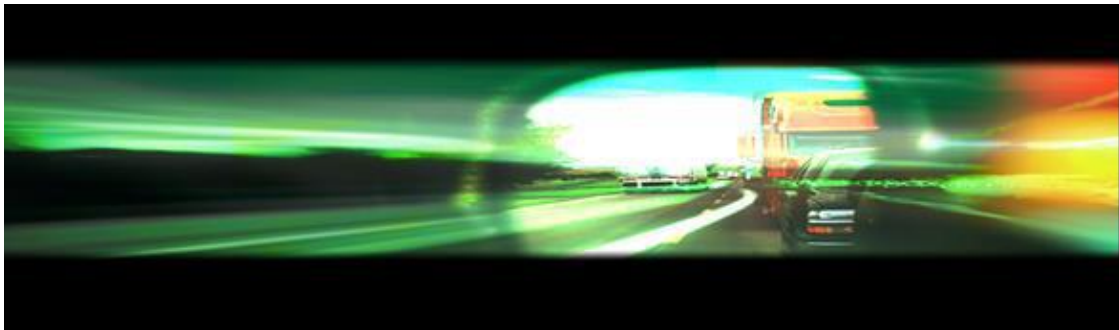


# **A Systematic Evaluation of the Impacts of Traffic Condition Information on the Reduction of On-road Mobile Emissions**

**Final report**



**TranLIVE**

**Yi Qi, Lei Yu, Ameena Padiath, Qun Zhao and Yubian Wang**

**July 2016**

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|  |  |  |           |
|--|--|--|-----------|
| 1. Report No.  | 2. Government Accession No.                          | Recipient's Catalog No.  |           |
| 4. Title and Subtitle<br>A Systematic Evaluation of the Impacts of Traffic Condition Information on the Reduction of On-road Mobile Emissions  |  | 5. Report Date<br>July 2016  |           |
|  |  | 6. Source Organization Code<br>KLK900-SB-003   |           |
| 7. Author(s)<br>Yi Qi, Lei Yu, Ameena Padiath, Qun Zhao and Yubian Wang  |  | 8. Source Organization Report No.<br>No. N   |           |
|  |  | 10. Work Unit No. (TRAIS)  |           |
| 9. Performing Organization Name and Address<br>Innovative Transportation Research Institute<br>Texas Southern University, 3100 Cleburne Avenue, Houston, TX<br><br>Source Organization name and Address<br>TranLIVE/NIATT, University of Idaho<br>875 Perimeter Dr, MS0901, Moscow, ID 83844-0901  |  | 11. Contract or Grant No.<br>DTRT12-G-UTC17  |           |
|  |  | 13. Type of Report and Period Covered<br>Final report  |           |
| 12. Sponsoring Agency Name and Address<br><br>US Department of Transportation<br>Research and Special Programs Administration<br>400 7th Street SW<br>Washington, DC 20509-0001  |  | 14. Sponsoring Agency Code<br><br>USDOT/RSPA/DIR-1   |           |
|  |  | 15. Supplementary Notes  |           |
| 16. Abstract<br>Current Advanced Traveler Information Systems (ATIS) allow travelers to change their route, mode, departure time, route choice or destination to avoid delays and congestions, which results in improved traffic flow. This means higher vehicle speed, lower travel time and delay, and less extreme vehicle acceleration and deceleration events for the facility, and reduced total on-road vehicle emissions.<br>The goal of this research is to evaluate the impacts of ATIS on the reduction of on-road mobile emissions. To achieve the research objectives, emission levels at different congestion levels on freeway and arterial road stretches were estimated using extensive data collection and processing. The emission estimation was done with MOVES software from the EPA. This study prepared the primary input, i.e., operating mode ID distribution, required for running MOVES and developed models to estimate emissions for different types of roadways under different congestion levels. The study results were then used to develop a framework to estimate the effects of ATIS on air quality. To demonstrate application of the developed framework, a case study was done to evaluate the impacts of ATIS on vehicle emissions under an incident condition. Results from this study will provide transportation planners and environmental analysts with a qualitative assessment method for evaluating the impacts of ATIS on air quality. |  |  |           |
| 17. Key Words<br><br>Emission, Advanced Traveler Information System, MOVES   |  | 18. Distribution Statement<br>Unrestricted; Document is available to the public through the National Technical Information Service; Springfield, VT. |           |
| 19. Security Classify (of this report)<br>Unclassified   | 20. Security Classify (of this page)<br>Unclassified | 21. No. of Pages<br>100  | 22. Price |

# **A Systematic Evaluation of the Impacts of Traffic Condition Information on the Reduction of On-road Mobile Emissions**

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Research Report TranLIVE/15KLLK900-SB-003

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June 2016

## **NOTICE**

Mention of trade names or commercial products does not constitute endorsement or recommendation for use. Trade and manufacturers' names appear herein solely because they are considered essential to the object of this report.

## **ACKNOWLEDGEMENTS**

The activities reported herein were performed by Texas Southern University (TSU) as part of a project entitled " A Systematic Evaluation of the Impacts of Traffic Condition Information on the Reduction of On-road Mobile Emissions ", which was sponsored by the Transportation for Livability by Integrating Vehicles and the Environment (TranLive) University Transportation Center.

The authors also recognize that support for this research was provided by a grant from the U.S. Department of Transportation, University Transportation Centers Program to the TranLive center.

## **EXECUTIVE SUMMARY**

Current Advanced Traveler Information Systems (ATIS) allow travelers to change their route, mode, departure time, route choice or destination to avoid delays and congestions, which results in improved traffic flow. This means higher vehicle speed, lower travel time and delay, and less extreme vehicle acceleration and deceleration events for the facility, which will reduce the emission rate, and hence the total amount of on-road vehicle emissions.

The goal of this research is to evaluate the impact of ATIS on the reduction of on-road mobile emissions. To this end, the following specific research objectives were established:

1. Review and synthesize ATIS evaluation studies.
2. Estimate emission levels for different roadway congestion levels on both freeway and arterial facilities.
3. Develop a framework for estimating the impacts of ATIS in regards to the reduction of on-road mobile emissions.
4. Conduct a case study to evaluate the effects of ATIS on emission reduction during an incident scenario.

To achieve the research objectives, emission levels at different congestion levels on freeway and arterial road stretches were estimated based on extensive data collection and processing. Fifty hours of GPS probe vehicle data from different road stretches in the city of Houston, Texas were collected for this study. The emission estimation was done with MOVES software from the EPA. This study developed operating mode ID distributions for different

roadway congestion levels, which is a primary input required for running MOVES.

Subsequently, models were developed to estimate emissions for different types of roadways under different congestion levels. The study results were then used to develop a framework to estimate the effects of ATIS on air quality. To demonstrate application of the developed framework, a case study was done to evaluate the impacts of ATIS on vehicle emissions under an incident condition. The case study demonstrated the benefits of using ATIS in terms of total system travel time and total amount of on-road vehicle emissions. The case study also illustrated the usefulness of the framework recommended in this study. Practitioners can use the operating mode ID distributions and framework developed in this study to carry out similar evaluation studies for any type of pollutant.

The results of this study provide transportation planners or environmental analysts with guidelines on qualitative assessments of the impacts of traffic condition information on air quality.



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# CHAPTER 1: INTRODUCTION

## 1.1 BACKGROUND

Transportation related air pollution problems have gained increased attention in recent years. The transportation sector alone is responsible for 28% of greenhouse gas (GHG) emissions in the United States (*FHWA, 2013*). Toxic air pollutants released from on road mobile sources are known to cause cancer, respiratory diseases and other health ailments. The major types of pollutants causing these harmful effects are NO<sub>x</sub>, VOC, CO, PM2.5, PM10, and others.

Contemporary environmental concerns have shifted aims in the transportation sector toward being more environmentally conscious and proactive in emission reduction strategies. Federal and state governments have mandated that air quality concerns be addressed and that new transportation projects must conform with Environmental Protection Agency (EPA) regulations. In 1990, the Clean Air Act Amendment listed 188 hazardous air pollutants and addressed the need to control toxic emissions from transportation.

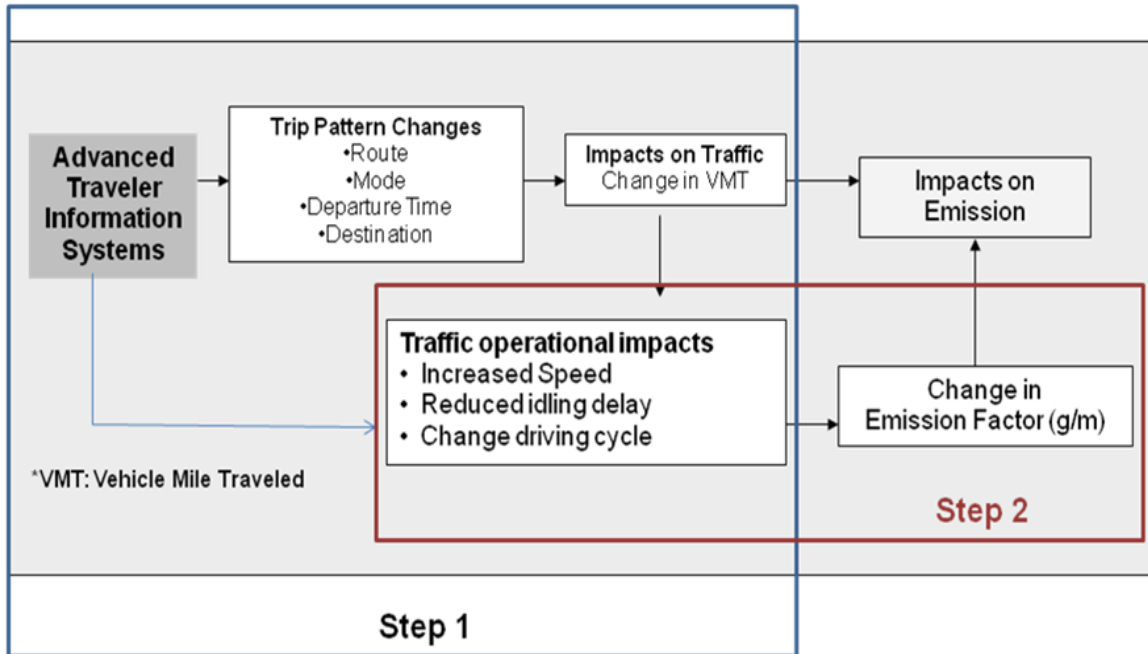
The Federal Highway Authority (FHWA) is currently working on understanding and quantifying the contribution of mobile sources to air emissions for establishing policies addressing mobile source emissions in environmental reports (*FHWA, 2013*). One important strategy is the deployment of the Advanced Traveler Information System (ATIS) to alleviate traffic congestion and associated impacts on air quality. ATIS is an integral part of an Intelligent Transportation System (ITS) and includes both static and real-time information on traffic conditions, and schedules, road and weather conditions, special events, and tourist information.

With the rapid pace in the development of Information/Communication Technologies (ICT), ATIS are achieving higher penetration in the consumer market. ATIS use technologies that assemble and process travel-related data and disseminate useful information to travelers. These include internet-based traffic information, dynamic message signs, smartphone-based travel information systems and in-vehicle navigator systems, which are becoming more accessible to travelers. Information provided by these systems includes traffic conditions (e.g., travel times, accidents, and delays), availability and conditions of public transportation, and availability of parking, emergency alerts, etc.

The immediate impacts of ATIS are improved traffic operation and reduced congestion. With the availability of ATIS, travelers can change their route, mode, departure time, route choice or destination to avoid delay and congestion, which results in improved traffic flow. This means higher vehicle speed, lower travel time and delay, and less extreme vehicle acceleration and deceleration events, which reduces the emission rate and hence the total amount of on-road vehicle emissions. Figure 1 shows a flowchart illustrating the impacts of ATIS on traffic conditions and hence emissions.

According to this figure, the first step towards evaluating the impacts of ATIS on vehicle emission is to investigate the impact of ATIS on congestion reduction. The second step is to investigate emission levels corresponding to different congestion levels. Most ongoing research focuses on the first step, the relationship between ATIS and congestion reduction. However, very limited research has been conducted focusing on the second step. To fill this gap, this research will focus on the second step, which is to estimate emission rates under different roadway congestion levels. Next, a framework was developed for estimating the impacts of ATIS on the

reduction of on-road mobile emissions. Finally, a case study was done to evaluate the impacts of ATIS on roadway vehicle emissions under a specific scenario for incident management.



**Figure 1. Impacts of ATIS on traffic conditions and emissions**

## 1.2 RESEARCH GOALS AND OBJECTIVES

The goal of this research is to evaluate the impact of ATIS on the reduction of on-road mobile emissions. To this end, the research attempts to achieve the following specific objectives:

1. Review and synthesize evaluation studies on ATIS.
2. Estimate emission levels for different roadway congestion levels on both freeway and arterial facilities.
3. Develop a framework for estimating the impacts of ATIS on the reduction of on-road mobile emissions.
4. Conduct a case study to evaluate the effects of ATIS on emission reduction during an incident scenario.

The results of this study will provide transportation planners and environmental analysts with qualitative assessments regarding impact on air quality from different types of traffic condition information. The work also supports traffic engineer work to appropriately deploy the most effective traveler information systems that achieve additional environmental benefits.

### **1.3 OUTLINE OF THIS REPORT**

This report documents all the research activities and findings throughout this project. Chapter 2 presents a review of existing prior studies related to quantification of emission levels under different traffic conditions. Chapter 3 presents the methodology, study procedures, and data collection of the study. Chapter 4 presents the data processing and results, develops the framework, and reviews the case study. Finally, Chapter 5 presents conclusions for this research.



## **CHAPTER 2: LITERATURE REVIEW**

This chapter introduces previous and current research done regarding the impact of ATIS on traveler behavior, traffic congestion and emissions.

The first section of this chapter is a brief introduction of the available technologies for ATIS. The next two sections review previous studies on the quantitative effects of ATIS on traffic flow and the impacts of traffic flow changes on emissions. The last section deals with different types of emission models followed by a brief summary on existing gaps in the literature.

### **2.1 ADVANCED TRAVELER INFORMATION SYSTEM**

Advanced Traveler Information Systems provide information regarding traffic conditions, availability and conditions of public transportation, availability of parking, travel time, etc. The information is disseminated using different systems. Following are some of the most widely used systems:

Variable/changeable Message Sign (VMS) is often installed at roadsides. It can provide en-route traveler information for accidents, work zone, congestion information, lane closure and travel time using different routes.

Highway Advisory Radio (HAR) are licensed low-power AM radio stations set up by local transport departments to provide bulletins to motorists and other travelers regarding traffic and other delays. They are often near highways and airports, and occasionally at tourism areas such as national parks (*Wikipedia*).

Traffic TV and radio provide live traffic situation, delays and traffic jam information. Both traffic TV and radio have limited geographic coverage.

Route guidance devices provide alternative route and travel time information. The most common devices people usually use are global positioning systems (GPS), which is a space-based satellite navigation system. People can access traffic information via GPS devices and smartphones.

Nowadays, it is very convenient and popular to check route information via smartphones.

E-mail Alerts can be sent to travelers by smartphone, personal digital assistant (PDA) or personal computer (PC) both pre-trip and en-route. Travelers can select specific routes for which they want to receive email alerts.

ATIS Kiosk is used to receive information from a traffic or transit management center and will interact with users to provide travel and tourist information, including scheduled times, status and expected wait time for buses or trains.

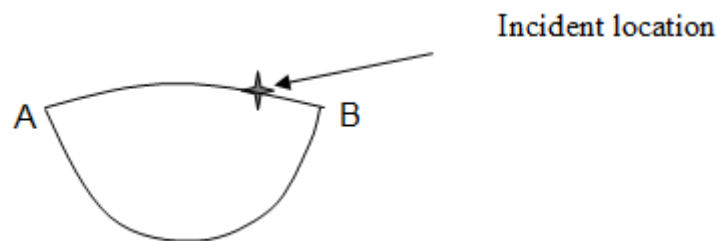
With the availability of the information provided by these systems, commuters can change their trip routes, modes, departure times, route choices or destinations to make trips with greater speed and fewer idle delays.

## **2.2 EFFECTS OF ATIS ON TRAFFIC FLOW**

This section introduces literature that have mainly focused on quantification of the effects of ATIS on traffic flow conditions. The reviewed literature can be categorized into two groups: 1) effects of ATIS on trip pattern: the traveler information provided by ATIS will impact the route choice decision, departure time, travel mode and destination, and 2) effects of ATIS on driving behavior: for example, the ATIS provides drivers with warning information, which results in changes in their second-by-second driving profiles.

### 2.2.1 ATIS on Trip Pattern

*Aldeek et al. (1995)* presented an analytical method for evaluating the impacts of ATIS on reduction of traffic delay caused by accidents. The authors introduced a two link corridor and simulated an incident on the shorter of the two routes. The study was carried out to analyze the implications of having ATIS penetration in a stream of traffic to traverse through a route with an incident. The queuing diagram based on the scenario was used to analytically determine travel time and idling delays. In the first phase of the study, a queuing diagram was used to analytically determine the queuing delay for traveler “without ATIS” and “with ATIS” scenario. In the “with ATIS” scenario, the travelers are diverted to the alternate route until both routes reach equilibrium. Then, the number of vehicles using the route was estimated and the total VMT was derived by multiplying the number of vehicles by the route length. In the second part of the work, MOBILE 5a was used to estimate the emission factors for CO, NO<sub>x</sub> and VOC for different speed ranges. According to the results of a numerical example, emissions of CO and VOC were reduced with higher ATIS market-penetration levels, while emission NO<sub>x</sub> increased for small ATIS market-penetration levels.



**Figure 2. Corridor diagram with incident on shorter route**

*Khattak et al. (1996)* conducted a study to explore changes in travel behavior in the presence of an ATIS that provided qualitative information. Traveler routes, departure times, and

mode selection decisions were investigated through a survey of Bay Area automobile commuters. The effects of various factors such as sources of congestion information (radio traffic reports versus observation), trip characteristics, and route attributes on traveler responses to unexpected congestion were investigated. Respondents were asked to report whether they would change travel decisions to earlier or later if they were alerted of a similar delay situation by a special device that gives accurate information on delays. A stated preference survey was carried out to investigate pre-trip response to future ATIS technologies. A combined revealed preference and stated preference model of traveler response was developed by using a multinomial logit formulation. The results showed that Advance Traveler Information were important determiners of changes in travel decisions in response to unexpected congestion. The results indicate that ATISs overcome behavioral inertia and that individuals were more likely to change their travel patterns in response to prescriptive information.

*Aldeek et al. (1998)* developed an analytical method with a focus on evaluating the effects of ATIS on traveler route-choice behaviors. This work combined a travel behavior model for route choice and a queuing model to evaluate the impact of ATIS under incident conditions. The scenario was tested for a two link network where an incident is simulated in the shorter of the two routes, which is same as the scenario presented in Figure 2.

In this study, a cumulative queuing diagram of the scenario was constructed and a microscopic time slice approach was used to estimate the delay. A traffic assignment model was developed in the study which assumes three different types of traveler:

1. Traveler unequipped with information devices and is not able to observe delay caused by incidents.

2. Traveler unequipped with information devices and is able to observe delay based on queuing conditions
3. Traveler equipped with a radio (less accurate information)
4. Traveler equipped with ATIS (accurate information)

A type 1 traveler, who is completely uninformed, was assigned their usual route. The rest of the travelers were assigned to the routes probabilistically, with those receiving traffic information from radio and ATIS being more likely to divert under incident conditions than the unequipped travelers who are only able to observe traffic condition based on the queuing conditions. The probabilities of diversion were based on traveler's responses to a behavioral survey conducted in the Chicago area (Khattak, 1991). A discrete event simulation model was developed to emulate real-world traveler behaviors under a given incident condition. The simulation was carried out for 21 different scenarios with different percentages of travelers with no knowledge of incident, travelers with ATIS, and travelers with radio. The results of the simulation showed a tendency towards reduced travel times with increased radio and ATIS penetration rates.

*Hu et al. (2009)* presented a network wide traffic assignment based methodology to evaluate the effects of ATIS on congestion reduction. The study was done in a triangular region in North Carolina. A revealed preference survey was carried out in the region, and a behavior model was built based on the data. The study then used a dynamic assignment traffic simulation model called DYNASMART- P to evaluate the scenarios with various ATIS penetration rates as follows:

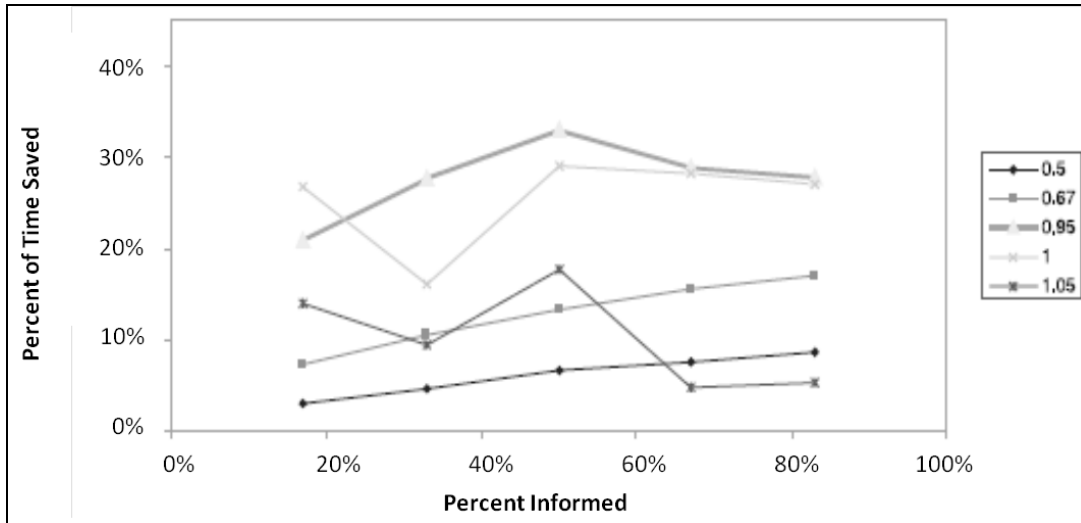
- No work zone case
- No ATIS (0% penetration rate, no path change with work zone)

- Existing ATIS (up to 10% penetration rate)
- Planned ATIS (up to 20% penetration rate)
- Planned ATIS (up to 30% penetration rate)

Simulation results were validated through comparison with field speed data. Based on the simulation results, the benefits of ATIS alternatives were estimated by calculating the travel time savings of the ATIS alternatives in comparison with the no ATIS scenario. The travel time savings were converted into monetary values using average hourly wage to estimate the benefits from each alternative scenario. The capital cost was calculated by multiplying the number of units and the initial investment cost per unit year and thereby the benefit cost ratio was calculated for each alternative. The results of this study show that alternative cases with high ATIS penetration rates, i.e., 20% and 30%, showed high benefit cost ratios of 18 and 33.9, respectively.

*Levinson (2003)* analyzed ATIS systems from a theoretical economic perspective. The model in the study was developed by considering the economics of alternative route choices. The research also conducted a traffic simulation based study to calculate the time saved associated with the use of ATIS for different levels of market share and traffic congestion. There were two classes of drivers in the model: informed and uninformed drivers. First, the study simulated scenarios without incident and examined information levels over a range of congestion levels (volume to capacity ratios of 0.50, 0.67, 0.95, 1.00, and 1.05). Figure 3 show the percent of time saved (uninformed travelers) by congestion level and percent informed. The results show that the amount of time saved with information is greatest at flows around 95% of capacity for the subject route. They also suggest that increasing penetration level will save little travel time for informed drivers, while it can significantly reduce travel time for uninformed drivers. The study also simulates incident scenarios. This showed that the travel time of an informed driver

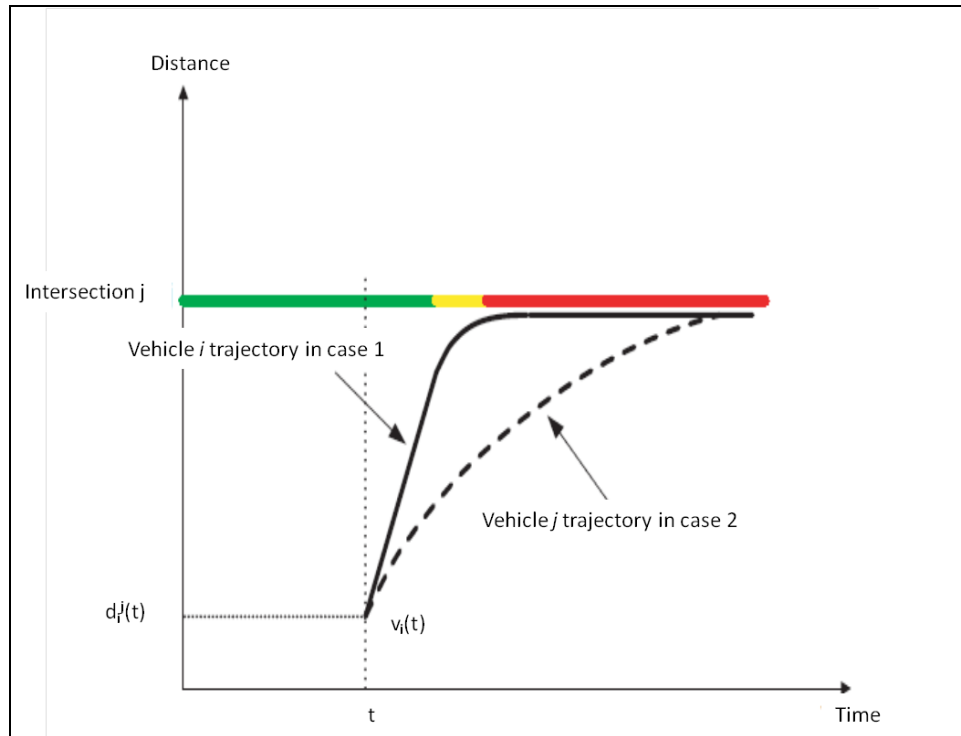
increases with an increase of penetration level since more informed drivers switch to the parallel route. However, uninformed drivers benefit more with an increase in penetration level.



**Figure 3. Percent of time saved (uninformed travelers) by congestion level and percent informed**

### 2.2.2 ATIS on Driving Behavior

*Wu et al. (2010)* evaluated the impact of advanced driving alert systems (ADAS) on traffic energy and emission reductions at signalized intersections. The system utilizes traffic signal status (TSS) information, which can provide a warning to drivers when there is no chance of crossing through an intersection before the signal turns red. Thus, drivers can gradually slow down some distance away from an intersection. This can avoid unnecessary hard braking and reduce fuel consumption and emissions. Figure 4 shows two vehicle trajectories with and without TSS information.



**Figure 4. Vehicle trajectories with and without TSS information (Source: Wu et al., 2010)**

This study focuses on two major types of ADAS: stationary ADAS and in-vehicle ADAS. Stationary ADAS are installed at roadside to provide alerts to all the drivers passing through. In-vehicle ADAS can provide customized alerts to drivers. The study evaluated the benefits of the ADAS systems by both analytical and simulation based approaches. For analytical evaluation, a set of hypothetical vehicle trajectories was created for without ADAS and with ADAS. For simulation evaluation, the study uses PARAMICS to simulate vehicle trajectories. Both the analytical and simulation analysis results indicate that ADAS can reduce fuel consumption and CO<sub>2</sub> emissions and shows that in-vehicle ADAS is more effective.

The simulation and analytical method study the dynamics of driving behavior or speed profile in response to advanced traveler information systems. Limited real-world implementation



of these information systems has made it difficult to observe and study how drivers respond to real-time information.

## **2.3 IMPACTS OF TRAFFIC FLOW CHANGES ON EMISSIONS**

Many studies focus on the relationship between congestion and vehicle emission. Several studies show that traffic congestion levels can influence motor vehicles emissions. Traveling at a steady-state velocity might produce lower emissions compared to a stop-and-go driving pattern related to congestion. However, lower speeds produce less emission when compared to higher speeds. It is important to understand the relationship between congestion and emission to be able to mitigate emission through traffic improvement strategies. The following section introduces studies that focus on congestion indicators for emission estimation and also the studies that examine the impacts of traffic flow changes on on-road emissions.

### ***2.3.1 Congestion Indicators for Emission Estimation***

Efforts have been made by many researchers to understand and quantify congestion. However, very little work has been done on facility wise quantification of congestion, which is essential for classifying emission rates. The formal HCM LOS method requires density or traffic volume and speed which all involve a spatial parameter and hence are difficult to estimate. There is a need to define traffic congestion on a rational basis and use that for measurement of road service levels. Hence it is important to be able to quantify different levels of congestion. The following section discusses literature that deals with congestion indicators for emission estimation.

*Smit et al. (2008)* examined three average speed-based emission models, MOBILE, EMFAC and COPERT, to assess the extent of congestion indicated by the selected driving cycles for these models. For detailed introduction about these three models see Section 4. Since most emission models do not explicitly include congestion indicators directly to emission factors, the authors investigated the driving cycles used in the above mentioned emission models. The study used real driving cycle data that were used in the development of these models for light duty vehicles. The authors point out that although average speeds are used to directly link emission factors in average speed based emission models, they are not sufficient indicators for congestion levels because congestion is road-type specific. In this study, potential congestion indicators were selected from the literature, such as unit idle time, acceleration noise, coefficient of variation of speed, proportion of speed fluctuation, speed reduction congestion index, delay rate, etc. These congestion indicators are briefly introduced in the following paragraph.

Acceleration noise is the standard deviation of instantaneous acceleration ( $a_t$ ):

$$S\sigma_{at} = \sqrt{\frac{\int_0^{T_{run}} (a_t - a)^2 dt}{T_{run}}} \quad (2.1)$$

where  $a$  (m/s<sup>2</sup>) is the average acceleration rate (excluding zero acceleration when stopped), which is zero if final speed equals initial speed, and  $T_{run}$  is the running time (s), which is defined as travel time minus stopped time.  $\sigma_{at}$  is a function of the number, duration and rate of vehicle speed fluctuations (accelerations and decelerations).

The proportion of speed fluctuation is given by

$$p_{\text{acc+dec}} = 100 \frac{(T_{\text{acc}} - T_{\text{dec}})}{T} \quad (2.2)$$

The delay ratio ( $d_{\text{ratio}}$ ) is calculated as the ratio of  $\bar{d}$  to mean unit travel time:

$$\frac{\bar{d}}{\bar{T}} \quad (2.3)$$

A similar congestion indicator, the speed reduction congestion index (SRCI) is an index which is normalized to a scale of 0 to 10. It is based on mean travel speed reduction due to congestion using the mean free-flow travel speed as a reference:

$$\text{SRCI} = \frac{(\bar{v}_{\text{ff}} - \bar{v}_i)}{\bar{v}_{\text{ff}}} \quad (2.4)$$

The average unit idle time is given by:

$$T_{\text{idle}}^* = \frac{T_{\text{idle}}}{d} \quad (2.5)$$

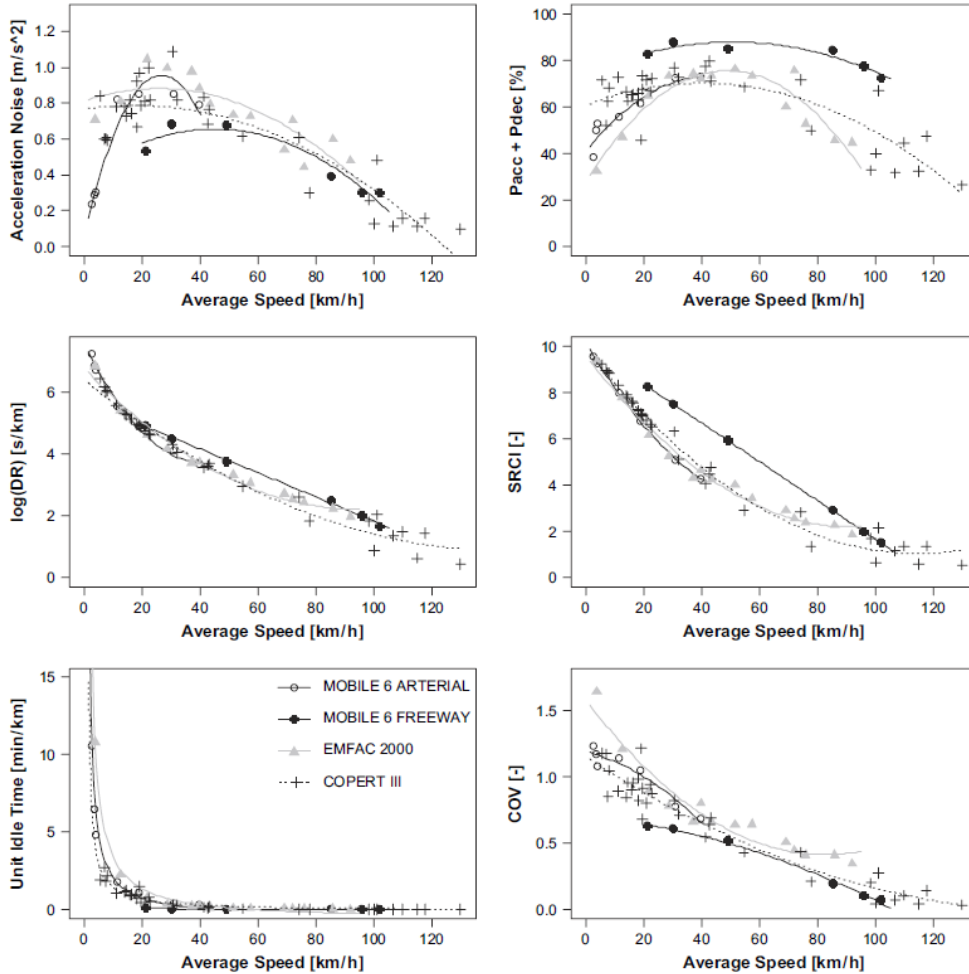
Where,  $T_{\text{idle}}$  is the stopped time in a driving cycle (min) and  $d$  is the delay experienced.

The coefficient of variation is computed as the ratio of the standard deviation of speed to mean of speed and is given by:

$$\text{COV} = \frac{\sigma}{v} \quad (2.6)$$

By computing selected congestion indicators for the driving cycles used to formulate the respective average speed based rates by different emission models (MOBILE 6 ARTERIAL,

MOBILE 6 FREEWAY, EMFAC 200 and COPERT III), the indicators were plotted against average speed for each model as Shown in Figure 5.



**Figure 5. Congestion in three average speed models as predicted with different variables**

Figure 5 shows that acceleration noise, positive kinetic energy and proportion speed fluctuation (Pacc +Pdec) are ambiguous indicators since the respective congestion indices vary nonlinearly. However, Delay Rate (DR) and Speed Reduction Congestion Indices (SRCI) explain congestion better with a monotonic function.

*Greenwood (2003)* developed a modeling framework for predicting highway traffic congestion levels. The approach utilized acceleration noise as a measure of congestion impacts,

which was defined as the standard deviation of the accelerations. Acceleration noise level was estimated and used to determine the impact on fuel consumption and vehicle emissions. This study analyzed 15-minute interval data to estimate the additional fuel consumed and vehicle emissions and compared this to a base case of steady speed travel. Fuel consumption was estimated using the simulation program ACCFUEL, which only shows an increment of fuel consumption for different speed levels and acceleration noise values. For each 15-minute period, vehicle emissions for both congested and un-congested conditions were calculated. The results showed a consistent under-prediction of about 25 percent when compared with on-road test results for a given level of acceleration noise. This under-prediction was largely due to the assumption that the acceleration noise data conformed to a normal distribution.

*Kamble et al. (2008)* developed a driving cycle to represent heterogeneous traffic behavior to estimate vehicular emissions and fuel consumption. Driving cycle was developed using micro-trips extracted from real-world data. This was constructed taking into account important parameters of the time–space profile, namely: percentage acceleration, deceleration, idle, cruise, and average speed. This methodology was illustrated using a case study based on the data collected from Pune city in India. The proposed methodology was compared with existing driving cycles. Although the study describes the purpose of developing the driving cycles as to estimate vehicular emissions and fuel consumption, it was unclear how this was carried out.

The literature reviewed mainly focused on different congestion indicators to demarcate emission levels at different traffic operation conditions. The LOS defined by HCM is also an indicator of traffic operating characteristic, but requires knowledge of space mean speed and traffic volume or density. Hence some of the congestion indicators introduced in the above section can be used to demarcate the different levels of congestion.

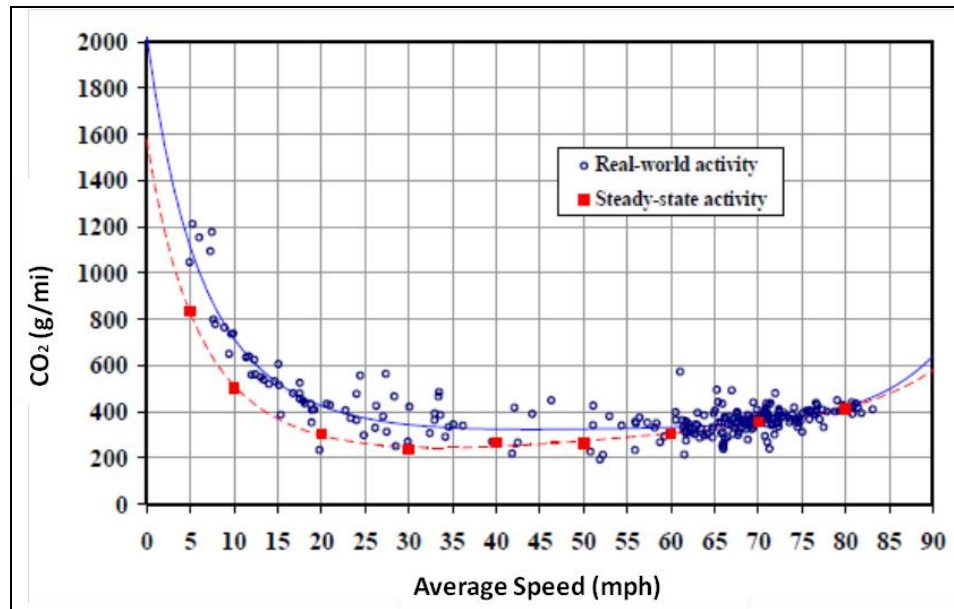
### ***2.3.2 Congestion Level and Emission Rate***

Several studies have focused on how different traffic congestion levels affect emissions. These studies mainly focus on quantifying emissions as a function of average speed. These studies were done using field data or simulated data. Emissions were modeled using emission models like MOVES, MOBILE, CMEM, etc. This section briefly introduces how different researchers have approached measuring emissions using congestion level parameters.

*Bigazzi et al. (2010)* explored the effects of traffic speeds, freeway capacity, travel demand, and alternative efficiency strategies on freeway emissions. Marginal emissions rates were modeled as functions of average travel speed and the Bureau of Public Roads (BPR) model for macroscopic volume-speed relations was used for estimating the average speed at different congestion levels (indicated by V/C ratios). Then, the total emissions at different congestion levels was estimated based on the estimated emission rates (which was determined by the V/C ratios) and travel demand. Vehicle emissions rates were estimated using MOVES 2010 and based on on-road vehicle fleets for freeways in the Portland, Oregon metropolitan region. In this study volume-speed relationships were used to calculate total emissions over a peak period – including emissions from queued or delayed vehicles. Results of this study indicated that at a given speed limit, emissions rates per vehicle-mile do not have a monotonic relationship with the actual speed. When the speed is low (which indicates that the congestion level is high), a slight increase of speed will significantly reduce the emission rate. The gradients have low absolute values at around 30-65 mph, meaning that speed changes over this range have a small effect on marginal emissions. The study also states that capacity expansions that reduce marginal emissions rates by increasing travel speeds are likely to increase total emissions in the long run through induced demand. In summary, capacity-based strategies to mitigate congestion in

homogenous freeway sections can lead to higher overall emissions in the long-run, though this outcome is less probable for sections with heavier initial congestion (LOS F).

*Barth et al. (2008)* focused on and analyzed traffic congestion and its impact on CO<sub>2</sub> emissions. To estimate energy and emissions impacts from congestion, the study examined velocity patterns of vehicles operating at different levels of congestion and input a set of real word freeway vehicle activity data into the Comprehensive Modal Emissions Model (CMEM). This set of vehicle activity data was collected by probe vehicles and Performance Measurement Systems (PeMS). The velocity trajectories in the database were split into snippets with consistent LOS. At the end, there were 241 remaining snippets that were used to estimate the corresponding CO<sub>2</sub> emissions. The estimated CO<sub>2</sub> emissions were plotted as a function of average running speed (please see Figure 6). A curve was then used to fit the data points, shown as a solid line in the figure and expressed mathematically in Equation (2.7).



**Figure 6. CO<sub>2</sub> emissions (g/mi) as a function of average trip speed (mph)**

$$\ln(y) = b_0 + b_1x + b_2x^2 + b_3x^3 + b_4x^4 \quad (2.7)$$

Where,  $y$  is CO<sub>2</sub> emission in g/mi;  $x$  is average trip speed in mph.

This equation can be used to estimate CO<sub>2</sub> emissions given an average running speed. **Figure 6** also illustrates CO<sub>2</sub> emissions for perfectly constant, steady-state speeds, which can be considered as the lower bound of CO<sub>2</sub> emissions for any vehicle traveling at that particular speed. This figure indicates that small changes in traffic speed can have significant effects on CO<sub>2</sub> emission rates under heavy congestion conditions (average speed less than 20 mph), and there is a relatively flat area at a speed range of 30-60 mph. This paper also examined several emission reduction strategies based on traffic operation improvements. Congestion mitigation strategies can increase average traffic speeds from slower and heavily-congested speeds. Speed management techniques focus on reducing excessively high speeds to safe speeds. Traffic flow smoothing techniques aim at eliminating stop-and-go effects and reducing the number and severity of accelerations and decelerations.

*Barth et al. (1999)* explained in detail the conventional model's speed correction factor methodology, followed by a description of the facility-congestion cycles developed for MOBILE6. Further details on the NCHRP modal emissions model are then provided. This is followed by a description of the analysis and the corresponding results.

Conventional emissions models use baseline emission factors (in grams per mile) that are modified by several correction factors, such as temperature, fuel type, and speed. SCF equations have been established by measuring emissions factors for a large number of vehicles by using over 12 different driving cycles with average speeds in the range of 4 to 104 km/h (2.5 to 65 mph). Regression analysis was then applied to determine various coefficients associated with the different average speed values.

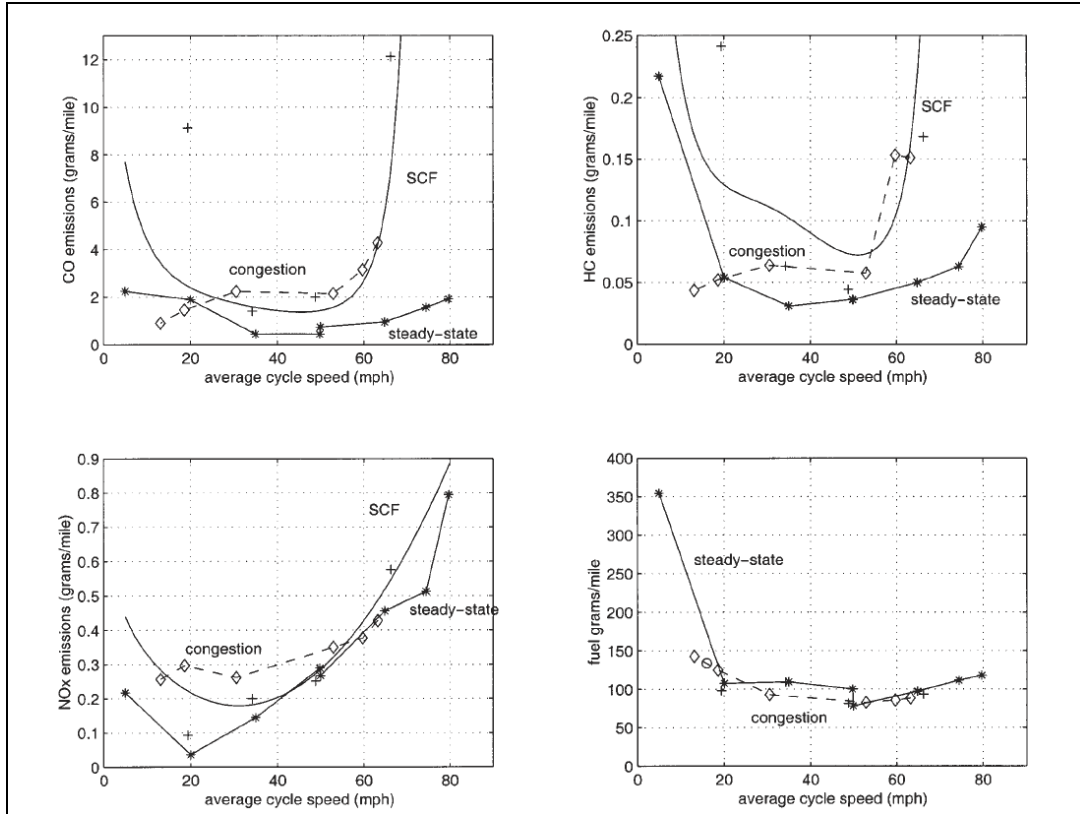


Several facility-specific driving cycles were created based on matching speed-acceleration frequency distributions for a wide range of roadway types and congestion levels. These cycles were developed on the basis of a large amount of “chase car” and instrumented vehicle data and the congestion level was recorded as different level-of-service (LOS) values based on traffic densities observed from the chase car. Six driving cycles were developed for freeway driving. These cycles range from high-speed driving (LOS A, where vehicles have little or no interaction with other vehicles) to driving in near gridlock conditions (LOS F).

For the comprehensive emission model many in-use vehicles were recruited and tested by a detailed dynamometer testing procedure, which resulted in 315 valid vehicle tests. The focus of the study was on the stoichiometric cruise section or “hill” that was designed to measure emissions associated with constant-speed cruises and included a total of nine steady-state cruise events at different speeds: 8, 56, 80, 104, 128, 120, 80, and 32 km/h, (5, 35, 50, 65, 80, 75, 50, and 20 mph). At four of the constant-speed plateaus, there were “speed fluctuation” events, consisting of mild accelerations and decelerations [approximately  $\pm 1.6$  kph ( $\pm 1$  mph)]. For all cycles in the NCHRP dynamometer testing protocol, second-by-second engine-out and tailpipe emissions (CO, HC, NO<sub>x</sub>, and CO<sub>2</sub>) data were collected. These emissions data were then used to establish a modal emissions model. The model uses a physical, power-demand modal modeling approach based on a parameterized analytical representation of emission production.

Comparisons were done between these three methodologies and the emissions associated with the steady state events in the cruise hill were called steady-state emissions. The emission associated with the mild speed fluctuations at the cruise plateaus are called fluctuation emissions, which are emissions associated with a speed correction factor methodology (SCF) and the emission of the average speed of the driving cycle for each LOS is described at the congestion

emissions. Figure 7 illustrates a plot where steady-state emissions are represented by stars, fluctuation emissions by pluses, congestion emissions by diamonds, and SCF emissions by a solid line.



**Figure 7. Emissions and fuel rates (average grams per mile) versus speed**

The steady-state emissions are in all cases the lowest emissions that are produced given a particular speed. Emissions associated with slight speed fluctuations (while maintaining near constant speed) are in most cases significantly higher than the steady-state emissions, particularly at higher speeds. In many cases, the congestion-based emissions are higher at better LOS flow conditions (in this case, freeway LOS). This is again caused by brief enrichment events that occur with mild accelerations at high speeds.

*Papson & Kuo (2012)* examined vehicle emissions at congested and uncongested signalized intersections. Emissions were analyzed under three traffic intersection scenarios: 1) a

baseline intersection with light volume and low congestion (LOS B), 2) a project scenario with heavy volume and high congestion (LOS E), 3) a mitigated project scenario with expanded intersection geometry and low congestion (LOS B). The study calculated emissions using a time-in mode (TIM) methodology that combined emissions factors for each activity mode (acceleration, deceleration, cruise and idle) based on the percentage of vehicle travel time in that mode. The results demonstrated the contribution of each mode to total emissions.

The results show that the largest sources of emissions were cruising and acceleration. As congestion level worsen from LOS E to LOS B, total emissions and idle time increase considerably. After the intersection geometry is expanded, emissions of NO<sub>x</sub> and PM decreases by 15% and 18% separately, while travel delay drops by 40%. Since idling has the lowest emissions factor, the emission reductions were smaller than expected.

## **2.4 EMISSION MODELS**

Overall, the current emission models can be categorized into three groups (Yu, 2009): 1) travel-based models, which combine the calculated emission factors in certain regions with a region's travel data to generate emissions inventories for emissions estimations; 2) fuel-based models, utilize fuel-use data, which are available from tax records in a traffic database; 3) modal and instantaneous emission models that predict second-by second tailpipe emissions as a function of the vehicle's operating mode.

### ***2.4.1. Travel-based Models***

Travel-based models are usually used for national/regional/county level emission conformity analysis. There are two major travel-based models, MOBILE and MOVES, which were both developed by United States Environmental Protection Agency (EPA).

#### **1) MOBILE**

MOBILE 1, which was developed by U.S. EPA in 1978, was the first model for highway vehicle emission factor. Since then, the MOBILE series has been updated with new and improved data in many areas based on the growing understanding of vehicle emissions, including periodic updates to reflect improved data, changes in vehicle, engine, and emission control system technologies, changes in applicable regulations and emission standards and test procedures, and improved understanding of in-use emission levels and the factors that influence them (MOBILE 6.2 user guide). Based on average link speeds, by inputting fuel characteristics, distribution of VMT, I/M, etc., MOBILE can estimate current and future pollution, such as hydrocarbon (HC), oxides of nitrogen (NO<sub>x</sub>), and carbon monoxide (CO) from highway vehicles, such as passenger cars, motorcycles, and light and heavy-duty trucks. Over 30 years, MOBILE has been widely used at a national and local level, but has been limited to project-level analysis. The latest and the last version of MOBILE was MOBILE 6.2, which was released on 2004. Subsequently, the MOBILE series was replaced by MOVES in 2010 as the official EPA emission model.

#### **2) MOVES**

The latest version of Motor Vehicle Emission Simulator (MOVES2010b), which was released in June 2012 by the U.S. EPA, has been widely used in emission estimation since then and replaced the EPA's previous emission model MOBILE 6.2. MOVES changed the basis for mobile source emission estimation from average speed to model activity (*Song, 2008*). The model is based on analyses of millions of emission test results and considerable advances in the agency's understanding of vehicle emissions. Compared to previous tools, MOVES incorporates the latest emissions data, more sophisticated calculation algorithms, increased user flexibility, new software design, and significant new capabilities. MOVES can estimate national, county and project level emission. When analysis is done at a county level based on a MOVES database or local data, a researcher needs to prepare input data for Meteorology, I/M, Fuel Formulation, Fuel Supply, Age Distribution, etc. (*MOVES manual; Kall, 2013*).

### 3) IVE

The International Vehicle Emissions (IVE) Model was developed in a joint effort by the University of California at Riverside, College of Engineering – Center for Environmental Research and Technology (CE-CERT), Global Sustainable Systems Research (GSSR) and the International Sustainable Systems Research Center (ISSRC) and was funded by the U.S. EPA. By inputting vehicle fleet and vehicle activity, the model makes estimates of local air pollutants (criteria pollutants), greenhouse gas emissions, and toxic pollutants. The prime purpose is to estimate emissions from motor vehicles in developing countries. It is compatible with EMFAC and has been used to measure data in Mexico and Sao Paulo (*IVE Model Users Manual*).

### 4) EMFAC

EMFAC is a model developed by the California Air Resources Board (CARB) that has a similar structure and functions as MOBILE, but is used to enhance compliance with stricter emission standards in California. The latest version, EMFAC 2011, was released on September 2011.

#### ***2.4.2 Fuel-based Model***

Fuel-based models are typically used for regional/county level emission conformity analysis. As an example, COPERT 4 is a software tool used worldwide to calculate air pollutant and greenhouse gas emissions from road transport. The development of COPERT was coordinated by the European Environment Agency (EEA). It has a similar structure as MOBILE, but utilizes regional fuel sales data as a traffic data alternative.

#### ***2.4.3 Modal and Instantaneous Emission Models***

Modal and instantaneous emission models are usefully for project-level analysis. Project level analysis allows the user to model emission effects from a group of specific roadway links and/or a single off-network common area. The definition of a roadway link is a section of any road where a vehicle is moving for more than three seconds. An off-network common area may include project boundaries where a vehicle starts, has extended idling, and where evaporative emissions are produced.

##### **1). CMEM**

The Comprehensive Modal Emission Model (CMEM), which was sponsored by the National Cooperative Highway Research Program (NCHRP), was developed at the University of California, Riverside in August 1995. It utilizes a physical, power-demand modeling approach.

In this approach, the model breaks down the emissions process into components that reflect the physical operations and emission characteristics of a vehicle. Each of the components is then modeled based on various parameters characteristic of the selected component. The parameters are specific to different vehicle categories and based on specifications associated to that vehicle type (e.g., vehicle mass, number of gears, number of cylinders, engine displacement, etc.). CMEM is comprehensive in the sense that it is able to predict emissions for a wide variety of LDVs in various states of condition (e.g., properly functioning, deteriorated, malfunctioning).

## 2) MOVES

The EPA's current official model for estimating air pollution emissions from on-road mobile sources is called Motor Vehicle Emission Simulator (MOVES). MOVES can be used for estimating running exhaust, starting exhaust, brake wear, tire wear and a series of other permeation, vent and leak emissions. MOVES can be used for all states, except California, where the air quality standards are different and the model mandated is called the Comprehensive Modal Emissions Model (CMEM).

MOVES utilizes the same emission rates and correction factors at a county and national scale, while MOVES can also be used for project-level analysis. When analysis is done at a project level, other than the parameters mentioned above, a researcher need to prepare link level files, including links, link source type, off network, either link drive schedule or Operation Mode ID distribution as input. Some researchers obtain second-by-second speed profiles from traffic simulation models like VISSIM (*Ghafghazi, 2013*), TRANSIMS, PARAMICS (*Zhao, 2013*), NGSIM (*Shabihkhani, 2013*), etc., as a link to drive schedule input. Some researchers obtain real

world travel data, including second-by-second speed profile, local time and location from GPS, calculate the VSP, then convert this into an Operation Mode ID distribution (Liu, 2013) as input.



## **CHAPTER 3: STUDY DESIGN**

The objective of this study is to assess the effects of ATIS on air quality during incident conditions. This requires the estimation of vehicle emission levels at different congestion levels on both freeway and arterial road stretches. This chapter lists and describes the methodologies involved in data collection and data analysis for this study.

The first section introduces the study methodology, including study procedure, identified congestion index, and emission modeling procedure. The second section presents the data collection process.

### **3.1 METHODOLOGY**

The objective of this study is to assess the effects of ATIS on air quality under incident conditions. To achieve this objective, a study procedure was developed as shown in .

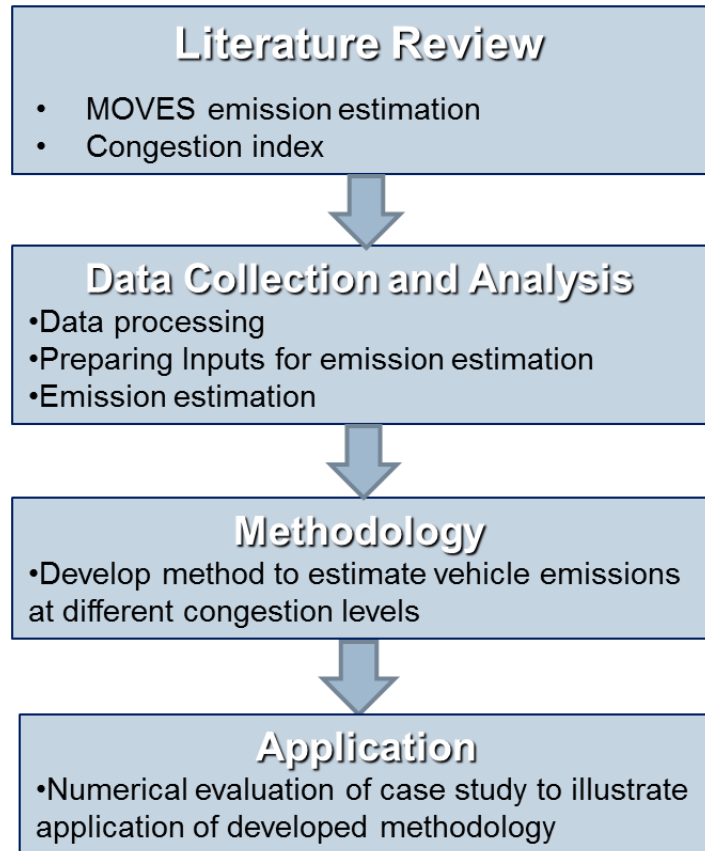
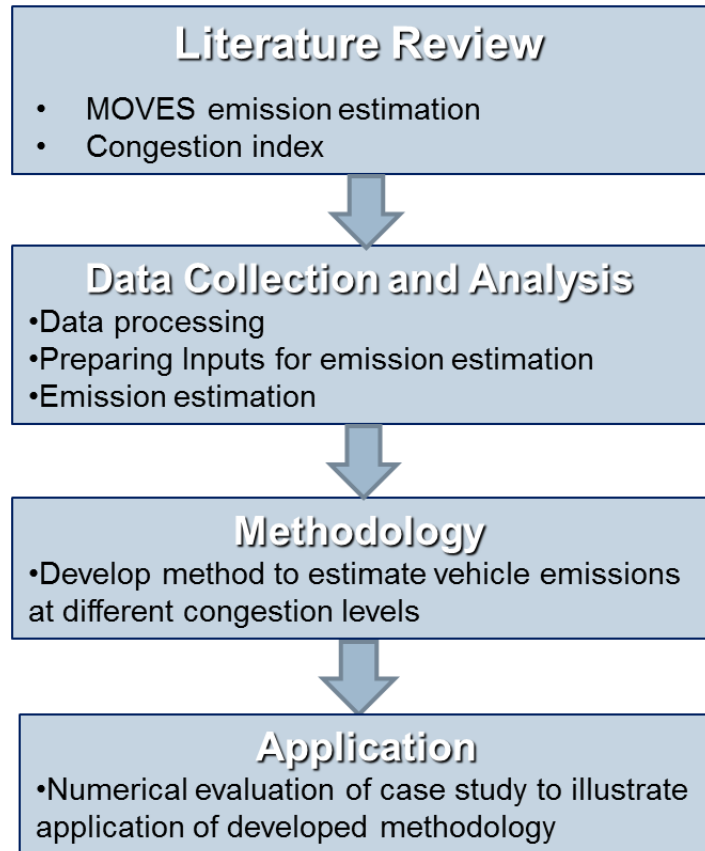


Figure 8. In this procedure, the first step identifies a sufficient congestion indicator. This was done thru a literature review that identified the most feasible congestion indicator. The Speed Reduction Congestion Index (SRCI) was identified as the congestion indicator for this study. Speed and free flow speed of the section under consideration are the key data for calculating this index.

Estimating the emission levels for different congestion levels was the next step. For this The Motor Vehicle Emission Simulator (MOVES) was used, which is a emission modeling system developed by the EPA to determine air quality .



**Figure 8. Study Procedure**

conformity studies, was used to estimate the emission levels at different levels of roadway traffic congestion. MOVES can be used to estimate emission levels separately on freeway and arterial sections. MOVES quantifies emission as a function of a vehicle's modal activities and hence the vehicle operating mode ID distribution is the most vital input to running MOVES. Preparation for operating mode ID requires the distribution of vehicle specific power, mandated by rules specified by the EPA (*U.S. EPA, 2010*). The data vital to calculating the VSP distribution includes second-by-second speed data on the corridor stretches under consideration. The data required for the study includes free flow speed levels of the corridor section under consideration and second-by-second vehicle speed profiles.

The following sections describe important methods/equations available from literature that have been used in this study. The first section briefly describes the congestion index identified from the literature. The subsequent section describes the emission modeling procedure used in this study.

### ***3.1.1 Identified Congestion Index***

The Speed Reduction Congestion Index (**SRCI**) was identified as an indicator of traffic congestion for congestion related studies. SRCI is given by

$$\text{SRCI} = \frac{(\bar{v}_{\text{ff}} - \bar{v}_i)}{\bar{v}_{\text{ff}}} \quad (3.1)$$

Where,

$\bar{v}_{\text{ff}}$  is the free flow speed of the respective roadway facility and

$\bar{v}_i$  is the mean speed.

The free flow speed was estimated using the following method recommended by the Florida Department of Transportation. The linear equation was

$$\bar{v}_{\text{ff}} = \bar{v}_{\text{sl}} + 5 \quad (3.2)$$

Where,  $\bar{v}_{\text{sl}}$  is the posted speed limit in miles per hour and  $\bar{v}_{\text{ff}}$  is the free flow speed in miles per hour. Hence the free flow speeds used for freeways and arterials were 5 mph greater than the posted speed limits in the study (65 mph and 35 mph respectively).

### 3.1.2 Emission Modeling Procedure

The MOVES emission model was used in this study, which is the emission modeling system developed by EPA for air quality conformity studies for regulations set by state and federal agencies. The previous version of MOVES was MOBILE 6.2, which estimated emissions based on average speeds and hence did not have an emphasis on vehicle operating modes.

MOVES uses vehicle specific power (VSP), which is the instantaneous power demand of the vehicle divided by its mass as the primary variable in modeling emissions (*Jimenez, 1998*). This metric includes numerous physical factors significant to vehicle fuel consumption and emissions: vehicle speed, acceleration, road grade, and road load parameters such as aerodynamic drag and rolling resistance. This study used the equation provided by Jiménez (1998) to determine vehicle instantaneous VSP values:

$$\text{VSP} = v [1.1\alpha + 9.81 * g (\%) + 0.132] + 0.00030 (v + v_w)^2 v \quad (1)$$

Where,

$v$  is the vehicle speed (m/sec),

$\alpha$  is the acceleration (m/sec<sup>2</sup>), and

$g$  (%) is the grade of road section, which is assumed to be 0 in this study since all the field data were collected from a relatively flat terrain.

$v_w$  is the headwind into the vehicle, which is assumed to be 0 according to Song and Yu (2011).

MOVES quantifies emission as a function of vehicle operating mode, and hence, preparation of an operating mode distribution is an essential input to running MOVES at the project level. One of the biggest challenges in using MOVES is preparation of an operation mode ID distribution for different traffic and roadway conditions. This requires significant amount of effort in terms of data collection and processing.

MOVES stores emission rates as average emissions within a discrete source and operating mode bins. Table 1 is a list of the emission process and associated operating mode parameters. This study assumes running exhaust as a contributor to the emission process involved due to congestion.

**Table 1. Operating mode parameters by emission process**

| <b>Emission Process</b>                | <b>Operating Mode Parameter</b>       |
|--|---------------------------------------|
| Running Exhaust, Break Wear, Tire Wear | Average Speed, Vehicle Specific Power |
| Start Exhaust, Hot Soak                | Soak Time                             |
| Diurnal                                | Tank Pressure                         |
| Running Loss                           | Time Since Start                      |

Table 2 lists the operating mode id definitions listed by the EPA for a running exhaust process.

**Table 2. Operating mode ID definition**

| <b>Operating Mode ID Code</b> | <b>Operating Mode Description</b>  |
|-------------------------------|--|
| 0                             | Braking; $a_t \leq -2.0$ OR, ( $a_t \leq -1.0$ AND $a_{t-1} \leq -1.0$ AND $a_{t-2} \leq -1.0$ ); $a_t$ is the acceleration rate at second $t$ . |
| 1                             | Idling; $-1.0 \leq \text{Speed} < 1.0$   |
| 11                            | Low Speed Coasting; $\text{VSP} < 0$ ; $1 \leq \text{Speed} < 25$  |
| 12                            | Cruise/Acceleration; $0 \leq \text{VSP} < 3$ ; $1 \leq \text{Speed} < 25$  |
| 13                            | Cruise/Acceleration; $3 \leq \text{VSP} < 6$ ; $1 \leq \text{Speed} < 25$  |
| 14                            | Cruise/Acceleration; $6 \leq \text{VSP} < 9$ ; $1 \leq \text{Speed} < 25$  |
| 15                            | Cruise/Acceleration; $9 \leq \text{VSP} < 12$ ; $1 \leq \text{Speed} < 25$   |
| 16                            | Cruise/Acceleration; $12 \leq \text{VSP}$ ; $1 \leq \text{Speed} < 25$   |
| 21                            | Moderate Speed Coasting; $\text{VSP} < 0$ ; $25 \leq \text{Speed} < 50$  |
| 22                            | Cruise/Acceleration; $0 \leq \text{VSP} < 3$ ; $25 \leq \text{Speed} < 50$   |
| 23                            | Cruise/Acceleration; $3 \leq \text{VSP} < 6$ ; $25 \leq \text{Speed} < 50$   |
| 24                            | Cruise/Acceleration; $6 \leq \text{VSP} < 9$ ; $25 \leq \text{Speed} < 50$   |
| 25                            | Cruise/Acceleration; $9 \leq \text{VSP} < 12$ ; $25 \leq \text{Speed} < 50$  |
| 26                            | Cruise/Acceleration; $12 \leq \text{VSP}$ ; $25 \leq \text{Speed} < 50$  |
| 27                            | Cruise/Acceleration; $12 \leq \text{VSP} < 18$ ; $25 \leq \text{Speed} < 50$   |
| 28                            | Cruise/Acceleration; $18 \leq \text{VSP} < 24$ ; $25 \leq \text{Speed} < 50$   |
| 29                            | Cruise/Acceleration; $24 \leq \text{VSP} < 30$ ; $25 \leq \text{Speed} < 50$   |
| 30                            | Cruise/Acceleration; $30 \leq \text{VSP}$ ; $25 \leq \text{Speed} < 50$  |
| 33                            | Cruise/Acceleration; $\text{VSP} < 6$ ; $50 \leq \text{Speed}$   |
| 35                            | Cruise/Acceleration; $6 \leq \text{VSP} < 12$ ; $50 \leq \text{Speed}$   |
| 36                            | Cruise/Acceleration; $12 \leq \text{VSP}$ ; $50 \leq \text{Speed}$   |
| 37                            | Cruise/Acceleration; $12 \leq \text{VSP} < 18$ ; $50 \leq \text{Speed}$  |
| 38                            | Cruise/Acceleration; $18 \leq \text{VSP} < 24$ ; $50 \leq \text{Speed}$  |
| 39                            | Cruise/Acceleration; $24 \leq \text{VSP} < 30$ ; $50 \leq \text{Speed}$  |
| 40                            | Cruise/Acceleration; $30 \leq \text{VSP}$ ; $50 \leq \text{Speed}$   |



### 3.2 DATA COLLECTION AND TOOLS USED

This study used over 50 hours of GPS probe vehicle data collected from road stretches in the city of Houston, Texas. GPS tracking recorders were used to record travel records of probe vehicles. Figure 9 is a photo of the GPS device used for the study.



**Figure 9. GPS tracking recorder**

Fifty hours of GPS probe vehicle data is a huge database as a log for each second is provided by the GPS unit that includes speed, latitude, longitude, time stamp, data stamp, etc. Processing and analyzing such a huge volume of data requires a platform with greater processing capacity than a spreadsheet. Thus, MATLAB®, which is a high-level language for numerical computation and visualization, was used in this study to analyze data, develop algorithms, and to create models and applications. After collecting the data along each of the corridors, entries with missing or unrealistic values were removed. The data was extracted by using MATLAB programs and was separated based on the road types. Study corridors were identified to separate the GPS data points by using a Geographical Information Systems (GIS) platform. ArcGIS is a GIS platform that helps combine a geographical database and maps for the mapping and spatial analysis that was used for this analysis.

## **CHAPTER 4: RESULTS**

This chapter discusses the key results from this study, which include: 1) data processing results, 2) the developed framework for evaluation of impacts of ATIS on air quality, and 3) the results of the case study.

### **4.1 DATA PROCESSING**

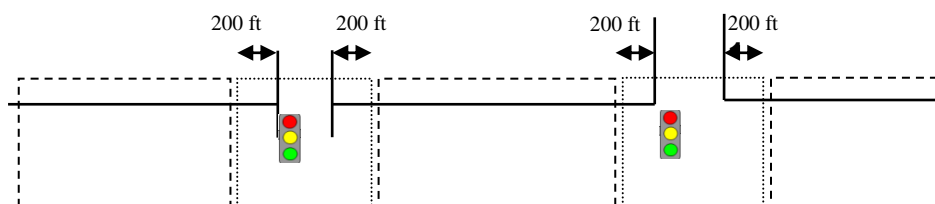
The main purpose of processing the data was to estimate emission levels for each congestion level. To do this, the speed profile data had to be categorized based on road type and congestion level. Subsequently, emissions levels were estimated for each speed level. The following section describes the steps to categorize the speed data based on road type and congestion levels.

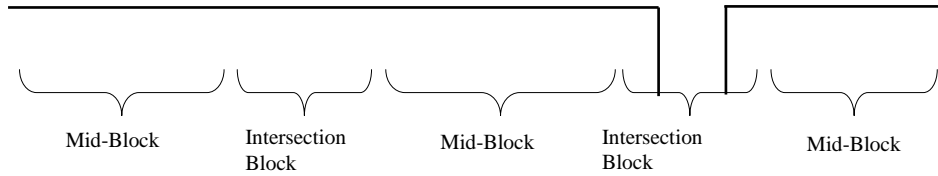
#### ***4.1.1 Categorizing Speed Data Based on Road Type and Congestion Level***

Over 50 hours of second-by-second data was collected and separated based on road classification using ArcGIS spatial function tools. The speed limit of the study's freeway and arterial sections were 65 mph and 35 mph, respectively. For arterial sections, due to high variability in the speed profiles of vehicles traveling through mid-block sections and signalized intersection zones (zones in which vehicles decelerate, stop, and accelerate), a separate set of operating mode distributions was prepared for each section. As such, the arterial data were further broken down into mid-block sections and intersections, respectively. Mid-block sections began 200 feet from intersection stop lines, and the remaining section was classified as an intersection zone. For intersection zones, the vehicle speed profiles that stopped at the intersections were archived to analyze the amount of emissions generated at signalized intersections per stop. The following paragraphs introduce the data processing procedure for processing the GPS speed profile data.

**Freeway:** Freeway speed profiles were broken down into short speed-profile segments called speed snippets using a “change-point detection method” based on a standard normal deviation. A snippet is a short speed profile segment used to define a short-term and relative stable driving pattern during a long driving cycle. Some previous studies have also called it a “micro-cycle” (Yu et al., 2008). When a significant jump in the speed profile is detected, the speed profile is broken off at that point and saved in the array of speed snippets. A break point was detected if the difference between the mean of the first five speed data points and the sixth speed data point was greater than the standard deviation of the first five points. The resulting speed snippets were binned into different speed categories, where each category had a 10-mph range. In total, there were eight categories, ranging from 0-10 mph to 70-80 mph. Different speed ranges represent different congestion levels, since the freeway flow speed is 65 mph. Note that, consistent with Barth and Boriboonsomsin (2008), snippets shorter than 10 seconds were discarded from the data set in order to exclude short-term vehicle speed disturbances due to unexpected events (such as a hard break caused by vehicles cutting in front of the probe vehicle) rather than traffic congestion. This step was done in order to build separate operating mode distributions for different speed bins or congestion levels.

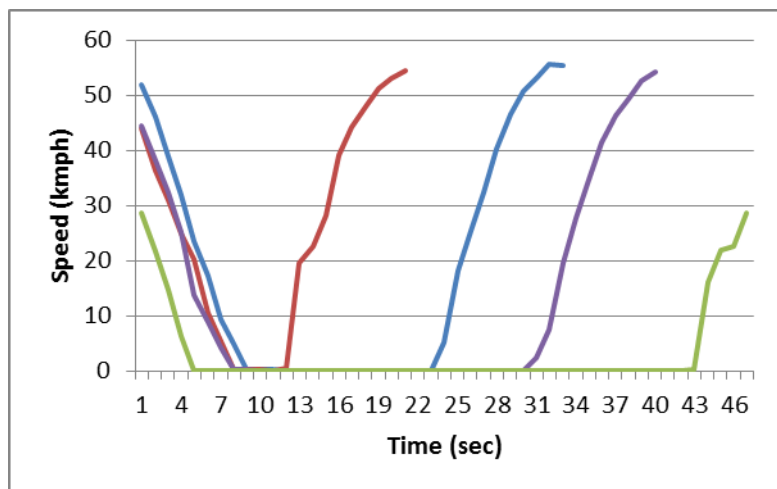
**Arterial mid-block:** The mid-block section was assumed as not affected by stop and go traffic characteristic at intersections. Figure 10 shows a sketch of an arterial road type categorized as mid-block and signalized intersection zone. Similar to the procedure for processing freeway data, speed snippets were generated based on the data collected from mid-block sections, which were then binned into speed categories ranging from 20–30 mph to 40–50 mph. There were only a limited sample of speed snippets in other speed-range categories and, hence, these were not considered in this study.





**Figure 10. Arterial road categorized into mid-block and intersection block**

**Arterial intersection block:** The intersection block (200 ft upstream and downstream from the intersection) was assumed to capture vehicle deceleration, stop, and acceleration activities required by the signal. Speed snippets were derived based only on the speed profile of the trips by the probe vehicle during which stops were made at the intersection. A total of 88 intersection-stop speed profiles were extracted for this study period, which included right turns, left turns, and through movements. Figure 11 illustrates four example speed profiles captured from the intersection data. Different vehicles had different stop times, although their acceleration and deceleration profiles were quite similar. In this study, the intersection emission estimation was based primarily on the probability that vehicles must stop at intersections, and assumes no effect from traffic congestion for “need-to-stop” cases. For cases in which vehicles can pass through intersections without stopping, same operating mode distributions as for the mid-block sections were used.



**Figure 11. Second-by-second speed profile of vehicle stop and go at signalized intersections**

The speed profiles were separated based on the road type and speed level it fell within. The next step towards determining the relationship between congestion levels and emission levels was to estimate the emissions for each congestion level using MOVES. Of the three levels in MOVES, national level, county level and project level, our corridor-level study falls within the project level. The section below describes the steps to perform emission modelling using MOVES software at a project level.

#### ***4.1.2 MOVES Input Preparation for Emission Modeling***

The project level in MOVES allows for emission modeling of freeway links, arterial links, bus stops and parking lots. Running MOVES at a project level requires links to specific inputs, which include:

- Regional data such as county, temperature, humidity, date, time of day, etc.
- Vehicle Age Distribution
- Fuel Supply Fuel Supply
- Fuel Formulation
- Link Source Type
- Link Drive Schedules
- Operating Mode Distribution
- Off-Network (only relevant for some projects like bus stops or parking lot emission modeling)

This study used national level source distribution values for link source distribution and the age distribution of vehicles. The default values from MOVES 2010b were used as input for Fuel Supply and Formulation. Developing operating mode ID distribution was the most advanced input required

to run MOVES at a project level. Operating mode ID distribution was derived by estimating the operating mode ID values for the vehicle speed for each second.

Table 2 in Chapter 3 illustrates the operating mode ID definitions listed by EPA. These rules are limited to running exhaust processes. One can refer to *EPA (2010)* for further definitions of all vehicle emission processes. The next section describes the development of operating mode ID distributions for this study using EPA-mandated rules for different congestion levels.



#### ***4.1.3 Developing Operating mode ID Distributions for Different Congestion Levels***

The first step to prepare the operating mode ID distribution for different congestion levels for freeway and arterial was categorizing the speed snippets that are then used to prepare the operating mode ID distribution into respective categories.

**Table 3** illustrates the categories for the speed snippets and how they were classified in this study. The speed profiles were broken down into speed snippets based on SRCI levels and road types.



**Table 3. Classification of speed snippets**

|                                 |  |   |   |
|---------------------------------|--|---|---|
| <b>Operating Mode ID Values</b> | <b>Freeway Section</b><br>(speed limit 65 mph)   | <b>Arterial Section</b><br>(speed limit 35 mph)   |   |
|                                 |  | <u>Mid-Block</u>  | <u>Intersection Block</u><br>(for veh. with stops at intersections) |
|                                 | <b>Congestion Levels</b>   | <b>Congestion Levels</b>  | <b>Stop and Go at Intersection</b>                                  |
|                                 | Different SRCI Levels<br> | Different SRCI Levels<br> | Single Value  |

The operating mode ID values for each road type, which were freeway, arterial midblock and intersection block, were calculated using VSP values corresponding to each data point in the speed snippet sets using rules defined by the EPA (refer to

Table 2). VSP values were estimated using Equation 4.1 for each second in the speed profile snippet set that were prepared for different road types and speed levels.

This study used the equation provided by Jiménez (1998) to determine a vehicle's instantaneous VSP values:

$$\text{VSP} = v [1.1\alpha + 9.81 * g (\%) + 0.132] + 0.00030 (v + v_w)^2 v \quad (4.2)$$

Where,

$v$  is the vehicle speed (m/sec),

$\alpha$  is the acceleration (m/sec<sup>2</sup>), and

$g$  (%) is the grade of road section, which is assumed to be 0 in this study since all the field data were collected from a relatively flat terrain.

$v_w$  is the headwind into the vehicle, which is assumed to be 0 according to Song and Yu (2011).

The modeling scenario was done for a typical weekday of March, 2013 in Harris County, Texas, which was also where the speed profiles were collected. The pollutants of interest in the study were CO<sub>2</sub>, CO, NO<sub>x</sub> and VOC. Only running exhaust emission was considered in the study since the objective of the study concentrates on evaluating emission levels at the link level or corridor level.

The second batch of inputs prepared were the project level input files, which were as follows:

- Link Characteristic: used scenario specific values listed above
- Link Sources: used national level source distribution values
- Meteorology: used county level values specific to the study

- Age Distribution of Vehicles: used national level age distribution values
- Fuel Supply and Formulation: used default values from MOVES 2010b
- Operating Mode ID distribution: scenario specific operating mode ID distribution generated. Details briefly discussed in the following paragraph.

The calculated operating mode ID values under each category were presented as operation ID distributions. Each category of congestion level presented in

**Table 4** reflects traffic conditions varying from 0-10 mph to 60-70 mph for freeways and 20-30 mph to 30-40mph for arterial mid-block sections. The operating Mode ID distribution for vehicles that make stops at the signalized intersection is also provided in

**Table 4.** The operating mode ID distribution data from this table can be used as input for running MOVES to estimate emission levels for different types of roads at different traffic speed levels.

This study used SRCI as defined in Equation 3.1 in Chapter 3 as the congestion Index. Hence,

Table 4 is re-illustrated as

**Table 5** to list the Operation ID distributions for different SRCI levels for freeways and arterials respectively.

**Table 4. Operating mode ID distributions for freeway and arterials under different speed ranges**

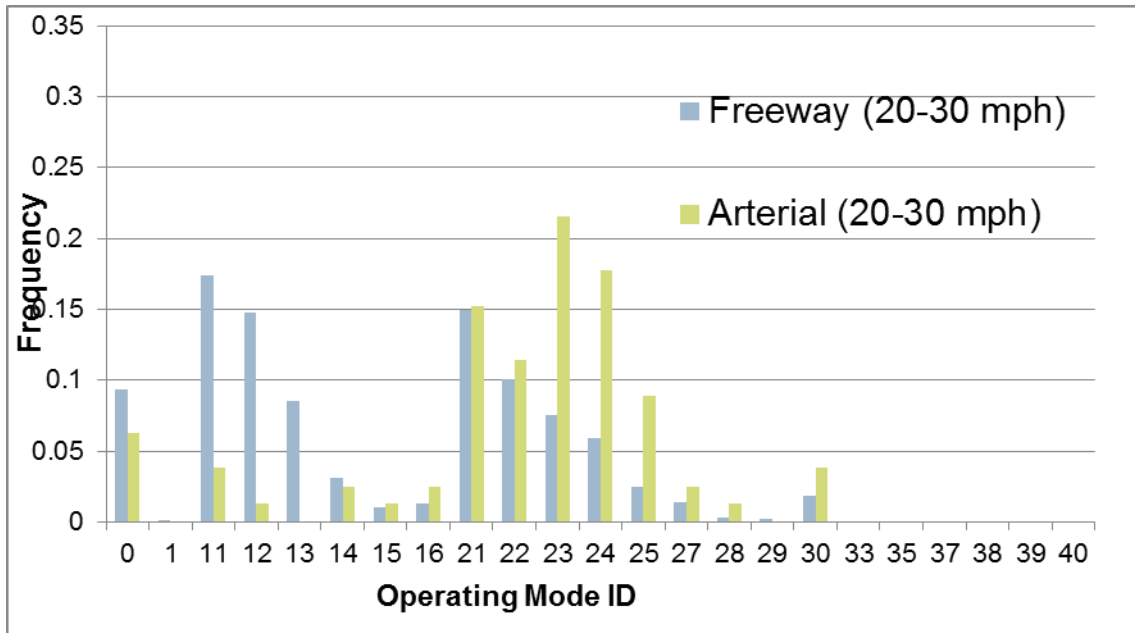
| Operating Mode ID | Freeway Section<br>(speed limit 65mph) |                 |                 |                 |                 |                 |                 | Arterial Section<br>(speed limit 35 mph) |                 |                 |   |
|-------------------|--|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|--|-----------------|-----------------|---|
|                   |  |                 |                 |                 |                 |                 |                 | Mid Block                                |                 |                 | Intersection block<br>(for veh. with stops) |
|                   | Speed 0-10 mph                         | Speed 10-20 mph | Speed 20-30 mph | Speed 30-40 mph | Speed 40-50 mph | Speed 50-60 mph | Speed 60-70 mph | Speed 0-20 mph                           | Speed 20-30 mph | Speed 30-40 mph | Stop and go Speed profile                   |
| 0                 | 0.100                                  | 0.138           | 0.093           | 0.105           | 0.078           | 0.049           | 0.024           | 0.119                                    | 0.063           | 0.027           | 0.192                                       |
| 1                 | 0.178                                  | 0.012           | 0.001           | 0.000           | 0.000           | 0.000           | 0.000           | 0.061                                    | 0.000           | 0.000           | 0.516                                       |
| 11                | 0.251                                  | 0.288           | 0.174           | 0.016           | 0.003           | 0.000           | 0.000           | 0.154                                    | 0.038           | 0.000           | 0.014                                       |
| 12                | 0.394                                  | 0.332           | 0.148           | 0.013           | 0.004           | 0.000           | 0.000           | 0.310                                    | 0.013           | 0.000           | 0.026                                       |
| 13                | 0.039                                  | 0.110           | 0.085           | 0.008           | 0.000           | 0.000           | 0.000           | 0.279                                    | 0.000           | 0.000           | 0.023                                       |
| 14                | 0.013                                  | 0.041           | 0.031           | 0.003           | 0.000           | 0.000           | 0.000           | 0.034                                    | 0.025           | 0.000           | 0.028                                       |
| 15                | 0.006                                  | 0.013           | 0.010           | 0.002           | 0.000           | 0.000           | 0.000           | 0.011                                    | 0.013           | 0.000           | 0.026                                       |
| 16                | 0.017                                  | 0.030           | 0.013           | 0.000           | 0.000           | 0.000           | 0.000           | 0.013                                    | 0.025           | 0.000           | 0.081                                       |
| 21                | 0.000                                  | 0.019           | 0.149           | 0.222           | 0.167           | 0.009           | 0.000           | 0.014                                    | 0.152           | 0.179           | 0.008                                       |
| 22                | 0.000                                  | 0.004           | 0.101           | 0.151           | 0.111           | 0.006           | 0.000           | 0.002                                    | 0.114           | 0.143           | 0.004                                       |
| 23                | 0.000                                  | 0.001           | 0.075           | 0.153           | 0.148           | 0.008           | 0.000           | 0.000                                    | 0.215           | 0.332           | 0.005                                       |
| 24                | 0.000                                  | 0.002           | 0.059           | 0.138           | 0.106           | 0.008           | 0.000           | 0.002                                    | 0.177           | 0.180           | 0.007                                       |
| 25                | 0.000                                  | 0.001           | 0.025           | 0.074           | 0.078           | 0.004           | 0.000           | 0.001                                    | 0.089           | 0.081           | 0.014                                       |
| 27                | 0.000                                  | 0.001           | 0.014           | 0.058           | 0.095           | 0.003           | 0.000           | 0.001                                    | 0.025           | 0.050           | 0.034                                       |
| 28                | 0.000                                  | 0.000           | 0.003           | 0.012           | 0.025           | 0.001           | 0.000           | 0.000                                    | 0.013           | 0.002           | 0.016                                       |
| 29                | 0.000                                  | 0.000           | 0.002           | 0.004           | 0.007           | 0.000           | 0.000           | 0.000                                    | 0.000           | 0.002           | 0.004                                       |
| 30                | 0.001                                  | 0.009           | 0.018           | 0.021           | 0.014           | 0.001           | 0.000           | 0.000                                    | 0.038           | 0.003           | 0.001                                       |
| 33                | 0.000                                  | 0.000           | 0.000           | 0.008           | 0.058           | 0.330           | 0.238           | 0.000                                    | 0.000           | 0.000           | 0.000                                       |
| 35                | 0.000                                  | 0.000           | 0.000           | 0.003           | 0.046           | 0.315           | 0.337           | 0.000                                    | 0.000           | 0.000           | 0.000                                       |
| 37                | 0.000                                  | 0.000           | 0.000           | 0.003           | 0.023           | 0.162           | 0.242           | 0.000                                    | 0.000           | 0.000           | 0.000                                       |
| 38                | 0.000                                  | 0.000           | 0.000           | 0.000           | 0.016           | 0.051           | 0.098           | 0.000                                    | 0.000           | 0.000           | 0.000                                       |
| 39                | 0.000                                  | 0.000           | 0.000           | 0.000           | 0.003           | 0.013           | 0.024           | 0.000                                    | 0.000           | 0.000           | 0.000                                       |
| 40                | 0.001                                  | 0.000           | 0.000           | 0.006           | 0.016           | 0.038           | 0.035           | 0.000                                    | 0.000           | 0.000           | 0.000                                       |



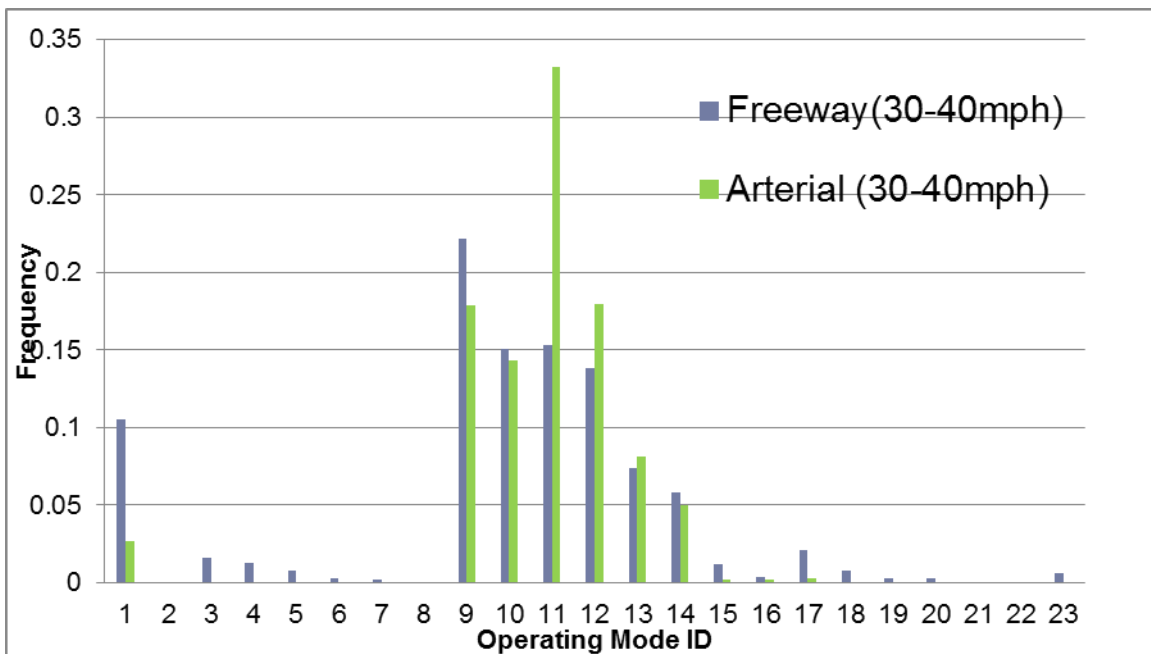
Graphs were plotted to compare the operating mode ID distributions of freeway and arterial road sections for the same speed ranges. Figure 12 and Figure 13 show a comparison of operating mode ID distributions for a speed range of 20-30 mph and 30-40 mph, respectively. There was a significant difference between the operating mode ID distributions of freeway and arterial road sections even within the same speed range. These results indicate that speed itself is not directly related to the operating mode ID distributions and roadway emission levels. In fact, as indicated in Smith (2008), roadway congestion levels have significant effects on emission levels. Therefore, the operating mode ID distributions were classified based on the congestion indicator, SRCI, as identified by Smith (2008) (see the definition in Equation 3.1 in Chapter 3). Hence,

**Table 4** is re-illustrated as

**Table 5** to list the Operation ID distributions for different SRCI levels for freeways and arterials, respectively.



**Figure 12. Comparison of Operating Mode ID distributions for a speed range of 20-30 mph for freeway and arterial road sections**



**Figure 13. Comparison of Operating Mode ID distributions for speed range 30-40 mph for freeway and arterial road sections**

**30-40 mph for freeway and arterial road sections**

**Table 5. Operating mode ID distributions for freeway and arterials under different SRCI**

| Operating Mode ID | Freeway Section<br>(speed limit 65mph) |                 |                 |                 |                 |                 |               | Arterial Section<br>(speed limit 35 mph) |                 |               |   |
|-------------------|--|-----------------|-----------------|-----------------|-----------------|-----------------|---------------|--|-----------------|---------------|---|
|                   |  |                 |                 |                 |                 |                 |               | Mid Block                                |                 |               | Intersection block<br>(for veh. with stops) |
|                   | SRCI<br>01-.85                         | SRCI<br>.85-.72 | SRCI<br>.72-.57 | SRCI<br>.57-.42 | SRCI<br>.42-.28 | SRCI<br>.28-.14 | SRCI<br>.14-0 | SRCI<br>01-.50                           | SRCI<br>.50-.25 | SRCI<br>.25-0 | Stop and go Speed profile                   |
| 0                 | 0.100                                  | 0.138           | 0.093           | 0.105           | 0.078           | 0.049           | 0.024         | 0.119                                    | 0.063           | 0.027         | 0.192                                       |
| 1                 | 0.178                                  | 0.012           | 0.001           | 0.000           | 0.000           | 0.000           | 0.000         | 0.061                                    | 0.000           | 0.000         | 0.516                                       |
| 11                | 0.251                                  | 0.288           | 0.174           | 0.016           | 0.003           | 0.000           | 0.000         | 0.154                                    | 0.038           | 0.000         | 0.014                                       |
| 12                | 0.394                                  | 0.332           | 0.148           | 0.013           | 0.004           | 0.000           | 0.000         | 0.310                                    | 0.013           | 0.000         | 0.026                                       |
| 13                | 0.039                                  | 0.110           | 0.085           | 0.008           | 0.000           | 0.000           | 0.000         | 0.279                                    | 0.000           | 0.000         | 0.023                                       |
| 14                | 0.013                                  | 0.041           | 0.031           | 0.003           | 0.000           | 0.000           | 0.000         | 0.034                                    | 0.025           | 0.000         | 0.028                                       |
| 15                | 0.006                                  | 0.013           | 0.010           | 0.002           | 0.000           | 0.000           | 0.000         | 0.011                                    | 0.013           | 0.000         | 0.026                                       |
| 16                | 0.017                                  | 0.030           | 0.013           | 0.000           | 0.000           | 0.000           | 0.000         | 0.013                                    | 0.025           | 0.000         | 0.081                                       |
| 21                | 0.000                                  | 0.019           | 0.149           | 0.222           | 0.167           | 0.009           | 0.000         | 0.014                                    | 0.152           | 0.179         | 0.008                                       |
| 22                | 0.000                                  | 0.004           | 0.101           | 0.151           | 0.111           | 0.006           | 0.000         | 0.002                                    | 0.114           | 0.143         | 0.004                                       |
| 23                | 0.000                                  | 0.001           | 0.075           | 0.153           | 0.148           | 0.008           | 0.000         | 0.000                                    | 0.215           | 0.332         | 0.005                                       |
| 24                | 0.000                                  | 0.002           | 0.059           | 0.138           | 0.106           | 0.008           | 0.000         | 0.002                                    | 0.177           | 0.180         | 0.007                                       |
| 25                | 0.000                                  | 0.001           | 0.025           | 0.074           | 0.078           | 0.004           | 0.000         | 0.001                                    | 0.089           | 0.081         | 0.014                                       |
| 27                | 0.000                                  | 0.001           | 0.014           | 0.058           | 0.095           | 0.003           | 0.000         | 0.001                                    | 0.025           | 0.050         | 0.034                                       |
| 28                | 0.000                                  | 0.000           | 0.003           | 0.012           | 0.025           | 0.001           | 0.000         | 0.007                                    | 0.013           | 0.002         | 0.016                                       |
| 29                | 0.000                                  | 0.000           | 0.002           | 0.004           | 0.007           | 0.000           | 0.000         | 0.000                                    | 0.000           | 0.002         | 0.004                                       |
| 30                | 0.001                                  | 0.009           | 0.018           | 0.021           | 0.014           | 0.001           | 0.000         | 0.000                                    | 0.038           | 0.003         | 0.001                                       |
| 33                | 0.000                                  | 0.000           | 0.000           | 0.008           | 0.058           | 0.330           | 0.238         | 0.000                                    | 0.000           | 0.000         | 0.000                                       |
| 35                | 0.000                                  | 0.000           | 0.000           | 0.003           | 0.046           | 0.315           | 0.337         | 0.000                                    | 0.000           | 0.000         | 0.000                                       |
| 37                | 0.000                                  | 0.000           | 0.000           | 0.003           | 0.023           | 0.162           | 0.242         | 0.000                                    | 0.000           | 0.000         | 0.000                                       |
| 38                | 0.000                                  | 0.000           | 0.000           | 0.000           | 0.016           | 0.051           | 0.098         | 0.000                                    | 0.000           | 0.000         | 0.000                                       |
| 39                | 0.000                                  | 0.000           | 0.000           | 0.000           | 0.003           | 0.013           | 0.024         | 0.000                                    | 0.000           | 0.000         | 0.000                                       |
| 40                | 0.001                                  | 0.000           | 0.000           | 0.006           | 0.016           | 0.038           | 0.035         | 0.000                                    | 0.000           | 0.000         | 0.000                                       |

The results developed in this study can be generalized and applied to any freeway or arterial if the SRCI value is known. For example, to estimate the impacts of traffic operating conditions on emission levels of CO<sub>2</sub>, for different road types, SRCI values can be used to obtain the corresponding operational ID distributions from



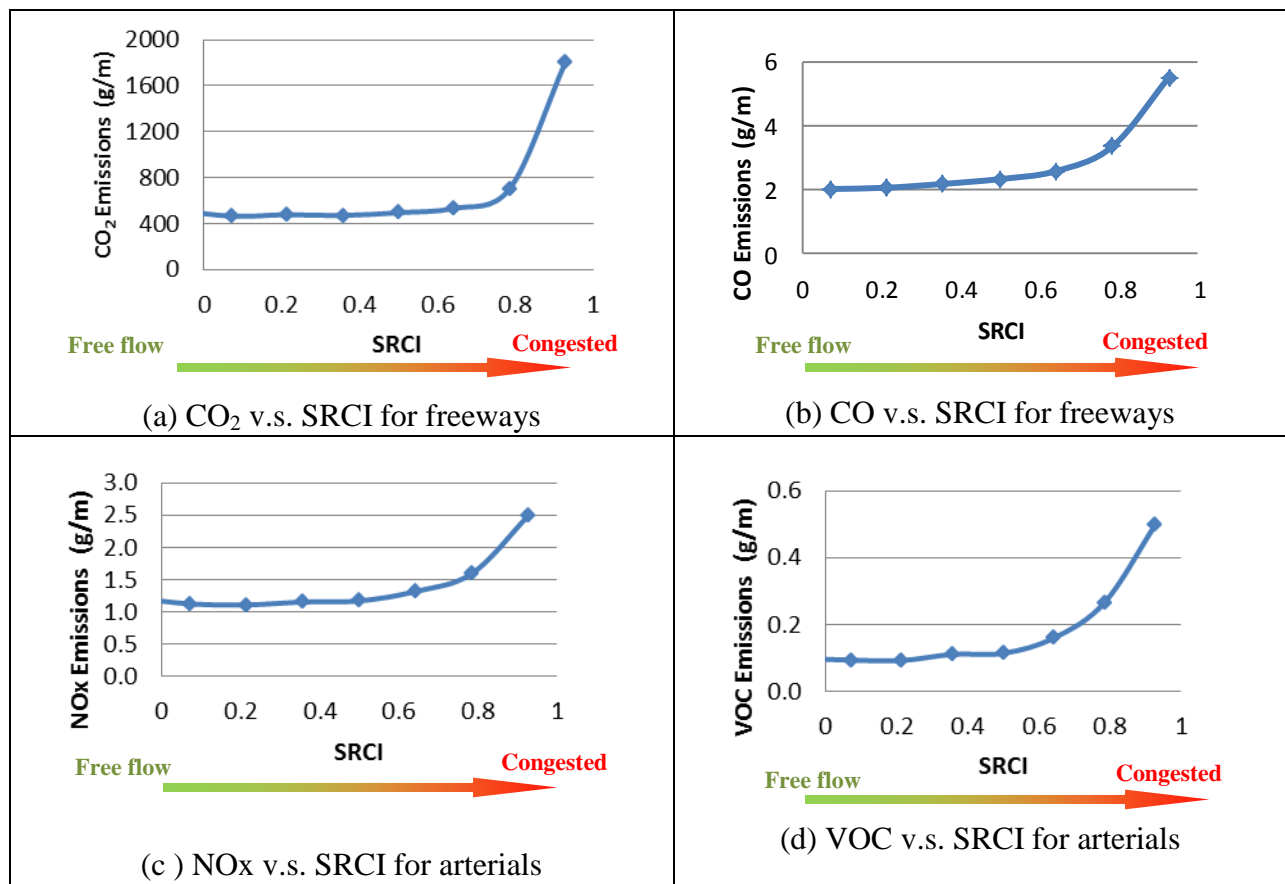
**Table 5.** These distributions can be used as inputs to run MOVES to estimate emission levels for different scenarios. Moreover, the operating mode ID distributions of stop and go profiles can be used to estimate emission levels at an intersection. The next section shows results from running MOVES under different congestion levels for freeways, arterial mid sections and intersection blocks for the four different pollutants considered in this study: CO<sub>2</sub>, CO, NO<sub>x</sub>, VOC.

#### ***4.1.4 Developing Emission Factors for Different Congestion Levels***

The emission factors for different pollutants at different congestion levels can be estimated using the exercise described in the previous section on emission modeling and operating mode ID distributions provided in

**Table 5.** The emission factors estimated using this procedure for four different pollutants ( $\text{CO}_2$ , CO,  $\text{NO}_x$ , and VOC) were plotted against the SRCI values for freeways and arterials, respectively. Figure 14 and Figure 15 shows the emission factors versus SRCI level for freeway and arterial sections respectively. Figure 16 shows the comparison between the emission rates for arterial and freeway for each pollutant considered in this study.

Table 6 lists the emission factors for these pollutants for the respective SRCI values. Researchers and practitioners can use extrapolation techniques to obtain the emission factors for other SRCI values.



**Figure 14. Emission factors for different SRCI values for different pollutants on freeways**





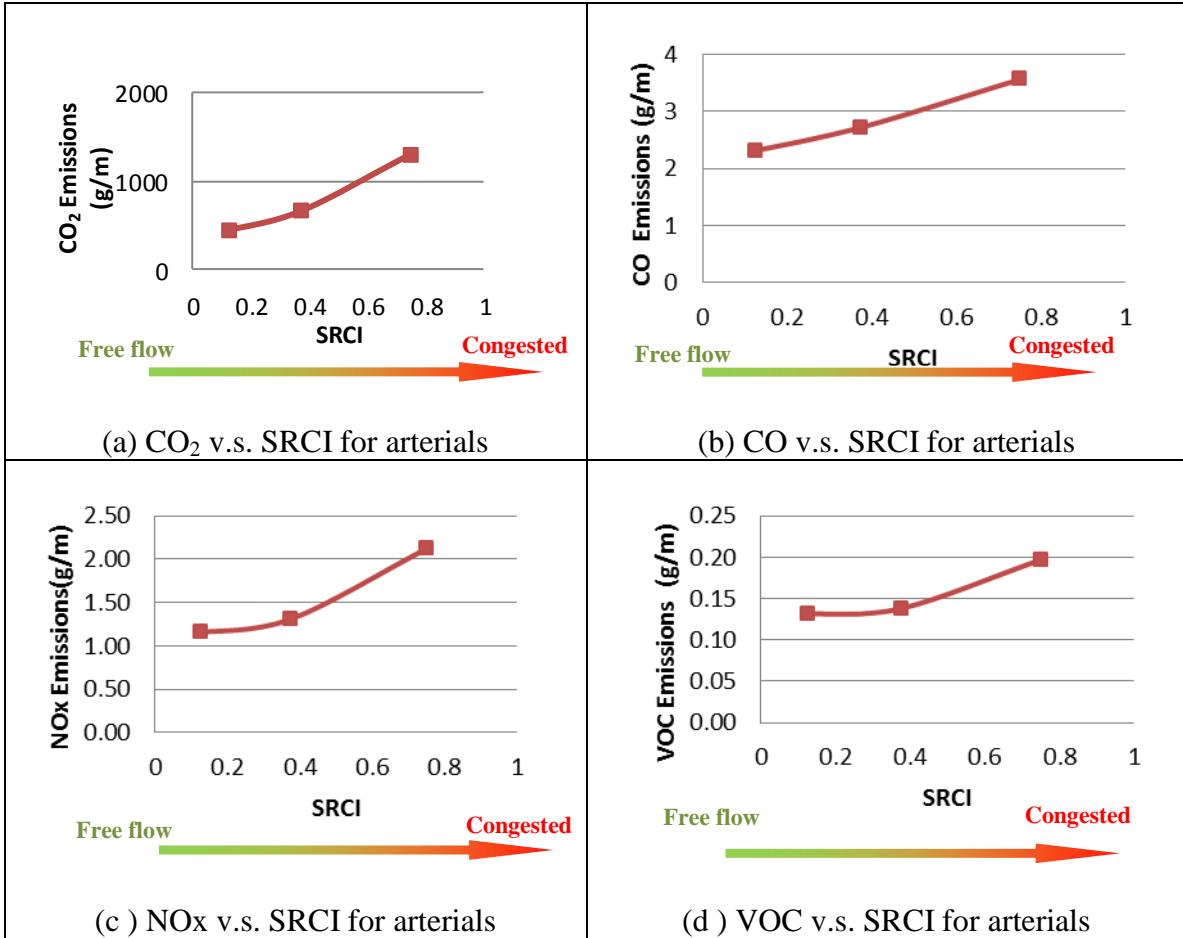


Figure 15. Emission factors for different SRCI values for different pollutants on arterials

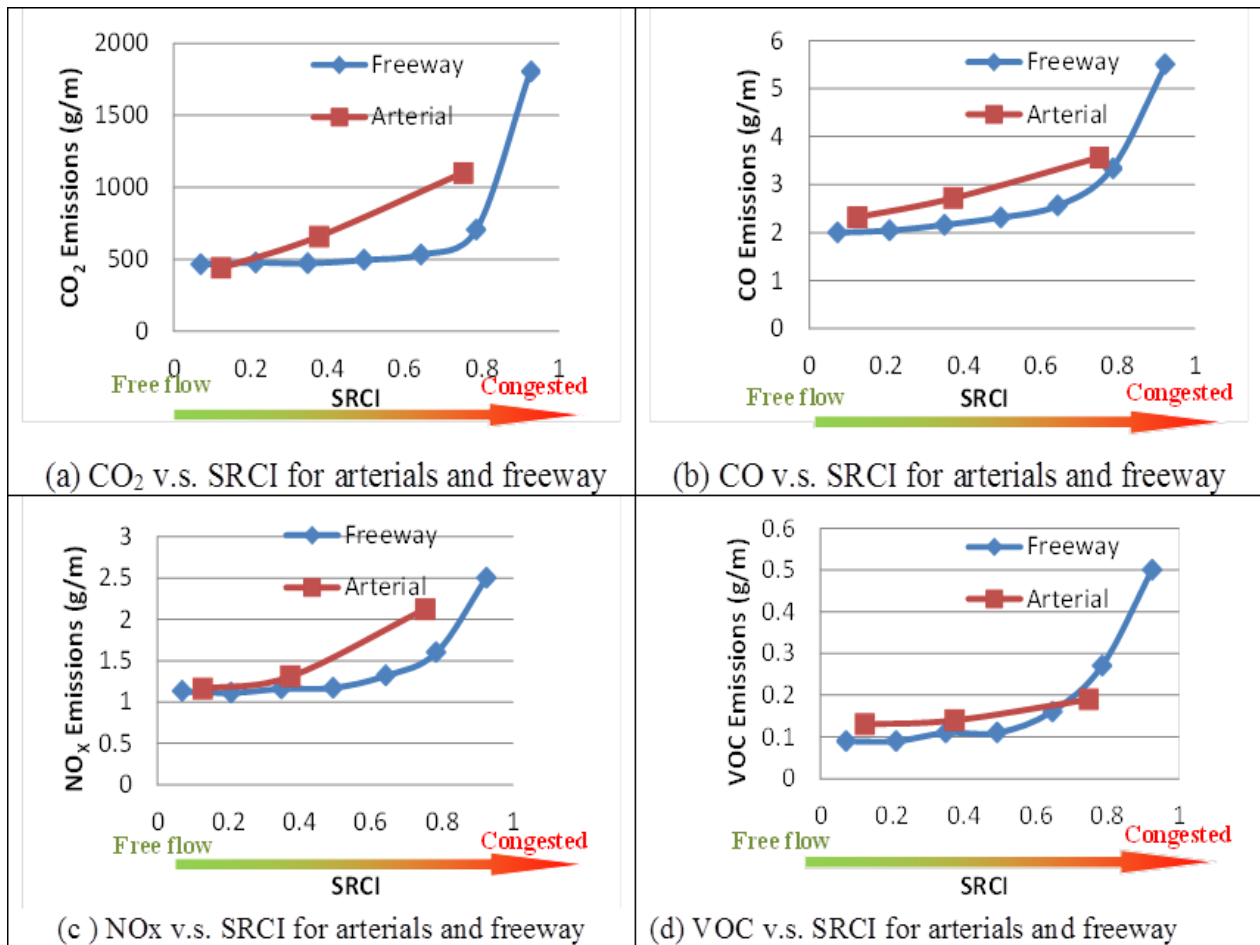


Figure 16. Emission factors for different SRCI values for different pollutants

Table 6. Emission factors for pollutants at different SRCI ranges for Freeway and Arterial

| SRCI values     | CO <sub>2</sub> | CO   | NO <sub>x</sub> | VOC  |
|-----------------|-----------------|------|-----------------|------|
| <b>Freeway</b>  |                 |      |                 |      |
| 01 -.85         | 1804.33         | 5.50 | 2.50            | 0.50 |
| .85-.72         | 705.07          | 3.33 | 1.60            | 0.27 |
| .72-.57         | 533.04          | 2.56 | 1.32            | 0.16 |
| .57-.42         | 495.63          | 2.31 | 1.17            | 0.11 |
| .42-.28         | 471.62          | 2.16 | 1.16            | 0.11 |
| .28-.14         | 477.33          | 2.04 | 1.11            | 0.09 |
| .14- 0          | 465.22          | 2.00 | 1.13            | 0.09 |
| <b>Arterial</b> |                 |      |                 |      |
| 01-.50          | 1100.43         | 3.56 | 2.12            | 0.19 |
| .50-.25         | 657.97          | 2.72 | 1.31            | 0.14 |
| .25-00          | 441.82          | 2.32 | 1.16            | 0.13 |

These Figures and Table facilitate the understanding of the relationship between congestion levels and emission factors for different pollutants. The next section briefly enumerates a framework to carry out ATIS related air quality impacts studies.

## **4.2 DEVELOPED FRAMEWORK FOR EVALUATION OF IMPACTS OF ATIS ON AIR QUALITY**

Based on the study results, the framework for evaluation of impacts of ATIS on air quality can be developed. The following section presents the framework that was developed in seven steps.

**Step 1:** Predict changes in travel pattern, including changes in route, mode, departure time or changes in destination.

**Step 2:** Estimate the resulting change in traffic volume for each route, which will directly impact the congestion levels for each route.

**Step 3:** Estimate the Speed Reduction Congestion Index (SRCI)

The change in speed can be estimated using the Bureau of Public Roads (BPR) model for macroscopic volume-speed relations given by Equation (4.2).

$$v = \frac{v_o}{1 + \alpha \left( \frac{V}{C} \right)^\beta} \quad (4.2)$$

Where,

$v$  is mean speed,

$v_o$  is free flow speed,

$V$  is link volume per unit time,

$C$  is practical capacity of the link per unit time (defined as 80% of actual capacity HCM 2010),

$\beta$  is 10,

$\alpha$  is .20 for unrestricted facilities (e.g. freeway) and .05 for restricted facilities (e.g., arterial).

Free flow speeds and practical capacities for the facilities can be determined using guidelines from Dowling et al. (1997) and HCM 2010. Scenarios for both before and after ATIS implementation were estimated using the BPR equations. Then, the before and after mean speeds are converted to the respective congestion indicator value, SRCI, using the following equation

$$SRCI = \frac{(\bar{v}_{ff} - \bar{v}_i)}{\bar{v}_{ff}} \quad (4.3)$$

Where  $\bar{v}_{ff}$  the free flow is speed and  $\bar{v}_i$  is the mean speed of the respective road type under consideration.

**Step 4:** Prepare operating mode ID distributions for the estimated congestion levels.



**Table 5** lists the operating mode ID distributions for different ranges of SRCI values, which can be used as input in MOVES to estimate the emission factors before and after the implementation of ATIS. For arterial stretches with signalized intersections, the column from

**Table 5** listing operating mode ID distributions for an intersection block can be used as inputs to run MOVES.

**Step 5:** Estimate emission factors for different congestion levels.

To run MOVES at project level, the following project specific fields can be used as inputs:

- Regional data such as county, temperature, humidity, date, time of day, etc.
- Vehicle age distribution
- Fuel Supply Fuel Supply
- Fuel Formulation
- Link Source Type
- Link Drive Schedules
- **Operating Mode Distribution** (The results from Step 4)
- Off-Network (only relevant for some projects such as for bus stops or parking lot emission modeling)

National level distribution values for link source distribution and age distribution of vehicles can be used. The default values from MOVES 2010b can be used as input for fuel supply and formulation.

**Step 6:** Estimate and compare total emission for each scenario.

The total emission for each scenario (before and after cases) can be calculated by multiplying the total volume by the emission factor and total vehicle miles traveled. Then the change in emissions that are a result of employing ATIS can be estimated by the following equation:



$$\Delta E = \sum_{i=1}^n [(E_i^b * VMT_i^b) - (E_i^a * VMT_i^a)] \quad (4.4)$$

Where,

$E_i^b$  is the emission factor for route i, before implementing ATIS (zero diversion)

$E_i^a$  is the emission factor for route i, after implementing ATIS (equilibrium state)

$VMT_i^b$  is the vehicle miles traveled on route i, before implementing ATIS

$VMT_i^a$  is the vehicle miles traveled on route i, after implementing ATIS

n is number of routes that will be affected by ATIS

$\Delta E$  is the change in emissions

The following section provides details of a case study developed to evaluate the effects of ATIS on an incident management scenario for vehicular emissions.

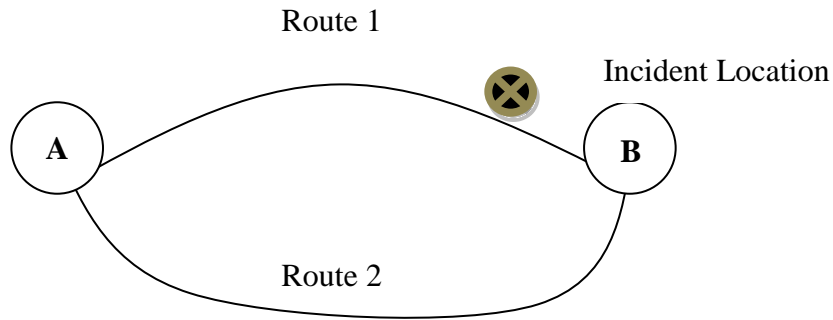
### 4.3 CASE STUDY

A case study was developed to evaluate the impact of ATIS on emissions and was conducted for an accident scenario to demonstrate the usefulness of the proposed framework. The three pollutants of interest in the case study were CO, NO<sub>x</sub>, and VOC.

#### 4.3.1 Case Study, Assumptions and Design

A real world incident management scenario was designed and analyzed to illustrate the use of the framework developed in the study. The design and assumptions for the case study were developed based on work from Hu et al. (2009), Al-deek et al. (1995) and Levinson (2003). In this case study, a base network was used as a two-route corridor that has two routes to get to from point A to point B as shown in Figure 17. Route 1 is a freeway with free flow travel time,  $T_1$  and capacity  $C_1$ . Route 2 is an arterial with free flow travel time,  $T_2$ , capacity,  $C_2$  and an

average of two intersections per unit mile. It is assumed that  $T_1 < T_2$  and  $C_1 > C_2$ . In this case study, an incident is simulated on Route 1, which reduces the capacity by 70%. Table 7 provides a summary of traffic and geometric characteristics for Route 1 and Route 2.



**Figure 17. Sketch of corridor for case study**

**Table 7. Traffic and geometric characteristics for Route 1 and Route 2**

| Traffic and Geometric Characteristics | Route 1                   | Route 2  |
|---------------------------------------|---------------------------|--|
| Road type                             | Freeway                   | Arterial   |
| Facility type                         | Restricted                | Unrestricted, avg. of 2 signalized intersections per unit mile |
| Link Length                           | 10 (miles)                | 15 (miles)   |
| Speed limit                           | 65 (mph)                  | 35 (mph)   |
| Free flow speed                       | 70 (mph)                  | 40 (mph)   |
| Practical capacity                    | 1540 (pcphpl)             | 760 (pcphpl)   |
| Link volume                           | 729 (vphpl)               | 334 (vphpl)  |
| Number of lanes                       | 4                         | 3  |
| Capacity reduction due to incident    | 70% reduction of capacity | -  |

#### ***4.3.2 Numerical Illustration to Evaluate the Impacts of ATIS on Vehicular Emissions***

The framework for evaluating the impacts of ATIS on air quality, developed in Section 4.2, is numerically illustrated using the designed case study. The parameters evaluated in the case study are total system travel time and total system CO<sub>2</sub> emission for ‘with ATIS’ and ‘without ATIS’ conditions.

The evaluation assumed that all travelers in the study corridor have access to ATIS for the ‘with ATIS’ scenario. It is assumed that ATIS guides users to attain a user optimal state, i.e., the user equilibrium state (*Wardrop, 1952*). To evaluate the impact of ATIS on the scenario designed, following steps as described in Section 4.2 were applied:

**Step 1:** Predict changes in travel pattern, including changes in route, mode, departure time or changes in destination.

In this case study, the incident on Route 1 causes a reduction of capacity by 70%. This leads to a speed reduction on Route 1. Assuming that all travelers have access to ATIS, guided users divert to the Route 2 to go toward their destination.

**Step 2:** Estimate resulting change in traffic characteristics, which will directly impact congestion levels on each route.

The case study assumes Route 1 to be the more popular route to reach point B from point A due to less travel time. The accident on Route 1 causes an increase in travel time and ATIS prompts users to divert to Route 2. The Bureau of Public Roads (BPR) model for macroscopic volume-speed relations (*Dowling et al., 1997*) was used to estimate the change in speeds and travel time on Route 1 and Route 2.

$$v = \frac{v_o}{1 + \alpha \left( \frac{V}{C} \right)^\beta} \quad 4.5$$

Where,

$v$  is mean speed,

$v_o$  is free flow speed,

$V$  is total volume of link per unit time,

$C$  is practical capacity of the link per unit time ,

$\beta$  is 10,

$\alpha$  is .20 for unrestricted facilities (e.g., freeway) and .05 for restricted facilities (e.g., arterial).

- The free flow speeds were computed to be 70 mph and 40 mph for a freeway and arterial road, respectively (Dowling et al., 1997, HCM 2010).
- The practical capacities were estimated to be 1540pcplph and 760pcplph for freeway and arterial, respectively (defined as 80% of capacity or capacity at level of service C) (HCM, 2010).

To determine the diversion rate at an equilibrium state, the travel time on Route 1 and Route 2 were first determined using the BPR travel time function given by

$$t = t_o \left( 1 + \alpha \left( \frac{v}{C} \right)^\beta \right). \quad (4.6)$$

Where

$t$  is mean travel time,

$t_o$  is free flow travel time,

$V$  is volume of link per unit time,

$C$  is practical capacity of the link per unit time (defined as 80% of actual capacity),

$\beta$  is 10,

$\alpha$  is .20 for unrestricted facilities (e.g., freeway) and .05 for restricted facilities (e.g., arterial).

The user equilibrium state is the state when all routes from a common origin and destination experience the same travel time. The diversion rate at which the study corridor attains an equilibrium state is calculated by solving for diversion rate  $x$ , wherein the travel time on Route 1 and Route 2 becomes equal. To solve for the diversion rate, the BPR travel time functions on Route 1 and Route 2 were equated as:

$$t_1^o \left( 1 + \alpha_1 \left( \frac{V_1 \times (1-x)}{C_1} \right)^\beta \right) = t_2^o \left( 1 + \alpha_2 \left( \frac{V_2 + V_1 \times (x)}{C_2} \right)^\beta \right) \quad 4.7$$

Where,

$t_1^o$  is the free flow travel time on Route 1

$t_2^o$  is the free flow travel time on Route 2

$\alpha_1$  is .20 for unrestricted facilities (Route 1)

$\alpha_2$  is .05 for arterial facilities (Route 2)

$V_1$  and  $V_2$  are total volumes on Route 1 and Route 2 respectively

$C_1$  and  $C_2$  are practical capacities on Route 1 and Route 2 respectively

$\beta$  is 10 and

$x$  is the diversion rate of vehicles from Route 1 to Route 2

In this case study, the solution for diversion rate to attain user equilibrium state was estimated as 19.4 %.

**Step 3:** Estimate the Speed Reduction Congestion Index (SRCI)

To analyze the relationship of CO<sub>2</sub> emissions at user equilibrium state and no diversion state ('with ATIS' and 'without ATIS'), the respective mean speeds were calculated using the BPR equation (Equation 4.5). The mean speeds were converted to SRCI using the equation

$$\text{SRCI} = \frac{(\bar{v}_{ff} - \bar{v}_i)}{\bar{v}_{ff}} \quad 4.8$$

Where  $\bar{v}_{ff}$  free flow is speed and  $\bar{v}_i$  is the mean speed of the respective road type under consideration.

**Step 4:** Prepare the operating mode ID distributions for the estimated congestion levels

The SRCI values estimated in the previous step were used to determine the corresponding operating mode id distribution from





**Table 5.**

**Step 5:** Estimate emission factors for different congestion levels

MOVES was run in project level by inputting project specific fields that included:

- Regional data - Project specific data
- Vehicle age distribution - National default data
- Fuel Supply Fuel Supply - MOVES default data
- Fuel Formulation - MOVES default data
- Link Source Type – Project specific data
- **Operating Mode Distribution** (The results from Step 4)

It is assumed that Route 2 has an average of two intersections per unit mile and the probability of a vehicle having to stop at a signalized intersection is assumed to be 0.33. The operating mode ID distribution for intersection stop-and-go activity from **Table 5** was used to estimate CO<sub>2</sub> emissions using MOVES.

**Step 6:** Estimate the total emission for each scenarios

The total emission for each scenario (equilibrium state and no diversion) was calculated by multiplying the total volume by the emission factor obtained from running MOVES and total vehicle miles traveled given by the following equation:

$$\Delta E = \sum_{i=1}^n [(E_i^b * VMT_i^b) - (E_i^a * VMT_i^a)] \quad (4.9)$$

Where,

$E_i^b$  is the emission factor for route i, before implementing ATIS (zero diversion)

$E_i^a$  is the emission factor for route i, after implementing ATIS (equilibrium state)

$VMT_i^b$  is the vehicle miles traveled on route i, before implementing ATIS

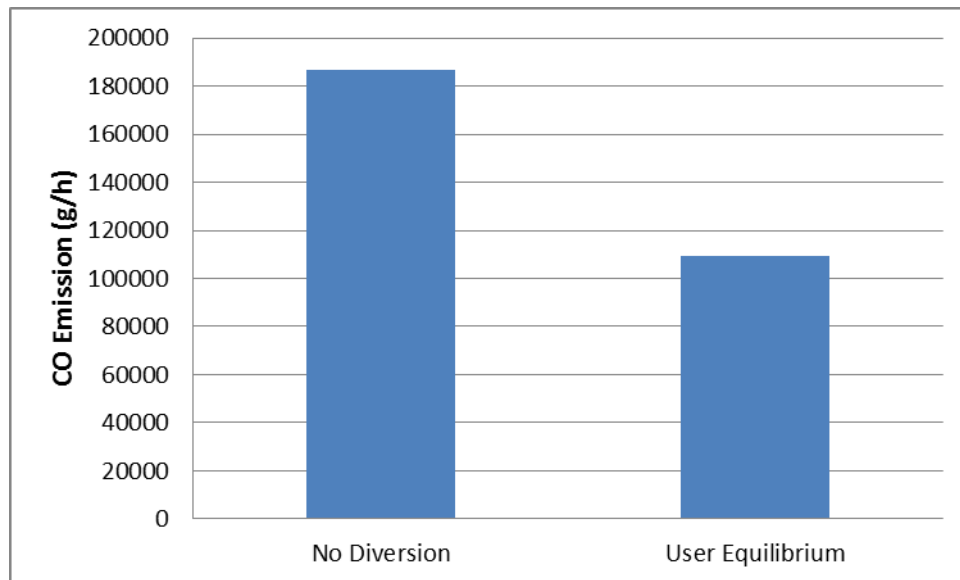
$VMT_i^a$  is the vehicle miles traveled on route i, after implementing ATIS

n is number of routes that will be affected by ATIS

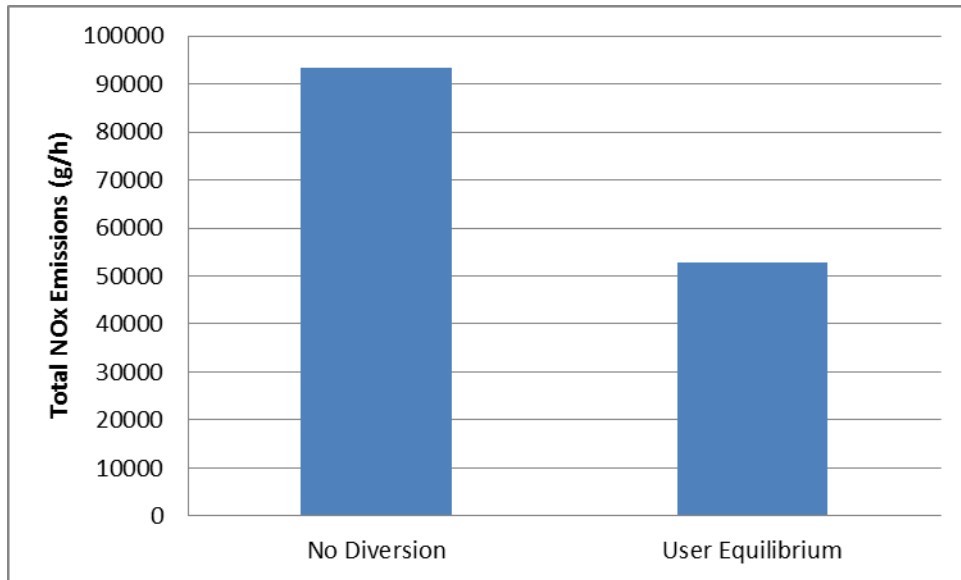
$\Delta E$  is the change in emissions

$\Delta E$  calculated will give the change in emissions due to employing ATIS.

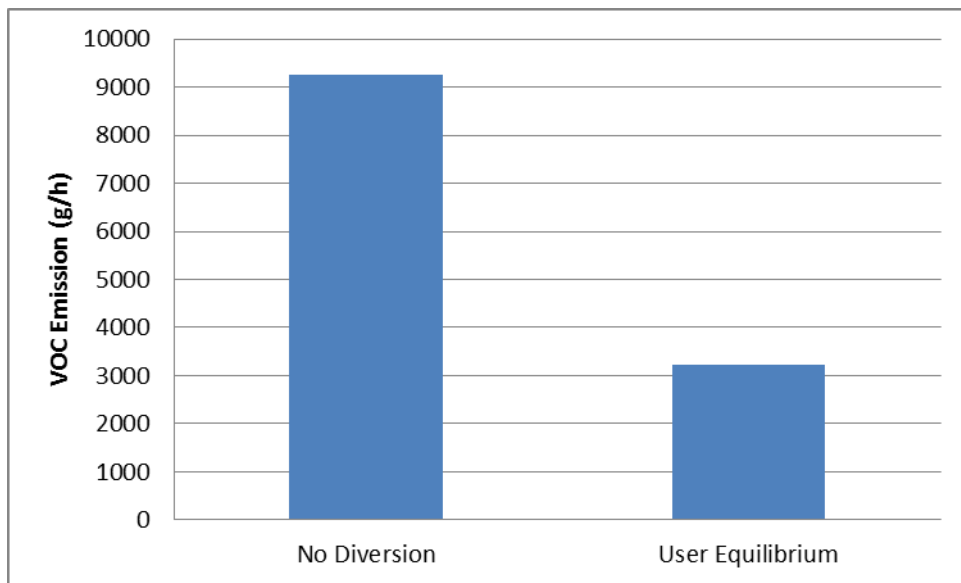
As a result, the total emission factors were estimated using Equation 4.10 for the three pollutants considered in this study, namely, CO, NOx and VOC. Figures 16 through 18 compare emission factors at no diversion and user equilibrium state for CO, NOx and VOC, respectively.



**Figure 188. Emissions at no diversion and user equilibrium state for CO**



**Figure 199. Emissions at no diversion and user equilibrium state for NOx**

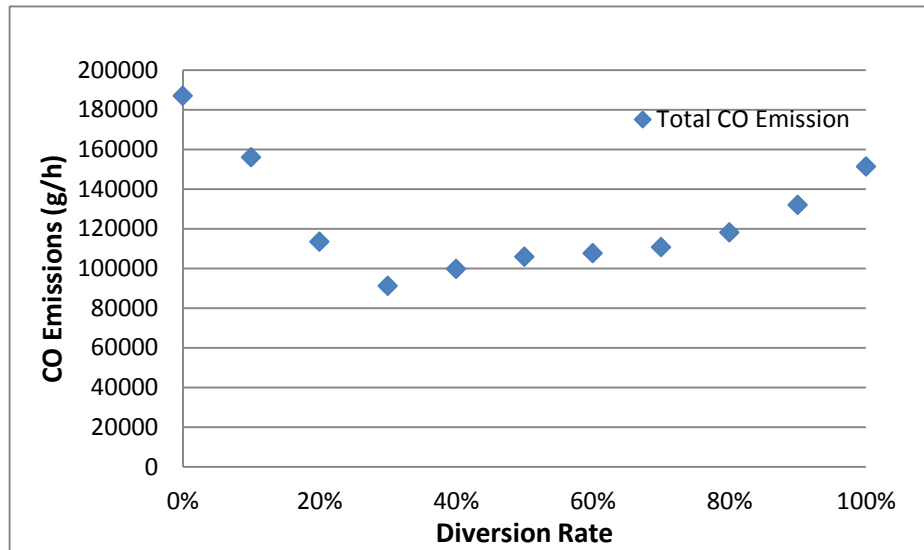


**Figure 20. Emissions at no diversion and user equilibrium state for VOC**

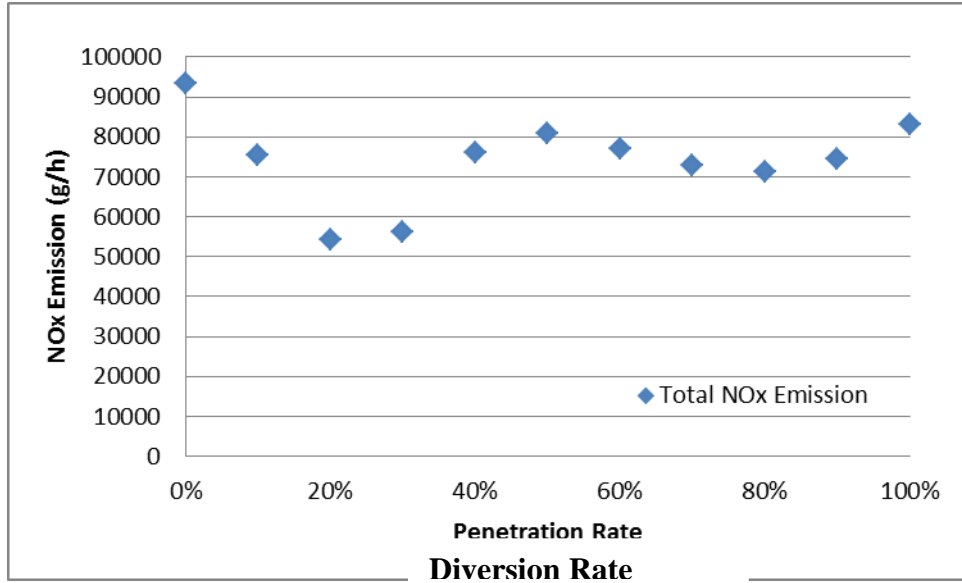
It was observed that compared with the “no diversion” scenario, CO emission rates were reduced by 42%, NOx emission rates were reduced by 43.5%, and VOC emission rates were reduced by 75.2 % in a scenario where traffic was diverted to route 2 and the network reached a user equilibrium state.

Furthermore, we attempted to analyze the relationship between total system emission rates and different diversion rates from Route 1 to Route 2 during the incident scenario.

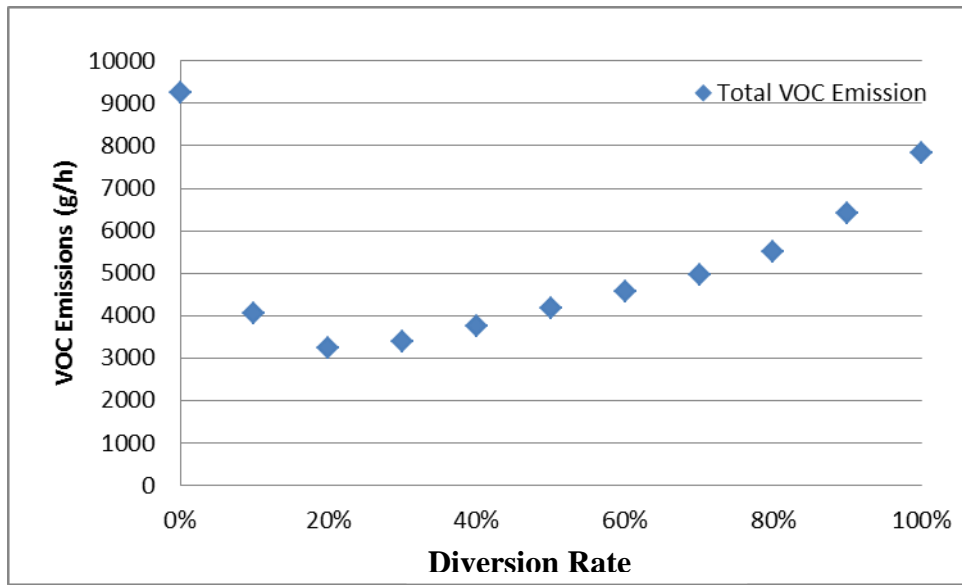
Once an incident occurs and the capacity of Route 1 reduces by 70%, the mean speed on this route is likely to reduce. As vehicles entering Route 1 are diverted to Route 2, the mean speed on Route 1 will improve, while the mean speed on Route 2 will decline. The speed reductions on both routes were calculated using the Bureau of Public Roads (BPR) (Equation 4.5) for different diversion rates. The mean speeds determined were converted according to the congestion indicator values, SRCIs, by using Equation (4.8). Emission levels were estimated for each of these speed levels and plotted. Figure 19 through Figure 21 shows the total system emission rates (g/h) for CO, NO<sub>x</sub> and VOC at different diversion rates.



**Figure 21. Total system CO emission for different diversion rates**



**Figure 22. Total system NOx emission for different diversion rates**



**Figure 23. Total system VOC emission for different diversion rates**

The results of the case study showed that the total system travel time was highest for no diversion case (0% Diversion Rate). These results demonstrated the benefits of using ATIS in terms of total system travel time and total emission reductions. The framework developed in this study will aid practitioners carrying out similar emission impact assessments to evaluate traffic demand management and congestion mitigation strategies.



## CHAPTER 5: CONCLUSIONS

Evaluating the impacts of traffic condition information on on-road mobile emissions is important. Such research facilitates the work by transportation planners and environmental analysts to carry out qualitative assessments of impacts on air quality for different types of traffic condition information. Results from such research also helps traffic engineers to appropriately deploy the most effective traveler information systems in order to maximize environmental benefits.

The goal of this research was to evaluate the impacts of ATIS on the reduction of on-road mobile emissions. This research completed the following objectives:

1. Reviewed and synthesized evaluation studies on ATIS.
2. Estimated emission factors for different roadway congestion levels on both freeway and arterial facilities.
3. Developed a framework for estimating the impacts of ATIS on the reduction of on-road mobile emissions.
4. Conducted a case study to evaluate the effects of ATIS on emission reduction during an incident scenario using the developed framework.

To achieve the research objectives, emission factors at different congestion levels on freeway and arterial road stretches were estimated. This study prepared the primary input, i.e., operating mode ID distributions, that are required for running MOVES and developed models for estimating emissions for different types of roadways under different congestion levels. The study results were then used to develop a framework for estimating the effects of ATIS on air quality. To demonstrate the application of developed framework, a case study was done to evaluate the

impacts of ATIS on vehicle emissions under an incident condition. The case study demonstrated the benefits of using ATIS in terms of total system travel time and total emission levels. The results of the case study showed that the total system travel time was highest for the no diversion case. For a scenario where all travelers had access to ATIS (user equilibrium state was attained); the total network emission was reduced by about 50% from the no diversion case. The evaluation results demonstrated the benefits of using ATIS in terms of total system travel time and total emission reductions. The case study also illustrated the usefulness of the framework recommended in this study. Practitioners can use the operating mode ID distributions developed in this study to carry out similar evaluation studies.

Although the case study presented in this paper only focuses on estimating three major pollutants, namely, CO, NO<sub>x</sub> and VOC, the developed operating mode ID distributions can be used as input to run MOVES and obtain the emission factors of any pollutant. The results of this study will facilitate the evaluation of transportation operation and demand management strategies with respect to their impacts on air quality.

Note that because of some simplifications made during the modeling process, such as discarding short snippets and reducing the operation at intersections to a single emission rate per stop, some bias will likely be introduced in the estimated emission rates. Thus, the developed method is primarily recommended for conducting emission comparison studies, such as the case study presented in this paper, and is not recommended for directly developing actual expected emission inventories.

Furthermore, this study did not distinguish operating mode ID distributions for different turning movements as well as for different congestion levels at intersections. Intersection progression rate also has strong impacts on emission rates. Very few studies have focused on the



relationship between intersection traffic conditions and emission rates. A study to further investigate the relationship between traffic congestion levels, progression rates, and turning movements on intersection emission rates would be of benefit to researchers and practitioners.

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