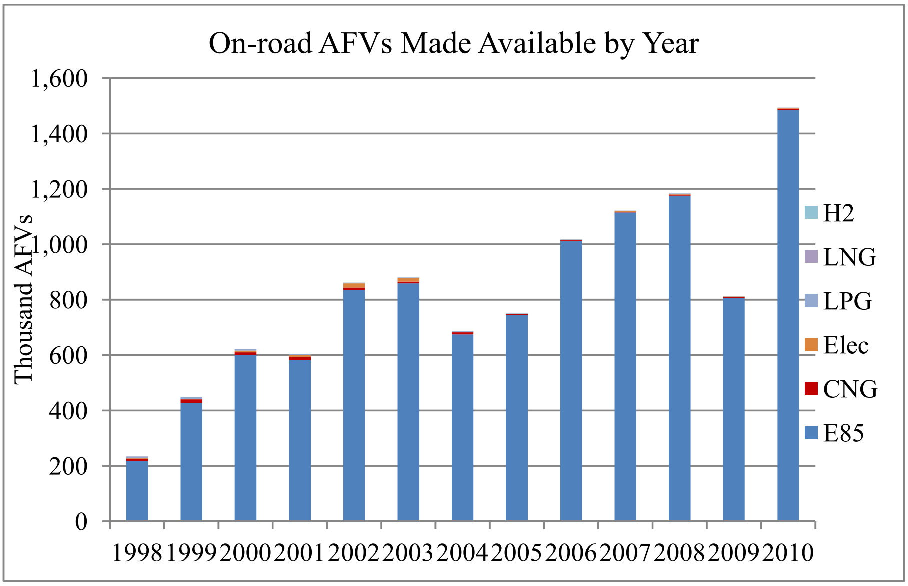


Figure 2-2 On-Road AFVs Made Available by Year [Source: U.S. Department of Energy (USDOE), Accessed 2011a]

The use of AFVs on the road also increases over time. The estimated number of AFVs in use, by fuel type, is given in Table 2-1.

Table 2-1 Alternative Fuel Vehicles in Use by Fuel Type from 2006-2008 [Source: USDOE, Accessed 2011b]

Fuel Type	**2006**	**2007**	**2008**
Natural Gas	118,929	117,172	117,074
Electric	53,526	55,730	56,901
E85	297,099	364,384	450,327
LPG	164,846	158,254	151,049
Other Fuels	162	226	316
Total	**634,562**	**695,766**	**775,667**

2.2 Overview of Managed Lane Facilities in the U.S.

HOV lanes first appeared in 1969, the oldest of which is along I-395 in Virginia. As of 2008, a total of 345 HOV lane facilities are under operation, planning or construction stages in the U.S., with the largest number (88) in California, followed by Minnesota, Washington, Texas and Virginia with 83, 41, 35, 21 facilities, respectively (Booz Allen Hamilton, 2008). HOV lanes are designated for exclusive use by HOVs. To be categorized as high occupancy, it is necessary that the vehicle carries two, three and sometimes more occupants. These lanes provide travel time savings and increased trip time reliability for their users. HOV lanes improve person-throughput rather than vehicle-throughput and encourage travelers to change from driving alone to carpooling, vanpooling, and transit.

While HOV lanes encourage ridesharing, some realistic problems make the formation of HOVs difficult, such as trip chaining in family activities and scarcity in potential carpool matches, which result in underutilization and, therefore excess HOV lane capacity. To take advantage of this excess roadway capacity, and to provide travelers with more choices, the concept of (HOT) lanes emerged.

HOT lanes allow vehicles that do not meet the minimum occupancy requirement to gain access to it by paying a toll. Generally, HOVs are allowed to use HOT lanes at a discounted fee or free of charge. If a fee is charged, the amount could vary depending on the time of day or level of congestion. As of 2012, twelve HOT lane facilities existed in the U.S.: the I-15 express lanes in San Diego, the I-394 MnPASS program and I-35W express lanes in Minnesota, the I-25 HOT lanes in Denver, the I-10 Katy & Northwest Freeway managed lanes in Houston, the US-290

HOT lane in Houston, the I-95 HOT lanes in Miami, the I-680 and I-880 HOT lanes California, the I-15 express lanes in Salt Lake City, and the SR-167 HOT lanes in Seattle (Federal Highway Administration, Accessed 2012; Metro.net, Accessed 2012). Most HOT lane facilities require single occupant vehicles to pay a toll. Some facilities permit three or more occupants to avoid paying a toll.

Because it is difficult to enforce HOT lane facility usage rules, violation rates can be quite high. Consequently, interest in ETLs is on the rise. ETLs operate under regulations that are stricter than HOT lanes: all vehicles pay a toll or are pre-registered. As of 2011, ETLs have been installed along I-680, I-25, I-405/SR 167, I-91, I-85 and I-95. Vehicles that qualify for ETL exemptions along the I-85 express lanes include: transit buses, registered vehicles with three or more passengers, and qualified AFVs. However, hybrid vehicles do not qualify. In contrast to I-85, hybrid vehicles qualify for use of the ETLs along I-95. This comparison highlights differences between policies concerning vehicle exemptions that exist from facility to facility.

2.3 Federal Legislation on Managed Lane Access Exemption

The use of managed lanes by ILEVs dates back to 1990 when the Clean Air Act Amendments (CAAA) were passed. The CAAA created the clean-fuel vehicle program, which designates that ILEVs can use HOV lanes without meeting the minimum occupancy requirement. The CAAA aimed to encourage the purchase and use of these vehicles. With the Transportation Equity Act for the 21st Century (TEA-21), enacted in 1998, states are allowed to authorize ILEVs to use HOV lane facilities. The USEPA administers the certifications, labeling, and other regulatory provisions of an ILEV program and updates the list of certified ILEVs.

In 2005, SAFETEA-LU expanded the exempt vehicle classification from only ILEVs to include LEEVs. SAFETEA-LU ruled that the exemption for ILEVs and LEEVs not satisfying the minimum occupancy requirement would expire after September 30, 2009. This expiration date has been subsequently extended with each successive congressional reauthorization of the transportation bill. Before the expiration date, the exemption could be terminated earlier than expected by states. The USEPA takes the responsibility to establish certification and labeling requirements for LEEVs, as well as provides guidelines on the eligibility of vehicles with collaboration from the Federal Highway Administration (FHWA). A proposed rule-making document for determining clean vehicle eligibility was issued in 2007. However, the final guideline has not yet been established and is still on its way. States may develop more stringent certification standards of qualifying vehicles based on the USEPA rules without relaxing restrictions.

While SAFETEA-LU gives states the authority to allow low emitting and energy-efficient vehicles to use HOV lane facilities, it requires the highway operating agencies of the state to monitor the use of the HOV lane facilities by such vehicles and evaluate their impact on the performance of those facilities. If those vehicles cause significant performance degradation for the facility (i.e. if the average vehicular speed drops below a threshold, discussed in more detail in Section 3.2), the state is required to restrict or eliminate the use of HOV lane facilities by such vehicles.

The Moving Ahead for Progress in the 21st Century Act (MAP-21) signed into law on July 6, 2012 has similar requirements and makes several suggestions for measures that can be taken to return HOV lane performance to prior levels.

2.4 State Incentives on Managed Lane Access Exemption

In alignment with SAFETEA-LU, states began to issue incentives and legislation. Since 1997 when Arizona passed legislation approving the use of HOV lanes by AFVs regardless of the number of passengers, at least 11 states have issued HOV lane exemption legislation for ILEVs, AFVs or LEEVs (specifically hybrids) that meet the low emission standards set by the USEPA. These states include: Arizona, California, Colorado, Florida, Georgia, Maryland, New Jersey, New York, Tennessee, Utah, and Virginia. An additional eight states - Hawaii, Connecticut, Massachusetts, Michigan, Minnesota, Texas, Washington, and Nevada - have proposed similar HOV lane access exemption bills. These bills, however, are still under review by states' environmental and transportation related committees and are awaiting approval from the FHWA. Similar bills have been submitted in two states (Minnesota and Texas) that would allow LEEVs to use HOT lanes without paying a toll. Such HOT lane exemption legislation has been officially passed in Colorado and Florida.

For the purpose of facilitating the recognition of qualifying vehicles and enhancing the management of HOV/HOT lane operations, decals or special plates that differentiate certified alternative clean-fuel vehicles from conventional gasoline-powered vehicles are issued by the motor vehicle administration of some states. Individuals need to apply for such decals or plates. Moreover, they may need to equip their “Green Vehicles” with transponders when traveling in HOT lanes or ETLs. The available number of decals or plates issued is capped and often varies by state. The number ranges from 2,000 decals in Colorado to 85,000 in California. In some states, several types of decals or stickers are adopted to classify qualifying low emission vehicles. For instance, California issues white clean air vehicle stickers to so-called zero emission vehicles, such as 100% electricity-powered, hydrogen fuel cell and CNG vehicles, while qualifying hybrids are identified by yellow clean air stickers.

In terms of eligible AFVs, ILEVs powered by compressed natural gas, electricity, hydrogen and propane are permitted to access the managed lanes without meeting the occupancy or toll requirement. Under the SAFETEA-LU authority, hybrids and other LEEVs are added to the list of qualifying vehicles if they are certified by the USEPA and obey federal legislation. Information relative to existing legislation, as well as bills that have been introduced and are under review for managed lane access exemption by states as of March 2011 are listed in Tables 2-2 and 2-3, respectively.

Table 2-2 Existing Legislation for Managed Lane Access Exemption by State [Source: [a] USDOE, Accessed 2011c; [b] HybridCenter.org, Assessed 2011]

Exemption	State	Duration	Qualifying Vehicles	Reference	Note
HOV	AZ	1997 - Present	Dedicated AFV	Arizona Revised Statutes 28-337, 28-2416	HOV lane use may be restricted if certain maximum volume and speed criteria are met.
		02/2007- Present halted for new applicants	Hybrid, LEEV	S.B. 1320 - 491R	On 07/13/09, the use of HOV lane by hybrids was formally banned and instead opens to LEEV. Program is halted until the impact of SOVs on

Exemption	State	Duration	Qualifying Vehicles	Reference	Note
					HOV lane use is assessed.
HOV/HOT	CA	01/2000 - 01/2015	AFV, PHEV	A.B. 1500, S.B.353,CA Vehicle Code 5205.5 and 21655.9	Unlimited number of clean air vehicle stickers for AFVs; Limited number of stickers for qualified PHEV and LEEVs.
		09/2004 - 07/2011	Hybrid		
HOV/HOT	CO	1998 - Present	ILEV	TEA-21	CDOT would restrict or terminate HOV lane use if ILEVs cause significant decrease in HOV LOS or impair receipt of federal funds.
		05/2008 - 12/2010	Hybrid	CCR 204-28	
HOV/HOT	FL	2003 - Present	ILEV	H.B.971, Florida Statutes 316.0741	HEV must satisfy California emission standards. 3-wheeled vehicles are considered as ILEVs.
		08/2005 - Present	Hybrid		
HOV/HOT /ETL	GA	1998 - Present	AFV	Georgia Code 32-9-4 and 40-2-76	The program of allowing HEVs to use HOV lanes will be implemented after final ruling made by USEPA.
		2004 - Present	Hybrid		
HOV	MD	10/2010 - 09/2013	Plug-in Electric Vehicle	S.B.602, H.B.674, Maryland Statutes, Transportation Code 25-108	MVA and SHA must report plug-in electric vehicles use in HOV lanes to the governor.
HOV	NJ	04/2006 - Present	AFV, Hybrid	NJTA Title 19: 9-1.24	The New Jersey Turnpike Authority (NJTA) allows qualifying vehicles to use the left travel lanes of a portion of the NJ Turnpike.
HOV	NY	03/2006 - Present	Hybrid, LEEV	Clean Pass Program	All commercial vehicles are prohibited from HOV lanes regardless of vehicle type.
HOV	TN	01/2009 - Present	ILEV, LEEV of G.V.W< 26000 lbs	Tennessee Code 55-8-188	HOV lane use by qualifying SOVs will be discontinued if exemption violates

Exemption	State	Duration	Qualifying Vehicles	Reference	Note
					federal guidelines or prevents receipt of federal funds.
HOV	UT	2001 -12/2010	ILEV, Hybrid	Utah Code 41-1a-1211, 41-6-53.5, and 63-55-241	Qualifying vehicles will be issued with clean fuel group license plates.
HOV	VA	1994 - Present	ILEV	Virginia Code 33.1-46.2 and 46.2-749.3	State legislation allows vehicles with clean special fuel license plates to use HOV lanes exempt from occupancy requirement. New clean fuel license plates were created in 2006.
		2007 - 07/2011	Hybrid		For HOV lanes serving the I-95/I-395 corridor, only registered vehicles displaying Clean Special Fuels license plates issued before July 1, 2006, are exempt from HOV lane requirements.

A.B.: Assembly Bill
CDOT: Colorado Department of Transportation
G.V.W.: Gross Vehicle Weight
H.B.: House Bill
HEV: Hybrid Electric Vehicle
LOS: Level of Service
MVA: Motor Vehicle Administration
PHEV: Plug-in Hybrid Electric Vehicle
S.B.: Senate Bill
SHA: State Highway Administration
SOV: Single Occupant Vehicle

Table 2-3 Bills for Managed Lane Access Exemption by State [Source: HybridCenter.org, Accessed 2011]

Exemption	State	Bill	Date	Qualifying Vehicle
HOV	Hawaii	S.B. 2358	Introduced on 01/22/10	Electric vehicle
		S.B. 295	Introduced on 01/23/09	Hybrid
HOV	Connecticut	H.B. 5507	Introduced on 01/09	Hybrid and AFV
HOV	Massachusetts	S.B. 1920	Filed on 01/13/09	Hybrid and AFV
HOV	Michigan	H.B. 6611	R.T.C. on 11/14/06	Hybrid
HOV/HOT	Minnesota	H.F. 1956	Introduced on 03/19/09	Hybrid
HOV/HOT	Texas	H.B. 4071	Introduced on 03/23/09	Hybrid
HOV	Washington	H.B. 2931	Introduced on 01/17/06	AFV and Hybrid with highway MPG of at least 40 mile/gallon
HOV	Nevada	N.R.S. 484A.463	2009	LEEV

R.T.C.: Referred to Committee
N.R.S.: Nevada Revised Statutes

Chapter 3: Literature Review

3.1 Effects on Purchase of Alternative Fuel Vehicles and Hybrids

Several studies conducted on AFV and hybrid adoption examine the impact of state or federal government incentives. These previous studies analyze vehicle sales and U.S. registration data.

Abbanat (2001) explored the effects of HOV lane access privilege for single occupant vehicles (SOVs) on the decision to purchase CNG vehicles. This work was based on the results of semi-structured personal interviews of 18 people in California. It was concluded that HOV lane access exemption and environmental concerns were key factors in the decision to purchase CNG-fueled vehicles. Government financial subsidies, such as tax credits and buy-down rebates, were deemed as extra benefits, but not the primary motivating factors in purchase decisions.

A series of regression analyses of hybrid registration data over time were employed to investigate the relationship between hybrid adoption and a variety of socioeconomic and policy variables. Moreover, changes in hybrid adoption patterns were examined in association with policy changes to determine whether significant impacts on hybrid adoption patterns exist due to policy changes (Diamond, 2008a; Diamond, 2008b; Diamond, 2009). Two data sets were used to perform the above analyses: one contained monthly hybrid registration statistics of three models – Honda Civic Hybrid, Toyota Prius, and Ford Escape Hybrid - from 2001 to May 2007. The other included registration details for every hybrid titled in Virginia as of April 2007. The research found that gasoline price is the primary factor in hybrid market share. The case study of hybrid adoption in Virginia illustrates that the hybrid HOV lane occupancy exemption positively affects hybrid sales, but only in certain geographic areas. In fact, the HOV exemption incentive significantly influenced the hybrid market share in Northern Virginia but not in the Hampton Roads area. The most likely reason for this difference is the different nature of local highway and HOV lane systems in these two areas. Commuters in the Hampton Roads area did not gain as much travel time savings as those commuters in Northern Virginia. The study also indicated that the hybrid market share is highly sensitive to the implementation of HOV exemption policy. As a matter of fact, the hybrid market share dropped dramatically after the suspension of HOV exemption for hybrids.

Gallagher and Muehlegger (2011) studied how hybrid vehicle sales responded to different levels and types of state tax incentives, rising gasoline prices, and access to HOV lanes by analyzing sales transaction data. They concluded that HOV lane access was positively correlated with hybrid sales in Virginia.

In contrast to the purchase preference for LEEVs, other studies demonstrated that permission to travel on HOV lanes with one occupant was not significant in consumers' willingness to pay for clean vehicles (Potoglou and Kanaroglou, 2007). Furthermore, concerns for limited fuel availability also weakened the consideration on adoption of AFVs or hybrids (Abbanat, 2001; Potoglou et al., 2007).

3.2 Effects of Exemptions on Managed Lane Use

Even though states offer HOV lane exemption incentives, the policy is conditional. The HOV lane operation must comply with the requirements that a minimum average operating speed of HOV lane facilities must be maintained after integrating exempt vehicles (as defined in Section 166(d)(2) of Title 23 U.S. Code). A HOV lane facility is considered degraded if it fails to maintain 45 miles per hour (mph) free flow speeds for an HOV lane facility with a speed limit of 50 mph or greater, or not more than 10 mph below the speed limit for a facility with a speed limit of less than 50 mph, for 90% of the time over a consecutive 180-day period during morning or evening weekday peak hour periods (Federal Highway Administration, 2008).

As initiated in SAFETEA-LU and related state legislation, assessments of the addition of exempt vehicles in HOV lanes were conducted in several states. The California Transportation Department (CALTRANS) compared level of service (LOS) measures for a 2-week period in 2005 with measures for the same period in 2006 along relevant freeways. A LOS C corresponding to a density of less than 26 vehicles per mile per lane was set as the threshold to determine acceptable operating conditions and a LOS higher than C was considered as breakdown conditions. A breakdown frequency of between 3 and 5 percent was observed, but there was no significant HOV lane breakdown directly attributable to hybrid vehicle use (CALTRANS, 2006).

In 2003 and 2005, two HOV Enforcement Task Force reports were submitted by the Virginia Secretary of Transportation and state police in which a number of issues associated with HOV lanes were examined, including HOV lane usage by vehicles with clean special fuel license plates (Farley and Martin, 2003; Morrison and Counts, 2005). Traffic count data were collected by the Metropolitan Washington

Council of Governments (MWCOG) covering HOV lane facilities on I-95, I-395, I-66, and the Dulles Toll Road. They found that congestion stemmed mostly from an increase in vehicle volume on I-95/I-395 HOV lanes, including HOVs and those registered with clean special fuel license plates. Clean special fuel vehicles accounted for up to 19% of the volume on the I-95 HOV lanes during the morning restricted period, which made the facility operate at unacceptable levels of service at over 1900 vehicles per lane per hour.

In addition to field traffic counts, micro-simulation models have been employed to evaluate the impact of HOV lane exemption policies. A study on the freeway network in Orange County, California was conducted by combining traditional planning models for demand estimation and analysis with a calibrated microscopic simulation model in PARAMICS for measuring system performance in terms of average travel speed, vehicle miles traveled (VMT), vehicle hours traveled (VHT), level of service distribution, temporal and spatial speed distribution along HOV lanes, and speed difference between HOV lanes and general purpose lanes (Nesamani et al., 2010). There were four scenarios that corresponded to conditions under varying number of clean fuel decals that could be issued. It was indicated that the HOV lane incentive could have a significant negative impact on HOV lane performance if there is insufficient reserve capacity to support the additional traffic.

3.3 Effects of Exemptions on Emissions

To quantify the benefits from stimulating the adoption of low-emitting vehicles, it is necessary to use emission estimation models. These models use vehicle speed/acceleration trajectories to estimate emissions under various vehicle conditions (i.e. idling, cruising, and acceleration and deceleration maneuvers). Fuel consumption and tailpipe emission of pollutants can also be obtained.

By using the Comprehensive Modal Emission Model (CMEM) developed by University of California, Riverside, HOV lane exemption incentives were found to contribute to air quality benefits in a noticeable reduction of pollutants (CO_2, CO, HC, NOx) and fuel consumption (Nesamani et al., 2010) as mentioned in Chapter 1. Scenarios were constructed corresponding to different amounts of hybrid vehicles that are allowed to receive a permit for using the HOV lane, and an investigation of the changes in traffic operations and air quality was conducted. While relevant, the effects of these exemptions and increasing hybrid vehicle share within the traffic composition on emission changes were confounded. Thus, one cannot discern the effects on emissions that result solely from exemptions. Positive benefits may be due entirely to increasing hybrid vehicle share of the traffic rather than exemptions. Note, too, that CMEM does not account for alternative fuels; it considers only gasoline and diesel. It also does not estimate emissions for Particulate Matter, SO_x, and CH_4, and other GHG emissions and pollutants considered herein, specifically $PM_{2.5}$, CH_4, PM_{10}, and SO_x, could not be estimated.

Xie et al. (2010) studied the potential impact of AFVs on total emissions and fuel consumption, as well as emissions per VMT. PARAMICS was used to simulate traffic and the USEPA’s Motor Vehicle Emissions Simulator (MOVES) tool was used to assess emissions effects. The study considered scenarios involving 10%, 20%, 30%, and 40% market share for AFVs powered by ethanol, electricity and CNG. A share of the AFV passenger cars was assumed to run on ethanol and the remainder of the AFV passenger cars on electricity. Buses were incorporated in the model and were assumed to run on CNG or ethanol. Experimental results suggest a strong linear trend in the changes in emission rates and fuel consumption with respect to changes in AFV market share. They concluded that switching 40% of transit buses from diesel to CNG would reduce overall transit bus sulfur dioxide emissions by 34%. No comparison between benefits of alternative fuel types was made. While this work did not consider managed lane exemptions, its findings in terms of emissions impact of increased AFV use are relevant.

Chapter 4: Experimental Environment

This study takes advantage of a microscopic simulation platform, VISSIM, and emission estimation model, ORSEEM. These tools are described in more detail in this chapter.

4.1 Microscopic Traffic Simulation Modeling

Microscopic traffic simulation models are designed to emulate the movement and behavior of individual vehicles on urban and freeway road networks. These modeling frameworks are well-suited for forming conclusions about the impact of managed lane access exemptions on the environment. These models can capture travel delays in managed lanes that results from inter-vehicle interactions and provide detailed statistics (including estimates of travel time, speed, delay and density) and necessary records needed for emissions estimates that capture the effects of such interactions. VISSIM, in particular, models vehicle driving behavior. In addition, traffic simulation models can capture the effects of roadway grades on vehicle speed/acceleration profiles. A number of customizable parameters and functions are provided in these simulation models to replicate the real traffic conditions for any particular site. When a new traffic management strategy is employed, these models are able to simulate the related lane change behavior, routing decisions and car following movements of vehicles, providing estimates of various traffic measurements.

4.2. Emission Modeling

VISSIM, while a comprehensive and rather sophisticated traffic simulation tool, is limited in its ability to estimate fuel consumption and emissions resulting from vehicular movements and roadway characteristics. Its built in features work only intermittently, and thus, are unreliable. Moreover, these built in features are applicable only under very limited circumstances as they were designed for estimating fuel consumption and emissions at controlled intersections using average values. Effects on fuel consumption and emissions due to changes in operations or roadway geometry cannot be captured even if the tool were made more reliable. Thus, this study relies on ORSEEM to estimate fuel consumption and emissions.

4.2.1 On -Road Simulation Emission Estimation Model (ORSEEM)

4.2.1.1 ORSEEM Overview

ORSEEM is a simulation-based module for GHG and other air pollutant emissions estimation for on-road vehicles. It captures the effects of second-by-second vehicular parameters (e.g. velocity, acceleration, idling), vehicle characteristics (e.g. vehicle type, age, weight, engine size, fuel type) and roadway geometry characteristics (e.g. grade) on emissions production. Second-by-second speed and acceleration profiles from VISSIM provided the needed input for the instantaneous emission estimates. Such instantaneous estimates are needed, because they are sensitive to changes in vehicle behavior and roadway geometry, and can capture the effects of changes in behavior and traffic movements due to exemptions. By analyzing and determining emission rates for second-by-second vehicle record data, ORSEEM produces more accurate emissions estimates compared to conventional methods. ORSEEM is a portable tool that relies on data that can be collected from field studies or through simulation. ORSEEM is comprehensive and lists estimates of air pollutants except air toxics, including: CO_2, CO, CH4, THC, NOx, SOx, PM_{10} and $PM_{2.5}$.

4.2.1.2 ORSEEM Development Methodology

ORSEEM was developed to accurately capture the effects of traffic conditions, changes to roadway geometry, and driving behavior. Vehicular velocity and acceleration are taken into account, as are starts, stops, and idling. Additionally, a variety of fuel types and other aspects of roadway geometry are considered. A comprehensive description of ORSEEM is given in (Miller-Hooks et al., 2012).

For the purpose of demonstrating, understanding, and studying policy/program impacts, a combination of macro- and micro-scopic approaches are necessary. Therefore, ORSEEM uses a meso-scopic approach with microscopic inputs and variables to accurately capture emission production. ORSEEM builds on two existing emissions modeling approaches: MOVES and CMEM.

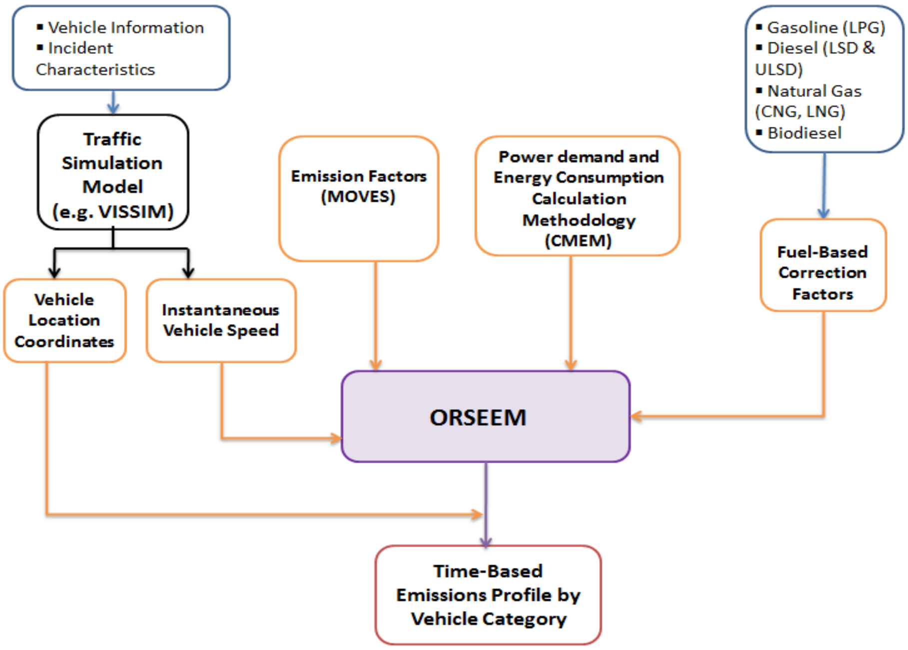


Figure 4-1 Illustration of ORSEEM Development from MOVES and CMEM [Source: GHG Emissions Tool to Support Emission Estimation in On-Road Transport along Freeway and Arterials, Miller-Hooks et al., 2012].

As is described in (Miller-Hooks et al., 2012), some of the limitations of using these models lie in the scope of the variables they cover, level of detail captured in the outputs, and the limited flexibility they offer users. Specifically, at the project-level, MOVES can either use basic inputs and the built-in database or users may enter local data into distribution templates (e.g. vehicle miles traveled, age, road and type) that would replace the default values. It must be noted that the distribution templates average variables for the time period chosen, aggregate vehicles by generic categories (non-tier based), use modal parameter averages (i.e. average speed/acceleration) for emissions calculations and cannot provide second-by-second estimates. Also, while MOVES accounts for alternative fuels, it does not cover all vehicle-fuel combinations. Moreover, as MOVES is designed on a MYSQL platform, data input and output generation in MOVES requires the use and knowledge of MYSQL software (USEPA, 2011).

CMEM, on the other hand, is user-friendly in that it is offered on various platforms like Java, Linux and DOS and data input/output can be either manually entered or Excel-based. Also, CMEM offers tier level-classified vehicle categories and second-by-second vehicle emission estimates (microscopic). However, it does not account for vehicles with gross vehicle weight rating (GVWR) greater than 8,500 lbs (such as semi-trailers, long-haul trucks, buses, etc.) or the new Tiered vehicles, i.e. post-2004 light-duty vehicles (Tier 2) or post-2000 heavy-duty vehicles (Tier 1 and 2). Additionally, CMEM does not account for fuels other than gasoline and diesel (i.e. alternative fuels) or air pollutants other than CO_2, CO, HC and NOx. While the current vehicle categories may be tweaked to account for Tier 2 vehicles, since the model uses very detailed vehicle characteristics (e.g. vehicle- specific engine details, emission coefficients), which were mostly obtained through extensive lab and dynamometer testing, accounting for this category of vehicles in CMEM is difficult. Moreover, CMEM cannot function as a plug-in with all traffic simulation models (e.g. VISSIM). Therefore, both CMEM and MOVES vary in their ability to provide vehicle-specific emissions estimates required to encompass the level of detail and the scope of scale required for assessing incentives in the transportation sector (CMEM, 2010).

The power demand approach used by CMEM and MOVES best describes the physical processes of emissions production and, hence, provides accurate emission estimates. However, both models use the power demand equation, and subsequently calculate fuel consumption rate, incorporating varying level of detail with regard to the parameters used. For example, MOVES does not include the road grade parameter while calculating power demand; whereas, CMEM includes road grade and also, several other vehicle-specific parameters (e.g. efficiency, air-to-fuel ratios, etc) to estimate fuel consumption rate.

4.2.1.3 ORSEEM Model Components

ORSEEM is a spreadsheet tool programmed in Visual Basic for Application (VBA) with Microsoft Excel interface.

ORSEEM is composed of three parts:

1. ORSEEM User Interface;
2. Emission Factor Database;
3. ORSEEM Calculation Core Module.

As a first step, users import vehicle record data through a user interface. A background emission factor database contains emission rates, fuel-based correction factors, and emission/pollutant conversion ratios. Once the emission factors are retrieved from the database, the core module computes the corresponding amount of emissions, pollutants and fuel consumption for each vehicle record. In ORSEEM, each line of input data is regarded as a vehicle record at a certain time step. By aggregating the emissions obtained for each vehicle record, total emissions are quantified.

Two levels of emission estimates are reported through the output module: single estimate values for each time step and aggregated estimate values for a given time period. Figure 4-2 demonstrates the model structure of ORSEEM.

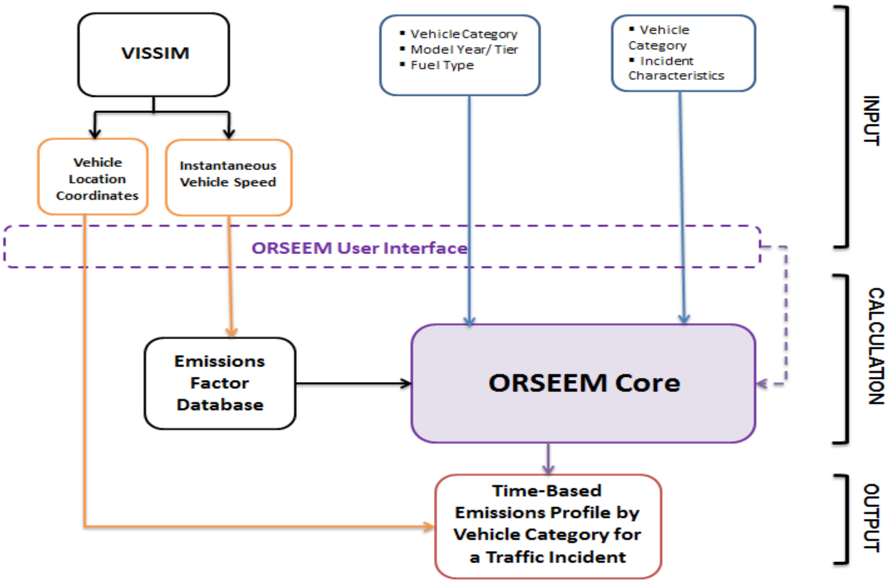


Figure 4-2 Schematic of Model Structure of ORSEEM [Source: GHG Emissions Tool to Support Emission Estimation in On-Road Transport along Freeway and Arterials, Miller-Hooks et al., 2012]

4.3 Modeling Framework

Figure 4-3 shows how VISSIM and ORSEEM are used in numerical experiments herein to capture the effects of changing vehicle dynamics resulting from tested exemption policies.

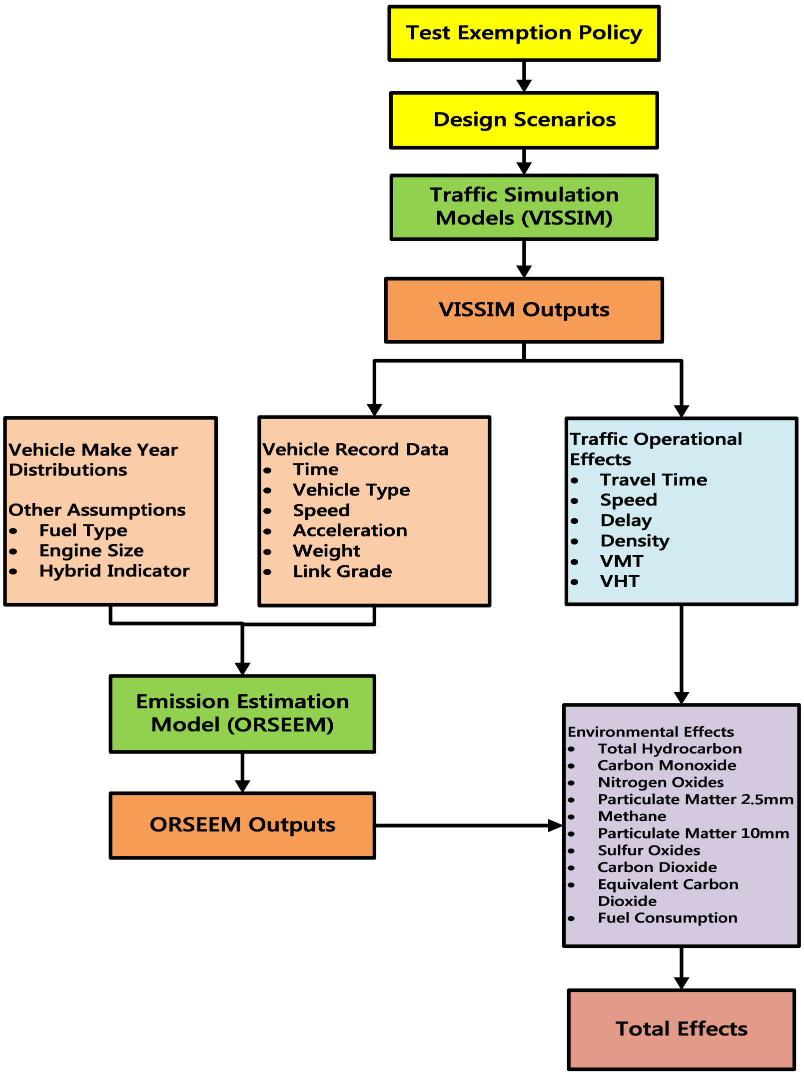


Figure 4-3 Modeling Framework Integrating VISSIM and ORSEEM

Chapter 5: Case Study

To investigate the potential impact of discussed exemptions for low-emitting vehicles, simulation experiments were run on a case study involving I-270 in Maryland. I-270 stretches between the Capital Beltway, which circles the Washington, D.C. area, and I-70. In this chapter, a description of the developed micro-simulation models used in the experiments is given. This is followed by explanation of the experimental design. Results of the experimental runs and analysis are given in Chapter 6.

5.1 Micro-simulation Model Construction

5.1.1 Roadway Geometry

To examine the potential effects of HOV and ETL exemptions, two models were developed and used. These models build on prior efforts to replicate existing operations, which include continuous access HOV lanes and a proposed ETL design, described in (Miller-Hooks et al., 2011). The models include general purpose (GP) lanes, HOV lanes, interchange characteristics and connector-distributor (CD) lanes. The prior study model of existing operations was successfully calibrated using travel time measurements. In this study, experiments were run based solely on the southbound lanes for AM peak hours of operation, specifically 6:00 a.m. to 9:00 a.m.

The existing roadway extends for 29.9 miles on the southbound portion of I-270 from the I-70 interchange to the spur, where the roadway intersects with I-495. It continues 4.4 miles from the start of the Northern spur to the Connecticut Avenue exit on eastbound I-495 and 6.8 miles from the start of the Southern spur to the

Georgetown Pike exit on I-495. For the remainder of this thesis, this network is referred to as the 'HOV network'.

The HOV network contains a single continuous access HOV lane, which starts 0.7 miles north of I-370 and ends 0.8 mile south of MD 187 within the northern spur and 0.6 miles south of Democracy Boulevard within the southern spur. CD lanes are modeled as separate links concomitant with GP lanes. CD lanes start from I-370 and end 1 mile before reaching the spur.

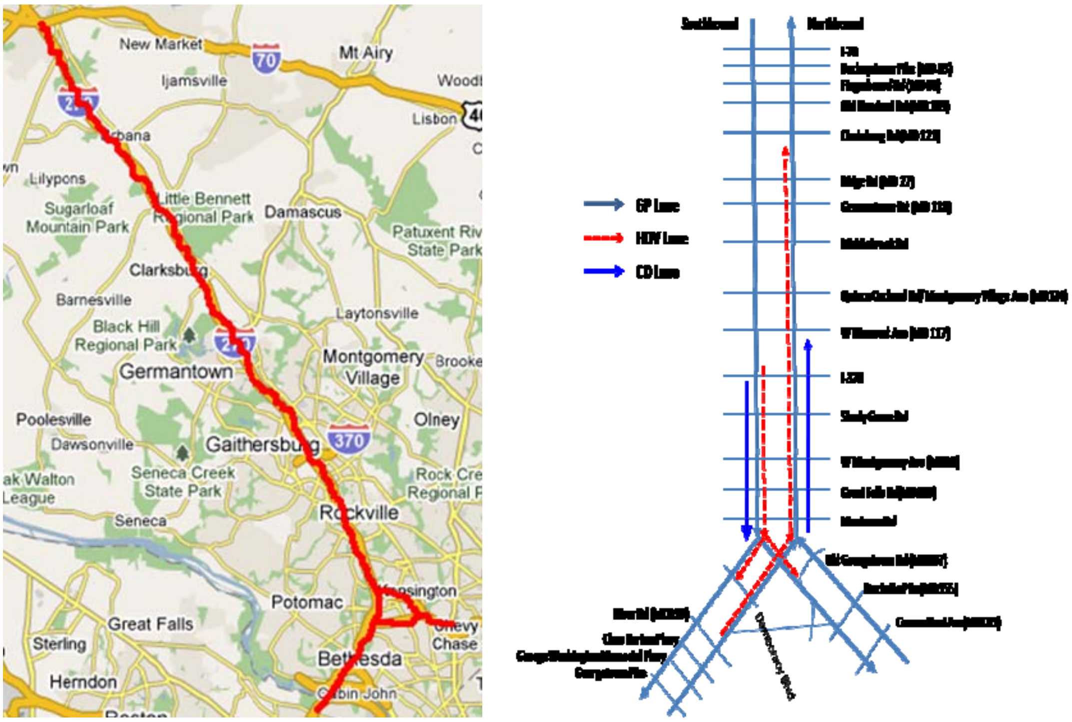


Figure 5-1 Study Area and Lane Type Configurations along I-270 and Connecting 495 Beltway of the HOV Network [Source: Concurrent Flow Lane – Phase III Report, Miller-Hooks et al., 2011]

The proposed alternative involves two ETLs in place of the HOV lane design. It would stretch between I-70 and I-370 in the southbound direction. As described in (Miller-Hooks et al., 2011), the design for the southern portion of the model between I-370 and MD 109 was extracted from CORSIM models provided by the Maryland

State Highway Administration (SHA). The northern portion of the model, from MD 109 to I-70, were proposed as part of the I-270/US15 Multi-Modal Corridor Study, referred to as "Express Toll Lanes Alternatives 6A/B, 7A/B". The model configuration details associated with the southern portion are given in Figure 5-2. The network incorporates an ETL in portions and thus is referred as the 'ETL network'. Major revisions are planned for ETL entrance/terminus, slip ramps to/out ETLs, and interchanges at MD-75, Newcut Road, Watkins Mill Road and Metro Grove Road.

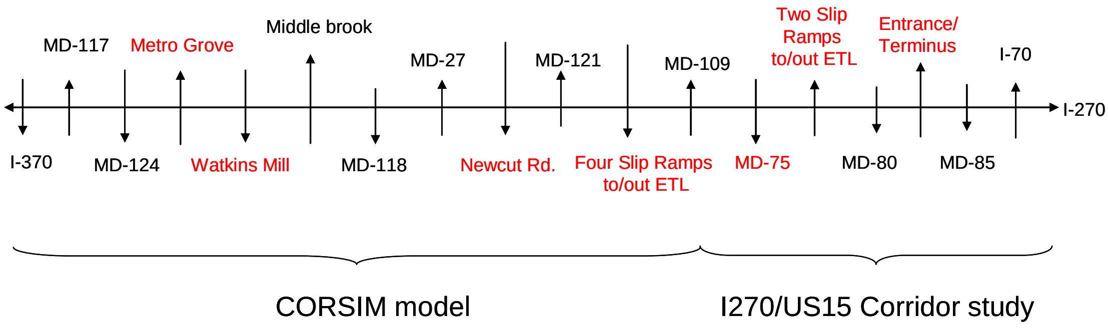


Figure 5-2 Conceptual Locations of Interchanges and Network Designs in the ETL Exemption Network [Source: Concurrent Flow Lane – Phase III Report, Miller-Hooks et al., 2011]

There are several important differences between ETL and HOV networks.

1. In the HOV network, there is no barrier between GP and HOV lanes, therefore, GP and HOV lanes are modeled as one link.
2. In the ETL network, the ETLs are modeled as a separate link.
3. Barrier separation is placed between ETL and GP lanes in all locations except at access points; whereas, the HOV lane operates with continuous access for most of its length
4. Three proposed interchanges were modeled, including:
    (1) Watkins Mill Road interchange,

    (2) Newcut Road interchange, and
    (3) MD 75 interchange.

5. Revised interchange designs include MD 80 and MD 85.
6. Three slip ramps between GP and ETLs for SB lanes of I-270 were modeled.
7. ETL on- and off-ramps at Metro Grove were added, and
8. An ETL entrance and a terminus for the southbound direction near the battlefield in Germantown were modeled.

Gradient information is not directly added to the network; instead, it is incorporated in emission models to capture the effects of grade changes on vehicle power demand and emission variation. Gradients were calculated using elevation data downloaded from Google Map at approximately 100 meters.

5.1.2 Input Volume and Turning Proportions

The input volume for the HOV network was obtained from 2010 average daily traffic (ADT) volumes and Western Mobility Study 2005 Volumes provided by SHA (Miller-Hooks et al., 2011). Traffic volumes were averaged over the morning peak period to represent prevailing peak hour traffic. The turning proportion data were obtained from the "GP, CD, Slip Ramp Distributions" file provided by SHA. Volume wiring diagrams were drawn to depict the provided data as given in the Figure 2-2 (Miller-Hooks et al., 2011).

Input volumes at each on-ramp, as well as turning proportion at each off-ramp and slip-ramp between GP lanes and ETLs of the ETL network, were provided by SHA for the segment between MD 109 and I-70 and extracted from the CORSIM files for the segment between I-370 and MD 109. All input volumes of the ETL network were estimated for Year 2030. Additional information can be found in the Appendix 4-1 (Miller-Hooks et al., 2011).

5.1.3 Vehicle Classes, Occupancy, and Composition

The HOV lane facility only permits motorcycles, transit buses, and light-duty vehicles (LDV) (passenger cars and vans) and LDT with 2 or more occupants. Vehicles with a single occupant and heavy-duty trucks are restricted. Vehicles with multiple occupants are permitted to use the lanes regardless of vehicle fuel source type. According to HOV lane exemption rules in some locations, only single occupant vehicles that are powered by a hybrid energy source or alternative fuel can benefit from the exemption. In Maryland, however, only plug-in electric vehicles are permitted to use the HOV lanes without meeting these access restrictions (USDOE, Accessed 2012). Hence, it is necessary to specify vehicle classes by both fuel type and occupancy. The same vehicle class definition scheme is applied in both HOV and ETL networks. Table 5-1 gives the 11 vehicle classes defined by vehicle type, fuel type and occupancy.

Table 5-1 Vehicle Classes Defined in both HOV and ETL Network

Vehicles Categories	Description
1 LDV Hybrids	Light duty hybrid vehicle with single occupant
1 LDV Non-Hybrids	Light duty non-hybrid vehicle with single occupant
2+ LDV Hybrids	Light duty hybrid vehicle with 2/2+ occupants
2+ LDV Non-Hybrids	Light duty non-hybrid vehicle with 2/2+ occupant
1 LDT Hybrids	Light duty hybrid truck with single occupant
1 LDT Non-Hybrids	Light duty non-hybrid truck with single occupants
2+ LDT Hybrids	Light duty hybrid truck with 2/2+ occupants
2+ LDT Non-Hybrids	Light duty non-hybrid truck with 2/2+ occupants
Bus	Buses
MHD	Medium heavy-duty truck
HHD	Heavy heavy-duty truck

The average vehicle occupancy data for morning peak-hours in the HOV network were obtained from the database of the Internet Traffic Monitoring System (I-TMS website). All occupancy data were collected in 2008. Thus, it is assumed that the vehicle occupancy pattern in 2010 was the same as in 2008. The occupancy data were obtained from six different survey stations. The locations of vehicle occupancy survey stations are provided in Figure 5-3. The occupancy data was analyzed to compute the fraction of single and multi-occupant vehicles of LDVs and LDTs over the total number of vehicles in each roadway segment. These fractions were further applied to estimate the composition percentages of single and multi-occupant LDVs and LDTs. Occupancy data is presented in Table 5-2.

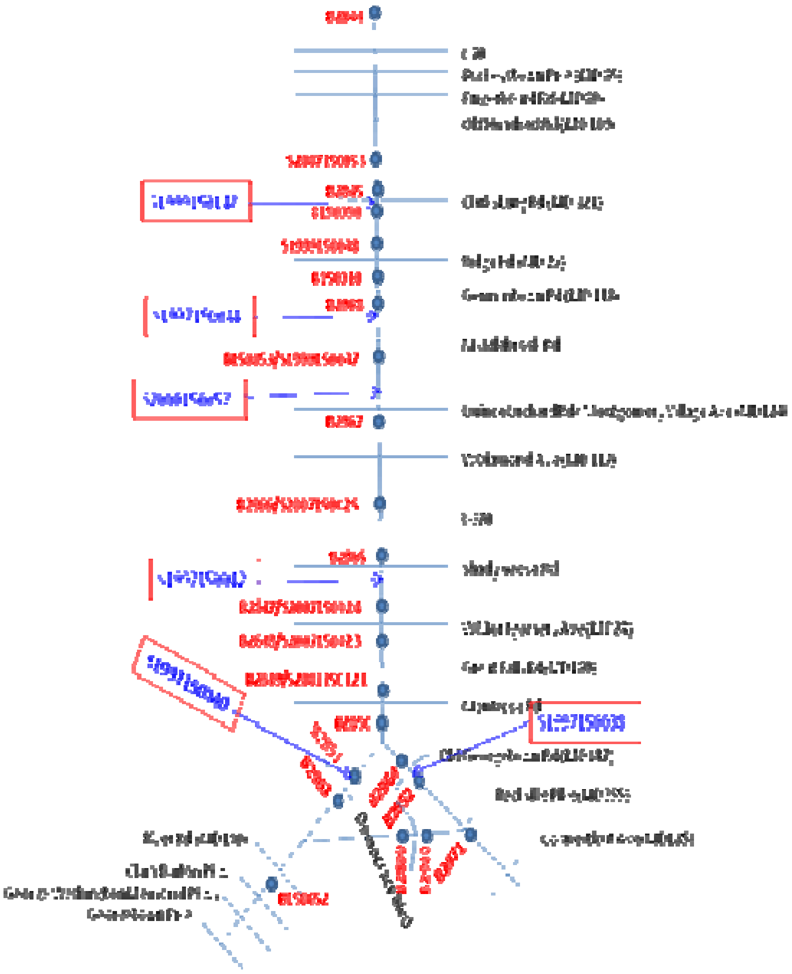


Figure 5-3 Vehicle Occupancy and Composition Survey Station Locations [Source: Concurrent Flow Lane – Phase III Report, Miller-Hooks et al., 2011]

Table 5-2 Fraction within Each Vehicle Occupancy Category in 2008 [Source: Concurrent Flow Lane – Phase III Report, Miller-Hooks et al., 2011]

Location	Total	1		2+		Buses		Trucks	
S1999150147	4288	3695	86.16%	448	10.46%	12	0.29%	133	3.09%
S1997150044	4856	4276	88.06%	354	7.29%	19	0.39%	207	4.26%
S2000150057	5554	4980	89.67%	339	6.10%	24	0.43%	211	3.81%
S1997150042	7884	6445	81.75%	1209	15.33%	28	0.36%	202	2.56%
S1997150040	5411	4769	88.14%	486	8.98%	10	0.18%	147	2.71%
S1997150038	3878	3268	84.29%	470	12.12%	23	0.60%	116	2.99%

Traffic data for 23 survey stations along I-270 was provided by SHA to compute the vehicle composition in the HOV network. Traffic counts by vehicle class as shown below were recorded at one hour intervals.

Class 1 – Motorcycles (MC) (LDV);

Class 2 – Passenger Cars (LDV);

Class 3 – Light Trucks (LDT);

Class 4 – Buses;

Classes 5-9 – Single-Trailer Trucks (medium heavy-duty trucks (MHD)); and

Classes 10-13 – Multi-Trailer Trucks (heavy heavy-duty trucks (HHD)).

Vehicle composition for the HOV network model using traffic count data is shown in Table 5-3. The same occupancy and vehicle composition were applied to the ETL network.

Table 5-3 Vehicle Composition in 2009

Station	Location	LDV	LDT	Buses	MHD	HHD
B2844	IS270-.10 MI S OF FREDERICK CO/L	79.01%	14.14%	0.55%	6.22%	0.08%
S2007150053	IS 270 between MD 121 & MD 109	80.27%	15.63%	0.48%	3.56%	0.06%
B2845	IS270-.50 MI N OF MD121	79.59%	14.49%	0.47%	5.33%	0.11%
B150050	IS270-.40 MI S OF MD121 (ATR0004)	78.12%	14.36%	0.57%	6.62%	0.33%
S1999150048	IS 270 -.10 MI SOUTH OF STRUC#15040(LITTLE SENECA CREEK)(ATR#04)	77.82%	15.04%	0.39%	6.66%	0.10%
B150010	IS270-.40 MI N OF MD118	78.35%	13.57%	0.43%	7.52%	0.13%
B2968	IS270-.10 MI S OF MD118	80.42%	12.39%	0.37%	6.55%	0.27%
B150053	IS270-.50 MI S OF MIDDLEBROOK RD (ATR0060)	80.43%	12.88%	0.51%	6.10%	0.08%

Station	Location	LDV	LDT	Buses	MHD	HHD
B2967	IS270-.10 MI S OF MD124	81.30%	12.73%	0.48%	5.36%	0.13%
B2966	IS270-.10 MI N OF IS370	81.12%	12.46%	0.56%	5.70%	0.15%
B2965	IS270-.10 MI N OF SHADY GROVE RD	80.46%	12.51%	0.61%	6.13%	0.29%
B2847	IS270-.50 MI N OF MD28	81.15%	12.02%	0.60%	6.10%	0.12%
B2848	IS270-.10 MI S OF MD28	80.31%	12.02%	0.56%	6.81%	0.30%
B2849	IS270-.20 MI N OF MD927 (MONTROSE RD)	81.95%	11.65%	0.63%	5.61%	0.17%
B2850	IS270-.10 MI N OF TUCKERMAN LA	80.71%	12.71%	0.57%	5.80%	0.21%
B2851	IS270Y-.50 MI N OF DEMOCRACY BLVD	82.89%	13.46%	0.64%	2.95%	0.07%
B2963	IS270Y-.10 MI S OF DEMOCRACY BLVD	83.42%	13.53%	0.42%	2.57%	0.06%
B150052	IS495-.10 MI E OF STRUC #15105(PERSIMMON TREE RD) (ATR0040)	80.25%	12.89%	0.92%	5.84%	0.10%
B2964	IS270-.30 MI N OF MD187B	81.34%	12.65%	0.46%	5.47%	0.08%
B2852	IS270-.10 MI S OF MD187	80.74%	12.91%	0.58%	5.68%	0.10%
B2971	IS495-.20 MI E OF MD355	77.74%	14.13%	0.98%	6.91%	0.24%
B2900	IS495-.30 MI E OF MD187	80.13%	13.54%	0.71%	5.47%	0.15%
B2899	IS495-.50 MI W OF MD187	77.73%	14.32%	0.98%	6.81%	0.15%

5.1.4 Vehicle Registration Data

To obtain the current percentages for hybrid vehicles in Montgomery County, vehicle registration data provided by the Maryland Department of the Environment (MDE) was analyzed. The dataset covers vehicles registered in 2010. A stratified sampling method was applied to extract a sample database at 95% significance level.

Registration statistics after sampling are shown in Table 5-4. This is discussed further in the following.

Vehicle make year and model as well as vehicle type were examined for each sample to determine whether the vehicle is or is not a hybrid. Tables 5-5 and 5-6 demonstrate the make year distribution of non-hybrid and hybrid vehicles for LDVs and LDTs, respectively. The percentages of non-hybrid and hybrid LDVs and LDTs were used to estimate the share of non-hybrid and hybrid vehicles in single and multi-occupant LDVs and LDTs. Additionally, vehicle registration data were analyzed to obtain vehicle make year distributions, which were also used to determine the vehicle characteristics. Additional detail is given in Section 5.6.1.

Table 5-4 Statistic of Sampled Vehicle Registration Data up to 2010 [Source: GHG Emissions Tool to Support Emission Estimation in On-Road Transport along Freeway and Arterials, Miller-Hooks et al., 2012]

Age	Year Interval	Quantity	Share in Total	Number of selected VINs by group
0-3	2010-2007	183,201	25.14%	126
4-5	2006-2005	109,747	15.05%	75
6-7	2004-2003	112,065	15.37%	77
8-9	2002-2001	96,955	13.30%	67
10-14	2000-1996	150,422	20.64%	103
15-19	1995-1991	49,097	6.74%	34
20+	1990-	27,354	3.75%	19
Total		**728,841**	**100%**	**501**

Table 5-5 Make Year Distribution for Non-hybrid and Hybrid Light Duty Vehicles

Make Year	LDV Non-Hybrid	% of LDV Non-Hybrid	LDV Hybrid	% of LDV Hybrid
2010	13	4.87%	1	7.69%
2009	17	6.37%	1	7.69%
2008	16	5.99%	2	15.38%
2007	20	7.49%	2	15.38%
2006	13	4.87%	1	7.69%
2005	20	7.49%	4	30.77%
2004	20	7.49%		
2003	24	8.99%		
2002	16	5.99%	2	15.38%
2001	16	5.99%		
2000	25	9.36%		
1999	11	4.12%		
1998	7	2.62%		
1997	7	2.62%		
1996	14	5.24%		
≤1995	28	10.49%		
Total Number	267	100.00%	13	100.00%
% of LDV Non-hybrid	95.36%			
% of LDV Hybrid	4.64%			

Table 5-6 Make Year Distribution for Non-hybrid and Hybrid Light Duty Trucks

Make Year	LDT Non-Hybrid	% of LDT Non-Hybrid	LDT Hybrid	% of LDT Hybrid
2010	9	4.09%		
2009	12	5.45%		
2008	15	6.82%		
2007	17	7.73%	1	100%
2006	19	8.64%		
2005	18	8.18%		
2004	15	6.82%		
2003	18	8.18%		
2002	17	7.73%		
2001	16	7.27%		
2000	12	5.45%		
1999	11	5.00%		
1998	9	4.09%		
1997	4	1.82%		
1996	3	1.36%		
≤1995	25	11.36%		
Total Number	220	100.00%	1	100.00%
% of LDT Non-hybrid	99.56%			
% of LDT Hybrid	0.45%			

5.2 Micro-simulation Model Calibration

Calibration minimizes the differences between estimated and known values, enabling the identification of the optimal set of experimental parameters. The parameters of the micro-simulation model must be set so that the traffic measures from the simulation model best match actual field measurements. Miller-Hooks et al. (2011) identified five parameters requiring changes from the VISSIM default values for the test networks. These are synthesized in Table 5-7. The prior study model of HOV lane existing operations was successfully calibrated using travel time measurements as shown in the Tables 3-6 to 3-9 in (Miller-Hooks et al., 2011). These calibrated parameters of driving and car-following behavior in (Miller-Hooks et al., 2011) were adopted.

Table 5-7 Parameters Selected for Calibration [Source: Concurrent Flow Lane – Phase III Report, Miller-Hooks et al., 2011]

Parameter	Definition	Final Value
CC1	Headway time: *higher value, more cautious driver*	0.9 second
CC2	Following variation: *desired safety following distance*	39.37 ft
CC4&5	Lower & Upper following threshold	0.1 mph
SDRF	Safety distance reduced factor: *effects safety distance during lane changing*	0.1
LBD	Look back distance: *defines the distance at which vehicles will begin to attempt to change lanes*	3280.83 meters

Note: the sign of Lower following threshold (CC4) is '-' and the sign of Upper following threshold (CC5) is '+'.

5.3 Experimental Design

Ten scenarios were created to investigate the effects of allowing single occupant hybrid vehicles access to HOV lanes. Of the ten scenarios, five were created to represent HOV lane operations with legislative exemptions and another five scenarios to represent HOV lane operations without exemptions. Associated with each scenario is a level of hybrid penetration as a portion of the traffic composition. The base scenario without exemption represents the existing HOV lane operation, i.e. it does not allow single occupant hybrids or AFVs access to HOV lanes. The traffic composition in the base scenario is referred to as the current composition in which the average percentage of hybrid vehicles is 3.85% as determined from analysis of a stratified random sample of the 2010 vehicle registration data supplied by the MDE.

The base scenario with exemption represents the HOV lane operation after exempting the initial share of hybrid vehicles (3.85%). Scenarios 1 through 4 operate with exemption and represent the HOV lane operations for increased hybrid penetration rates. The differences between scenarios are captured by changing the percentage of single occupant LDV and LDT hybrid vehicles. As the scenario number increases, the percentage of hybrid vehicles increases and the percentage of single occupant LDV and LDT non-hybrid vehicles decreases to maintain a constant traffic volume within the model. For example, if a 10% deduction is applied to single-occupant LDV and LDT non-hybrid vehicles, then that 10% is added to the LDV and LDT hybrid vehicle share.

As HOV exemption is designed to prompt single occupant vehicle owners to switch from non-hybrid to hybrid vehicles. Switch rates (i.e. percentage of single occupant LDV and LDT non-hybrid vehicles replaced by comparable hybrid vehicles) for Scenarios 1 through 4 are assumed to be 10%, 20%, 30% and 40%, respectively. The percentages of multi occupant vehicles and trucks were assumed fixed. Thus, increasing the switch rates increases the penetration rates of hybrid vehicles. Table 5-8 lists the scenarios designed for the hybrid HOV exemption experiments and the penetration rates of hybrid vehicles according to each level of switch rate. Similarly, Scenarios 1 through 4 under without exemption circumstance represent the HOV lane operation with increasing hybrid penetration rates. These two groups of scenarios for with and without exemption circumstance and designed to capture the effects of the exemption policies.

Table 5-8 Switch Rates from Single Occupant Non-Hybrids to Hybrids and Corresponding Hybrid Penetration Rates

With Hybrid HOV Exemption					
Scenario	Base	1	2	3	4
Switch Rate	0%	10%	20%	30%	40%
Hybrid Penetration Rate	3.85%	11.42%	18.99%	26.56%	34.12%
Without Hybrid HOV Exemption					
Scenario	Base	1	2	3	4
Switch Rate	0%	10%	20%	30%	40%
Hybrid Penetration Rate	3.85%	11.42%	18.99%	26.56%	34.12%

In studying the effects of allowing hybrid vehicles to use the ETLs, a percentage of single occupant non-hybrid vehicles and multi-occupant non-hybrid vehicles is shifted to its hybrid counterpart.

The same scenarios were created for studying ETL exemption; however, instead of applying the switch rate only to single occupant non-hybrid vehicles, it is also applied to multi-occupant non-hybrid vehicles. The base scenario under without exemption represents the ETLs operation using traffic demand estimates for 2030, but the same traffic composition as in the base scenario of HOV network.

Table 5-9 lists the switch rates from single/multi occupant non-hybrids to hybrids and the corresponding hybrid penetration rates.

Table 5-9 Switch Rates from Single/Multi Occupant Non-Hybrids to Hybrids and Corresponding Hybrid Penetration Rates

<table>
<tr><th colspan="6">With Hybrid ETL Exemption</th></tr>
<tr><td>Scenario</td><td>Base</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td>Switch Rate</td><td>0%</td><td>10%</td><td>20%</td><td>30%</td><td>40%</td></tr>
<tr><td>Hybrid Penetration Rate</td><td>3.85%</td><td>12.87%</td><td>21.89%</td><td>30.91%</td><td>39.94%</td></tr>
<tr><th colspan="6">Without Hybrid ETL Exemption</th></tr>
<tr><td>Scenario</td><td>Base</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td>Switch Rate</td><td>0%</td><td>10%</td><td>20%</td><td>30%</td><td>40%</td></tr>
<tr><td>Hybrid Penetration Rate</td><td>3.85%</td><td>12.87%</td><td>21.89%</td><td>30.91%</td><td>39.94%</td></tr>
</table>

Additional experiments were run to consider the changes in emissions for AFVs instead of hybrids. For this study, AFVs were assumed to run on E85. Tables 5-10 and 5-11 list the scenario designs for HOV and ETL exemptions offered to AFVs, respectively. It is noted that no study of traffic operations effects are conducted for AFVs. Only the emissions from allowing AFVs to use the managed lanes are compared to that produced by allowing hybrid use of these lanes.

Table 5-10 Switch Rates from Single Occupant Non-AFVs to AFVs and Corresponding AFV Penetration Rates

With AFV HOV Exemption					
Scenario	Base	1	2	3	4
Switch Rate	0%	10%	20%	30%	40%
AFV Penetration Rate	3.85%	11.42%	18.99%	26.56%	34.12%
Without AFV HOV Exemption					
Scenario	Base	1	2	3	4
Switch Rate	0%	10%	20%	30%	40%
AFV Penetration Rate	3.85%	11.42%	18.99%	26.56%	34.12%

Table 5-11 Switch rates from Single/Multi Occupant Non-AFVs to AFVs and Corresponding AFV Penetration Rates

With AFV ETL Exemption					
Scenario	Base	1	2	3	4
Switch Rate	0%	10%	20%	30%	40%
AFV Penetration Rate	3.85%	12.87%	21.89%	30.91%	39.94%
Without AFV ETL Exemption					
Scenario	Base	1	2	3	4
Switch Rate	0%	10%	20%	30%	40%
AFV Penetration Rate	3.85%	12.87%	21.89%	30.91%	39.94%

5.4 Modeling Exemptions in the Simulation Environment

The lane closure property function in VISSIM is used to model vehicle movements that result from the HOV exemption policy. The HOV lanes are set as “closed” to all vehicles that are ineligible. As shown in Table 5-12, single occupant hybrid vehicles belong to the vehicle categories “1 LDV hybrids” and “1 LDT Hybrids”. With exemption, the HOV lanes will be set to “open” for this category of vehicles. The GP lane is set to “open” for all vehicle classes. Figures 5-4a and b illustrate HOV lane access under with and without HOV exemption policies, respectively.

Table 5-12 Lane Closure Property by Vehicle Categories Under With and Without HOV Exemption Circumstances in HOV network

Vehicles Categories	Without HOV exemption	With HOV exemption
	HOV lane closure	HOV lane closure
1 LDV Hybrids	Close	Open
1 LDV Non-Hybrids	Close	Close
2+ LDV Hybrids	Open	Open
2+ LDV Non-Hybrids	Open	Open
1 LDT Hybrids	Open	Open
1 LDT Non-Hybrids	Close	Close
2+ LDT Hybrids	Open	Open
2+ LDT Non-Hybrids	Open	Open
Bus	Open	Open
MHD	Close	Close
HHD	Close	Close

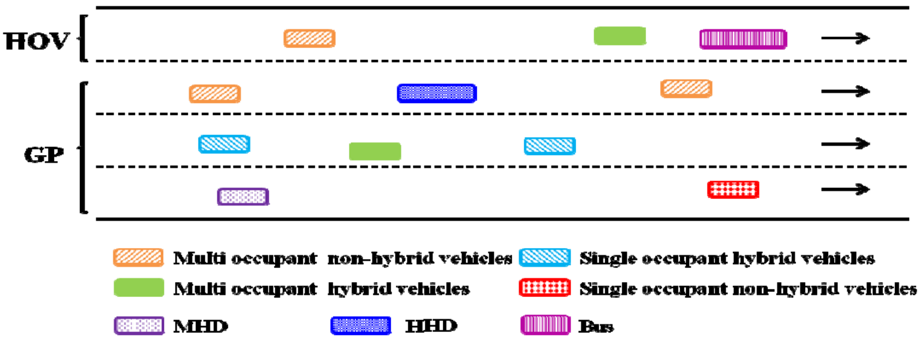


Figure 5-4a Illustration of HOV Lane Access without Exemption

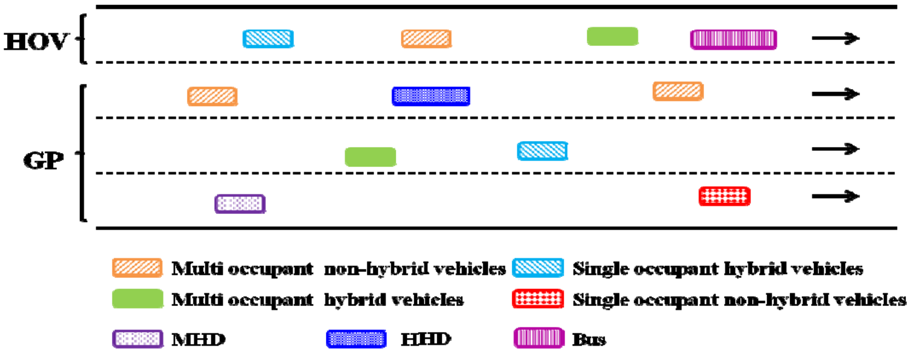


Figure 5-4b Illustration of HOV Lane Access with Exemption

For studying ETL exemption, the lane closure property of both ETLs and GP lanes is set as “open”. It is assumed that owners of qualifying hybrids would choose to use ETLs rather than GP lanes regardless of traffic conditions. That is, the model forces exempted vehicles into the ETLs. Thus, results of models employing these models will capture extreme effects of allowing hybrid vehicles to use ETLs without charge. Since ETLs are modeled as a separate link parallel to GP lanes, three additional routing decisions are placed at ETL access points to force hybrids/AFVs to use them. The first routing decision is added to the northern-most end of the ETLs.

The second one is placed before the slip ramp to the ETLs between MD 75 and MD 80, and the third one is located before the slip ramp to the ETLs between MD 109 and MD 121.

5.5 Performance Measures

5.5.1 System-Level Performance Measures

In this study, system-level and lane-level (managed and GP lane) performance are considered. System-wide total emissions and emissions per VMT are also evaluated. System-level performance measures include:

(1) Vehicle Hours Traveled

(2) Vehicle Miles Traveled

(3) Average Travel Speed

(4) Total Network Delay

(5) Average Vehicle Delay

5.5.2 Lane-Level Performance Measures

SAFETY-LU performance requirements as described in Section 3.2 assert that the HOV lane operation has deteriorated if the average speed in the HOV lane during peak hours falls below 45 mph for a sustained period of time due to exemptions. Whether this occurs will be investigated for both HOV lanes and ETLs. In addition to speed reduction, travel times and average delay were considered. According to CALTRANS (Brownstone et al., 2008), a change in travel time along managed lanes in excess of 20% is classified as degradation in performance. This rate is employed in this study, as well. Similarly, an increase in average delay by 20% is regarded as significant. As required by California's bill AB 2628, a degradation in LOS in the managed lanes due to exemptions to a level below C is considered substantial, as discussed in Section 3.2, and would justify their termination. Thus, a third measure of effectiveness (MOE), LOS, is considered herein.

5.5.3 Air Quality Performance

Air quality performance in terms of total emissions and fuel consumption, as well as emissions and fuel consumption per VMT, were evaluated. Inputs to ORSEEM, the on-road emissions estimation tool used herein to evaluate the performance of different scenarios with respect to air quality, are vehicle speed and the acceleration profile, vehicle characteristic parameters and road grade at 20 second increments. Total emissions were derived by scaling emission values by time step increment (i.e. multiplying the result by 20 in this case). In this study the following were measured:

(1) Total Hydrocarbon (THC)
(2) Carbon monoxide (CO)
(3) Particulate Matter 2.5mm ($PM_{2.5}$)
(4) Particulate Matter 10mm (PM_{10})
(5) Methane (CH_4)
(6) Nitrogen Oxides (NOx)
(7) Sulfur Oxides (SOx)
(8) Carbon Dioxide(CO_2)

(9) Equivalent Carbon Dioxide (CO_2e)

(10) Fuel Consumption

5.6 Data Integration with ORSEEM

5.6.1 Vehicle Make Year Assignment

ORSEEM requires a set of parameters as inputs. These parameters consist of vehicle characteristics (i.e. vehicle make year, vehicle age group, vehicle weight, engine size, and fuel type), vehicle speed/acceleration profile, and roadway grades. There are 116 vehicle categories that cover all the make years and vehicle classes for LDVs and LDTs in the sampled Montgomery County, Maryland 2010 vehicle record data. These categories can be applied to the vehicles post-simulation, since only generic categories (e.g. single occupant hybrid) are required for the simulation runs. Therefore, model year distributions, as in Tables 5-5 and 5-6, are applied to relevant vehicle record data for the county in which the tested roadway resides. The model year is applied via a roulette selection method to assign vehicle make year and corresponding age group for each vehicle. In roulette selection, the chance of a vehicle being assigned with a certain make year is proportional to the percentage of that make year in the distribution. A randomly generated number was used to determine the vehicle make year. The process of integrating VISSIM output with make year distributions is illustrated as one of the parts in the modeling framework of this study (Figure 4-3).

5.6.2 Other Assumptions

The average make year of MHDs and HHDs was assumed to be 2000, because as of July 2011, the average age of trucks in the U.S. was 10.8 years (USATODAY.com, Accessed 2012). The average make year of buses was assumed to be 2003, because the average age of transit buses in the US was about 7.8 years as of 2009 (Research and Innovative Technology Administration, Accessed 2012). The fuel used by LDVs and LDTs is assumed to be gasoline and diesel is assumed to be the fuel source for buses, MHDs and HHDs. In this study, buses that run on CNG, LPG, or other alternative fuel are not considered. Total traffic volume is maintained constant regardless of exemption.

In the next chapter, results of the numerical experiments are reported and their implications are analyzed.

Chapter 6: Results and Analysis

Each experiment scenario was simulated for 1 hour and 30 minutes. The first 30 minutes of simulation time was considered as a warm-up period and only the last hour of simulation was analyzed. Each scenario was run for three random seeds and the average results are reported.

6.1 Effects of HOV Exemption

6.1.1 System-Level Performance

In this section, results of the simulation runs involving the scenarios with and without HOV exemption for hybrid vehicles are analyzed. The analysis is completed in terms of VMT, VHT, total delay, average speed, and average vehicle delay. Effects on emissions and fuel consumption are discussed in Section 6.1.3. Results of this analysis are presented in Table 6-1. Performance measures of with and without scenarios are compared for each considered hybrid penetration value.

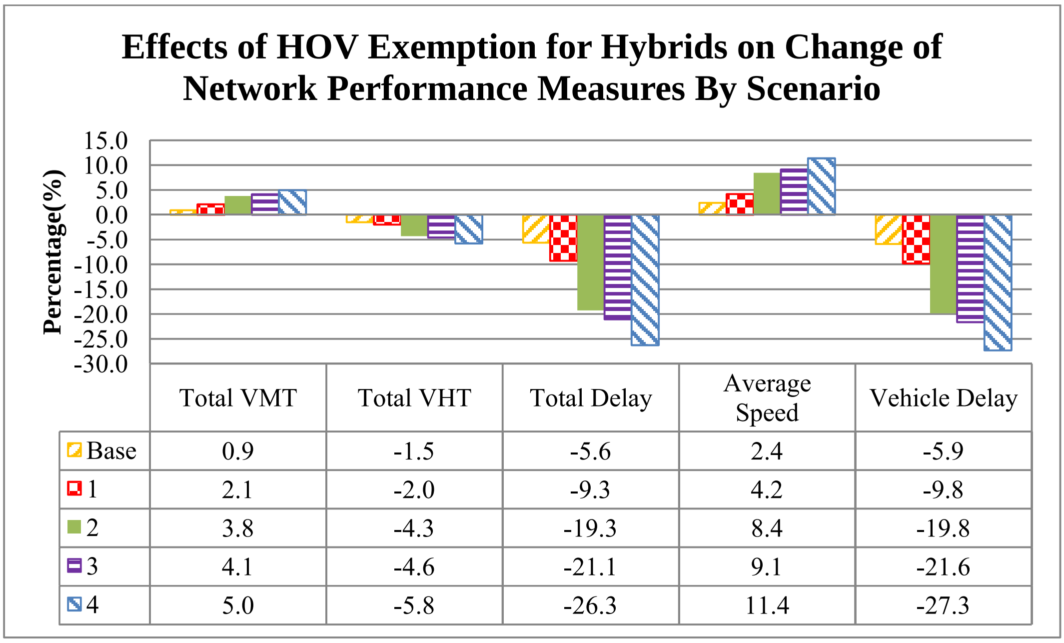
As shown in Table 6-1, VMT and network-wide average speed increase if hybrid vehicles are exempted from restrictions on the use of the HOV lane. Since hybrids vehicles choose to use the HOV lanes, the congestion level in the adjacent GP lanes decreases and, as a result, VMT increases. Furthermore, VHT, network total delay and average vehicle delay are reduced by offering HOV exemption to qualifying hybrids.

Figure 6-1 illustrates the sensitivity of performance measures to increasing hybrid penetration rates. Improvement is observed in all performance measures with increased hybrid vehicle share. At a hybrid penetration rate of 34.12% (or Scenario 4), total delay was shown to be reduced by 26.3% with exemption. Generally, more network-wide benefits can be gained at higher shares of hybrids in the total traffic with exemption.

Statistical analysis was conducted to test the significance of effects on network-wide measures at a confidence level of 95%. A null hypothesis that the mean of performance measure with exemption is not statistically different from the mean of that without exemption was postulated. Acceptance of this hypothesis indicates that there is no significant difference between their effects. As shown in Table 6-2, exemption would significantly improve network-wide performance measures if the hybrid share of the traffic composition exceeds 18.99% (or Scenario 2).

Table 6-1 Network Performance Comparison for HOV Exemption

Scenario	Total VMT (miles)			Total VHT (hours)			Total Delay (hours)			Average Speed (mph)			Vehicle Delay (seconds)		
	With	Without	Change	With	Without	Change	With	Without	Change	With	Without	Change	With	Without	Change
Base	232282	230173	2110	6725	6827	-101	2360	2501	-140	35	34	1	208	221	-13
1	236715	231789	4927	6655	6789	-134	2208	2433	-226	36	34	1	194	215	-21
2	242616	233781	8835	6476	6767	-291	1916	2374	-458	37	35	3	168	209	-42
3	244679	234937	9742	6437	6745	-308	1839	2330	-491	38	35	3	161	205	-44
4	247586	235900	11686	6357	6746	-389	1706	2314	-608	39	35	4	148	204	-56



	Total VMT	Total VHT	Total Delay	Average Speed	Vehicle Delay
Base	0.9	-1.5	-5.6	2.4	-5.9
1	2.1	-2.0	-9.3	4.2	-9.8
2	3.8	-4.3	-19.3	8.4	-19.8
3	4.1	-4.6	-21.1	9.1	-21.6
4	5.0	-5.8	-26.3	11.4	-27.3

Figure 6-1 Percentage Change of Network Performance Measures for HOV Exemption

Table 6-2 Significance Test on Network Performance Measures for HOV Network

Measures	If -t<T<t, accepted				
	Base	1	2	3	4
VMT	Accepted	Rejected	Rejected	Rejected	Rejected
VHT	Accepted	Accepted	Rejected	Rejected	Rejected
Total Delay	Accepted	Rejected	Rejected	Rejected	Rejected
Average Speed	Rejected	Rejected	Rejected	Rejected	Rejected
Vehicle Delay	Accepted	Rejected	Rejected	Rejected	Rejected

6.1.2 Lane-Level Performance

Performance measures of travel time, speed, delay, and density are analyzed for both GP and HOV lanes. In the HOV network, travel time is analyzed for two segments as depicted in Figure 6-2. One segment starts from the beginning of the HOV lane at the intersection with I-370 on I-270 southbound (SB) to the intersection with MD 187 on I-495 eastbound (EB), referred as the “I270 SB to I495 EB” segment. The other segment starts from the intersection with I-370 to the intersection with Democracy Blvd on I-495 southbound, referred as the “I270 SB to I495 SB” segment.

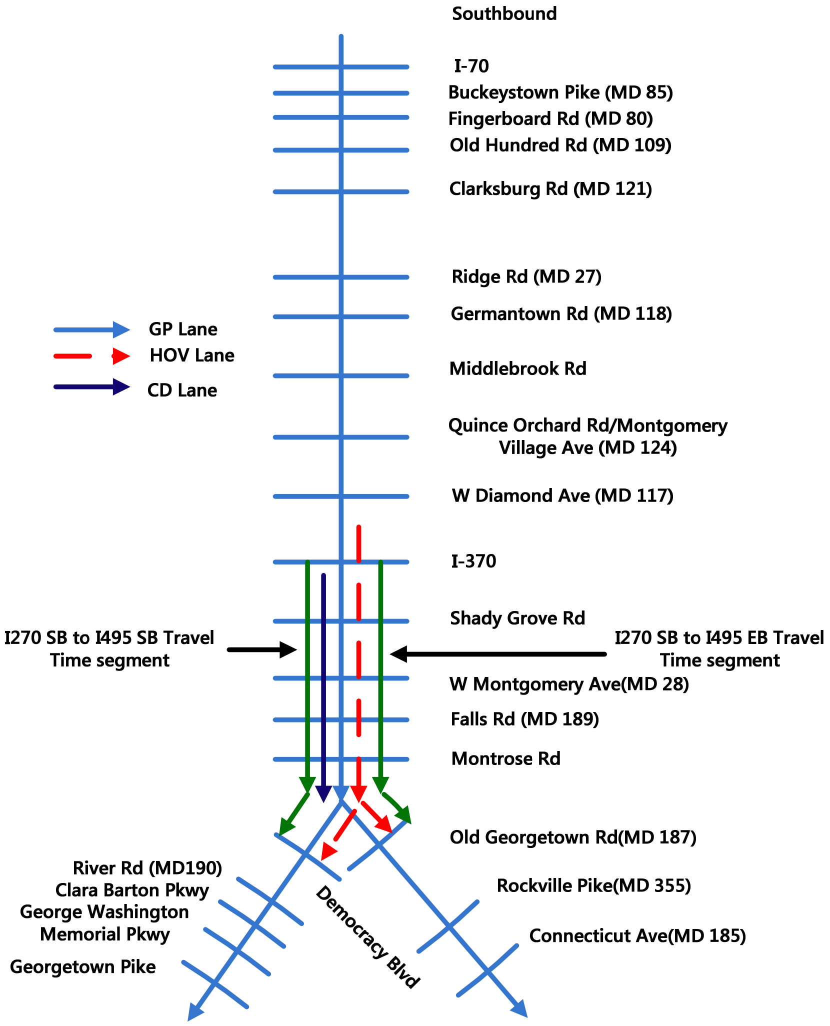
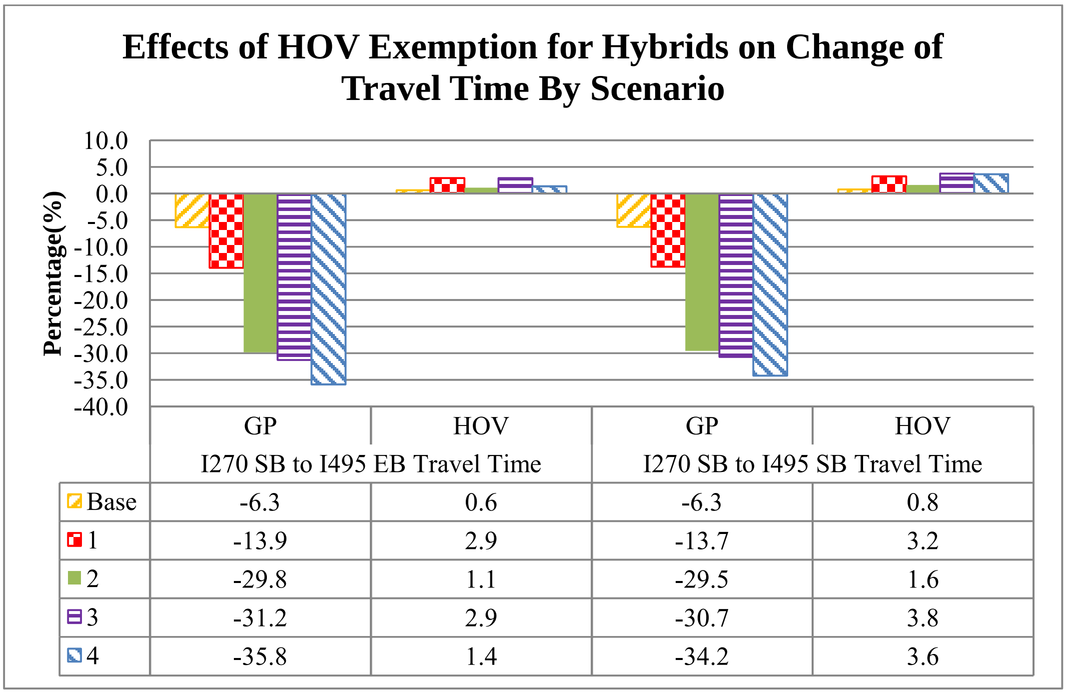


Figure 6-2 Illustration of Travel Time Segments Along the I-270 HOV Lane

Table 6-3 compares travel time with and without exemptions for GP and HOV lane. After allowing hybrids to use the HOV lane, travel time on GP lanes is reduced while travel time on the HOV lane is increased. Savings of between 65.8 and 347.0 seconds were noted for the GP lanes in the “I270 SB to I495 EB” segment and between 65.3 and 331.8 seconds for GP lanes in the “I270 SB to I495 SB” segment where the HOV lane is open to all hybrids. Figure 6-3 illustrates the trend of travel time changes due to increasing hybrid penetration rate. As noticed in Figure 6-3, travel times in the HOV lane for these two segments are slightly increased for all levels of hybrid shares with exemption, indicating that the HOV lane operations would not be negatively affected in terms of travel time by the exemptions. Moreover, the HOV lane travel time increases at lower penetration rates, but decreases at higher penetration rates. This trend might be due to the fact that at higher hybrid penetration rates, the traffic conditions on GP lanes are better than on the HOV lane so that vehicles divert from the HOV lane back to the GP lanes.

Table 6-3 Travel Time Comparison for HOV Exemption

Scenario	I270 SB to I495 EB Travel Time (seconds)						I270 SB to I495 SB Travel Time (seconds)					
	GP			HOV			GP			HOV		
	With	Without	Change	With	Without	Change	With	Without	Change	With	Without	Change
Base	976.6	1042.4	-65.8	606.4	602.5	3.9	979.1	1044.4	-65.3	607.6	602.8	4.7
1	835.0	970.2	-135.2	607.9	590.5	17.3	838.2	971.6	-133.4	610.0	590.8	19.2
2	712.2	1014.8	-302.6	606.7	600.0	6.7	716.3	1016.6	-300.3	609.9	600.2	9.7
3	667.8	971.2	-303.5	599.7	582.6	17.1	674.9	973.2	-298.3	605.3	583.3	22.0
4	621.1	968.0	-347.0	590.0	582.1	8.0	638.2	970.0	-331.8	604.2	583.0	21.2



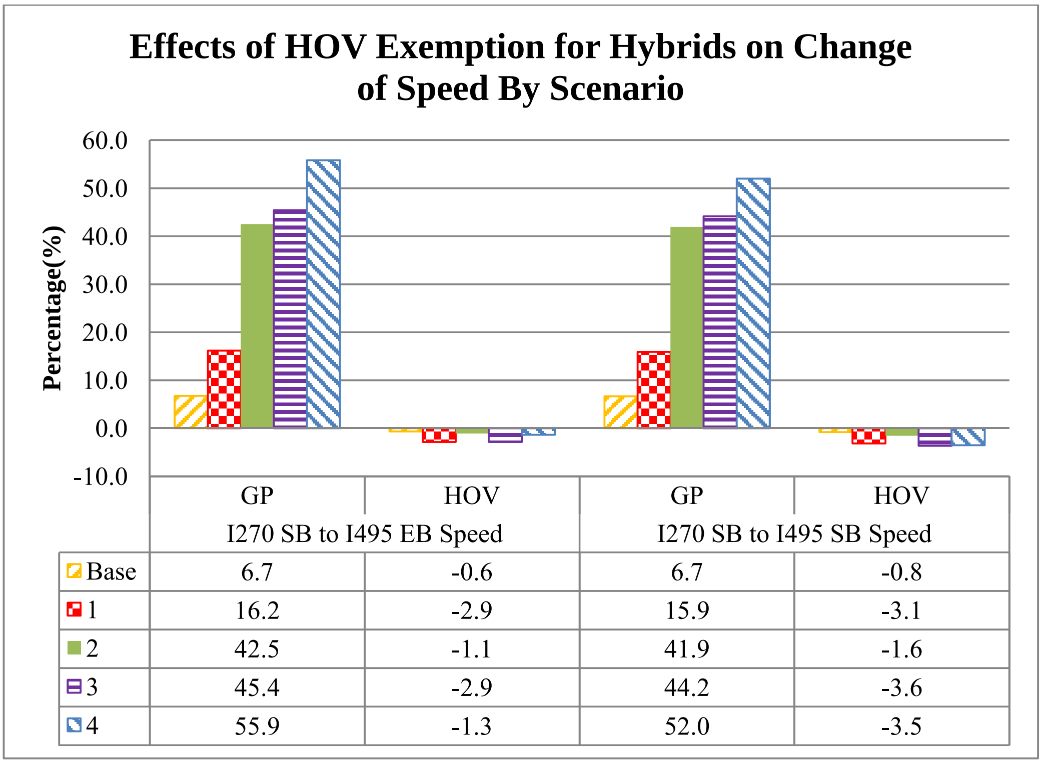
	GP	HOV	GP	HOV
	I270 SB to I495 EB Travel Time		I270 SB to I495 SB Travel Time	
▨ Base	-6.3	0.6	-6.3	0.8
▦ 1	-13.9	2.9	-13.7	3.2
■ 2	-29.8	1.1	-29.5	1.6
▤ 3	-31.2	2.9	-30.7	3.8
▧ 4	-35.8	1.4	-34.2	3.6

Figure 6-3 Percentage Change of Travel Time for HOV Exemption

Comparison of speed on GP and HOV lanes is given in Table 6-4 and Figure 6-4. When compared to scenarios without exemptions, the speed in the GP lanes with exemptions is significantly increased. However, the speed in the HOV lane slightly decreased due to single occupant hybrid traffic. For both segments, HOV lane speeds with exemption are greater than the critical speed of 45mph mentioned in Section 3.2 for all levels of hybrid penetration. However, the speed difference between the GP and HOV lanes with exemption drops from 20.4 mph to 2.5 mph for the "I270 SB to I495 EB" segment with increasing hybrid penetration levels. Similarly, for the "I270 SB to I495 SB" segment, the speed difference between GP and HOV lanes drops from 21 mph to 3 mph. Note that a difference of less than 10 mph results from a hybrid penetration rate greater than 18.99%. If a difference greater than 10 mph is required, the exemption incentive should be suspended when the hybrid share exceeds 18.99%.

Table 6-4 Speed Comparison for HOV Exemption

Scenario	I270 SB to I495 EB Speed (mph)						I270 SB to I495 SB Speed (mph)					
	GP			HOV			GP			HOV		
	With	Without	Change	With	Without	Change	With	Without	Change	With	Without	Change
Base	33.8	31.7	2.1	54.2	54.5	-0.3	34.2	32.1	2.1	55.2	55.6	-0.4
1	39.6	34.1	5.5	54.0	55.6	-1.6	40.0	34.5	5.5	54.9	56.7	-1.8
2	46.4	32.6	13.8	54.1	54.7	-0.6	46.8	32.9	13.8	54.9	55.8	-0.9
3	49.5	34.0	15.5	54.8	56.4	-1.6	49.6	34.4	15.2	55.4	57.5	-2.1
4	53.2	34.1	19.1	55.7	56.4	-0.8	52.5	34.5	18.0	55.5	57.5	-2.0



	GP I270 SB to I495 EB Speed	HOV I270 SB to I495 EB Speed	GP I270 SB to I495 SB Speed	HOV I270 SB to I495 SB Speed
Base	6.7	-0.6	6.7	-0.8
1	16.2	-2.9	15.9	-3.1
2	42.5	-1.1	41.9	-1.6
3	45.4	-2.9	44.2	-3.6
4	55.9	-1.3	52.0	-3.5

Figure 6-4 Percentage Change of Speed for HOV Exemption

As shown in Table 6-5, opening the HOV lane to hybrids causes a delay reduction for GP lanes, but contributes to an increase in delays for HOV lanes. Figure 6-5 indicates that delays in both measured segments would be increased by over 10.8% with exemption if the hybrid shares exceed 11.42%. Significant degradation occurs for the “I-270 SB to I-495 SB” segment for hybrid traffic shares of 11.42%, 26.56% or 34.12% of the traffic composition.

Table 6-5 Delay Comparison for HOV Exemption

Scenario	I270 SB to I495 EB Delay (seconds)						I270 SB to I495 SB Delay (seconds)					
	GP			HOV			GP			HOV		
	With	Without	Change	With	Without	Change	With	Without	Change	With	Without	Change
Base	455.5	521.3	-65.8	86.3	83.7	2.6	459.7	526.8	-67.0	91.6	88.2	3.4
1	313.8	448.8	-135.1	89.0	72.4	16.5	318.8	454.0	-135.1	94.8	76.6	18.2
2	191.4	493.9	-302.5	87.5	75.3	12.2	197.3	499.4	-302.1	94.7	79.9	14.8
3	146.9	450.1	-303.3	80.4	67.5	12.9	155.7	456.0	-300.4	90.0	72.1	17.9
4	100.2	446.7	-346.5	72.2	65.2	7.0	119.5	452.7	-333.2	90.4	70.0	20.3

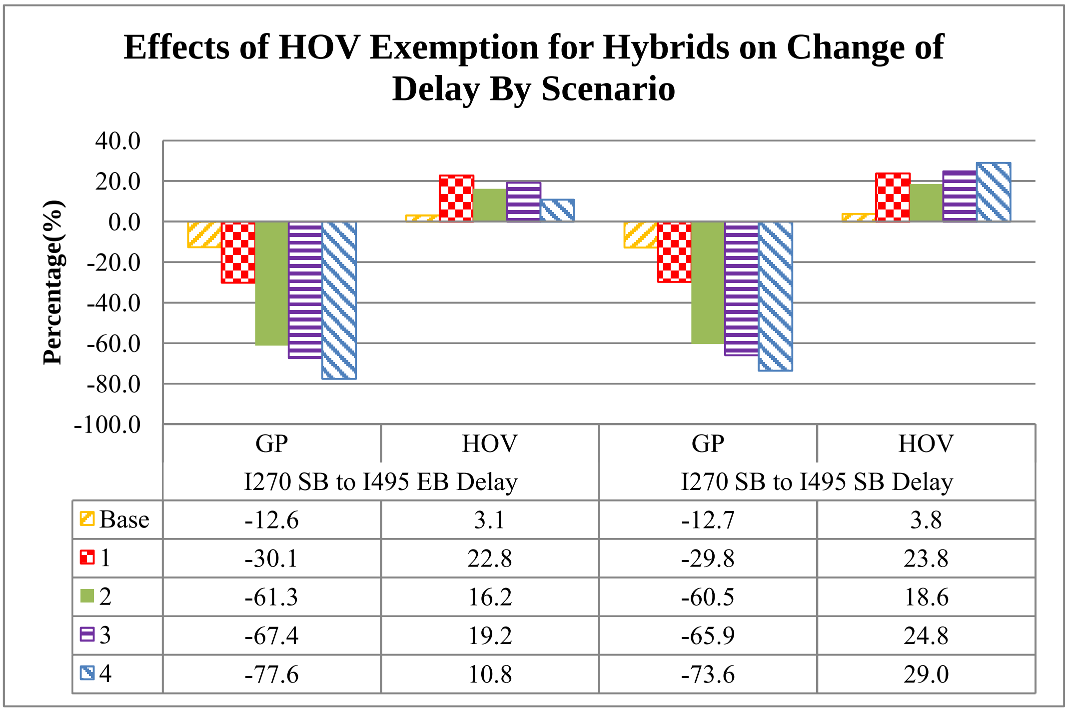


Figure 6-5 Percentage Change of Delay for HOV Exemption

Density on both GP and HOV lanes with exemption is examined as follows. The roadway containing the HOV lane is divided into eight segments for collecting density data. Figure 6-6 depicts the location of each segment. The length of each segment varies from 4,598 to 9,887 feet. The densities on each segment are analyzed and thereby LOS levels are determined.

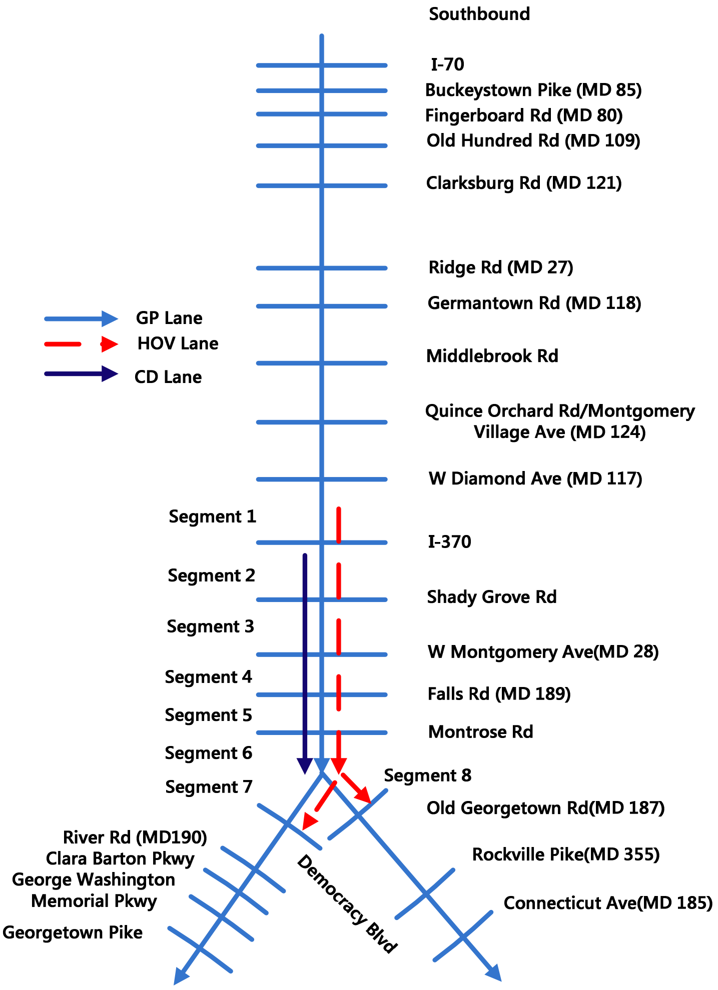
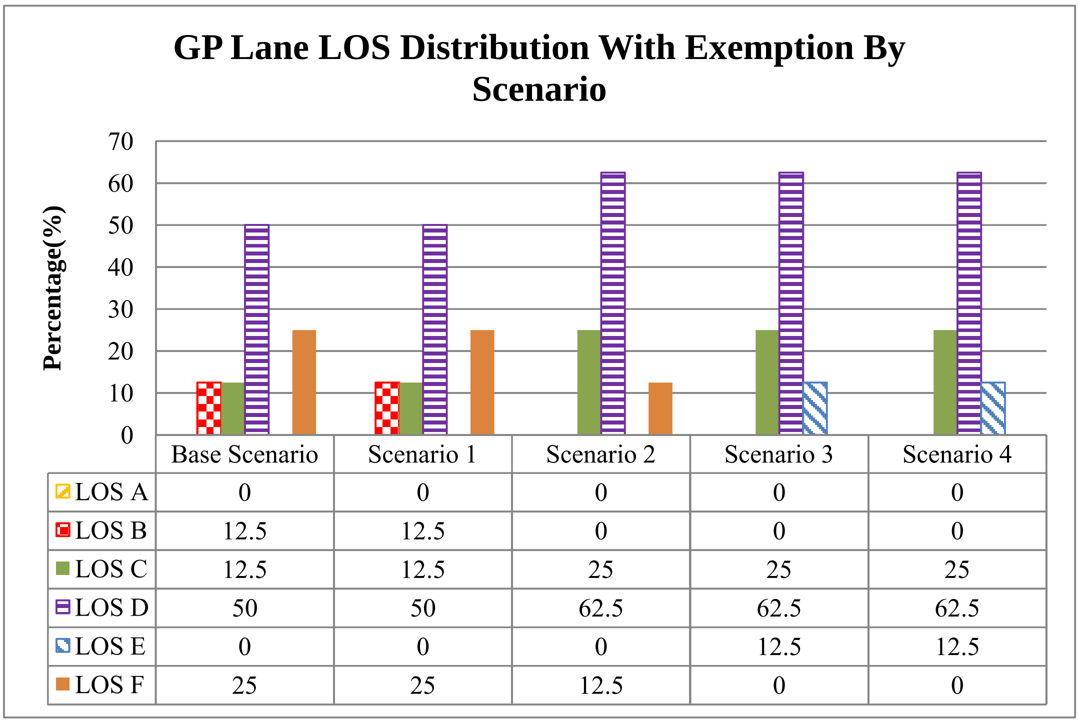


Figure 6-6 Illustration of Segments for Collecting Density Data Along I-270 HOV Lane

Table 6-6 shows the percentage of segments that operate at or less than LOS C (26 vehicles per mile per lane (vpmpl)) on both GP and HOV lanes. Figures 6-7 and 6-8 illustrate the LOS distributions on GP and HOV lanes. As the hybrid penetration rate increases, 25% to 75% of segments on the HOV lane drop to a LOS below C when the hybrid share ranges between 18.99% (Scenario 2) and 34.12% (Scenario 4). Note that the LOS of segments of the GP lanes is not significantly improved due to exemption. As more vehicles enter the network and less congestion is noted in the upstream traffic, the GP lane volume increases. This increase offsets the effects of improving LOS resulting from exemption.

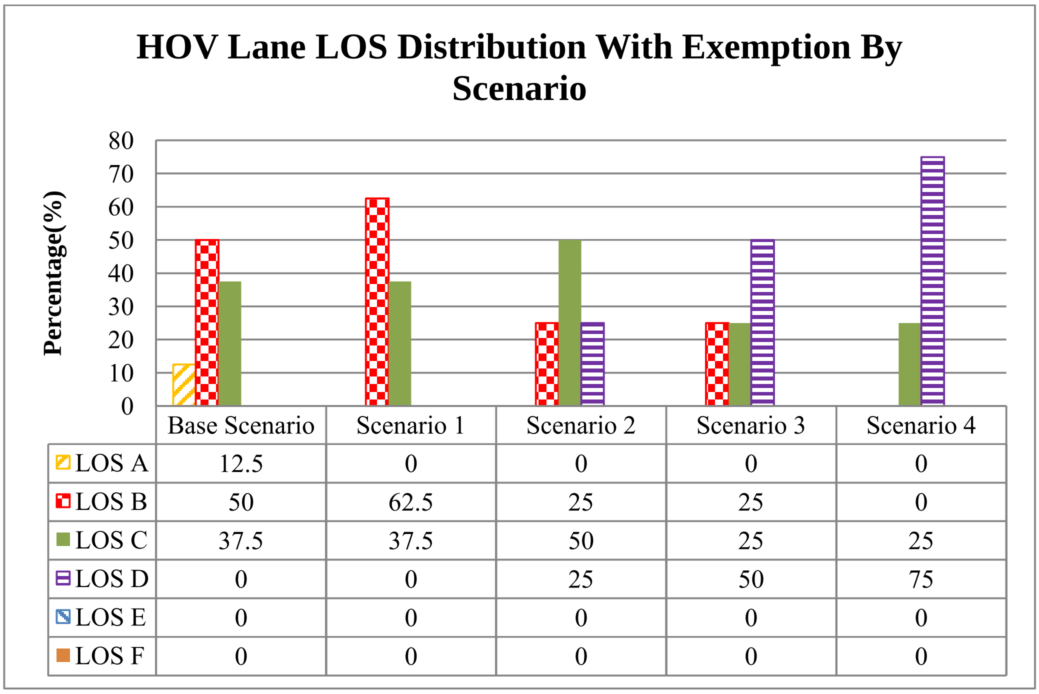
Table 6-6 Percentage of Segments That Operate at LOS C or Better for HOV Exemption

Scenario	GP Lane		HOV Lane	
	With	Without	With	Without
Base	25%	25%	100%	100%
1	25%	25%	100%	100%
2	25%	25%	75%	100%
3	25%	25%	50%	100%
4	25%	25%	25%	100%



	Base Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
LOS A	0	0	0	0	0
LOS B	12.5	12.5	0	0	0
LOS C	12.5	12.5	25	25	25
LOS D	50	50	62.5	62.5	62.5
LOS E	0	0	0	12.5	12.5
LOS F	25	25	12.5	0	0

Figure 6-7 GP Lane LOS Distribution With HOV Exemption



	Base Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
▨ LOS A	12.5	0	0	0	0
▦ LOS B	50	62.5	25	25	0
■ LOS C	37.5	37.5	50	25	25
▤ LOS D	0	0	25	50	75
▧ LOS E	0	0	0	0	0
■ LOS F	0	0	0	0	0

Figure 6-8 HOV Lane LOS Distribution With HOV Exemption

6.1.3 Air Quality Performance

To support emissions and fuel consumption analyses, requiring data intensive processes within ORSEEM, a time step at 20 second intervals is used in simulation model.

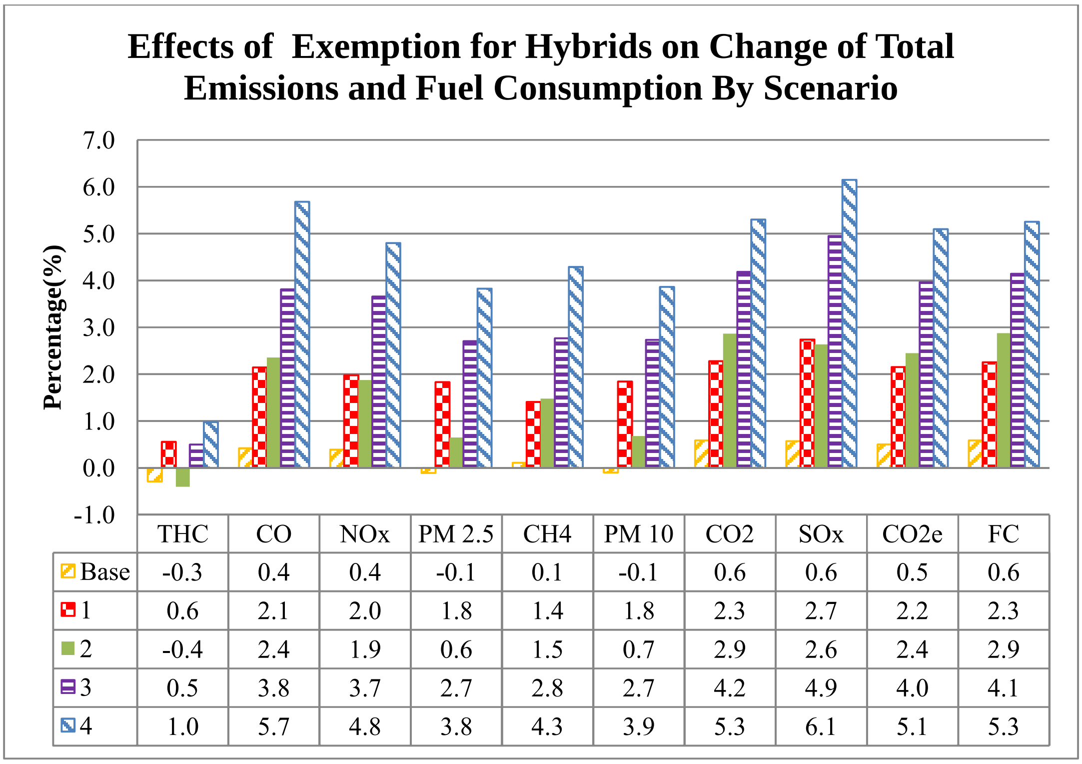
Table 6-7 compares air quality measures. As shown, almost all the types of emissions and fuel consumption increase with an increase in hybrid use of the HOV lane (Figure 6-9). This unexpected result can be explained by the increase in traffic conditions, especially speed. Fuel consumption, and hence emissions, increase at higher speed levels due to increased power demand. More telling performance measures are emissions and fuel consumed per VMT. As observed in Figure 6-10, both measures decrease for most emission types, because total vehicle throughout increases as a consequence of the hybrid exemptions.

Statistical analysis is performed to test the significance of effects on emissions at a confidence level of 95%. The null hypothesis states that the exemptions do not have significant impact on emission changes. As presented in Table 6-8, when the percentage of hybrids in the traffic composition qualified for exemption reaches 11.42%, total emissions of CO, CO_2, CO_2e and total fuel consumption significantly increased. However, it is noticed that if the percentage of hybrids reaches 18.99%, exemption have no significant impact on air quality measures. This may be because traffic reaches a state at which a trade-off occurs between emissions from vehicles running at higher speeds and that from vehicles running at lower speeds. After the percentage of hybrids exceeds 26.56%, the exemptions lead to a significant increase in several types of emissions, as well as fuel consumption. Table 6-9 presents the significance test results on emissions and fuel consumption by VMT. The results indicate that exemptions do not have significant impact on changing the emissions and fuel consumed when considered by VMT.

Table 6-7 Emissions and Fuel Consumption Comparison for HOV Exemption

Scenario	THC (KG)			CO (KG)			NOx (KG)			$PM_{2.5}$ (KG)			CH_4 (KG)		
	With	Without	Change	With	Without	Change	With	Without	Change	With	Without	Change	With	Without	Change
Base	45.8	46.0	-0.1	847.9	844.3	3.5	261.1	260.1	1.0	8.0	8.0	0.0	1.5	1.5	0.0
1	43.7	43.5	0.2	805.3	788.4	16.9	256.5	251.5	5.0	8.0	7.8	0.1	1.4	1.4	0.0
2	41.2	41.3	-0.2	758.0	740.6	17.4	249.9	245.3	4.6	7.9	7.9	0.1	1.3	1.3	0.0
3	39.1	38.9	0.2	712.6	686.4	26.2	246.2	237.5	8.7	8.0	7.8	0.2	1.3	1.2	0.0
4	36.7	36.4	0.4	665.0	629.3	35.7	238.5	227.6	10.9	7.9	7.6	0.3	1.2	1.1	0.0

Scenario	PM_{10} (KG)			CO_2 (Tonnes)			SOx (KG)			CO_2e (Tonnes)			FC (*1000 Gallons)		
	With	Without	Change	With	Without	Change	With	Without	Change	With	Without	Change	With	Without	Change
Base	8.3	8.3	0.0	112.6	112.0	0.7	13.1	13.0	0.1	196.1	195.1	1.0	12.5	12.4	0.1
1	8.3	8.1	0.1	110.5	108.1	2.5	13.1	12.8	0.4	192.5	188.4	4.1	12.2	12.0	0.3
2	8.2	8.2	0.1	107.8	104.8	3.0	13.1	12.8	0.3	187.6	183.1	4.5	11.9	11.6	0.3
3	8.3	8.1	0.2	105.4	101.2	4.2	13.3	12.6	0.6	183.9	176.9	7.0	11.6	11.2	0.5
4	8.2	7.9	0.3	101.7	96.6	5.1	13.1	12.3	0.8	177.6	169.0	8.6	11.2	10.6	0.6

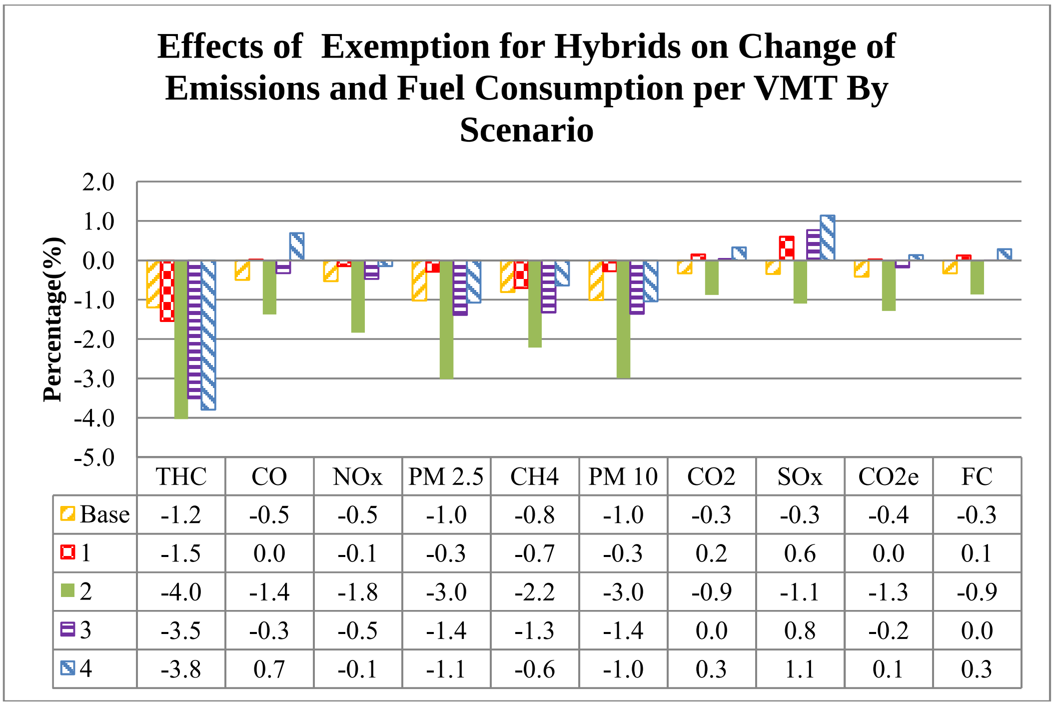


	THC	CO	NOx	PM 2.5	CH4	PM 10	CO2	SOx	CO2e	FC
▨ Base	-0.3	0.4	0.4	-0.1	0.1	-0.1	0.6	0.6	0.5	0.6
▦ 1	0.6	2.1	2.0	1.8	1.4	1.8	2.3	2.7	2.2	2.3
■ 2	-0.4	2.4	1.9	0.6	1.5	0.7	2.9	2.6	2.4	2.9
▤ 3	0.5	3.8	3.7	2.7	2.8	2.7	4.2	4.9	4.0	4.1
▧ 4	1.0	5.7	4.8	3.8	4.3	3.9	5.3	6.1	5.1	5.3

Figure 6-9 Percentage Change of Emissions and Fuel Consumption for HOV Exemption

Table 6-8 Significance Test on Emissions and Fuel Consumption for HOV Exemption

Measures	If -t<T<t, accepted				
	Base	1	2	3	4
THC	Accepted	Accepted	Accepted	Accepted	Accepted
CO	Accepted	Rejected	Accepted	Rejected	Rejected
NOx	Accepted	Accepted	Accepted	Rejected	Accepted
$PM_{2.5}$	Accepted	Accepted	Accepted	Accepted	Accepted
CH_4	Accepted	Accepted	Accepted	Rejected	Accepted
PM_{10}	Accepted	Accepted	Accepted	Accepted	Accepted
CO_2	Accepted	Rejected	Accepted	Rejected	Rejected
SOx	Accepted	Accepted	Accepted	Rejected	Rejected
CO_2e	Accepted	Rejected	Accepted	Rejected	Rejected
FC	Accepted	Rejected	Accepted	Rejected	Rejected



	THC	CO	NOx	PM 2.5	CH4	PM 10	CO2	SOx	CO2e	FC
Base	-1.2	-0.5	-0.5	-1.0	-0.8	-1.0	-0.3	-0.3	-0.4	-0.3
1	-1.5	0.0	-0.1	-0.3	-0.7	-0.3	0.2	0.6	0.0	0.1
2	-4.0	-1.4	-1.8	-3.0	-2.2	-3.0	-0.9	-1.1	-1.3	-0.9
3	-3.5	-0.3	-0.5	-1.4	-1.3	-1.4	0.0	0.8	-0.2	0.0
4	-3.8	0.7	-0.1	-1.1	-0.6	-1.0	0.3	1.1	0.1	0.3

Figure 6-10 Percentage Change of Emissions and Fuel Consumption per VMT for HOV Exemption

Table 6-9 Significance Test on Emissions and Fuel Consumption per VMT for HOV Exemption

Measures	If -t<T<t, accepted				
	Base	1	2	3	4
THC	Accepted	Accepted	Accepted	Rejected	Rejected
CO	Accepted	Accepted	Accepted	Accepted	Accepted
NOx	Accepted	Accepted	Accepted	Accepted	Accepted
$PM_{2.5}$	Accepted	Accepted	Accepted	Accepted	Accepted
CH_4	Accepted	Accepted	Accepted	Accepted	Accepted
PM_{10}	Accepted	Accepted	Accepted	Accepted	Accepted
CO_2	Accepted	Accepted	Accepted	Accepted	Accepted
SOx	Accepted	Accepted	Accepted	Accepted	Accepted
CO_2e	Accepted	Accepted	Accepted	Accepted	Accepted
FC	Accepted	Accepted	Accepted	Accepted	Accepted

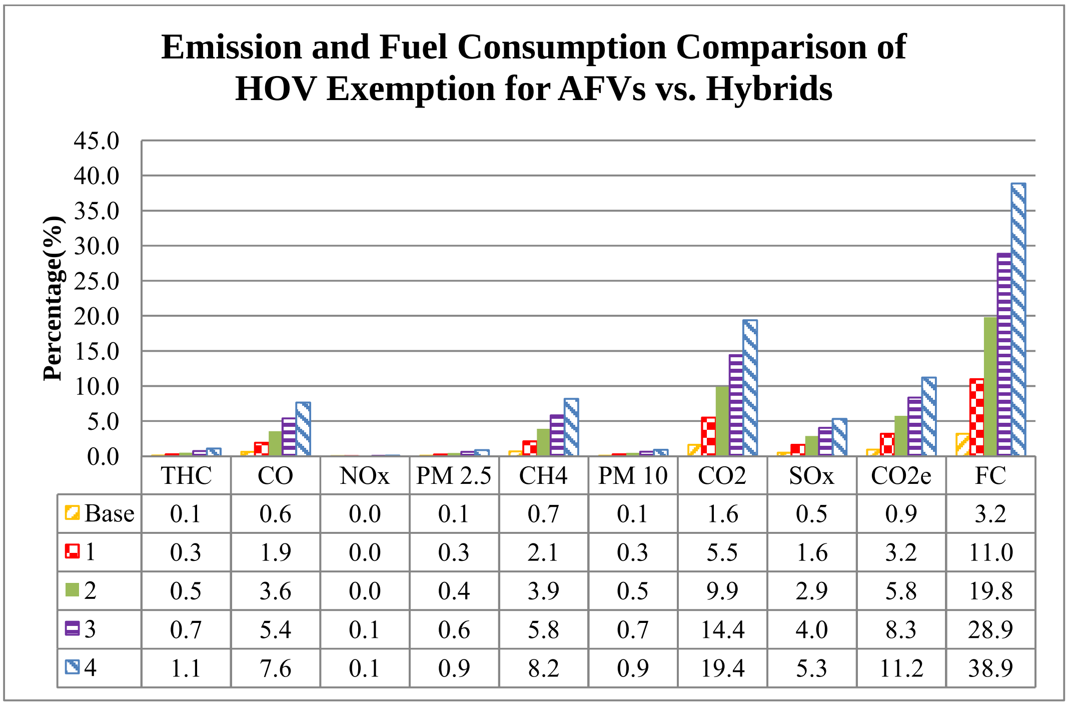
6.1.4 AFV Air Quality Performance

This study also examined the environmental effects of exemption on allowing AFVs to use the HOV lane. Single occupant vehicles that qualify for HOV exemption were assumed to run on alternative fuel E85 instead of hybrid energy. Table 6-10 shows the results of emissions and fuel consumption comparisons for AFVs and hybrids. As shown, at each level of penetration, allowing AFVs in the HOV lane would generate more emissions compared to allowing hybrids in the HOV lane. Figure 6-11 illustrates the percentage change of air quality measures from using alternative fuel. It is observed that the higher the penetration rate, the more emissions and fuel consumed from using E85 as compared with hybrid use. Significance test results in Table 6-11 indicate that the difference between some types of emissions and fuel consumed from using E85 and hybrid energy is significant at high penetration levels. In addition, Table 6-12 indicates that a significant increase in certain emission types and fuel consumption per VMT can be expected when the exempted vehicles operate on alternative fuel E85 rather than hybrid energy technologies.

Table 6-10 Emissions and Fuel Consumption Comparison of HOV Exemption for AFVs vs. Hybrids

Scenario	THC (KG)			CO (KG)			NOx (KG)			$PM_{2.5}$ (KG)			CH_4 (KG)		
	AFV	Hybrid	Change	AFV	Hybrid	Change	AFV	Hybrid	Change	AFV	Hybrid	Change	AFV	Hybrid	Change
Base	45.9	45.8	0.0	853.1	847.9	5.3	261.1	261.1	0.0	8.0	8.0	0.0	1.5	1.5	0.0
1	43.9	43.7	0.1	820.8	805.3	15.5	256.6	256.5	0.1	8.0	8.0	0.0	1.4	1.4	0.0
2	41.4	41.2	0.2	785.1	758.0	27.0	250.0	249.9	0.1	7.9	7.9	0.0	1.4	1.3	0.1
3	39.4	39.1	0.3	751.1	712.6	38.5	246.4	246.2	0.1	8.0	8.0	0.1	1.3	1.3	0.1
4	37.1	36.7	0.4	715.9	665.0	50.8	238.7	238.5	0.2	8.0	7.9	0.1	1.3	1.2	0.1

Scenario	PM_{10} (KG)			CO_2 (Tonnes)			SOx (KG)			CO_2e (Tonnes)			FC (*1000 Gallons)		
	AFV	Hybrid	Change	AFV	Hybrid	Change	AFV	Hybrid	Change	AFV	Hybrid	Change	AFV	Hybrid	Change
Base	8.3	8.3	0.0	114.5	112.6	1.8	13.2	13.1	0.1	198.0	196.1	1.9	12.9	12.5	0.4
1	8.3	8.3	0.0	116.6	110.5	6.1	13.3	13.1	0.2	198.6	192.5	6.2	13.6	12.2	1.3
2	8.3	8.2	0.0	118.5	107.8	10.7	13.5	13.1	0.4	198.4	187.6	10.8	14.3	11.9	2.4
3	8.4	8.3	0.1	120.6	105.4	15.2	13.8	13.3	0.5	199.3	183.9	15.4	15.0	11.6	3.4
4	8.3	8.2	0.1	121.4	101.7	19.7	13.8	13.1	0.7	197.6	177.6	19.9	15.6	11.2	4.4



	THC	CO	NOx	PM 2.5	CH4	PM 10	CO2	SOx	CO2e	FC
Base	0.1	0.6	0.0	0.1	0.7	0.1	1.6	0.5	0.9	3.2
1	0.3	1.9	0.0	0.3	2.1	0.3	5.5	1.6	3.2	11.0
2	0.5	3.6	0.0	0.4	3.9	0.5	9.9	2.9	5.8	19.8
3	0.7	5.4	0.1	0.6	5.8	0.7	14.4	4.0	8.3	28.9
4	1.1	7.6	0.1	0.9	8.2	0.9	19.4	5.3	11.2	38.9

Figure 6-11 Percentage Change of Emissions and Fuel Consumption of HOV Exemption for AFVs vs. Hybrids

Table 6-11 Significance Test on Emissions and Fuel Consumption of HOV Exemption for AFVs vs. Hybrids

Measures	If -t<T<t, accepted				
	Base	1	2	3	4
THC	Accepted	Accepted	Accepted	Accepted	Accepted
CO	Accepted	Accepted	Accepted	Rejected	Rejected
NOx	Accepted	Accepted	Accepted	Accepted	Accepted
PM$_{2.5}$	Accepted	Accepted	Accepted	Accepted	Accepted
CH$_4$	Accepted	Rejected	Rejected	Rejected	Rejected
PM$_{10}$	Accepted	Accepted	Accepted	Accepted	Accepted
CO$_2$	Accepted	Rejected	Rejected	Rejected	Rejected
SOx	Accepted	Accepted	Accepted	Rejected	Accepted
CO$_2$e	Accepted	Rejected	Rejected	Rejected	Rejected
FC	Accepted	Rejected	Rejected	Rejected	Rejected

Table 6-12 Significance Test on Emissions and Fuel Consumption per VMT of HOV Exemption for AFVs vs Hybrids

Measures	If -t<T<t, accepted				
	Base	1	2	3	4
THC	Accepted	Accepted	Accepted	Accepted	Accepted
CO	Accepted	Accepted	Accepted	Rejected	Rejected
NOx	Accepted	Accepted	Accepted	Accepted	Accepted
$PM_{2.5}$	Accepted	Accepted	Accepted	Accepted	Accepted
CH_4	Accepted	Rejected	Rejected	Rejected	Rejected
PM_{10}	Accepted	Accepted	Accepted	Accepted	Accepted
CO_2	Accepted	Rejected	Rejected	Rejected	Rejected
SOx	Accepted	Accepted	Accepted	Rejected	Accepted
CO_2e	Accepted	Rejected	Rejected	Rejected	Rejected
FC	Accepted	Rejected	Rejected	Rejected	Rejected

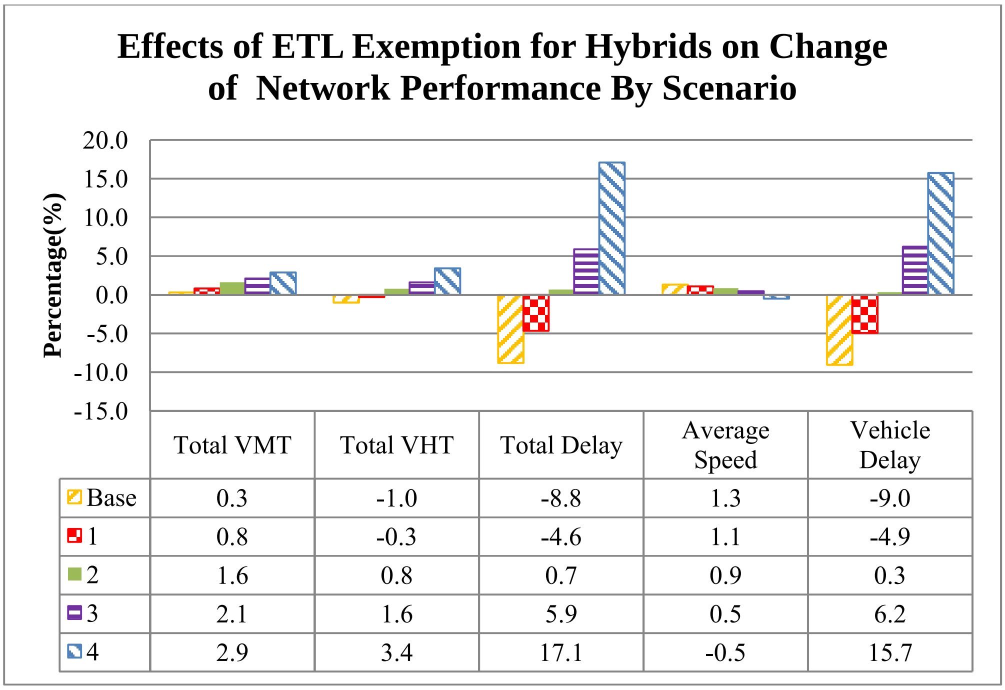
6.2 Effects of ETL Exemption

6.2.1 System-Level Performance

The changes in system-level performance that result from ETL exemption are shown in Table 6-13 and Figure 6-12. From Figure 6-12, it is observed that the overall VMT is increased due to exemption for all hybrid shares considered (3.85% - 39.94%). The total VHT, delay and average vehicle delay decrease for lower hybrid shares and increase at higher hybrid shares. Because all exempted vehicles are forced to use the ETLs, the ETLs become congested at higher percentages of hybrids in the traffic. Consequently, traffic conditions in the GP lanes improve with increasing hybrid share level, but ETL performance degrades; although, not lower than the critical 45 mph. Significance test results shown in Table 6-14 indicate that the changes in system-level performance resulting from exemptions are not statistically significant.

Table 6-13 Network Performance Measures Comparison for ETL Exemption

Scenario	Total VMT (miles)			Total VHT (hours)			Total Delay (hours)			Average Speed (mph)			Vehicle Delay (seconds)		
	With	Without	Change	With	Without	Change	With	Without	Change	With	Without	Change	With	Without	Change
Base	129805	129414	390	2675	2702	-27	315	346	-30	49	48	1	45	50	-4
1	130363	129316	1047	2685	2693	-8	323	339	-16	49	48	1	46	48	-2
2	131519	129415	2105	2722	2701	21	348	345	2	48	48	0	50	50	0
3	132048	129316	2732	2736	2693	43	359	339	20	48	48	0	51	48	3
4	133144	129415	3729	2794	2701	93	404	345	59	48	48	0	57	50	8



	Total VMT	Total VHT	Total Delay	Average Speed	Vehicle Delay
▨ Base	0.3	-1.0	-8.8	1.3	-9.0
▦ 1	0.8	-0.3	-4.6	1.1	-4.9
■ 2	1.6	0.8	0.7	0.9	0.3
☰ 3	2.1	1.6	5.9	0.5	6.2
▧ 4	2.9	3.4	17.1	-0.5	15.7

Figure 6-12 Percentage Change of Network Performance Measures for ETL Exemption

Table 6-14 Significance Test on Network Performance Measures for ETL Network

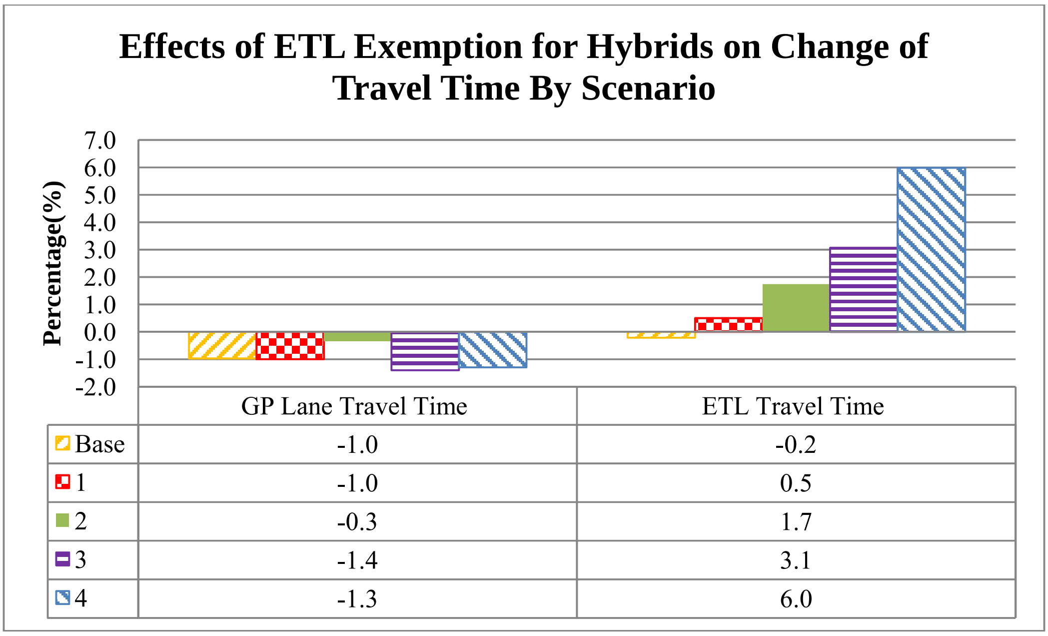
Measures	If -t<T<t, accepted				
	Base	1	2	3	4
VMT	Accepted	Accepted	Rejected	Accepted	Rejected
VHT	Accepted	Accepted	Accepted	Accepted	Accepted
Total Delay	Accepted	Accepted	Accepted	Accepted	Accepted
Average Speed	Accepted	Accepted	Accepted	Accepted	Accepted
Vehicle Delay	Accepted	Accepted	Accepted	Accepted	Accepted

6.2.2 Lane-Level Performance

In Table 6-15 and Figure 6-13, travel time for GP lanes and ETLs are analyzed. As hybrid share increases, ETL travel time increases by up to 6% due to exemption. GP lane travel time decreases slightly (between 0.3% and 1.4%). The reason that ETL operations do not degrade further is that there is excess capacity in these lanes, allowing for accommodation of the increased demand.

Table 6-15 Travel Time Comparison for ETL Exemption

Scenario	GP Lane Travel Time (seconds)			ETL Travel Time (seconds)		
	With	Without	Change	With	Without	Change
Base	1678.5	1694.9	-16.3	1555.3	1558.5	-3.3
1	1672.3	1689.1	-16.8	1564.2	1556.4	7.9
2	1689.1	1694.9	-5.7	1585.7	1558.5	27.2
3	1662.6	1686.1	-23.5	1604.3	1556.4	47.9
4	1673.0	1694.9	-21.8	1651.9	1558.5	93.3



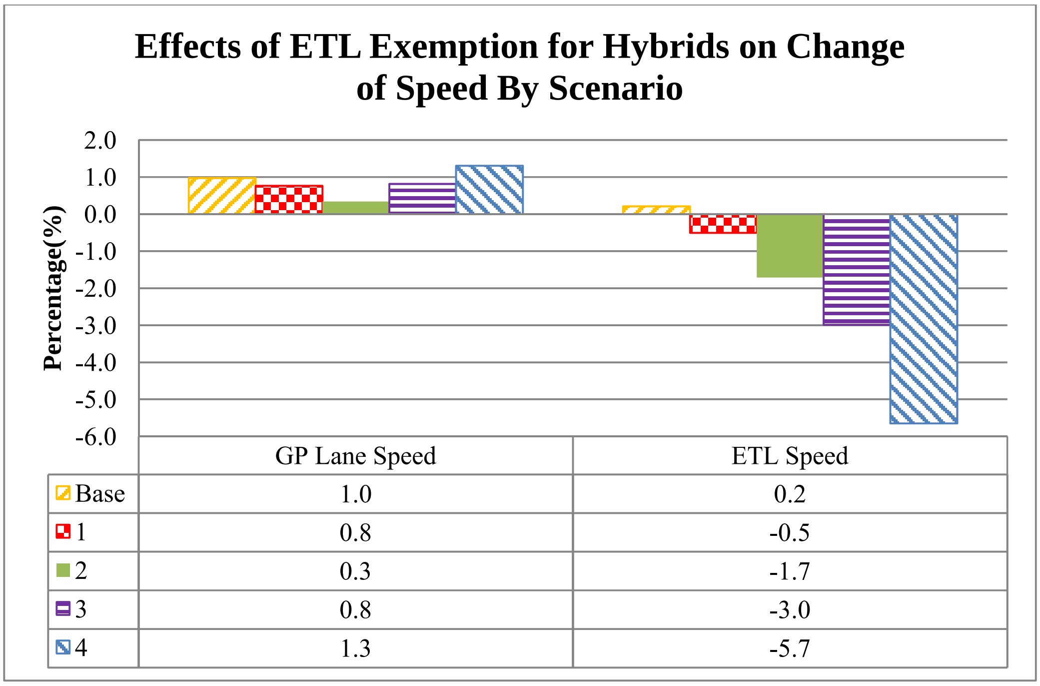
	GP Lane Travel Time	ETL Travel Time
▨ Base	-1.0	-0.2
▦ 1	-1.0	0.5
■ 2	-0.3	1.7
▤ 3	-1.4	3.1
▧ 4	-1.3	6.0

Figure 6-13 Percentage Change of Travel Time for ETL Exemption

Effects of exemption on changes in speed in GP lanes and ETLs are measured in Table 6-16 and Figure 6-14. At all levels of hybrid share, speeds in both GP lanes and ETLs are higher than 45 mph with exemption. No degradation occurs. The speed difference between GP lanes and ETLs drops from 4.0 mph to 0.6 mph with increasing hybrid penetration rate.

Table 6-16 Speed Comparison for ETL Exemption

Scenario	GP Lane Speed (mph)			ETL Speed (mph)		
	With	Without	Change	With	Without	Change
Base	50.8	50.3	0.5	54.8	54.7	0.1
1	51.0	50.6	0.4	54.5	54.8	-0.3
2	50.5	50.3	0.2	53.8	54.7	-0.9
3	51.3	50.9	0.4	53.2	54.8	-1.6
4	51.0	50.3	0.7	51.6	54.7	-3.1



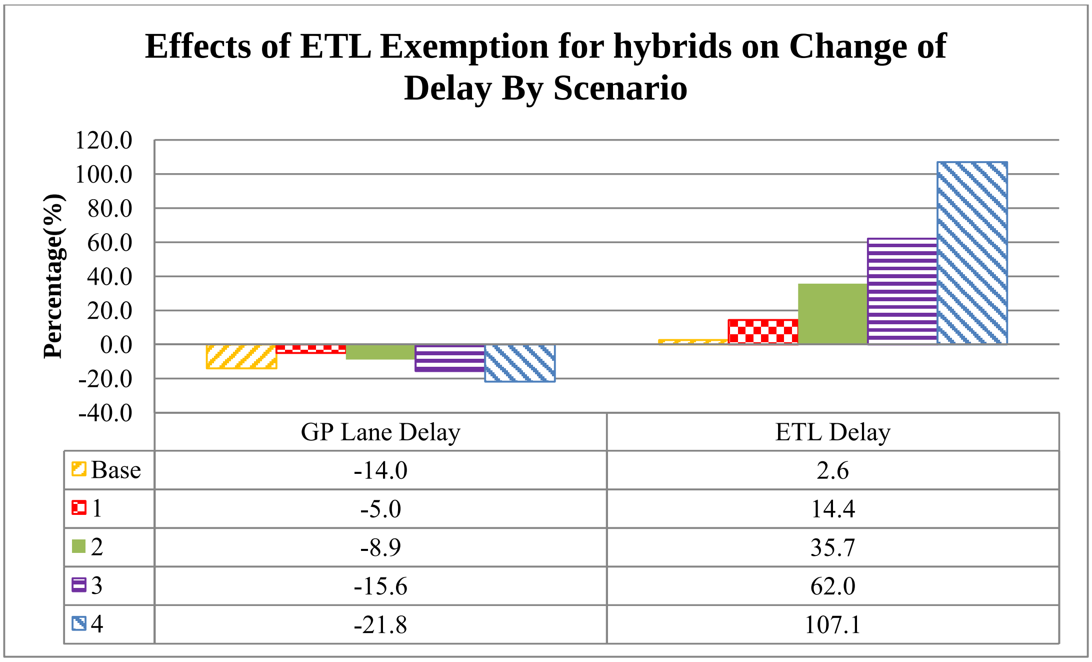
	GP Lane Speed	ETL Speed
▨ Base	1.0	0.2
▦ 1	0.8	-0.5
■ 2	0.3	-1.7
▤ 3	0.8	-3.0
▧ 4	1.3	-5.7

Figure 6-14 Percentage Change of Speed for ETL Exemption

In Table 6-17 and Figure 6-15, delays associated with GP lanes and ETLs are compared. As shown in Figure 6-15, delay incurred by vehicles traveling in the ETLs increases by 35.7% if the share of hybrid vehicles reaches 21.89% (Scenario 2) due to exemption. Thus, suspension of, or restrictions on, the exemption policy might be warranted for hybrid penetration rates greater than 21.89%.

Table 6-17 Delay Comparison for ETL Exemption

Scenario	GP Lane Delay (seconds)			ETL Delay (seconds)		
	With	Without	Change	With	Without	Change
Base	102.7	119.5	-16.8	107.8	105.1	2.7
1	98.8	104.0	-5.2	117.6	102.8	14.8
2	108.9	119.5	-10.6	142.7	105.1	37.5
3	87.8	104.0	-16.2	166.5	102.8	63.8
4	93.5	119.5	-26.0	217.7	105.1	112.6



	GP Lane Delay	ETL Delay
▨ Base	-14.0	2.6
▦ 1	-5.0	14.4
■ 2	-8.9	35.7
▤ 3	-15.6	62.0
▧ 4	-21.8	107.1

Figure 6-15 Percentage Change of Delay for ETL Exemption

Effects of exemptions on density and LOS related to GP lanes and ETLs were also studied. Similar to findings for the HOV lane network, eight segments were defined in the ETL network for collecting corresponding density data as depicted in Figure 6-16. As shown in Table 6-18, degradation in ETL performance starts at a 21.89% hybrid share with exemption. More than 12% of ETL segments operate at a LOS worse than C when the hybrid share eligible for exemption exceeds 21.89%.

Figure 6-17 and Figure 6-18 illustrate the change of LOS on GP lanes and ETLs. As observed, the percentage of segments operating at a LOS A or B increases with increasing hybrid share for GP lanes, while percentage of segments operating at a LOS C, D, or F increases for the ETLs due to exemption.

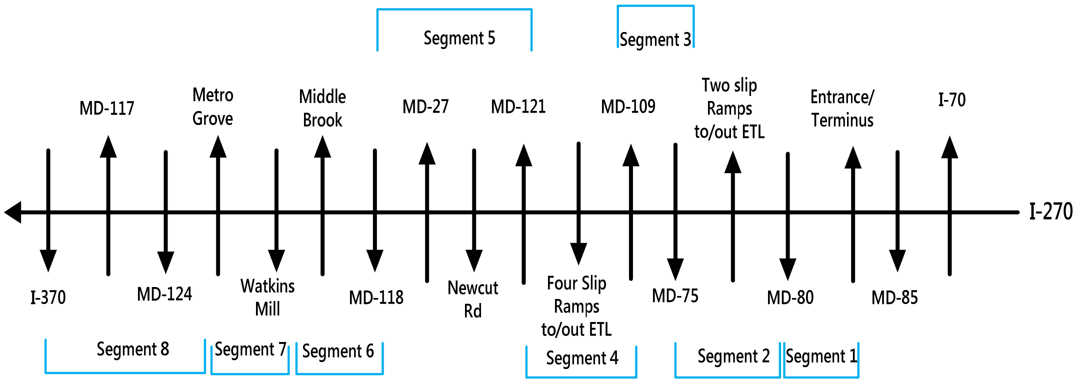
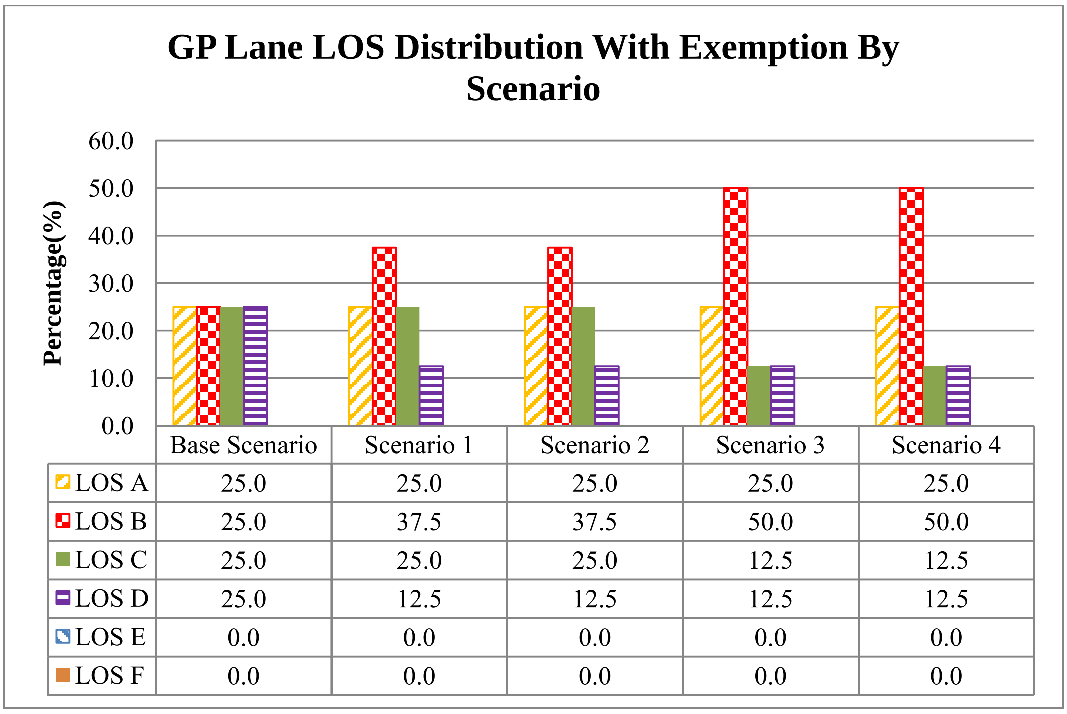


Figure 6-16 Illustration of Segments for Collecting Density Data Along ETLs

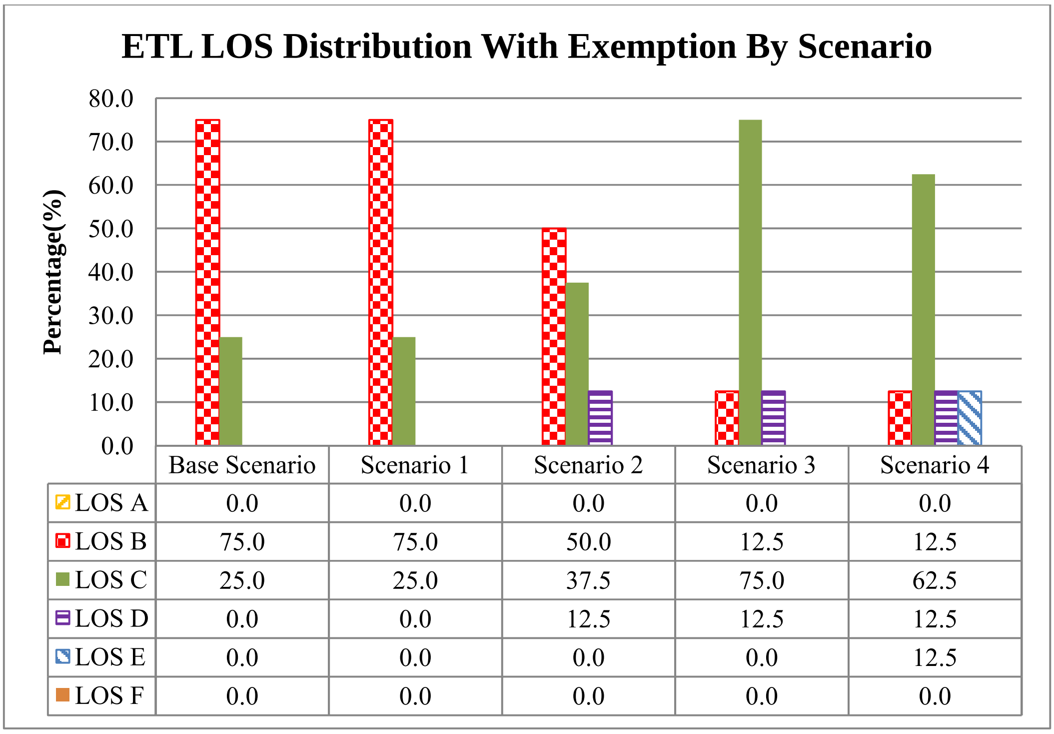
Table 6-18 Percentage of Segments That Operate at LOS C or Better for ETL Exemption

Scenario	GP Lane		ETL	
	With	Without	With	Without
Base	75%	75%	100%	100%
1	88%	75%	100%	100%
2	88%	75%	88%	100%
3	88%	75%	88%	100%
4	88%	75%	75%	100%



	Base Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
▨ LOS A	25.0	25.0	25.0	25.0	25.0
▦ LOS B	25.0	37.5	37.5	50.0	50.0
🟩 LOS C	25.0	25.0	25.0	12.5	12.5
▤ LOS D	25.0	12.5	12.5	12.5	12.5
▧ LOS E	0.0	0.0	0.0	0.0	0.0
🟧 LOS F	0.0	0.0	0.0	0.0	0.0

Figure 6-17 GP Lane LOS Distribution With ETL Exemption



	Base Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
▨ LOS A	0.0	0.0	0.0	0.0	0.0
▦ LOS B	75.0	75.0	50.0	12.5	12.5
🟩 LOS C	25.0	25.0	37.5	75.0	62.5
▤ LOS D	0.0	0.0	12.5	12.5	12.5
▧ LOS E	0.0	0.0	0.0	0.0	12.5
🟧 LOS F	0.0	0.0	0.0	0.0	0.0

Figure 6-18 ETL LOS Distribution with ETL Exemption

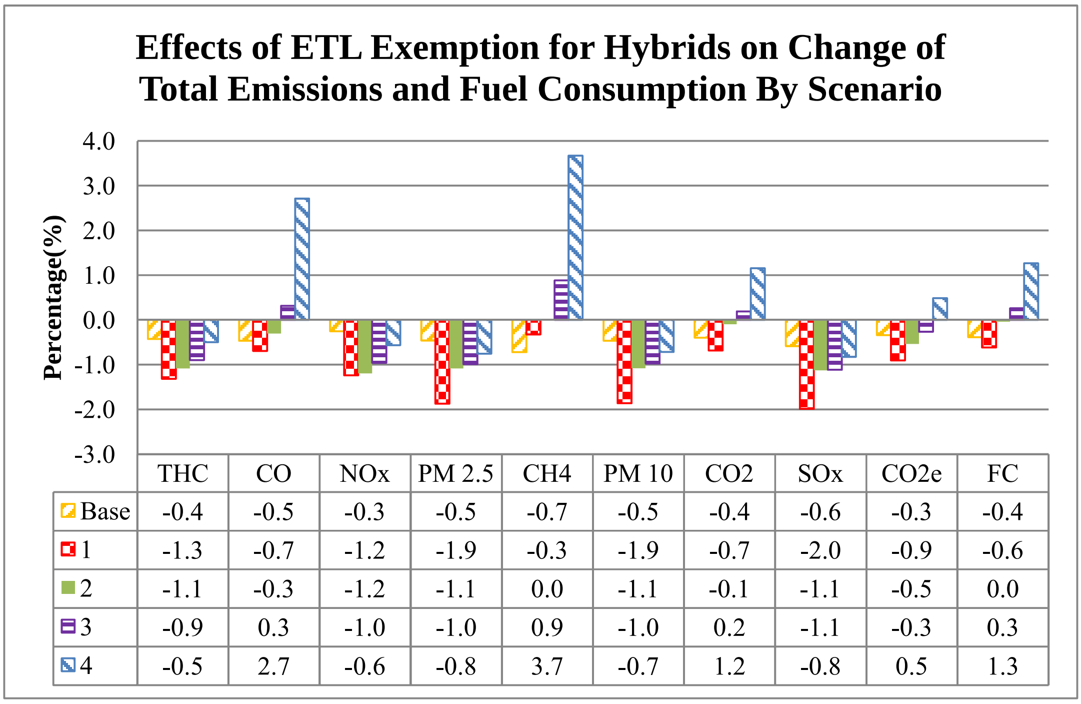
6.2.3 Air Quality Performance

The effects of ETL exemption on air quality are quantified in this section. Table 6-19 and Figure 6-19 show the changes in emissions and fuel consumption with increasing hybrid penetration rates. It is observed that emission types decrease by as much as 2.0% if ETL exemption is offered when hybrid shares are not greater than 21.89% of the total traffic. Emissions of CO, CH_4, CO_2, CO_2e and fuel consumption increase if hybrid shares exceed 21.89%. However, results of additional statistical analysis given in Table 6-20 that ETL exemptions do not significantly impact emissions. However, as indicated in Figure 6-20, exemption reduces almost all types of emissions per VMT at any penetration rate although it is noted that the effects of exemption on emissions and fuel consumption per VMT were not statistically significant (Table 6-21).

Table 6-19 Emissions and Fuel Consumption Comparison for HOV Exemption

Scenario	THC (KG)			CO (KG)			NOx (KG)			$PM_{2.5}$ (KG)			CH_4 (KG)		
	With	Without	Change	With	Without	Change	With	Without	Change	With	Without	Change	With	Without	Change
Base	21.5	21.5	-0.1	424.9	426.9	-2.0	119.4	119.7	-0.3	3.9	3.9	0.0	0.7	0.7	0.0
1	19.9	20.2	-0.3	387.7	390.4	-2.7	111.6	113.0	-1.4	3.7	3.8	-0.1	0.6	0.6	0.0
2	18.8	19.0	-0.2	359.0	360.2	-1.1	107.2	108.5	-1.3	3.7	3.8	0.0	0.6	0.6	0.0
3	17.5	17.6	-0.2	325.7	324.7	1.0	100.9	101.8	-1.0	3.6	3.7	0.0	0.5	0.5	0.0
4	16.3	16.4	-0.1	301.9	293.9	8.0	96.7	97.2	-0.5	3.6	3.6	0.0	0.5	0.5	0.0

Scenario	PM_{10} (KG)			CO_2 (Tonnes)			SOx (KG)			CO_2e (Tonnes)			FC (*1000 Gallons)		
	With	Without	Change	With	Without	Change	With	Without	Change	With	Without	Change	With	Without	Change
Base	4.0	4.0	0.0	53.9	54.1	-0.2	5.8	5.8	0.0	92.2	92.5	-0.3	6.0	6.0	0.0
1	3.9	3.9	-0.1	51.1	51.5	-0.4	5.5	5.6	-0.1	86.9	87.7	-0.8	5.7	5.7	0.0
2	3.9	3.9	0.0	49.2	49.2	0.0	5.5	5.6	-0.1	83.5	84.0	-0.5	5.5	5.5	0.0
3	3.8	3.8	0.0	46.7	46.6	0.1	5.3	5.4	-0.1	79.0	79.2	-0.2	5.2	5.2	0.0
4	3.8	3.8	0.0	44.9	44.4	0.5	5.3	5.3	0.0	75.8	75.4	0.4	5.0	4.9	0.1

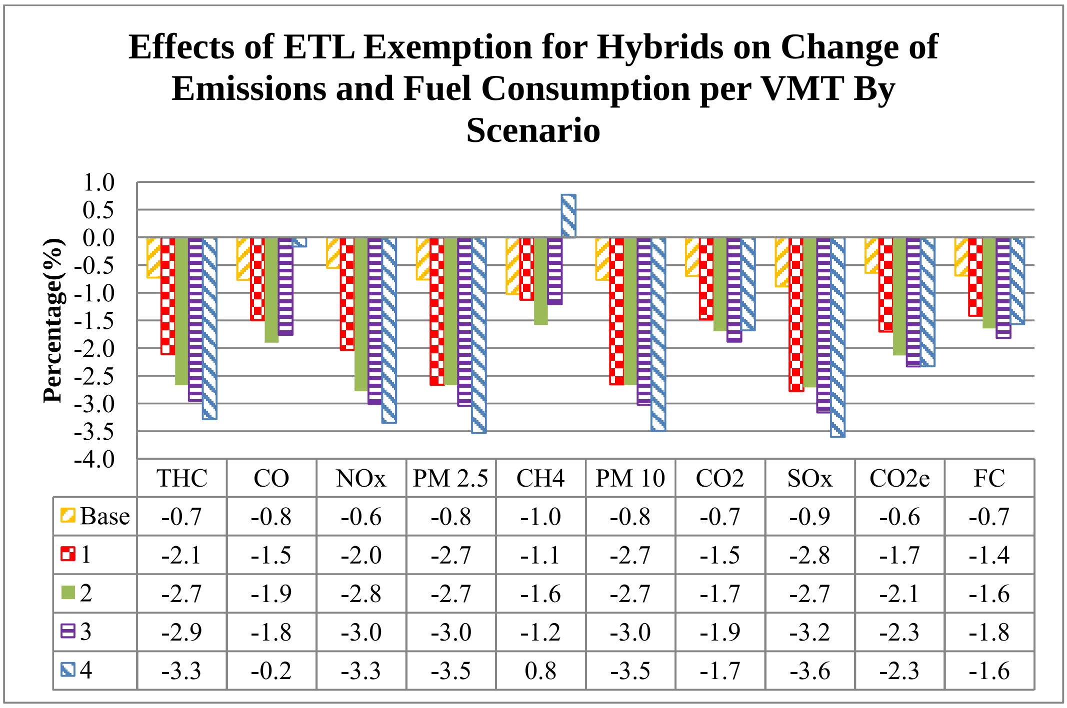


	THC	CO	NOx	PM 2.5	CH4	PM 10	CO2	SOx	CO2e	FC
▨ Base	-0.4	-0.5	-0.3	-0.5	-0.7	-0.5	-0.4	-0.6	-0.3	-0.4
🟥 1	-1.3	-0.7	-1.2	-1.9	-0.3	-1.9	-0.7	-2.0	-0.9	-0.6
🟩 2	-1.1	-0.3	-1.2	-1.1	0.0	-1.1	-0.1	-1.1	-0.5	0.0
▤ 3	-0.9	0.3	-1.0	-1.0	0.9	-1.0	0.2	-1.1	-0.3	0.3
▧ 4	-0.5	2.7	-0.6	-0.8	3.7	-0.7	1.2	-0.8	0.5	1.3

Figure 6-19 Percentage Change of Emissions and Fuel Consumption for ETL Exemption

Table 6-20 Significance Test on Emissions and Fuel Consumption for ETL Exemption

Measures	If -t<T<t, accepted				
	Base	1	2	3	4
THC	Accepted	Accepted	Accepted	Accepted	Accepted
CO	Accepted	Accepted	Accepted	Accepted	Accepted
NOx	Accepted	Accepted	Accepted	Accepted	Accepted
$PM_{2.5}$	Accepted	Accepted	Accepted	Accepted	Accepted
CH_4	Accepted	Accepted	Accepted	Accepted	Accepted
PM_{10}	Accepted	Accepted	Accepted	Accepted	Accepted
CO_2	Accepted	Accepted	Accepted	Accepted	Accepted
SOx	Accepted	Accepted	Accepted	Accepted	Accepted
CO_2e	Accepted	Accepted	Accepted	Accepted	Accepted
FC	Accepted	Accepted	Accepted	Accepted	Accepted



	THC	CO	NOx	PM 2.5	CH4	PM 10	CO2	SOx	CO2e	FC
Base	-0.7	-0.8	-0.6	-0.8	-1.0	-0.8	-0.7	-0.9	-0.6	-0.7
1	-2.1	-1.5	-2.0	-2.7	-1.1	-2.7	-1.5	-2.8	-1.7	-1.4
2	-2.7	-1.9	-2.8	-2.7	-1.6	-2.7	-1.7	-2.7	-2.1	-1.6
3	-2.9	-1.8	-3.0	-3.0	-1.2	-3.0	-1.9	-3.2	-2.3	-1.8
4	-3.3	-0.2	-3.3	-3.5	0.8	-3.5	-1.7	-3.6	-2.3	-1.6

Figure 6-20 Percentage Change of Emissions and Fuel Consumption per VMT for ETL Exemption

Table 6-21 Significance Test on Emissions and Fuel Consumption per VMT for ETL Exemption

Measures	**If -t<T<t, accepted**				
	Base	**1**	**2**	**3**	**4**
THC	Accepted	Accepted	Accepted	Accepted	Accepted
CO	Accepted	Accepted	Rejected	Accepted	Accepted
NOx	Accepted	Accepted	Accepted	Accepted	Accepted
$PM_{2.5}$	Accepted	Accepted	Accepted	Accepted	Accepted
CH_4	Accepted	Accepted	Accepted	Accepted	Accepted
PM_{10}	Accepted	Accepted	Accepted	Accepted	Accepted
CO_2	Accepted	Accepted	Accepted	Accepted	Accepted
SOx	Accepted	Accepted	Accepted	Accepted	Accepted
CO_2e	Accepted	Accepted	Accepted	Accepted	Accepted
FC	Accepted	Accepted	Accepted	Accepted	Accepted

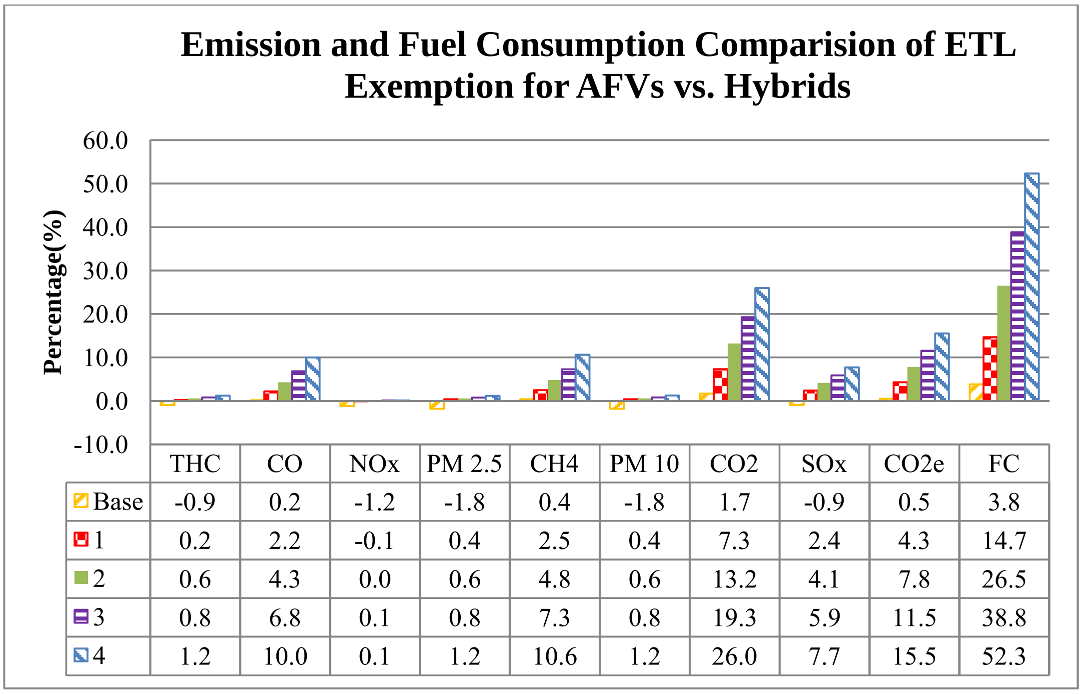
6.2.4 AFV Air Quality Performance

Comparisons in environmental effects from exempting AFVs in place of E85 hybrid vehicles are listed in Table 6-22. In this comparison, it is assumed that all hybrid vehicles are replaced by AFVs in the vehicle population. Thus, if the initial share of qualifying vehicles switches from using hybrid energy to E85, emissions of THC, NOx, $PM_{2.5}$, PM_{10} and SOx will decrease while CO, CO_2, CO_2e and fuel consumed will increase. Figure 6-21 illustrates the percentage change of air quality measures from using E85. Significance test results in Table 6-23 show that the difference in some types of emissions and fuel consumption from using E85 and hybrid energy is significant. Moreover, statistical analysis results are presented for the difference in emissions and fuel consumption per VMT in Table 6-24. As shown, emissions and fuel consumption per VMT from using E85 are significantly higher than that from using hybrid energy at high penetration levels.

Table 6-22 Emissions and Fuel Consumption Comparison of ETL Exemption for AFVs vs. Hybrids

Scenario	THC (KG)			CO (KG)			NOx (KG)			$PM_{2.5}$ (KG)			CH_4 (KG)		
	AFV	Hybrid	Change	AFV	Hybrid	Change	AFV	Hybrid	Change	AFV	Hybrid	Change	AFV	Hybrid	Change
Base	21.3	21.5	-0.2	425.6	424.9	0.8	118.0	119.4	-1.4	3.8	3.9	-0.1	0.7	0.7	0.0
1	19.9	19.9	0.0	396.3	387.7	8.6	111.5	111.6	-0.1	3.7	3.7	0.0	0.6	0.6	0.0
2	18.9	18.8	0.1	374.4	359.0	15.4	107.2	107.2	0.0	3.7	3.7	0.0	0.6	0.6	0.0
3	17.6	17.5	0.1	348.0	325.7	22.2	101.0	100.9	0.1	3.7	3.6	0.0	0.6	0.5	0.0
4	16.5	16.3	0.2	332.1	301.9	30.3	96.8	96.7	0.1	3.7	3.6	0.0	0.5	0.5	0.1

Scenario	PM_{10} (KG)			CO_2 (Tonnes)			SOx (KG)			CO_2e (Tonnes)			FC (*1000 Gallons)		
	AFV	Hybrid	Change	AFV	Hybrid	Change	AFV	Hybrid	Change	AFV	Hybrid	Change	AFV	Hybrid	Change
Base	3.9	4.0	-0.1	54.8	53.9	0.9	5.7	5.8	-0.1	92.7	92.2	0.5	6.2	6.0	0.2
1	3.9	3.9	0.0	54.9	51.1	3.7	5.7	5.5	0.1	90.6	86.9	3.8	6.5	5.7	0.8
2	3.9	3.9	0.0	55.7	49.2	6.5	5.7	5.5	0.2	90.0	83.5	6.5	6.9	5.5	1.4
3	3.8	3.8	0.0	55.7	46.7	9.0	5.6	5.3	0.3	88.1	79.0	9.1	7.2	5.2	2.0
4	3.8	3.8	0.0	56.6	44.9	11.7	5.7	5.3	0.4	87.6	75.8	11.8	7.6	5.0	2.6



	THC	CO	NOx	PM 2.5	CH4	PM 10	CO2	SOx	CO2e	FC
Base	-0.9	0.2	-1.2	-1.8	0.4	-1.8	1.7	-0.9	0.5	3.8
1	0.2	2.2	-0.1	0.4	2.5	0.4	7.3	2.4	4.3	14.7
2	0.6	4.3	0.0	0.6	4.8	0.6	13.2	4.1	7.8	26.5
3	0.8	6.8	0.1	0.8	7.3	0.8	19.3	5.9	11.5	38.8
4	1.2	10.0	0.1	1.2	10.6	1.2	26.0	7.7	15.5	52.3

Figure 6-21Percentage Change of Emissions and Fuel Consumption of ETL Exemption for AFVs vs. Hybrids

Table 6-23 Significance Test on Emissions and Fuel Consumption of ETL Exemption for AFVs vs. Hybrids

Measures	**If -t<T<t, accepted**				
	Base	**1**	**2**	**3**	**4**
THC	Accepted	Accepted	Accepted	Accepted	Accepted
CO	Accepted	Accepted	Rejected	Accepted	Rejected
NOx	Accepted	Accepted	Accepted	Accepted	Accepted
$PM_{2.5}$	Accepted	Accepted	Accepted	Accepted	Accepted
CH_4	Accepted	Rejected	Rejected	Rejected	Rejected
PM_{10}	Accepted	Accepted	Accepted	Accepted	Accepted
CO_2	Accepted	Rejected	Rejected	Rejected	Rejected
SOx	Accepted	Accepted	Accepted	Accepted	Rejected
CO_2e	Accepted	Accepted	Rejected	Rejected	Rejected
FC	Accepted	Rejected	Rejected	Rejected	Rejected

Table 6-24 Significance Test on Emissions and Fuel Consumption per VMT of ETL Exemption for AFVs vs. Hybrids

Measures	If -t<T<t, accepted				
	Base	1	2	3	4
THC	Accepted	Accepted	Accepted	Accepted	Accepted
CO	Accepted	Accepted	Rejected	Accepted	Rejected
NOx	Accepted	Accepted	Accepted	Accepted	Accepted
$PM_{2.5}$	Accepted	Accepted	Accepted	Accepted	Accepted
CH_4	Accepted	Rejected	Rejected	Rejected	Rejected
PM_{10}	Accepted	Accepted	Accepted	Accepted	Accepted
CO_2	Accepted	Rejected	Rejected	Rejected	Rejected
SOx	Accepted	Accepted	Accepted	Accepted	Rejected
CO_2e	Accepted	Accepted	Rejected	Rejected	Rejected
FC	Accepted	Rejected	Rejected	Rejected	Rejected

Chapter 7: Findings and Conclusions

This thesis studied the effects of exempting low-emitting vehicles in managed lane use. The effects of potential exemptions for hybrid vehicles that would allow their use of managed lanes without meeting occupancy restrictions on traffic operations and emissions was investigated using a simulation-based approach. Specifically, numerical experiments were conducted in a microscopic traffic simulation platform, VISSIM, and emissions estimates were developed using ORSEEM. The experiments involved various levels of hybrid penetration and results were studied to ascertain the effects of increasing their share in the traffic composition and ultimately the number of such vehicles exempted from occupancy requirements. Emission estimates that would result from various levels of AFV penetration levels were compared to those of hybrids at the same penetration levels to study the environmental effects of allowing AFVs in managed lane use rather than hybrids. The findings of this study are summarized next.

For HOV lane exemption:

1. Allowing qualified single occupant hybrid vehicles or AFVs to access the HOV lane increases total VMT and network-wide average speed while simultaneously decreasing total VHT, total delay and average per vehicle delay. Overall network performance measures are improved for all levels of hybrid vehicle shares studied (i.e. up to 34.12% of the traffic composition).
2. Traffic congestion along the GP lanes decreased with diversion of additional hybrid vehicles to the HOV lane. Consequently, travel time along the GP lanes

decreased significantly and travel time in the HOV lane slightly increased. It was noted that the travel time in the HOV lane with exemption increased for lower hybrid penetration levels and decreased for higher hybrid penetration levels. This may be because the hybrid traffic will divert back from the HOV lane to the GP lanes when conditions improve along the GP lanes and the difference in performance between these lane classes is small.

3. It was observed that the HOV lane maintains a speed greater than 45 mph with increasing hybrid penetration level with exemption. The speed difference between HOV and GP lanes drops from about 20 mph to 3 mph with increasing hybrid share with exemption.
4. Average delay as a measure is more sensitive to changes in penetration levels of vehicles with exemptions in the GP and HOV lanes than travel time and speed. Change in average delay on the HOV lane exceeds 20% for hybrid penetration rates of 11.42%, 26.56% and 34.12%. Significant changes of this level may warrant termination of an exemption policy to assure quality conditions along the HOV lane.
5. LOS distributions with and without exemption on both GP and HOV lanes were studied, as well. It was concluded that the percentage of segments operating at LOS C or below improves for GP lanes and degrades for HOV lanes with increasing hybrid penetration rate.
6. Counter to expectation, air quality performance measures indicated that exemptions would increase total network-wide emissions and fuel consumption due to improvements in average speed and related increases in power demand for

vehicles to maintain running a higher operating speed. Particularly, emissions of CO, CO_2, CO_2e and fuel consumption were noted to significantly increase with increased exemptions. However, emissions per VMT decrease due to exemption in that total vehicle throughput increases.

7. Effects on total emissions and fuel consumption of E85 and hybrid energy use were compared. The results suggest that AFVs using E85 emit more and consumed more fuel than hybrids for the same penetration rate with exemptions. This is expected, because E85, like many other alternative fuels, has lower energy capacity than gasoline. Thus, AFVs would consume more fuel than hybrids.

For ETL Exemption:

1. Unlike the method of modeling exemption in studying effects of HOV exemption, hybrid vehicles were forced to use the ETLs. Overall, network-wide performance improved at lower hybrid penetration levels and degraded at higher hybrid penetration levels when these vehicles were exempted from occupancy and toll requirements. This is because traffic conditions along the ETLs greatly worsened with the increase in traffic. Note, however, that speeds along the ETLs never fell below the critical 45 mph level. This may be because the ETL facility was designed with significant excess capacity.
2. Travel time marginally improved on GP lanes and was slightly worsened for ETLs with increasing hybrid penetration rates with exemption.
3. Delay on ETLs increased significantly at high hybrid penetration levels with exemptions.

4. LOS on the ETLs degraded with increase hybrid penetration levels with exemptions, but on the GP lanes remained largely unchanged. This may be at least in part due to a construct of the simulation modeling framework in that the number of so-called ‘lost’ vehicles, i.e. vehicles that could not enter the network during the simulation period due to bottlenecks, diminished from 900 to 300.
5. The impact of increasing hybrid penetration rates with exemptions on total air quality performance measures was found to have no statistical significance. Emissions per VMT, however, decrease with exemption rates for most of emission types.
6. Although some emissions decrease if AFVs using E85 replace hybrid vehicles where exemptions are provided, most emissions would be expected to increase with a switch from using hybrid energy to E85.

This thesis conducted a comprehensive and systematic study of the effects of exempting low-emitting vehicles from access exemption restrictions on managed lane use along freeways. Based on microscopic traffic simulation experiments conducted on a case study involving the entirety of I-270 and portions of I-495 in Maryland, it was concluded that exemptions would not significantly degrade the managed lane use when the percentage of qualified low-emitting vehicles is low, such as at the initial rate of 3.85%. However, performance deterioration in the HOV lane was noted at penetration levels of 11.42% and at 26.56% and higher, and performance in the ETLs degraded for penetration levels no lower than 21.89%. It was also concluded that exemptions would significantly relieve congestion on GP lanes without degrading the performance of the managed lane in terms of travel time, speed and LOS as long as the penetration rate of low-emitting vehicles is less than 11.42%. Additionally, network-wide emissions and fuel consumption would slightly increase due to exemptions. However, in general exemptions contribute to a reduction in emissions and fuel consumption per VMT. The comparison of emissions and fuel consumption from using E85 and hybrid energy technologies indicate that it is environmentally beneficial and potentially economical (depending on the relative price and availability of the chosen alternative fuel and AFV) to use hybrid energy as opposed to alternative fuel E85.

A number of limitations of the study conducted herein must be noted. Foremost, findings are based entirely on results from experiments on one roadway. Low-emitting vehicles were forced to use the ETL facility regardless of traffic conditions in these lanes, despite that users would not choose to use the facility if its performance were worse than that of the GP lanes. Thus, results related to ETL exemptions represent extreme conditions. Only AFVs running on E85 were considered. Other alternative fuels, such as CNG, can also be studied. Total demand for use of the roadway and splits at junctions do not change due to exemptions. However, it is possible that the introduction of exemptions would increase travel demand and change lane choice and other aspects of routing behavior of users to allow them to take advantage of managed lane facilities when eligible. Finally, the network effects of exemptions on traffic conditions associated with surrounding roadways were not considered.

References

Abbanat, B.A., 2001. *Alternative Fuel Vehicles: The case of Compressed Natural Gas (CNG) Vehicles in California Households*. M.S. Thesis, University of California, Davis. Available at: <http://pubs.its.ucdavis.edu/publication_detail.php?id=368>

Booz Allen Hamilton Inc., 2008. *A Compendium of Existing HOV Lane Facilities in the United States*. Technical Report, U.S. Department of Transportation Federal Highway Administration. Available at: < http://ops.fhwa.dot.gov/publications/fhwahop09030/fhwahop09030.pdf >

Brownstone, D., Chu, L., Golob, T., Nesamani K.S., Recker, W. 2008. *Evaluation of Incorporating Hybrid VehicleUse of HOV Lanes*. Research Report, Institute of Transportation Studies, University of California, Berkeley. UCB-ITS-PRR-2008-26. Available at: <http://www.path.berkeley.edu/PATH/Publications/PDF/PRR/2008/PRR-2008-26.pdf>

CALTRANS, 2006. *Determination Report: Hybrids on the High-Occupancy Vehicle Facilities in California*. Division of Traffic Operations, California Department of Transportation.

CMEM, 2010. *Comprehensive Modal Emissions Model (CMEM)*. Center for Environmental Research and Technology. Riverside, California. Available at: <http://www.cert.ucr.edu/cmem/>. Last Accessed: October, 2011.

Diamond, D. 2008a. *The Impact of HOV Lane Incentives for Hybrids in Virginia*. *Journal of Public Transportation* 11 (4), 57–76. Available at: <http://www.nctr.usf.edu/jpt/pdf/JPT11-4Diamond.pdf>

Diamond, D. 2008b. *Public Policies for Hybrid Electric Vehicles - The Impact of Government Incentives on Consumer Adoption*. Ph.D. Dissertation, School of Public Policy. George Mason University, Fairfax, VA. Available at: <http://digilib.gmu.edu:8080/dspace/bitstream/1920/2994/1/Diamond_David.pdf>

Diamond, D. 2009. *The Impact of Government Incentives for Hybrid Electric Vehicles: Evidence from United States*. *Energy Policy* 37 (3), 972-983. Available at: <http://www.sciencedirect.com/science/article/pii/S0301421508005466>

Farley, T.F., Martin T. 2003. *Report of the High-Occupancy Vehicle Enforcement Task Force. Technical Report.* Virginia Department of Transportation and Virginia Department of State Police. Available at:

<http://www.virginiadot.org/travel/resources/FINALHOVTaskForceReport8-15-03.pdf>

Federal Highway Administration, 2012. *Value Pricing Pilot Program Projects Involving Tolls: Priced Lanes. Tolling and Pricing Program*. FHWA. Available at: <http://www.ops.fhwa.dot.gov/tolling_pricing/value_pricing/>. Last Accessed, July 2012.

FHWA, 2008. *Federal-Aid Highway Program Guidance on High Occupancy Vehicle (HOV) lanes*. FHWA Available at: <http://ops.fhwa.dot.gov/freewaymgmt/hovguidance/hovguidance.pdf>

Gallagher, K.S., Muehlegger, E. 2011. *Giving Green to Get Green? Incentives and Consumer Adoption of Hybrid Vehicle Technology. Journal of Environmental Economics and Management* 61 (1), 1-15. Available at: <http://www.hks.harvard.edu/fs/emuehle/Research%20WP/Gallagher%20and%20Muehlegger%20Feb_08.pdf>

HybridCenter.org, 2011. *State and Federal Hybrid Incentives*. Available at: <http://go.ucsusa.org/hybridcenter/incentives.cfm>. Last Accessed, March 2011.

Metro.net, 2012. *HOT Lanes in the U.S.*. Available at: <http://www.metro.net/projects/expresslanes/expresslanes_us/>. Last Accessed, July 2012.

Miller-Hooks, E., Chou, C., Feng, L., and Faturechi, R., 2011. *Concurrent Flow Lanes – Phase III.* Technical Report, Maryland State Highway Administration, MD-11-SP009B4P.

Miller-Hooks, E., Qi, B., Melanta S., Avtesyan H., 2012. *GHG Emissions Tool to Support Emission Estimation in On-Road Transport along Freeway and Arterials*. Technical Report, Maryland State Highway Administration.

Morrison D.C., Counts, M., 2005. *Report of the High-Occupancy Vehicle Enforcement Task Force*. Virginia Department of Transportation.

NesamanI, K.S., Chu, L.Y., Recker, W., 2010. *Policy Implications of Incorporating Hybrid Vehicles into High-Occupancy Vehicle Lanes. Journal of Transportation Systems Engineering and Information Technology* 10 (2), 30-41.

Potoglou, D., Kanaroglou, P.S., 2007. *Household Demand and Willingness to Pay for Clean Vehicles. Transportation Research Part D: Transport and Environment* 12 (4), 264-274.

Research and Innovative Technology Administration, 2012. *Average Age of Urban Transit Vehicles*. Available at: <http://www.bts.gov/publications/national_transportation_statistics/2010/html/table_01_28a.html>

USATODAY, 2012. *Cars and Trucks Age*. Available at: <http://www.usatoday.com/money/autos/story/2012-01-17/cars-trucks-age-polk/52613102/1>. Last Accessed, July, 2012.

USDOE, 2011a. *Alternative Fuels Data Center*. Energy Efficiency & Renewable Energy. USDOE. Available at: <http://www.afdc.energy.gov/data/tab/vehicles/data_set/10299>.Last Accessed, 2011.

USDOE, 2011b. *Alternative Fuels Data Center*. Energy Efficiency & Renewable Energy. USDOE. Available at: <http://www.afdc.energy.gov/data/tab/vehicles/data_set/10300>. Last Accessed, 2011.

USDOE, 2011c. *State Incentives and Laws*. Alternative Fuels & Advanced Vehicles Data Center. USDOE. Available at: <http://www.afdc.energy.gov/afdc/laws/state>. Last Accessed, March, 2011.

USEPA, 2010. *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*, U.S.EPA. Available at : <http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1006DXP.PDF>

USEPA, 2011. *Motor Vehicle Emissions Model (MOVES)*. Modeling and Inventories. USEPA. Available at: <http://www.epa.gov/otaq/models/moves/index.htm>. Last Accessed, January 2011.

USEPA. 2012. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1999-2010*. Available at: <http://epa.gov/climatechange/emissions/usinventoryreport.html>**.** Last Accessed: July, 2012.

Xie, Y.C., Chowdhury, M.R., Bhavsar, P., and Zhou, Y., 2010. *An Integrated Tool for Modeling the Impact of Alternative Fueled Vehicles on Traffic Emissions: A Case Study of Greenville, South Carolina*. Paper submitted to Transportation Research Board 90th Annual Meeting, Washington DC.