FIELD IMPLEMENTATION AND TESTING ECO-TRAFFIC SIGNAL SYSTEM APPLICATIONS

Final Report

TranLIVE

Sherief Elbassuoni and Ahmed Abdel-Rahim

December 2016

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation, University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Field Implementation and Testing Eco-Traffic Signal System Applications		5. Report Date December 2016
		6. Performing Organization Code KLK915
7. Author(s) Elbaussuoni, Sherief; Abdel-Rahim, Dr. Ahmed		8. Performing Organization Report No. N16-07
9. Performing Organization Name and Address National Institute for Advanced Transportation Technology University of Idaho 875 Perimeter Drive, MS 0901 Engineering Physics Building 115 Moscow, ID 83844-0901		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTRT12GUTC17
12. Sponsoring Agency Name and Address		13. Type of Report and Period Covered Final Report: January 2012 - November 2016
		14. Sponsoring Agency Code USDOT/RSPA/DIR-1
15. Supplementary Notes		

16. Abstract

The report provide guideline on the implementation of eco-traffic signal system in the field. The results showed that corridor's operating speed and the percent of the through traffic on the corridor to the total network traffic play a major role in determining the optimization objective function that produces the coordination plan with the least environmental impact. The study results showed that, when the percent of through traffic on the corridor exceeds 70% of the total network traffic, coordination plans optimized for excess fuel consumption appear to produce minimal effects on the environment. Guidelines on how to develop signal control parameter for isolated intersections to reduce stops and minimize the environmental impact of traffic operations along with the potential impact of advanced controller settings such as rest-on-red, rest-on-green, and delayed detection are presented and discussed.

17. Key Words eco-traffic, signal systems, environmental impact, traffic detection, fuel consumption, traffic detection		18. Distribution Statement Unrestricted; Document is available to the public through the National Technical Information Service; Springfield, VT.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 128	22. Price …
Form DOT F 1700.7 (8-72)		Reproduction of completed page authorized.	

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The main goal of this report is to offer guidelines for ECO-traffic signal system operations in small and medium size city environments. The first part of this report synthesizes and documents different aspects of emissions inventories. This synthesis work is focused on two areas: fuel consumption and emission modeling tools and sources of emissions inventory and data used in the models.

The second part of this report deals with vehicle performance modeling using advanced engine modeling software (GT-Suite). The main goal of this part of the analysis is to document the fuel consumption and environmental cost of vehicle operations at signalized intersection approaches. The vehicle performance modeling was conducted on four different speed profiles:

- Idling (queued vehicles): vehicle stops at the intersection (0 mph) when the red display is shown
- Cruising (free-flow vehicles): vehicle is cruising at different speeds (25, 35, 45, and 55 mph) when the green display is shown.
- Accelerating from a stop position to different target speeds: vehicle is accelerating from a stopped condition to different target speeds (25 mph, 35 mph, 45 mph, and 55 mph). Three different acceleration values are used in the analysis a) mild acceleration: 40% of the maximum vehicle acceleration envelope, (4.7 ft. /s^2), b) normal acceleration: 60% of the maximum vehicle acceleration envelope, (7.1 ft. /s^2), and c) aggressive acceleration: 100% of the maximum vehicle acceleration envelope, (11.8 ft. /s^2).
- Accelerating from a non-zero speed to different target speeds (delayed vehicles): vehicle is accelerating from a non-zero speed to a target speed (25 mph, 35 mph, 45 mph, and 55 mph). Three acceleration values are also used in this part of the analysis (4.7 ft. /s^2, 7.1 ft. /s^2, and 11.8 ft. /s^2).

The third part of this report deals with minimizing the environmental impact of corridor traffic operations in small and medium size city environment. While corridor traffic in small and medium size cities does not experience the high levels of congestion typically present in large urban areas, it still generates a considerable amount of emissions and vehicle pollutants, negatively impacting the environment. The primary objective of this part of the analysis is to investigate different corridor traffic management plans and examine their potential impact in reducing vehicle emissions and fuel consumption. Corridor optimizations and microscopic traffic simulation models were used to develop and test corridor traffic management plans and to assess their operational and environmental impact. The corridor coordination plans were developed using different objective functions.

The results showed that corridor's operating speed and the percent of the through traffic on the corridor to the total network traffic play a major role in determining the optimization objective function that produces the coordination plan with the least environmental impact. The study results showed that, when the percent of through traffic on the corridor exceeds 70% of the total network traffic, coordination plans optimized for excess fuel consumption appear to produce minimal effects on the environment. In the fourth part of this report, guidelines on how to develop signal control parameter for isolated intersections to reduce stops and minimize the environmental impact of traffic operations are presented and discussed. The potential impact of advanced controller settings such as rest-on-red, rest-on-green, and delayed detection are also presente

CHAPTER 1: INTRODUCTION

Objectives and Goals

Although corridor traffic in small and medium size cities does not experience the high levels of congestion typically present in large urban areas, it generates a considerable amount of emissions and vehicle pollutants that negatively affect the environment. The main goal of this report is divided into the following topics:

1. Synthesize fuel consumption and emission modeling tools.

    The synthesis work focused on two main areas: fuel consumption and emission modeling tools and the sources of emissions inventory and data used in the models. The first part of this work includes a background covering different traffic-related pollutants; emission factors and data and different methods used to obtain them; and examples of the currently available emission inventories.

    In the second part, a review of fuel consumption and emission models suitable for modeling corridor traffic operations is presented covering three different analysis levels: microscopic, mesoscopic, and macroscopic.

2. Model vehicle performance at signalized intersection approaches using advanced engine modeling software (GT-Suite).

    An advanced engine modeling software was used to quantify the fuel consumption and environmental impact of vehicle operations at signalized intersection approaches. GT-SUITE was used because it offers a versatile toolbox for modeling vehicles and drivelines and simulation of vehicle dynamics. It also addresses a range of vehicle engineering issues like vehicle performance, fuel economy and emissions, and transmission dynamics.

3. Develop guidelines on how to optimize corridor management plans to minimize corridor emissions and fuel consumptions in small and medium size cities.

    In urban and suburban areas, corridor signal timing plans that are not optimized can cause an abundance of vehicle emission pollution. Prolonged idling can decrease fuel efficiency for users. Several corridor optimization models exist and have been

used to study the operational effects and benefits of re-timing coordinated signals. Multiple optimized signal timing plans were used to determine the most efficient optimization objective function to minimize negative impacts on the environment caused by poor corridor traffic management. Two optimization software tools were used in the analysis: TRANSYT-7F and PTV VISTRO. TRANSYT-7F was chosen to produce optimum timing plans with various objective functions because it is a widely used traffic signal optimization model. PTV VISTRO was chosen due to its recent release and similar capabilities of optimizing coordinated networks. Signal timing plans from both TRANSYT-7F and PTV VISTRO were simulated microscopically in INTEGRATION to produce estimates of fuel consumption, vehicle emissions and other environmental effects, and several operational measures of effectiveness.

4. Develop signal control parameter guidelines for isolated intersections to minimize stops, fuel consumption, and emissions focusing on advanced controller settings such as rest-on-red, rest-on-green, and delayed detection.

Report Organization

The report is organized into seven chapters and as follows:

1. Chapter 1 is an introduction to the report
2. Chapter 2 is a background and literature review
3. Chapter 3 includes a synthesize of different fuel consumption and emissions modeling tools and data sources. In this chapter, different emission factors, emission inventories, and some examples of the available emission modeling tools are presented and discussed.
4. In chapter 4, the results of the engine performance model (GT-Suite) are presented and discussed.
5. In chapter 5, multiple optimization signal timing plans are utilized to develop guidelines on how to develop control management plans to minimize the negative environmental impacts of corridor traffic.

6. Chapter 6 presents the guidelines for signal control parameters for isolated intersections focusing on advanced settings like rest on red, rest on green, and delayed detection.

7. Chapter 7 summarized the study conclusion, recommendations, and suggestions for further research.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

Introduction

According to the International Energy Agency (IEA), the transportation sector consumes around 106 quadrillion (10^{15}) kilojoules (KJ) of energy worldwide, mostly petroleum-based products including gasoline and diesel fuels. More than 7 Giga tons of CO_2 emissions are also attributed to the transportation sector, representing approximately 20% of the total CO_2 emissions from fuel combustion. Alternative transportation energy sources such as hybrid-electric technologies, bio-ethanol, and hydrogen fuel cells are emerging and are being broadly investigated as replacements for the conventional internal combustion engine. However, these new alternatives have not yet been able to replace petroleum-powered engines because of the challenges that relate to availability, cost, convenience, lack of technology, and accessibility. Consequently, there is a need to improve the efficiency of travel in urban, suburban, and rural areas. One of the key strategies for improving vehicle fuel efficiency is to improve the efficiency of the transportation system operations. The chapter highlights some of the research being conducted on the use of Intelligent Transportation System (ITS) and connected vehicle technologies to achieve these goals.

Estimating Fuel Consumption and Emission Levels for Vehicular Traffic

Vehicle fuel consumption levels are typically derived from a relationship between instantaneous fuel consumption rates and instantaneous measurements of various explanatory variables, including vehicle power, force (or tractive effort), acceleration, speed, and/or roadway grade. Numerous fuel consumption models have been developed that incorporate different explanatory variables in order to satisfy their specific objectives. One variable that stands out is vehicle power or vehicle specific power (VSP), which is the power exerted per unit mass. Vehicle power can be computed as the product of the total force exerted by the vehicle and the vehicle velocity. The total force includes both the net force and the force that is required to overcome the aerodynamic, rolling, and grade resistance forces. Assuming that the vehicle fuel consumption rate is proportional to the vehicle power, the fuel consumption can be estimated by computing the forces acting on the vehicle.

Post et al. developed a fuel consumption model that is a linear function of the instantaneous power demand. The model was built from chassis dynamometer experiments of 177 in-use vehicles (Post et al., 1984). This model was subsequently enhanced in later publications (Akcelik, 1989) and (Fisk, 1989). The Comprehensive Modal Emissions Model (CMEM) is another model that estimates the instantaneous fuel consumption rate based on power, engine friction, engine speed, and vehicle engine size (or displacement) (Barth et al., 1996) and (A. Barth et al., 2006). Another fuel consumption model that makes use of topographic and gear shifting information was developed by researchers from Linkőpings University. A full description of the various functional forms and the merits of each functional form can be found in Saerens et al. (Saerens et al., 2013a).

While the majority of fuel consumption models were developed as power-demand models, the VT- Micro model was developed as a statistical model from experimentation with numerous polynomial combinations of speed and acceleration levels to construct a dual-regime model (Ahn et al., 2002a), (Rakha et al., 2004b), (Rakha and Ahn, 2004a), and (Ahn et al., 2002b). These fuel consumption and emission models were developed using data that were collected on a chassis dynamometer at the Oak Ridge National Labs (ORNL), data gathered by the Environmental Protection Agency (EPA), and data gathered using an onboard emission measurement device (OBD). These data included fuel consumption and emission rate measurements (CO, HC, and NOx) as a function of the vehicle's instantaneous speed and acceleration levels. The VT-Micro fuel consumption and emission rates were found to be highly accurate with coefficients of determination ranging from 0.92 to 0.99. A detailed description of the model derivation is provided in the literature (Ahn et al., 2002b), and (Rakha et al., 2004b). The model is easy to use and is currently implemented in the INTEGRATION traffic simulation software, as will be described later.

Apart from the VT-Micro model, all models described in the literature produce a bang-bang type of control system (i.e. optimal control entails full-throttle input and full braking input). This occurs because the partial derivative of the fuel consumption rate (F) with respect to the engine torque (T) is not a function of torque (Del Re et al., 2010). A model that results in a bang-bang control system would indicate that the optimum fuel economy control would be

to accelerate at full throttle in order to reduce the acceleration time. This type of control, which is obviously incorrect, would recommend that the driver drives as aggressively as possible in order to minimize their fuel consumption level.

In an attempt to overcome the limitations of existing fuel consumption models, the Virginia Tech Comprehensive Power-based Fuel consumption Model (VT-CPFM) was developed (Rakha et al., 2011b). The model offers two advantages over existing modeling tools. First, it can be calibrated using publically available data without the need for vehicle dynamometer of field testing. Second, the model does not produce a bang- bang control system given that it is a second-order polynomial function of instantaneous power.

Intelligent Transportation Systems (ITS) and Connected Vehicle (CV) Applications

This section describes some ITS and CV applications and case studies. The case studies that are described include: ECO-routing, Eco-Cruise Control (ECC), Eco Adaptive Cruise Control (EACC), Eco-Cooperative Adaptive Cruise Control (ECACC) systems in the vicinity of traffic signals to minimize vehicle fuel consumption and carbon footprint levels. Given that limited space, the focus will be mainly on research conducted by the Virginia-Tech.

Eco-Routing

Drivers typically choose routes that are redicted to minimize their travel cost (e.g., travel time). Consequently, drivers occasionally select longer distance routes if they produce travel time savings. Recently, navigation tools and trip planning services have introduced a vehicle routing option that is designed to minimize vehicle fuel consumption and emission levels in response to rising energy costs and increased environmental concerns. Such a routing option is referred to as ECO-routing.

An earlier study by Ahn and Rakha investigated the impacts of route choice decisions on vehicle energy consumption and emission rates for different vehicle types using microscopic and macroscopic emission models (Ahn and Rakha, 2008). The results demonstrated that the

faster highway route choice was not always the ideal route from an environmental and energy consumption perspective. Specifically, the study found that significant improvements to energy and air quality could be achieved when motorists utilized a slower arterial route although they incurred additional travel time. The study also demonstrated that macroscopic emission models (e.g., MOBILE6) could produce erroneous conclusions given that they ignore transient vehicle behavior along a route. The findings suggested that an emission- and energy- optimized traffic assignment can significantly improve emissions over the standard user equilibrium (UE) and system optimum (SO) assignment formulations. Finally the study demonstrated that a small portion of the entire trip involved high engine-load conditions that produced significant increases in total emissions. By minimizing high-emitting driving behavior air quality could be improved significantly.

To address this need, a novel connected vehicle (CV) ECO-routing algorithm was developed and implemented in the INTEGRATION software to test and quantify the system-wide impacts of ECO-routing strategies. INTEGRATION is a microscopic traffic assignment and simulation software package that was developed in the mid-eighties and continues to be developed and enhanced (Van Aerde and Yagar, 1988), (Van Aerde, 1985), and (Van Aerde and Rakha, 2004). The INTEGRATION model is the only traffic modeling tool that allows the user to model a CV dynamic ECO-routing system (Rakha et al., 2011a). Vehicle fuel consumption levels are computed using the VT-Micro model using instantaneous speed and acceleration levels (Rakha et al., 2004b), (Rakha and Ahn, 2004a), (Ahn et al., 2002b), and (Ahn et al., 2004). The INTEGRATION model ensures that vehicle accelerations are valid using a mass-point vehicle dynamics model (Rakha and Ahn, 2004a), (Rakha et al., 2001a), and (Rakha et al., 2004d).

Two CV ECO-routing algorithms were recently added to the INTEGRATION routing logic (Rakha et al., 2011a). Both ECO- routing algorithms find a route that minimizes the vehicle fuel consumption level using a User Equilibrium (UE) incremental dynamic traffic assignment in which the increment is a single vehicle. The first routing, which is used here, is termed ECO-Subpopulation Feedback Assignment (ECO-SFA). In the ECO-SFA case, a vehicle route is selected based on the fuel consumption experiences of other vehicles within

the same vehicle class or other classes, as selected by the model user. All drivers within the vehicle class are divided into five subpopulations, each comprising 20% of all drivers. The paths for each of these subpopulations are then updated every "t" seconds during the simulation based on CV real-time measurements of link fuel consumption levels for the specific vehicle class (or classes) under consideration. Furthermore, the minimum path updates of each vehicle subpopulation are staggered in time to avoid situations in which all vehicles select identical paths if the minimum and next minimum path are similar. This logic results in 20% of the driver paths being updated every "t/5" seccods.

The selection of the next link that a vehicle should take is made using a vehicle-specific array that lists the entire sequence of links from a vehicle's current link to its destination. Upon the completion of any link, a vehicle simply sends its fuel consumption on the link via some of vehicle connectivity and then queries this array to determine which link it should utilize next to reach its ultimate destination in the most fuel- efficient manner. The vehicle may only use the experiences of other vehicles in the same class (if selected by the user) to update the fuel consumption estimates on a link. This allows for a multi-class (up to five classes), stochastic (introduced by adding white noise to the link cost function), dynamic (based on the update frequency specified by the user) ECO-routing system.

The system-wide impacts of implementing the proposed CV ECO-routing system considering various levels of market penetration, levels of congestion, and on two networks (downtown Cleveland and Columbus, Ohio) were evaluated (Ahn and Rakha, 2013). The study demonstrated that such ECO-routing systems reduce the network-wide fuel consumption and emission levels in most cases. In particular, the average network- wide fuel savings on the Cleveland and Columbus networks ranged between 3.3 and 9.3 percent when compared to the typical travel time minimization routing strategies. The study demonstrated that the fuel savings achieved through the ECO-routing system are sensitive to the network configuration and level of market penetration of the ECO-routing system.

An ECO-routing system typically reduced vehicle travel distance but not necessarily travel time. The transportation network configuration was found to be a significant factor in

defining the benefits of ECO-routing systems with larger fuel savings on grid networks compared to freeway corridor networks. The study also demonstrated that different vehicle types produce similar trends with regard to ECO-routing benefits. Finally, the study concluded that the system-wide benefits of ECO-routing generally increase with an increase in the level of the market penetration, as demonstrated in Figure 1.
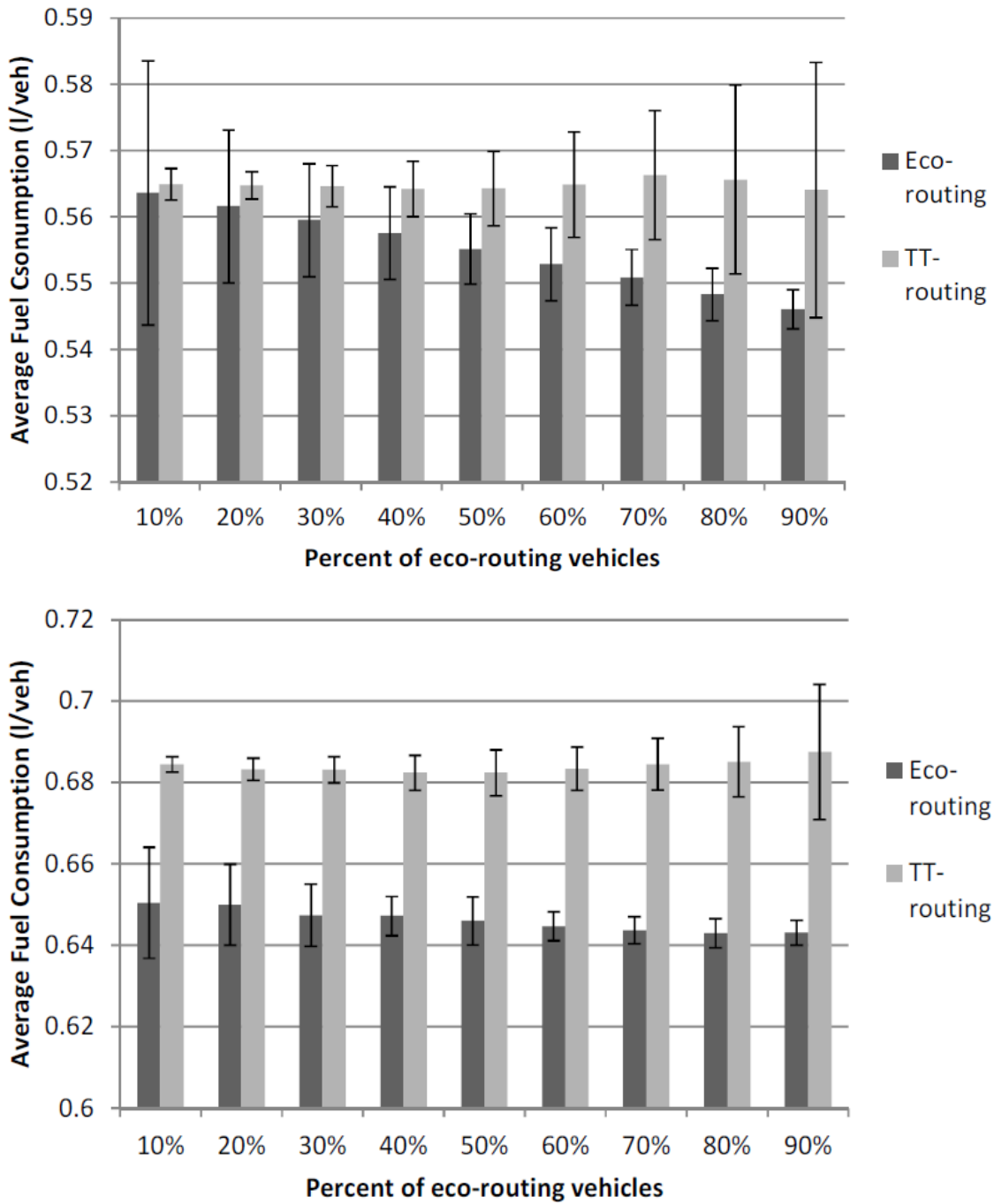
Figure 1 ECO-routing market penetration impacts on network-wide fuel consumption levels versus minimum travel time (TT) routing

ECO Cruise Control (ECC) and ECO Adaptive Cruise Control (EACC) Systems

Among other variables, the roadway grade has a significant influence on vehicle fuel consumption levels. For example, driving uphill requires extra engine power and thus fuel to overcome the gravitational acceleration. An earlier study (Park and Rakha, 2006) showed that a 6% increase in the roadway grade increases the fuel consumption level between 40 and 94%, while a 1% grade increase yields 8 to 18% extra fuel consumption. This knowledge can be used to lower the fuel consumption by simply avoiding hilly roads or adapting the velocity on hilly roads. The latter approach is used in heavy duty truck driving (Fröberg et al., 2006), and (Hellstr, 2005) and is mostly known as Predictive Cruise Control (PCC). PCC is a system that uses the downstream road profile to actively change the vehicle velocity through use of a cruise controller. This approach can also be adopted in driving a passenger vehicle (Park et al., 2011a), and (Ahn et al., 2011). In this application it is named ECO-Cruise Control (ECC) in accordance with "ECO-Driving."

The goal of an ECC system is to find an optimal vehicle velocity profile using an optimal control theory to minimize the vehicle fuel consumption level. Three factors have a significant influence on the resulting profile: 1) the fuel consumption model, 2) the cost function that is used in the optimization, and 3) the optimal control solution method. Some literature have a detailed description of these three components, and the analysis of the previous fuel consumption models (Saerens et al., 2013b), and (Saerens et al., 2013a). In this chapter, only one approach will be presented in an attempt to demonstrate a potential system application. Extension of the ECC system to avoid collisions with surrounding vehicles reverts the system to an EACC system. These systems combine car-following models (follow the leader models) with ECC systems (Ahn et al., 2013).

An earlier study developed an ECC system application that optimizes the vehicle controls using a widely used dynamic programming (DP) implementation of Dijkstra's shortest path algorithm. The VT-CPFM is used because of its simplicity, accuracy, and ease of calibration, as was described earlier (Rakha et al., 2011c). The system uses three parameters, namely: the stage length (d_s), the look-ahead distance (d_o), and the optimization implementation distance

(d_f), as illustrated in Figure 2. The stage length (d_f) is the unit of discretization used in solving the problem. In other words, the control variables (throttle, brake, and gear input) remain constant for the duration of a stage. The look-ahead distance (d_o) is the distance for which the optimization is performed. Finally, the optimization implementation distance (d_f) is the distance for which the optimized plan is implemented. The interested reader can refer to an earlier publication for more information on the system (Park et al., 2011b).

In order to maintain and adjust the vehicle speed, a vehicle powertrain model was integrated with the ECC system to model the instantaneous power and other powertrain characteristics. The powertrain model also includes a gear shifting model. The engine speed and torque are then used to compute the vehicle power using a parabolic vehicle engine model that was developed by Ni and Henclewood (Ni and Henclewood, 2008). A more detailed description of the powertrain model is provided in a work conducted by Dr. Hesham Rakha et. al. (Rakha et al., 2012).
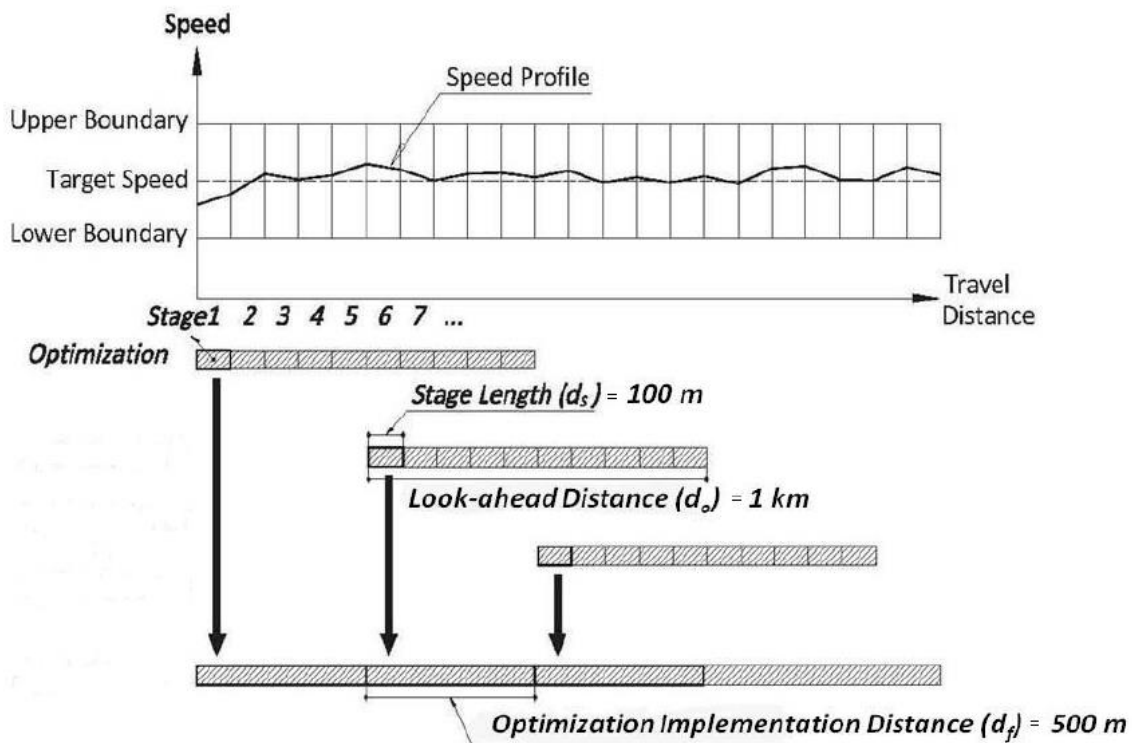
Figure 2 Proposed ECC logic

Given that the ECC system is valid only for free-flow conditions, an extension to the ECC system entails adding adaptive speed adjusting capabilities. This extension requires the measuring the spacing between the subject and lead vehicle using a radar system or some form of vehicle-to-vehicle (V2V) communication, as illustrated in Figure 3. This can then be used to compute the headway between the two vehicles. The model starts with driver input of a target speed, a speed range, and a desired vehicle spacing or headway (e.g. 1 second following headway) threshold. Typically, the target speed is based on the roadway speed limit. The speed range is set to the maximum and minimum speed the driver is willing to accept. Finally, the car-following headway is based on the driver or passenger comfort level. The optimal control estimates the throttle position and brake level that generates the desired speed profile while maintaining a safe following headway between the subject vehicle and a vehicle ahead of it.
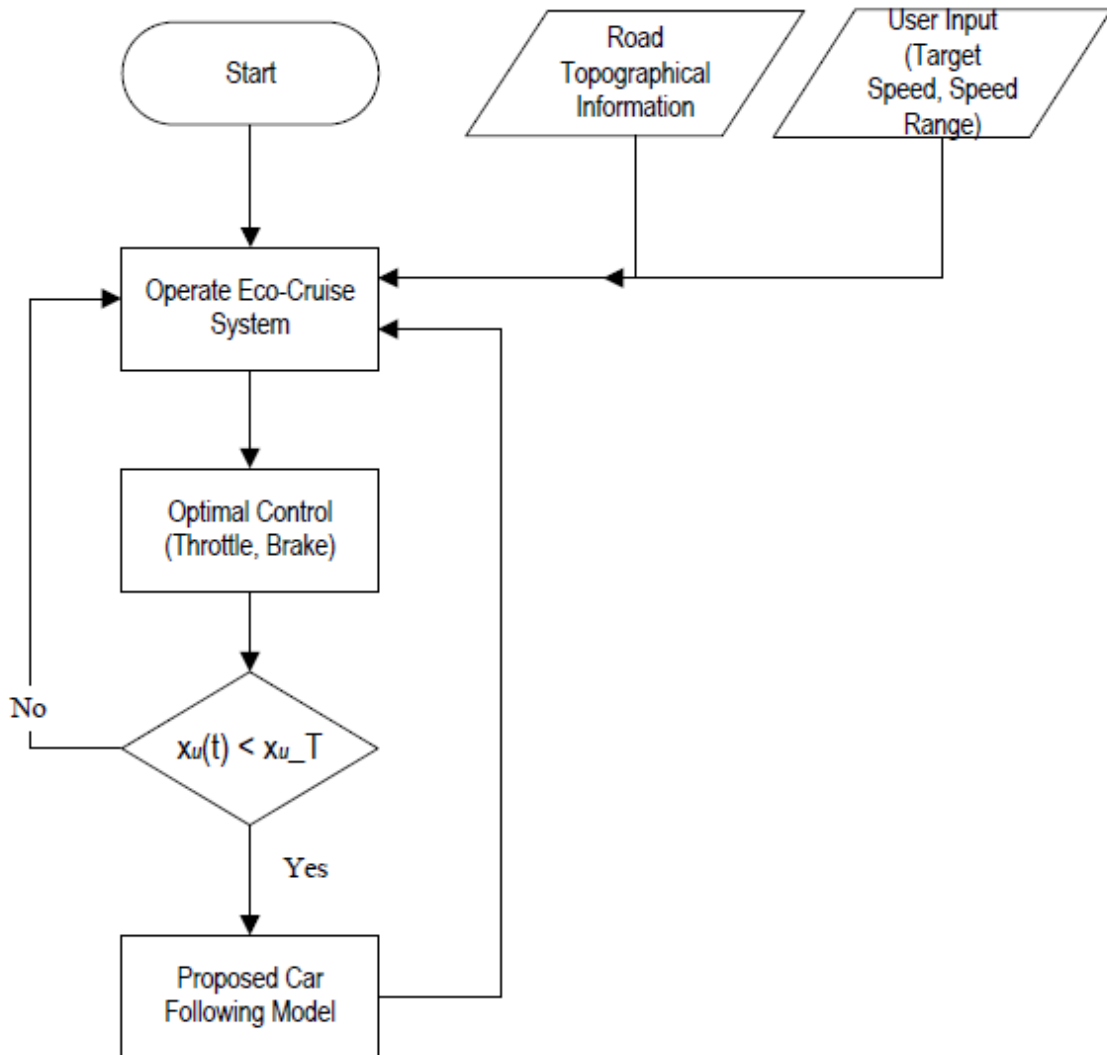
Figure 3 Proposed EACC algorithm logic

The proposed logic can be summarized as follows:

- If the spacing or headway between the subject and lead vehicle is greater than the car-following threshold (xu_T), proceed to step 3. Otherwise, proceed to step 2.
- Estimate the maximum vehicle acceleration at instant t based on the steady-state car-following model and collision avoidance constraints. Considering the steady-state model, the first step entails computing the maximum speed at t+Δt. The maximum acceleration is then computed using a mass point vehicle dynamics model, and the maximum speed at the end of the first stage (position xt+ds) can then be computed as

the minimum of the steady-state desired speed or the maximum attainable speed based on the vehicle dynamics model. The next step entails proceeding to step 4.

- Using the DP algorithm described earlier, the optimal vehicle speed trajectory over the look-ahead distance (d_o) is estimated considering a spatial discretization of d_s (stage length). The maximum car-following speed constraint that was computed in step 2 is considered in identifying the search space of stage 1.

- Move the vehicle and then go back to step 1 at the conclusion of time step Δt. Otherwise, end the simulation at t=T.

The developed ECC was refined to use an A* algorithm to compute the optimum trajectory in real-time. The system was tested on a 45-km freeway segment and was able to compute the optimal trajectory in less than 3 minutes with a gap in the objective function of less than 2 percent (Park et al., 2012). Testing of the system demonstrated that the largest fuel savings are achieved along hilly terrain sections. Fuel consumption savings are higher at lower speeds (72 km/h) versus higher speeds (120 km/h), with fuel savings relative to a conventional cruise control system in the range of 48 to 28 percent, respectively. Estimated savings for the US as a whole were estimated and found to be equivalent to approximately 4.2 percent of the total U.S. oil consumption, assuming a daily consumption of 20 million barrels of oil. In addition, the ECO-cruise control system produced a reduction of 113 million metric tons of CO_2 assuming that one liter of fuel produces 2.33 kg of CO_2. The average potential fuel savings were projected to be 14.2 billion gallons per year, which is equivalent to $46.2 billion per year when assuming that the price of gasoline is $3.25 per gallon.

With regards to the EACC system, the study demonstrated that the proposed system can significantly improve vehicle fuel efficiency without significantly increasing the inter vehicle spacing. Specifically, fuel savings in the range of 27 percent are achieved with an average vehicle spacing of 47 m along a study section of Interstate 81. The study also demonstrates that regular vehicles can benefit significantly by following a lead ECO-drive vehicle.

\ECACC Systems in the Vicinity of Signalized Intersections

Driving on highways and arterial roadways involves vehicle acceleration, braking, cruising, coasting, and idling episodes. As the vehicle speed deviates from its "fuel optimum speed," additional fuel is consumed and thus reducing the vehicle fuel efficiency. In order to address this issue a connected vehicle (CV) application entitled ECO-Cooperative Adaptive Cruise Control (ECACC) that uses Infrastructure-to-Vehicle (I2V) communication to receive Signal Phasing and Timing (SPaT) data was developed (Kamalanathsharma and Rakha, 2014a). The system predicts future constraints on a vehicle's trajectory and optimizes its trajectory to minimize the vehicle's fuel consumption level. The trajectory optimization is made using a moving horizon dynamic programming (DP) approach. A modified A-star algorithm was developed to enhance the computational efficiency of the DP for use in real-time implementations.

The overall ECACC system logic, presented in Figure 4, demonstrates that the ECACC optimization is repeated every Δt to adjust for changes in SPaT data (which occurs when pre-emptive and vehicle actuation calls are placed to the controller), (Kamalanathsharma and Rakha, 2014a), and (Kamalanathsharma and Rakha, 2014b). The inputs to the system are received through a communication module which can be adapted to the technology being used (such as cellular or Dedicated Short Range Communication (DSRC)) as well as from the vehicle's on-board units that track the vehicle's velocity and acceleration and a GPS unit that tracks the location of the vehicle. Using these data as well as the basic microscopic car-following, collision avoidance and vehicle dynamics models, the ECACC module optimizes the vehicle trajectory in order to minimize the total fuel consumption over a fixed distance of travel. The optimum speed advisory can then be displayed to the driver or to a speed-governance unit in an ACC system.
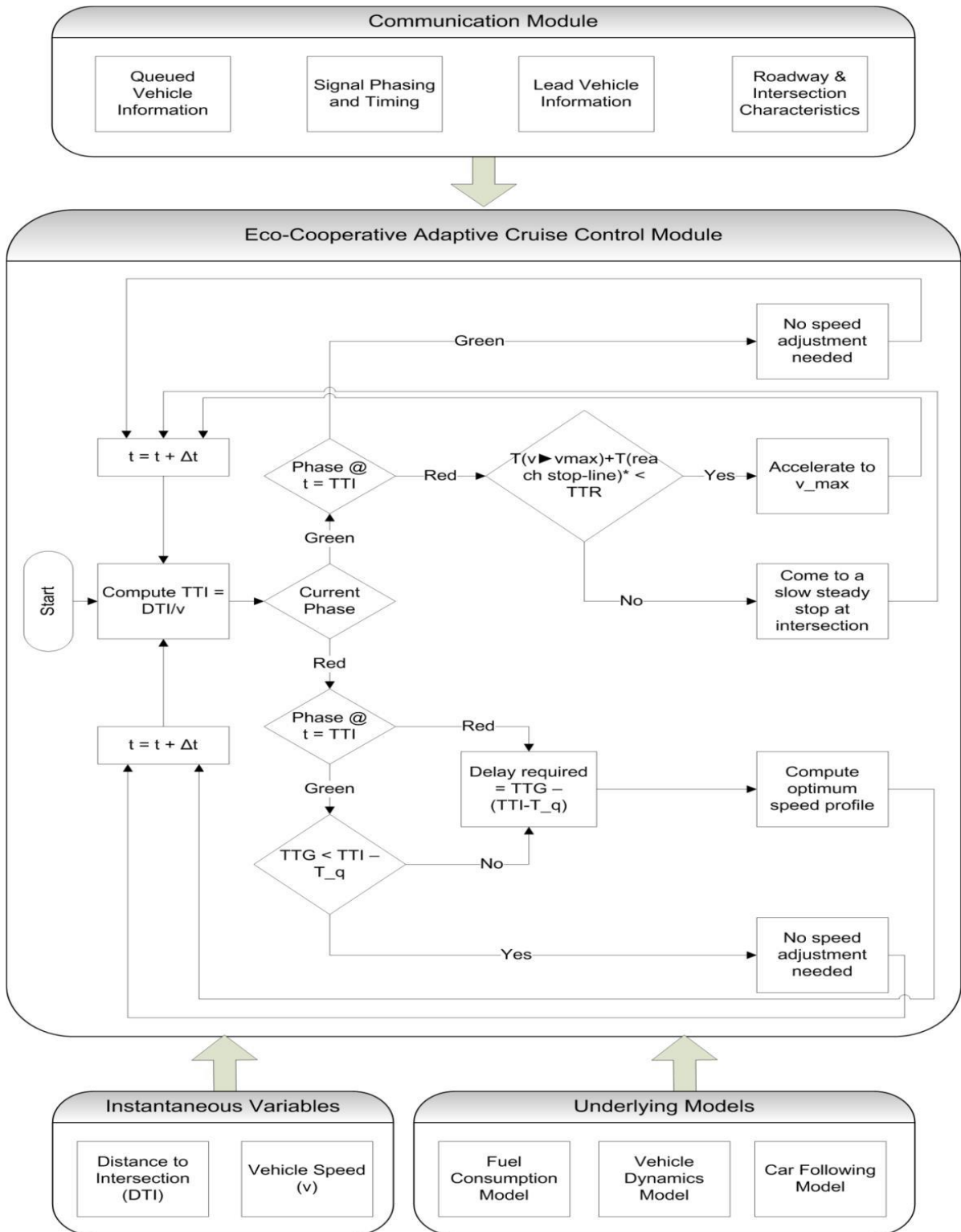
Figure 4 Proposed intersection ECACC logic

Figure 5 shows that according to a vehicle's time to intersection (TTI) computed from its speed and distance to intersection (DTI), a test-vehicle can be in one of the four scenarios, as illustrated in Figure 5 These scenarios are:

- **Scenario 1:** As the vehicle receives upcoming signal-change information from the intersection via I2V communication, it determines whether the vehicle will receive a green indication at the stop line if it proceeded at its current speed; if it does, then the optimal course of action is to proceed without any reductions in speed.

- **Scenario 2:** If the Time to Red (TTR) is not sufficient for the vehicle to pass through the intersection during a green signal indication if the vehicle continues at its current speed but is sufficient if the vehicle accelerates to the maximum allowed speed on the roadway, then the optimal course of action is to accelerate and proceed through the intersection in the current phase. This saves fuel by eliminating a stop and idling at the intersection.

- **Scenario 3:** If the TTR is not sufficient for the vehicle to proceed through the intersection and the time-to-green (TTG) to the next phase is large enough that the vehicle has to alter its trajectory, then the optimal course of action entails stopping and waiting for the next green indication.

- **Scenario 4:** This is when the TTG is longer than the vehicle's Time to Intersection (TTI) at the current speed. Hence, by reducing the average speed while traveling to the intersection, a delay can be incurred in the vehicle trajectory so that the TTI is sufficient to receive a green indication after clearing any available queues.

Scenario 4 provides most flexibility as far as fuel savings are concerned. While scenarios 1 through 3 are generally easy to optimize, the last scenario requires a simulation/optimization algorithm. This simulation/optimization algorithm must consider constraints imposed by the traffic signal and vehicle dynamics, as follows: (a) temporal constraints based on the signal timings, (b) temporal and spatial constraints based on the queue dissipation times and the travel time to the intersection, (c) speed constraints enforced by speed-limits, and (d) vehicle deceleration/acceleration constraints enforced by the vehicle dynamics. Since these scenarios

are defined based on TTI, it is possible to construct similar constraints when phase lengths are short resulting in multiple phases while the vehicle approaches the intersection stop-line. The above problem is a complex optimal control problem with the control variables being the brake pedal input and gas pedal input (throttle) that the driver applies. Deceleration and acceleration can be easily computed using these control variables (or vice-versa) using the vehicle dynamic equations.

The proposed ECACC system was developed and tested in the INTEGRATION software (Kamalanathsharma et al., 2014), (Kamalanathsharma and Rakha, 2014c), and . A set of simulations were conducted on an intersection in downtown Blacksburg, VA for different levels of congestion and different levels of market penetration on three major performance measures: (1) average fuel consumption per vehicle, (2) average overall emissions per vehicles and (3) average total delay per vehicle. The following observations were made:

- The vehicle fuel consumption level increased as the demand in the network increased with a more drastic increase beyond the peak volume traffic.
- The savings in fuel consumption was highest at 25 percent and 150 percent of the peak volume and fell within the 13 to 30 percent range at 100 percent Level of Market Penetration (LMP).
- Savings in CO, HC, CO_2 and NO_x emissions followed the fuel consumption savings very closely.
- The reduction in delay was significantly higher than that of energy or emissions with savings in the order of 38 to 65 percent.
- The fuel consumption savings were sensitive to the LMP. The average fuel consumption for an individual vehicle increased gradually for lower LMPs and declined for LMPs over 50 percent especially for higher levels of congestion. Consequently, the results suggest that in order to observe fuel savings the LMP should exceed 50 percent for congested conditions.
- Analysis of the total delay incurred by an average vehicle also showed a significant decrease for LMPs beyond 50 percent. This is due to the increase in acceleration/deceleration delay when there are less equipped vehicles in the mix.

- The stopped delay was reduced from 10 to 50 percent when the LMP increased from 0 to 100 percent with the highest reduction for the lowest volume.

While the results of this simulation study matches some of the previously researched attributes from the literature, unlike other studies the results demonstrate that higher LMPs (50 percent or more) are required to achieve the desired benefits. Further studies that encompass an arterial or multiple intersections are warranted to further test the algorithm.
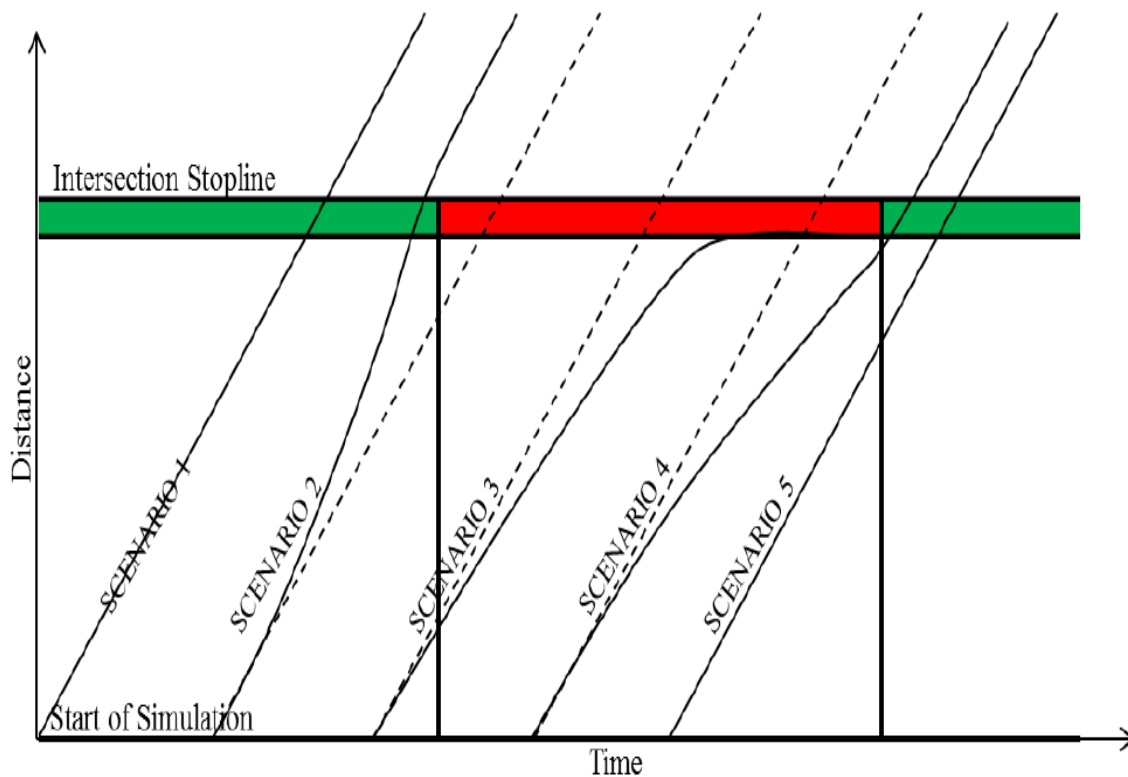
Figure 5 Possible Vehicle Scenarios

Summary

The chapter presented a number of ITS and IVS applications and test cases demonstrating the merits of advanced transportation and vehicle systems in reducing the carbon footprint of transportation systems. These systems range from routing systems, to driver assist systems, to fully-automated vehicle control systems. In addition, the exchange of information with other

vehicles and infrastructure can also assist in reducing the transportation system's carbon footprint.

References

Ahn, K., Rakha, H., 2013. Network-Wide Impacts of ECO-Routing Strategies: A Large-Scale Case Study. Transportation Research Part D: Transport and Environment 25, 119–130. doi:10.1016/j.trd.2013.09.006

Ahn, K., Rakha, H., 2008. The Effects of Route Choice Decisions on Vehicle Energy Consumption and Emissions. Transportation Research Part D: Transport and Environment 13, 151–167. doi:10.1016/j.trd.2008.01.005

Ahn, K., Rakha, H., Moran, K., 2011. ECO-Cruise Control: Feasibility and Initial Testing. Presented at the Transportation Research Board 90th Annual Meeting.

Ahn, K., Rakha, H., Park, S., 2013. Ecodrive Application: Algorithmic Development and Preliminary Testing. Transportation Research Record: Journal of the Transportation Research Board 2341, 1–11. doi:10.3141/2341-01

Ahn, K., Rakha, H., Trani, A., 2004. Microframework for Modeling of High-Emitting Vehicles. Transportation Research Record 1880, 39–49. doi:10.3141/1880-05

Ahn, K., Rakha, H., Trani, A., Van Aerde, M., 2002. Estimating Vehicle Fuel Consumption and Emissions based on Instantaneous Speed and Acceleration Levels. Journal of Transportation Engineering 128, 182–190. doi:10.1061/(ASCE)0733-947X(2002)128:2(182)

Akcelik, R., 1989. Efficiency and Drag in the Power-Based Model of Fuel Consumption. Transportation Research Part B: Methodological 23, 376–385. doi:10.1016/0191-2615(89)90014-3

Barth, A., An, E., Nielsen, L., 2006. Comprehensive Modal Emission Model (CMEM), Version 2.0 User's Guide (SAE Technical Paper No. 2006-01-1071). SAE International, Warrendale, PA.

Barth, M., An, F., Norbeck, J., Ross, M., 1996. Modal Emissions Modeling: A Physical Approach. Transportation Research Record 1520, 81–88. doi:10.3141/1520-10

Del Re, L., Allgöwer, F., Glielmo, L., Guardiola, C., Kolmanovsky, I. (Eds.), 2010. Automotive Model Predictive Control, Lecture Notes in Control and Information Sciences. Springer London, London.

Fisk, C.S., 1989. The Australian Road Research Board Instantaneous Model of Fuel Consumption. Transportation Research Part B: Methodological 23, 373–375. doi:10.1016/0191-2615(89)90013-1

Fröberg, A., Hellström, E., Nielsen, L., 2006. Explicit Fuel Optimal Speed Profiles for Heavy Trucks on a Set of Topographic Road Profiles (SAE Technical Paper No. 2006-01-1071). SAE International, Warrendale, PA.

Hellstr, E., 2005. Explicit Use of Road Topography for Model Predictive Cruise Control in Heavy Trucks Masters Thesis Performed in Vehicular Systems.

Kamalanathsharma, R., Rakha, H., 2014a. Agent-Based Simulation of Ecospeed-Controlled Vehicles at Signalized Intersections. Transportation Research Record: Journal of the Transportation Research Board 2427, 1–12. doi:10.3141/2427-01

Kamalanathsharma, R., Rakha, H., 2014b. Leveraging Connected Vehicle Technology and Telematics to Enhance Vehicle Fuel Efficiency in the Vicinity of Signalized Intersections. Journal of Intelligent Transportation Systems 1–12. doi:10.1080/15472450.2014.889916

Kamalanathsharma, R., Rakha, H., 2014c. Network-wide Impacts of Vehicle Eco-Speed Control in the Vicinity of Traffic Signalized Intersections. Transportation Research Record: Journal of the Transportation Research Board 2427, 1–12. doi:10.3141/2427-01

Kamalanathsharma, R., Rakha, H., Badillo, B., 2014. Simulation Testing of Connected Vehicle Applications in a Cloud-Based Traffic Simulation Environment. Presented at the Transportation Research Board 93rd Annual Meeting.

Ni, D., Henclewood, D., 2008. Simple Engine Models for VII-Enabled In-Vehicle Applications. IEEE Transactions on Vehicular Technology 57, 2695–2702. doi:10.1109/TVT.2008.917229

Park, S., Rakha, H., 2006. Energy and Environmental Impacts of Roadway Grades. Transportation Research Record: Journal of the Transportation Research Board 1987, 148–160. doi:10.3141/1987-16

Park, S., Rakha, H., Ahn, K., Moran, K., 2012. A Study of Potential Benefits of Predictive Eco-cruise Control Systems. Presented at the Transportation Research Board 91st Annual Meeting.

Park, S., Rakha, H., Ahn, K., Moran, K., 2011. Predictive ECO-Cruise Control: Algorithm and Potential Benefits, in: 2011 IEEE Forum on Integrated and Sustainable Transportation System (FISTS). Presented at the 2011 IEEE Forum on Integrated and Sustainable Transportation System (FISTS), pp. 394–399. doi:10.1109/FISTS.2011.5973639

Post, K., Kent, J.H., Tomlin, J., Carruthers, N., 1984. Fuel Consumption and Emission Modelling by Power Demand and a Comparison with Other Models. Transportation Research Part A: General 18, 191–213. doi:10.1016/0191-2607(84)90126-2

Rakha, H., Ahn, K., 2004. Integration Modeling Framework for Estimating Mobile Source Emissions. Journal of Transportation Engineering 130, 183–193. doi:10.1061/(ASCE)0733-947X(2004)130:2(183)

Rakha, H., Ahn, K., Faris, W., Moran, K., 2012. Simple Vehicle Powertrain Model for Modeling Intelligent Vehicle Applications. IEEE Transactions on Intelligent Transportation Systems 13, 770–780. doi:10.1109/TITS.2012.2188517

Rakha, H., Ahn, K., Moran, K., 2011a. INTEGRATION Framework for Modeling Eco-routing Strategies: Logic and Preliminary Results. Presented at the Transportation Research Board 90th Annual Meeting.

Rakha, H., Ahn, K., Moran, K., Saerens, B., Bulck, E.V. den, 2011b. Virginia Tech Comprehensive Power-Based Fuel Consumption Model: Model Development and Testing. Transportation Research Part D: Transport and Environment 16, 492–503. doi:10.1016/j.trd.2011.05.008

Rakha, H., Ahn, K., Trani, A., 2004a. Development of VT-Micro Model for Estimating Hot Stabilized Light Duty Vehicle and Truck Emissions. Transportation Research Part D: Transport and Environment 9, 49–74. doi:10.1016/S1361-9209(03)00054-3

Rakha, H., Lucic, I., Demarchi, S.H., Setti, J.R., Van Aerde, M., 2001. Vehicle Dynamics Model for Predicting Maximum Truck Acceleration Levels. Journal of Transportation Engineering 127, 418–425. doi:10.1061/(ASCE)0733-947X(2001)127:5(418)

Rakha, H., Snare, M., Dion, F., 2004b. Vehicle Dynamics Model for Estimating Maximum Light-Duty Vehicle Acceleration Levels. Transportation Research Record: Journal of the Transportation Research Board 1883, 40–49. doi:10.3141/1883-05

Saerens, B., Rakha, H., Ahn, K., Van Den Bulck, E., 2013a. Assessment of Alternative Polynomial Fuel Consumption Models for Use in Intelligent Transportation Systems

Applications. Journal of Intelligent Transportation Systems 17, 294–303. doi:10.1080/15472450.2013.764801

Saerens, B., Rakha, H., Diehl, M., Van den Bulck, E., 2013b. A Methodology for Assessing ECO-Cruise Control for Passenger Vehicles. Transportation Research Part D: Transport and Environment 19, 20–27. doi:10.1016/j.trd.2012.12.001

Van Aerde, M., 1985. Modelling of Traffic Flows, Assignment and Queueing in Integrated Freeway/traffic Signal Networks. University of Waterloo.

Van Aerde, M., Rakha, H., 2004. INTEGRATION © Release 2.40 for Windows: User's Guide – Volume I: Fundamental Model Features 2013, 140–149.

Van Aerde, M., Yagar, S., 1988. Dynamic integrated freeway/traffic signal networks: A Routing-Based Modelling Approach. Transportation Research Part A: General 22, 445–453. doi:10.1016/0191-2607(88)90048-9

CHAPTER 3: MODELING FUEL CONSUMPTION AND EMISSIONS MODELS: A SYNTHESIS OF DATA SOURCES AND ANALYSIS TOOLS

Overview

The main goal and contribution of this work is to document current practices used to model fuel consumption and emissions in an explanatory synthesis format. This will be beneficial for researchers and transportation engineers who would like to get one easy, organized, and concise document about transportation emissions sources and modeling.

According to the Michigan State University (MSU) English Department, an explanatory synthesis helps readers to understand a topic by dividing the subject into its main parts, then explains each of these. MSU also stated that, in a general way, synthesis papers present the facts in an objective manner instead of arguing a particular point (MSU, 2014).

The work in this chapter is divided into two main sections. The first section focuses on sources of vehicle emissions and fuel consumption data. The second section addresses vehicle emissions and fuel consumption modeling capabilities using different simulation modeling tools covering three analysis levels: microscopic, mesoscopic, and macroscopic. For each of the models, details are provided on how both the kinetics and kinematics components of vehicle motion are being represented and modeled. "Kinetics" refers to the movements of various bodies and the forces that can act on both bodies in motion and bodies at rest. "Kinematics" focuses only on the movement of various bodies, but does not address forces that can influence movement.

Sources of Vehicle Emissions and Fuel Consumption Data

Emission Inventories

An emission inventory is a "database that lists, by source, the amount of air pollutants discharged into the atmosphere during a given period from a certain activity." It is an important component in the air quality management process and is used to determine sources and quantities of different air pollutants and to build emission trends over time (EPA, 2012a). Some of the methods of collecting vehicle emissions and fuel consumption data to build emission inventories include: 1) continuous monitoring of actual emissions

measurements, 2) extrapolating the results from short-term source emissions tests, and 3) merging available activity levels data with associated emission factors.

Emission Factors

An emission factor is defined as a value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. Emission factors are typically expressed as the weight of a specific pollutant divided by the unit weight, volume, distance, or duration of the activity emitting the pollutant (Office of Air Quality Planning and Standards, 2012).The general equation for emissions estimations is:

$$E = A * EF * (1 - ER/100)$$
<div align="right">Equation 1</div>

Where:

- E = emissions;
- A = activity rate;
- EF = emission factor, and
- ER = overall emission reduction efficiency (%).

There are several emission inventories and factors' databases. An example is the Emission Factors (EMFAC) database that includes emission rates for different types of motor vehicles (passenger cars and heavy-duty trucks) operating on highways, freeways and local roads in California. EMFAC-2014 is the most recent version of this model. Data from 25 million registered vehicles in the vehicle registration data were used to update the populations in each vehicle class for 59 geographical areas. Travel activity data are provided by regional transportation planning agencies, while Vehicle Miles of Travel (VMT) and speed data are obtained from the Southern California Association of Governments, Bay area Metropolitan transportation commission, San Diego association of governments, and San Joaquin Valley councils of government (California Environmental Protection Agency - Air Resources Board, 2014).

Another extensive source of emission factors is the EPA's Air Pollutant (AP) -42 Documentation. This documentation was developed by the Emission Factor and Inventory

Group (EFIG). It addresses ozone-related pollutants (like total Organic Compounds, Oxides of Nitrogen (NO_x), and Carbon Monoxide (CO)), hazardous pollutants, and global warming gasses. (Office of Air Quality Planning and Standards, 2012) and (EPA, 2012b). Examples of emission inventories and their available resources are listed below.

National Emission Inventory (NEI):

NEI is a comprehensive and detailed estimate of air emissions and hazardous air pollutants from all air emissions sources. It is developed and maintained by the U.S. Environmental Protection Agency (EPA). NEI is updated every three years based on emission estimates and emission model inputs provided by state, local, and tribal air quality agencies from sources in their jurisdictions. The database is supplemented by data developed by the US EPA. (EPA, 2012a) and (EPA, 2013).

EPA Clearinghouse for Inventories & Emission Factors:

This database contains information on emissions inventories, emission factors, software and tools used for emissions inventories, and emissions modeling. All emission inventory data, tools, and resources could be downloaded from the EPA website (EPA, 2012c).

Biogenic Emissions Inventory System (BEIS):

The Biogenic emissions come from natural sources and need to be accounted for in photochemical grid models. These photochemical grid models could be defined as a large-scale air quality models that use a set of mathematical equations characterizing the chemical and physical processes in the atmosphere to simulate the changes in pollutant concentrations in the atmosphere. Often only the emissions from vegetation and soils are included, but other relevant sources include volcanic emissions, lightning, and sea salt. Biogenic emissions are typically computed using a model that includes spatial information on vegetation and land use and environmental conditions of temperature and solar radiation. The model inputs are typically horizontally allocated (gridded) data, using a fixed coordinate system with respect to the ground, and the outputs are gridded biogenic emissions that can then be speciated and used as input to photochemical grid models (EPA, 2013).

Emissions Modeling System for Hazardous Pollutants (EMS-HAP):

The Emissions Modeling System for Hazardous Pollutants (EMS-HAP) is an emissions processor that performs the steps needed to process an emission inventory for input into the Assessment System for Population Exposure Nationwide (ASPEN) model or the Industrial Source Complex Short Term Model, Version 3 (ISCST3) model. EMS-HAP is written in the SAS programming language and is designed to run on any UNIX workstation. The user will need a SAS license and some knowledge of SAS to use this program (EPA, 2012d).

NONROAD Vehicle & Engine Emission Modeling:

The primary use of the NONROAD Model is for estimating the air pollution inventories by professional mobile source modelers, such as state air quality officials and consultants. NONROAD2008 updates NONROAD2005 to include new non-road emission standards promulgated in 2008 related to small gasoline engines and pleasure craft (EPA, 2012e).

Sparse Matrix Operator Kernel Emissions (SMOKE):

It is a Linux software supported by the "Center for Environmental Modeling for Policy Development (CEMPD) at the University of North Carolina at Chapel Hill. SMOKE is an active open-source development project supported and distributed through the Community Modeling and Analysis System Center. All required information could be obtained from this following source (*SMOKE version 3.1*, 2012).

International Vehicle Emissions (IVE) Model:

The International Vehicle Emissions (IVE) Model is a computer model designed to estimate emissions from motor vehicles. The model is intended to help cities and regions develop emissions estimates to focus control strategies and transportation planning on those that are most effective; predict how different strategies will affect local emissions; and measure progress in reducing emissions over time. The model makes estimates of local air pollutants, greenhouse gas emissions, and toxic pollutants (ISSRC, 2012).

Comprehensive Modal Emissions Model (CMEM):

CMEM is a microscopic emission rate database. The model is based on a total of more than three hundred tested vehicles. These vehicles were tested using three primary driving cycles: 1) The EPA Federal Test Procedure (FTP); 2) the US06, Supplemental Federal Test Procedure (SFTP); and 3) the Modal Emission Cycle (MEC01). During the tests, second-by-second tailpipe and engine-out emissions data (gram emission/gram fuel) were collected [38](Barth et al., 2000a) and (Barth et al., 2000b). CMEM uses a physical, power-demand modal modeling approach based on the vehicle physical characteristics to generate emission tables. The vehicle emissions testing procedure was based on a second-by-second performance measurements of Carbon dioxide (CO_2), Nitrogen Oxides (NOx), Hydrocarbon (HC), and Carbon Monoxide (CO) over three separate driving cycles. The complete modal emissions model is composed of six modules. These models are:

- Engine power demand;
- Engine speed;
- Fuel/air ratio;
- Fuel-rate;
- Engine-out emissions; and
- Catalyst pass fraction (a function primarily of fuel/air ratio and engine-out emissions, and defined as the ratio of the tailpipe to engine-out emissions) (Barth et al., 2000a), and (Barth et al., 2000b)

Emission Inventory Guidebook:

This emission inventory is prepared by the United Nations European Environment Agency (EEA) and the Task Force on Emissions Inventories and Projections (TFEIP). This guidebook provides a comprehensive guide to state-of-the-art atmospheric emissions inventory methodology. The guidebook also supports the efforts of reporting under the United Nations Economic Commission for Europe (UNECE) Convention on Long- Range Trans-boundary Air Pollution and the European Union (EU) directive on national emission ceilings (United Nations Economic Commission for Europe, 2012), and (TFEIP, 2012).

Vehicle Emissions and Fuel Consumption Modeling Capabilities of Simulation Modeling Tools

In this part of the work, different simulation modeling tools are presented. Traffic simulation models were divided, based on the level of analysis into these three categories: microscopic, mesoscopic, and macroscopic (Yue, 2008). In the following sections, a brief summary of the characteristics of different models, as they relate to modeling fuel consumption and vehicle emissions will be presented and discussed. The reviews presented include the model's emission modeling capabilities, how vehicle kinematics and kinetics are being represented in the model, and how it could be used for research related to emissions and fuel consumption. As a differentiation between "kinetics" and "kinematics", "kinetics" is a mechanics branch that focuses on the movements of various bodies and the forces that can act on both bodies in motion and bodies at rest, however "kinematics" is solely focused on the movement of various bodies, without addressing the forces that can influence movement.

Microscopic Simulation Models

Microscopic simulation tools model the movement of individual vehicles on the basis of car-following and lane-changing theories. They describe both the system entities and their interactions at a high level of detail. These models are also designed for operations analyses of systems of road facilities (Lieberman and Rathi, 1997), (Dowling et al., 2002), and (Alexiadis et al., 2004). Using instantaneous speeds and acceleration of individual vehicles, microscopic models can calculate fuel consumptions. These models are usually used to evaluate individual transportation projects. There are several microscopic simulation models currently available. Examples of these models include: Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks (AIMSUN2), Corridor Simulation (CORSIM), INTEGRATION, MICSTRAN (Microscopic Simulator Model for Traffic Networks (MicroSim), Microscopic Traffic Simulator (MITSIM), Probabilistic Adaptive Simulation Model (PADSIM), PARAMICS, SimTraffic, VISSIM, and Wide Area Traffic Simulation (WATSim).

VISSIM

VISSIM is a stochastic, microscopic, time step, and behavior based traffic simulator. VISSIM's traffic model is based mainly on the psychophysical driver behavior model of R. Wiedemann, in which the driver's reactions are in response to the relative speed and distance of the preceding vehicle. VISSIM can simulate multi-modal traffic flows, including passenger cars, buses, light rail, trucks, pedestrians, and others. VISSIM was originally developed at the University of Karlsruhe, Germany in the early 1970s, while the commercial distribution, development, and maintenance started in 1993 by PTV Transworld AG and is still done by them today (Loren Bloomberg and Dale 2000), and (Gomes et al., 2004). VISSIM is formed mainly from two main parts; the first one is the simulator generator part, in which the user can import aerial photos and schematic drawings and can begin to build the simulation network graphically. The second main part is the signal state generator (SSG), in which the logic of the signal control exists, and in which the user can define lots of different signal operations like fixed time, and ramp metering (Loren Bloomberg and Dale 2000), and (Gomes et al., 2004).

VISSIM was used in several of the research work related to emissions. In one paper, researchers proposed a real-time signal control method to minimize CO_2 emissions (Umedu et al., 2012). This method integrated arrival times from the information that consists of position and speed from the vehicle to vehicle and vehicle to infrastructure communications. The paper speculates that the more signals that are controlled together, the more efficient control can be and thus the authors have decided to use this specification in their system. The process of analyzing emission used mathematic calculations of exhaust output and VISSIM simulation to provide travel times of a corridor.

VISSIM is supporting an add-on called EnViVer. Using the vehicle record data, EnViVer can calculate different types of emissions like CO_2, NO_x, and PM_{10}. The emission model in EnViVer is the microscopic exhaust gas/emission model VERSIT+ which is based on emission measurements for about 2,800 vehicles under different driving conditions. The main idea of EnViver is based on importing the VISSIM record files and then calculating the

emissions at spatial detail, and finally getting the output tabulated or graphed (PTV Group, 2012).

CORSIM

CORSIM is a microscopic simulation program developed by the Federal Highway Administration (FHWA), and part of the Traffic Software Integrated System (TSIS) which offers a window-based interface for running the model. CORSIM mainly includes two traffic simulation predecessor models, NETSIM, and FRESIM. NETSIM is concerned with arterials with at-grade intersections (urban street traffic); while FRESIM models uninterrupted facilities including interstate freeways and grade separated expressways (freeway traffic). CORSIM executes the simulation and measures the network efficiency to the user in predetermined Measures Of Effectiveness (MOEs) (Minnesota Department of Transportation, 2008), (Bloomberg and Dale, 2000), and (Park et al., 2004). When combined with NETSIM and FRESIM models, CORSIM is capable of simulating a large set of systems. These systems include freeways, urban streets, corridor or networks, different intersection control (e.g. pre-timed signals and actuated ones), almost any surface geometry, including turn pockets and the number of lanes, weaving sections, work-zones, and bus operations (Minnesota Department of Transportation, 2008), (Bloomberg and Dale, 2000), and (Park et al., 2004).

CORSIM is mainly based on a link-node structure network model, where links characterize roadway segments, and the nodes represent intersections, entry and exit points. CORSIM is a stochastic simulation model, which means that it uses random processes to model drivers' behavior, vehicle characteristics, and interactions into each run. Multiple runs may be required to get a true picture of the network because one run might be not representative. CORSIM creates tabulated data for fuel consumption and environmental emissions. It can also tabulate and graph the effect of traffic different control strategies on acceleration and fuel consumption. Because CORSIM's data was not updated for many years, FHWA recommends using the data for comparison analysis only and not as absolute indications (Minnesota Department of Transportation, 2008), (Bloomberg and Dale, 2000), (Park et al., 2004), and (FHWA, 2010).

The newer versions of CORSIM have adopted the Vehicle Transient Emissions Simulation Software (VeTESS) for the process of calculating fuel consumption and emissions. VeTESS was developed as a vehicle level tool for the simulation of fuel consumption and emissions for real traffic transient vehicle operation within the EU 5th framework project DECADE (2001-2003). VeTESS is capable of calculating emissions and fuel consumption made by a single vehicle during a defined "drive-cycle." For a given drive-cycle, VeTESS uses simple mathematical calculations to determine the engine's operating conditions from the force on the vehicle. These calculations involve gear ratios and their efficiencies. Using the equation of motion, Equation 2, VeTESS calculates the total force on the vehicle.

$$F_{total} = F_{accel} + F_{grad} + F_{roll} + F_{aero}$$
<div align="right">Equation 2</div>

Where:

- F_{total} = The total force acting on the vehicle,
- F_{accel} = The force required in order to cause an acceleration of the mass of the vehicle,
- F_{grad} = The component of the weight force of the vehicle acting parallel to the slope,
- F_{roll} = The rolling resistance,
- F_{aero} = The aerodynamic resistance.

The engine provides the force required to overcome the motion resistances as a torque. After that, driven wheels convert this torque from rotational to linear motion. VeTESS then evaluates the engine speed and engine torque from the forces acting on the vehicle and references the corresponding values for the emission components using emission maps. These maps are generated by operating the engine in a series of steady-state conditions (Beckx et al., 2007).

CORSIM was used in many research works related to emissions. One example of this type of research is Kosman et. al. who evaluated both CORSIM and VISSIM for project-level emission modeling (Kosman et al., 2003). The studied project-levels included the impacts of

traffic flow improvements resulting from changes in signal timing or other roadway improvements. CORSIM was compared to VISSIM for two different scenarios.

In the first scenario, outputs from the two models were compared to spot speed and average speed data collected from the field. Average speed, includes the total travel time along a link including idling, and this is why average speeds generated by simulation models depend on the effectiveness of queuing and delay prediction.

In the second scenario, the models' predicted emission reductions were compared to three Congestion Mitigation and Air Quality (CMAQ) projects. In the first scenario, researchers found that both CORSIM and VISSIM under-predicted the mid-block spot speed, with mixed results for the average speed. Overall predicted emissions (VOC and NO_x) in the first scenario from CORSIM, VISSIM, differed the field studies by less than 7%. In the second scenario, researchers found that CORSIM predictions differences in pre- and post-project speeds are greater than VISSIM predictions for all three projects. This resulted in causing greater reductions in emissions.

CMEM

The Comprehensive Modal Emissions Model (CMEM) is published by the Center for Environmental Research and Technology (CE-CERT) in Riverside, California. Development of CMEM began in the late 1990s with support from the Cooperative Highway Research Council and continued until the final phase was completed in 2005. CE-CERT has also received some support from the Environmental Protection Agency (EPA). CMEM is not a traffic simulator, which means that all vehicle activity data must come from another source. Because of this, microscopic traffic simulation software is often used to generate traffic network and activity data, and input to CMEM to calculate emissions. Several interface applications used to link CMEM with microscopic simulation software have been developed and used with success (Barth et al., 2005). CMEM is an open source and is available free for download.

CMEM is based on a deterministic physical power demand model, which is based on a parameterized analytical representation of emissions production. Emission rates depend on causal variables such as fuel delivery system, inspection maintenance effects, and vehicle age. Second-by-second vehicle tailpipe emissions are modeled as the product of three components: Fuel Rate (FR), engine-out emission indices (gram $_{emission}$/gram $_{fuel}$), and time-dependent catalyst pass fraction (M. Barth et al., 2006). Because the rates contained in CMEM are based on physical parameters, in theory it could be adapted to represent new vehicle technologies. However, the most recent major changes the CMEM emission rate database took place in 2005, which indicates that the emissions data contained in this software could be outdated.

CMEM data properly incorporate the physical variables that contribute to emission rates. Existing emission inventories were deemed too generalized by vehicle category and not detailed enough for this purpose. Instead, emission rates were developed "in-house" from tests conducted on several hundred recruited vehicles at the University of California Riverside Center for Environmental Research and Technology. CMEM is based on a simple parameterized physical approach.

This approach uses six modules that predict engine power, engine speed, air/fuel ratio, fuel use, engine-out emissions ($g_{emission}/g_{fuel}$), and the catalyst pass fraction. All emission data used in CMEM were collected in the USA, mostly at the Riverside facility. For the most part, emission data were collected on dynamometer tests, using a number of different drive cycles with the intent to capture the full range of operation in the resulting emission rates. Much of the data used in CMEM were collected before 1998, with additional low emitting vehicle data collected in 2002-2003 (M. Barth et al., 2006). The input operating variables in CMEM have some variables such as; (acceleration, air/fuel equivalence ratio, and fuel rate), second-by-second speed, road grade angle, and accessory use (such as air conditioning). The main output of the CMEM model is the instantaneous emission. This instantaneous emission could be calculated as the product of three components:

- Fuel rate,
- Mass of engine-out emissions per grams of fuel consumed, and

- The catalyst pass fraction which is the ratio of tailpipe emission to engine-out emission (An et al., 1997).

The instantaneous emissions equation is shown in Equation 3:

$$\text{Tailpipe emissions} = \text{FR} \cdot \left(\frac{g_{emission}}{g_{fuel}}\right) \cdot CPF \qquad \text{Equation 3}$$

Where:

- FR = fuel-use rate in grams/s,

- $g_{emissions}/g_{fuel}$ = grams of engine-out emissions per grams of fuel consumed, and

- CPF = the catalyst pass fraction, defined as the ratio of the tailpipe to engine-out emission.

The total tractive power requirements (in KiloWatt-KW) placed on the vehicle (at the wheels) is shown in Equation 4:

$$P_{tract} = A \cdot v + B \cdot v^2 + C \cdot V^3 + M \cdot a + M \cdot g \cdot v \cdot \sin\theta$$

$$P = \frac{P_{tract}}{\eta_{tf}} + P_{acc} \qquad \text{Equation 4}$$

Where:

- M = the vehicle mass with the appropriate inertial correction of rotating and reciprocating parts (kg),

- v = speed (m/sec.),

- a = acceleration (m/s^2),

- g = the gravitational constant (9.81 m/s^2), and

- θ = the road grade angle.

- P = the engine power output,

- η_{tf} = the combined efficiency of the transmission and final drive,

- P_{acc}= the engine power demand associated with the operation of vehicle accessories.

The fuel rate in any driving cycle for any vehicle model could be calculated using Equation 5:

$$FR \approx \left(KNV + \frac{P}{\eta}\right)\frac{1}{44}$$

Where,

- k = the engine friction factor,
- N = engine speed (revolutions per second),
- V = engine displacement (liter),
- $\eta \approx 0.4$ = a measure of indicated efficiency.

And finally the engine-out emission module could be calculated using Equation 6:

$$ECO \approx [C_0(1 - \phi^{-1}) + a_{co}]FR$$

$$EHC \approx a_{HC}FR + \gamma_{HC}$$

$$ENO_x = a_{1NOX}(FR - FR_{NOX})$$ If>0 and 0 otherwise, for $\phi<1.05$

$$ENO_x = a_{2NOX}(FR - FR_{NOX})$$ If>0 and 0 otherwise, for $\phi\geq1.05$

Where:

- C_0, a_{CO}, a_{HC}, and Υ_{HC} are calibrated constant coefficients that are slightly different from vehicle to vehicle,
- a_{1NOX} and a_{2NOX} are engine-out NO_X emission indexes in grams of emissions per gram of fuel use under optimum and enrichment conditions, respectively, and
- FR_{NOX} is fuel rate thresholds.

One of the examples of using CMEM in the emissions research work is Xia et al. (2012) that discussed the use of the ECO-Signal Operations approach technology. The ECO-approach technology means a traffic signal that broadcasts its signal phase and timing, and Geometric Intersection Description to the vehicle. An on-board system takes this information along with vehicle position and speed and provides speed recommendations to the driver. This speed would be an emission reducing optimal speed. Field tests were conducted using a test

vehicle equipped with the optimal speed algorithm. Based on the vehicle speed trajectories during the test, vehicle fuel consumption was calculated using CMEM. During the two tested scenarios, vehicle emissions were reduced compared to the control, an uninformed driver (Xia et al., 2012).

INTEGRATION

INTEGRATION is a trip-based microscopic traffic and emissions simulation model. It was developed in its current version under the direction of Dr. Hesham Rahka at Virginia Tech. The software includes a traffic assignment tool, in which Origin-Destination (O-D) matrices are entered along with departure time series histograms for each O-D pair. The INTEGRATION framework can model a range of on-road vehicle types and supports a total of 25 default options including passenger cars, light-duty trucks, and heavy-duty trucks. Similar to most industry standard traffic simulation software, vehicle operation is governed by proprietary car following, lane changing and gap acceptance models (Rakha, 2013).

INTEGRATION was designed with a strong basis in vehicle operation dynamics and is intended to represent acceleration and velocity accurately at high temporal resolution. In addition, the model is designed to offer flexibility in estimating acceleration rates of both large and small vehicles on varying road types and conditions. This accuracy and flexibility are a necessity for microscopic power-based emissions modeling (Rakha, 2013).

INTEGRATION allows the user to specify time series histograms for departures for each origin-destination pair in the simulation. The software generates individual vehicle departure time schedules from this information before the simulation is run. Departures can be fully random or any combination of random and uniform. Calibration of the O-D demand is achieved using a maximum likelihood approach (Rakha and Ahn, 2004b). Pipes and Greenshields car-following and traffic stream models were combined into a single regime model, based on desired speed and proximity to followed vehicle. This is referred to as Van Aerde's model after Michael Van Arde, the original developer of INTEGRATION. The model is calibrated using four parameters based on field data: free-speed, speed-at-capacity,

capacity, and jam density. Position, headway, and speed are computed in 0.1 second time steps (Rakha et al., 2004c), (Rakha et al., 2001b), and (Rakha et al., 2004e).

INTEGRATION uses a separate acceleration and deceleration logic. Deceleration is computed based on the existing speed, the speed of the vehicle or object that is necessitating the deceleration, and the time available to decelerate. According to the developers, this can lead to an asymptotic deceleration of a vehicle following another vehicle that is traveling at a constant speed. In any case, a vehicle will not continue to decelerate once it reaches the speed of the vehicle ahead of it (Rakha et al., 2004c).

Vehicle acceleration in INTEGRATION is simulated with the vehicle dynamics model, as opposed to the more common kinematic acceleration models. One of the problems identified with the state of practice models is in their ability to represent the speed/acceleration relationship at low vehicle speeds. Most models allow acceleration to vary as a function of speed, with higher acceleration in general associated with lower travel speeds. However, there are a number of different ways of modeling this and is no definitive relationship between these two parameters. According to the developers of INTEGRATION, industry-standard traffic models tend to overestimate acceleration at low speeds, which makes them poorly suited for emissions modeling (Rakha et al., 2004e), (Rakha et al., 2004c), (Rakha et al., 2001b). INTEGRATION addresses this issue by constraining vehicle acceleration to the physical limitations of the vehicle as described below.

In the INTEGRATION model, power is computed as the minimum of 1) maximum tractive effort based on tire/road surface friction and vehicle weight and 2) engine power, corrected for transmission efficiency and accessory power use. In addition to power, rolling resistance, aerodynamic drag, grade, and vehicle mass are all considered in acceleration computations. The model also accounts for the fact that drivers do not typically use the maximum power available in their vehicles. The configuration differs somewhat for light-duty and heavy-duty vehicles (LDV's and HDV's). The HDV model accounts for the loss of power at low speeds due to gear shifting (Rakha et al., 2001b). The LDV model is very similar but assumes that the low-speed power loss effect is negligible for passenger vehicles (Rakha et al., 2004e).

Both the LDV and HDV models were calibrated using field data collected at Virginia Tech's Smart Road test facility in Blacksburg, Virginia.

For the HDV model, four heavy-duty diesel trucks of model years, ranging from 1990 to 1998 were driven over the test course in the spring of 2001. Ten different load cases were tested for each vehicle. By changing the loading, researchers hoped to incorporate the range of power to weight ratios that would typically be observed in practice. This data was used to calibrate the power adjustment factor, which is a linear function relating engine power to vehicle speed. This factor is intended to capture the average power reduction due to gear shifting as a function of speed, as actual power fluctuates between the maximum value and zero as gear shifts take place (Rakha et al., 2001b).

Vehicle acceleration data were collected in the summer of 2001 using 13 test vehicles ranging from subcompact to light duty trucks. This data was used to calibrate and compare several state of practice vehicle acceleration models, including the dynamics model used in INTEGRATION. Comparisons were made for speed and acceleration versus time and distance, as well as acceleration versus speed. The results of the comparison, strongly supported the vehicle dynamics model over the other state of practice models. This was a relatively simple validation and did not involve any real world vehicle interaction or complex maneuvers (Rakha et al., 2004e).

The emissions model incorporated into INTEGRATION is the Virginia Tech Microscopic energy and emission model (VT-Micro). While a full discussion of the model structure is outside the scope of this report, the model will be described as it relates to INTEGRATION. Based on the instantaneous speed and acceleration levels of individual vehicles, VT-Micro, predicts the instantaneous fuel consumption and emission rates of HC, CO, NOX and CO2 (Ahn, 1998), (Rakha et al., 2000), and (Ahn et al., 2002c).

One important thing to note is that, when the performance characteristics, like acceleration characteristics, of the VT-Micro data, are exceeded in the input speed and acceleration data, emissions will be computed at the boundary of the VT-Micro data. That is to say, the

performance envelope of the VT-Micro data determines the maximum possible emission rates (Rakha et al., 2004c). Although INTEGRATION computes speed and acceleration in 0.1 second-time steps, these values are averaged over one second time steps for emission calculations. According to supporting documentation, this reduces the accuracy of the emissions estimates and is done to reduce the computational load.

Emission rates were collected using dynamometer tests and standardized drive cycles. The first study to develop non-high emitting vehicle emission rates was conducted in 1996 at the Oak Ridge National Laboratory (ORNL). Test vehicles included five light-duty automobiles and three light-duty trucks and were selected to be representative of the sales proportion in terms of engine displacement, based on sales data from 1995 and 1996. The vehicles used in the emission rate development were subjected to driving tests in order to develop practical performance limits that correlate to the actual vehicle capabilities (Rakha and Ahn, 2004b). The general VT-Micro equations used to calculate the instantaneous fuel consumption and emission rates of individual vehicles could be seen in Equation 7.

$$MOE_e = \sum_{i=0}^{3} \sum_{j=0}^{3} exp\left(k_{i,j}^e * v_{VT}^i * a^j\right), for\ a \geq 0$$

Equation 7

$$MOE_e = \sum_{i=0}^{3} \sum_{j=0}^{3} exp\left(l_{i,j}^e * v_{VT}^i * a^j\right), for\ a < 0$$

Where:

- MOE_e = Instantaneous fuel consumption or emission rate (Liter Per Second or milligram per second),
- a = Instantaneous acceleration of vehicle (km/h/s),
- v = Instantaneous speed of vehicle (km/h),
- $k_{i,j}^e$ = Vehicle-specific acceleration regression coefficients for MOEe, and
- $l_{i,j}^e$ = Vehicle-specific deceleration regression coefficients for MOEe.

Since the initial release, the VT-Micro model has been updated to include emissions data from 87 additional cars and trucks. This update is described in the documentation related

specifically to VT-Micro, but it is stated that the updated model has been included in the current release of INTEGRATION (Rakha and Ahn, 2004b). This data was gathered by the EPA using dynamometer tests at the Automotive Testing Laboratories, Inc., in Ohio and EPA's National Vehicle and Fuels Emission Laboratory (NVREL) in Michigan in the spring of 1997.

Vehicles of model years 1986 to 1996 were drafted at random from inspection and maintenance lanes in Ohio. Vehicles were screened to separate high emitting from non-high emitting vehicles, and separate rates developed for each group. In the screening process, 60 vehicles were identified as non-high emitters and 37 as high emitters. Each vehicle was tested in 14 to 16 different drive cycles to insure that the full range of acceleration/speed combinations was captured. In addition to the typical vehicle categories of light duty and heavy duty, statistical methods were used to define five LDV and two light-duty truck (LDT) categories.

Emission rates were developed from test data using the methods described in the VT-micro model supporting documentation (Rakha et al., 2004c). Regression equations were developed to represent emission rates as functions of speed, power, and acceleration. Separate regression equations were developed for positive and negative acceleration because engine power is exerted in positive acceleration while none is exerted in negative acceleration. An optimal temporal shift of approximately six– eight seconds was computed to deal with the time lag between acceleration and tailpipe emissions.

Aggregate and instantaneous emission rates were validated using a number of drive cycles, but no validation was performed (at least in the rate development studies) using microsimulation versus real world data. The documentation of the rate development studies is focused primarily on the emission vs. acceleration and speed relation, as opposed to the simulated versus real world relationship.

PARAMICS

Paramics is a microscopic traffic simulation software package published by Quadstone in Edinburgh Scotland. Interestingly, there are two similar microscopic traffic simulation software titles published under the name Paramics, the Quadstone product and "S-Paramics" that is published by the SIAS company in Edinburgh. According to the SIAS company website, the similarity in both name and underlying model is the result of a partnership between Quadstone and SIAS that was dissolved in 1998 (SAIS, 2012), and (Mahfoudh-Boussaid et al., 2012). Here the focus is on the Quadstone product for several reasons. One, Quadstone Paramics has more functionality in terms of emissions modeling. S-Paramics does have a built in emissions model, but it is out of date and has limited functionality. In addition, Quadstone Paramics contains "Paramics API", which is a tool for creating and utilizing added functionality, such as integrating Paramics with external emissions models (Quadstone, 2012).

Paramics allows a good deal of user flexibility in terms of vehicle behavior, signal timing, and data collection (Speirs and Braidwood, 2004). Paramics is advertised as "fully scalable", which means that a broad range of network scales can be modeled, from a single intersection to an entire city (Quadstone, 2012). Simulated vehicles are represented as "Driver-Vehicle units" (DVU's), each of which is assigned a number of physical and decision characteristics, including vehicle geometry and performance parameters, familiarity with the traffic network, aggressiveness, and origin-destination information. DVU route selection can be made in three different ways, including deterministic, stochastic cost weighting, and dynamic feedback that is a real-time decision structure based on driver familiarity and traffic conditions.

The "Advanced" version of the software also contains an OD estimating tool (Quadstone UGM, 2009). Vehicle movement across a network is determined by Quadstone's proprietary car-following and lane-change models (Speirs and Braidwood, 2004). For signal timing, Paramics can model fully actuated and demand responsive signal plans, with the option to change signal parameters as the model is running. This allows the user to make changes to

signal timing and immediately observe the effect on traffic flow. Paramics apparently does not include an automatic traffic signal optimization application, but does include a number of up to date tools designed to aid the user in visualizing and optimizing signal timing and other traffic control mechanisms (Quadstone, 2012).

One notable component of Quadstone Paramics is Monitor, a proprietary emission modeling tool. However, little documentation was found that describes either the methodology or underlying data used in this application. Based on the limited documentation available, it is clear that Monitor utilizes tables that contain vehicle exhaust emissions and fuel consumption rates as a function of vehicle type, speed, and acceleration (Barth et al., 2000a). The software simply looks up the values for each second in the analysis to compute pollutant quantities and fuel consumption. It is likely that, in most cases, emission rates will be provided by the user because of the inadequacy of emission data contained in Monitor. In one study, emission rates were computed for each second in the analysis using a CMEM plug-in developed in the Paramics API, which demonstrates the flexibility that the API tool provides (Barth et al., 2000a).

Another example of using PARAMICS in the emissions related research work is (Boriboonsomsin and Barth, 2008) who studied the impact of freeway High-Occupancy Vehicle (HOV) lane configuration, continuous access HOV and limited access HOV, on vehicle emissions. In this paper, the authors used an emissions modeling methodology that integrates PARAMICS, a microscopic traffic simulation model, with CMEM, a modal emissions model to estimate vehicle emissions from these two types of HOV lane configurations. Their research found that the emissions in freeways with continuous access HOV lane are consistently lower than emissions from freeways with limited access HOV lane. This result was justified by mentioning that the dedicated ingress/egress sections of the freeway with limited access HOV lane are having highly concentrated weaving maneuvers, which cause acceleration/deceleration events to occur with higher frequency and magnitude.

Mesoscopic Models.

Mesoscopic models combine the properties of microscopic and macroscopic simulation models. They represent most entities at a high level of detail but describe their activities and interactions at a much lower level of detail than would a microscopic model. They provide more coverage with less modeling detail than microscopic simulation. Similar to microscopic models, the mesoscopic models' unit of traffic flow is the individual vehicle. However, the movement of these vehicles in mesoscopic models follows the approach of the macroscopic models and is governed by the average speed on the travel link (Lieberman and Rathi, 1997), (Dowling et al., 2002), (Alexiadis et al., 2004).

The MEASURE Model

Researchers at The Georgia Institute of Technology developed the Mobile Emission Assessment System for Urban and Regional Evaluation (MEASURE). MEASURE is a GIS-based emissions model. It can calculate estimates of HC, CO, and NO_x. Two major modules are included in MEASURE. The first one is the start emissions module while the second one is the on-road emission module (Bachman et al., 2000). Refined tree-based regression analysis of vehicle emission test data was used to calculate the emission rates in MEASURE. In MEASURE, emission rates are a function of pollutant, vehicle model year, vehicle fuel delivery technology, high or normal emitter vehicle, and modal variables. Source of data is from EPA and California Air Resource Board.

Vehicle emissions for the On-Road Emission module are estimated based on different operating modes. These modes are idle, cruise, acceleration, and deceleration. Average travel speed, roadway characteristics, traffic flow, and volume to capacity ratio are used to build the vehicle operating modes. Vehicle registration data were used to get vehicle cold and hot-start characteristics distribution, and then estimate the start emission model. The start emission estimates will be based on start characteristics distribution and start emission rates (Bachman et al., 2000).

DYNASMART-P:

DYNASMART (DYnamic Network Assignment-Simulation Model for Advanced Road Telematics) is currently supported by the Federal Highway Administration through McTrans. DYNASMART-P provides lots of features like: the capability of modeling big networks, importing of network and demand data from other planning models, enhanced loading and display speed for large-scale network datasets, and emissions models for light-duty vehicles (Mehta et al., 2003).

The emission models used in DYNASMART-P are adapted from the lookup tables for fuel consumption and emissions developed at the Oak Ridge National Laboratory (ORNL) in the mid-1990s (ORNL models). These fuel consumption and emissions models are based on functions of vehicle speed and acceleration. DYNASMART-P is using ONROAD models developed at Texas Southern University for heavy-duty vehicles. EPA also accepted MOBILE 5 to be also interfaced with DYNASMART-P for additional analysis. More details of the development methodology of these used models, the look-up tables, and their evaluation of other emission models like INTEGRATION could be found in these resources: (West et al., 1997), and ((FHWA, 1999).

Macroscopic Models

Macroscopic simulation models are designed for operations analyses of systems of road facilities. The simulation in a macroscopic model takes place on a section-by-section basis rather than by tracking individual vehicles. Macroscopic models are based on the deterministic relationships of the flow, speed, and density of the traffic stream. In these models, entities and their activities and interactions are described at a low level of detail, while minor details, like the lane change maneuvers, would not be present at all (Lieberman and Rathi, 1997), (Dowling et al., 2002), and (Alexiadis et al., 2004).

MOVES (Motor Vehicle Emission Simulator)

The most recent release, MOVES2014, is the EPA's newest multi-scale on-road emissions model. It has replaced MOBILE 6 as the preferred software for State Implementation Plans

and Transportation Conformity Analyses. Although it is considered by the EPA to be capable of modeling at macro, meso, and micro scale, it is not a traffic simulator and vehicle activity data must be input by the user for smaller scale modeling.

In macro scale computed vehicle activity is based on nationwide vehicle miles traveled data, which is not precise enough for mesoscopic and microscopic scale analysis (EPA, 2012f). Despite this lack of precision, MOVES contains an impressive amount of emissions and vehicle data, and can be used with a microscopic traffic simulator to model system-level changes. Emissions data for light-duty passenger vehicles is based largely on inspection maintenance test data from the Phoenix, Arizona area. This data dates from 1995 to 2005 and was collected from approximately 62,500 vehicles (EPA, 2011a), and (EPA, 2011b). Heavy-duty and additional light duty vehicle and emissions data are based on a number of different studies, all using American vehicles and driving conditions.

In general, the EPA loosely based data requirements for each vehicle subgroup of the population of that vehicle type currently on the road. As a result, some emission rates (such as those for heavy duty gasoline vehicles) are based on a comparatively small quantity and range of actual data (EPA, 2011a). Some emission rates were determined using on-road vehicle operation; others were simply calculated from dynamometer tests using EPA standard drive schedules.

Over 60 different pollutants can be modeled separately in MOVES, which is likely the most of any emission model currently available. Basic emission rates in MOVES such as fuel consumption, NO_x, and CO are a function of vehicle specific power (VSP) and are in units of mass/time (EPA, 2011a), and (EPA, 2011b). Many minor pollutants and all air toxics are computed as fractions of major pollutant quantities. The software corrects for a number of scenario variables, including meteorological conditions, startup emissions, and local inspection and maintenance program effects. Simulation is conducted in one second-time steps and generates output in the form of MySQL database tables.

At the micro scale, there are two preferred methods to input vehicle activity information. The first method is to input data for each link in the modeling area in the form of a second-to-second vehicle velocity profile. This input can come from actual vehicle travel logs, EPA standard drive cycles, or from microscopic simulation output. This is used along with default vehicle characteristics to generate a time distribution of vehicle operating modes differentiated according to the MOVES classification system by VSP. Alternatively, the user can provide the operating mode distribution directly as an input table. Total activity is computed in units of time based on average speed and link geometry, and this is used by the operating mode distribution to compute the time spent in each emission rate-specific operating mode (EPA, 2011a), and (EPA, 2011b).

MOVES was used in many studies in the last ten years. In one example of these studies researchers reviewed a study conducted to compare the vehicle activity of a roundabout to other intersections based on testing the hypothesis that roundabouts are more efficient (Hallmark and Mudgal, 2012). The study used on-road instrumentation to record second by second vehicle activity, i.e. instantaneous speed and acceleration. This vehicle activity data were inputted into MOVES, and mathematical equations for the vehicle specific power (VSP) bins were used to estimate the emissions for the three different traffic controls. VSP is a variable for engine load that has been shown to be highly correlated with emissions. The VSP bins separated emissions rates and data was placed into bins based on the emissions rate recorded. With these bins, researchers were able to see where the majority of the data points lie. The data showed that roundabouts have higher vehicle emissions through the intersection however they are not in the "system" as long. This means more experimentation needs to be completed for vehicle emissions over a time period.

Another example for using MOVES is when Qiao et al. (2012) who evaluated the concept that if vehicles can communicate with stop signs, drivers will start to slow earlier without physically seeing the stop sign. Preemptively locating stop signs can result in more fuel-efficient stopping (Qiao et al., 2012). In order to communicate with the vehicles the authors of this study analyzed the use of Radio Frequency Identification (RFID) devices. RFIDs have already been implemented in the transportation discipline. MOVES was used

alongside incorporated VSP bin distributions and their related emissions rates. Average emissions were found from the MOVES binning and PEMS emissions data. Emissions rates were estimated for vehicles with and without the RFID. The vehicle with the RFID had lower emission rates no matter which direction the driver chose to go once leaving the intersection.

Watson Model

A fuel consumption model was developed by Watson et al. (1979) using average speed data. The changes in the positive kinetic energy during acceleration were used as a predictor variable in this model, But the effects of speed changes during the deceleration phase were not included (Watson, 1979). Also, the effect of aerodynamic drag on fuel consumption becomes significant at higher average speeds (at average speeds over 55 km/h), and this is also is not included in the study (Evans and Herman, 1978).

The fuel consumption-space mean speed relationship is in Equation 8:

$$F = K_1 + \frac{K_2}{V_s} + K_3 V_s + K_4 PKE$$

<div align="right">Equation 8</div>

$$PKE = \sum (V_f^2 - V_i^2)/(12.960 X_s)$$

Where,

- F = fuel consumed (L/km),
- V_s = space mean speed (km/hr),
- PKE represents the sum of the positive kinetic energy changes during acceleration in m/s^2,
- V_f = final speed (km/hr),
- V_i = initial speed (km/hr),
- X_s = total section length (km),
- $K1$: parameter representing idle flow rate ,
- $K2$: parameter representing fuel consumption to overcome rolling resistance,
- $K3$: parameter representing fuel consumption to overcome air resistance,

---

- $K4$: parameter related to fuel consumption due to positive acceleration.

Summary and Conclusion

This work is directed to researchers and transportation engineers who would like to get one organized document as a resource for information about transportation emissions sources and modeling tools. The main goal and contribution of this work is to synthesize and document current practices in modeling fuel consumption and emissions models in a synthesis format, which is presenting different facts in an organized, and reasonably objective manner instead of arguing a particular point.

The synthesis work presented in this work focuses on two main areas: fuel consumption and emission modeling tools, and sources of emissions inventory and data used in the models. In the first part of this work, the authors started providing some details about the definition, importance, and methods of calculation of emission inventories, emission factors, and some of the currently available emission inventories. In the second part, the authors reviewed currently available fuel consumption and emission models suitable for modeling traffic operations. The review in this second part included three different analysis levels: microscopic models, mesoscopic models, and macroscopic models. The organization of this section consisted of techniques that utilize mathematical models, simulation packages, and in-the-field systems.

A summary for all the previous work could be seen in the following four tables.

Table 1 Summary of the emission inventories and factors

Sources of Vehicle Emissions and Fuel Consumption Data	
Emission Inventories	A database that lists, by source, the amount of air pollutants discharged into the atmosphere during a given period from a certain activity. Two emission inventories examples are the National Emission Inventory (NEI), and the Biogenic Emissions Inventory System (BEIS).
Emission Factors	A value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. Emission factors are typically expressed as the weight of a specific pollutant divided by the unit weight, volume, distance, or duration of the activity emitting the pollutant

Table 2 Summary of Microscopic Models

Microscopic Models	
VISSIM	A stochastic, microscopic, time step, and behavior based traffic simulator, which is based mainly on the psychophysical driver behavior model of R. Wiedemann. VISSIM is supporting an add-on called EnViVer, which can calculate different types of emissions like CO_2, NO_x, and PM10
CORSIM	CORSIM is a microscopic simulation program developed by the (FHWA). CORSIM adopts the VeTESS software for the process of calculating fuel consumption and emissions.
CMEM	The Comprehensive Modal Emissions Model (CMEM) is based on a deterministic physical power demand model, which is based on a parameterized analytical representation of emissions product. Emission rates depend on causal variables such as fuel delivery system, inspection, maintenance effects, and vehicle age
INTEGRATION	INTEGRATION is a trip-based microscopic traffic and emissions simulation model. The emissions model incorporated into INTEGRATION is the VT-Micro model. Integration is used in lots of research work since it takes into consideration the vehicle kinetics.
PARAMICS	Paramics is a microscopic traffic simulation software package published by Quadstone in Edinburgh Scotland. PARAMICS incorporates the "Monitor" tool that utilizes tables that contain vehicle exhaust emissions and fuel consumption rates as a function of vehicle type, speed, and acceleration

It was noticed that microscopic models that take into consideration the vehicle kinetics are estimating fuel consumption and emissions more accurately than models that do not take into consideration this aspect. An example of these models is INTEGRATION.

Table 3 Summary of the Mesoscopic Models

Mesoscopic Models	
The MEASURE Model	MEASURE is basically a GIS-based emissions model. It can calculate estimates of HC, CO, and NO$_x$. Two major modules are included in MEASURE. The first one is the start emissions module while the second one is the on-road emission module
DYNASMART-P	DYNASMART is currently supported by the FHWA through McTrans. The used emission models in DYNASMART-P are adapted from the lookup tables for fuel consumption and emissions developed at Oak Ridge National Laboratory (ORNL) in the mid-1990s (ORNL models)

Table 4 Summary of Macroscopic Models

Mesoscopic Models	
Moves Model	Moves is supported by the EPA. In macro scale, MOVES computes vehicle activity based on nationwide vehicle miles traveled data, which is not precise enough for mesoscopic and microscopic scale analysis. Emissions data for light-duty passenger vehicles is based largely on inspection maintenance test data. This data dates from 1995 to 2005 and was collected from approximately 62,500 vehicles
Watson Model	A fuel consumption model was developed by Watson et al. (1979) using average speed data. The changes in the positive kinetic energy during acceleration were used as a predictor variable in this model, But the effects of speed changes during the deceleration phase were not included

All of this synthesis work will form a good base for those who are interested to take a comprehensive introduction to the research work done on the fuel consumption and emission fields.

This work of modeling fuel consumption and emission model has been accepted to be published in the 54th Annual Transportation Research Forum and was published in its procedure. This could be downloaded from:
http://www.trforum.org/forum/downloads/2013_program.pdf?i=03190818 (Elbassuoni, 2013)

References

Ahn, K., 1998. Microscopic Fuel Consumption and Emission Modeling. Virginia
Polytechnic Institute and State University.

Ahn, K., Rakha, H., Trani, A., Van Aerde, M., 2002. Estimating Vehicle Fuel Consumption
and Emissions Based on Instantaneous Speed and Acceleration Levels. Journal of
Transportation Engineering 128, 182–190.

Alexiadis, V., Jeannotte, K., Chandra, A., 2004. Traffic Analysis Toolbox Volume I: Traffic
Analysis Tools Primer (No. FHWA-HRT-04-038). FHWA, Washington, DC.

An, F., Barth, M., Norbeck, J., Ross, M., 1997. Development of Comprehensive Modal
Emissions Model: Operating Under Hot-Stabilized Conditions. Transportation Research
Record: Journal of the Transportation Research Board 1587, 52–62.

Bachman, W., Sarasua, W., Hallmark, S., Guensler, R., 2000. Modeling Regional Mobile
Source Emissions in a Geographic Information System Framework. Transportation
Research Part C: Emerging Technologies 8, 205–229.

Barth, M., An, F., Younglove, T., Scora, G., Levine, C., Ross, M., Wenzel, T., 2000a.
Comprehensive Modal Emissions Model.

Barth, M., An, F., Younglove, T., Scora, G., Levine, C., Ross, M., Wenzel, T., 2000b.
Development of a Comprehensive Modal Emissions Model.

Barth, M., Collins, J., Scora, G., Davis, N., Joseph, N., 2006. Modeling Extremely Low
Emitting Vehicles.

Barth, M., Younglove, T., Scora, G., 2005. Development of a Heavy-Duty Diesel Modal
Emissions and Fuel Consumption Model. California Partners for Advanced Transit and
Highways, Research Reports 125.

Beckx, C., Int Panis, L., Torfs, R., Janssens, D., Broekx, S., 2007. The Application of the
Simulation Software VeTESS to Evaluate the Environmental Impact of Traffic
Measures. Presented at the 10th International Conference on Computers in Urban
Planning and Urban Management, Iguassu Falls, Brazil.

Bloomberg, L., Dale, J., 2000. Comparison of VISSIM and CORSIM Traffic Simulation
Models on a Congested Network. Transportation Research Record: Journal of the
Transportation Research Board 1727, 1–23.

Boriboonsomsin, K., Barth, M., 2008. Impacts of Freeway High-Occupancy Vehicle Lane
Configuration on Vehicle Emissions. Transportation Research Part D: Transport and
Environment 13, 112–125. doi:10.1016/j.trd.2008.01.001

California Environmental Protection Agency - Air Resources Board, 2014. EMFAC 2014-
Technical Documentation.

Dowling, R., Holland, J., Huang, A., 2002. California Department of Transportation
Guidelines for Applying Traffic Microsimulation Modeling Software.

EPA, 2013. Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel
Economy Trends: 1975 - 2013 [WWW Document]. URL
http://darwin.phyloviz.net/ComparingPartitions/index.php?link=References

EPA, 2012a. Compilation of Air Pollutant Emission Factors, Modeling and Inventories
[WWW Document]. URL http://www.epa.gov/otaq/ap42.htm

EPA, 2012b. EPA - Air Quality Management (AQM) - Emissions Inventory [WWW Document]. EPA - Air Quality Management (AQM) - Emissions Inventory. URL http://www.epa.gov/air/aqmportal/management/emissions_inventory/

EPA, 2012c. EPA-Nonroad [WWW Document]. URL http://www.epa.gov/oms/nonrdmdl.htm

EPA, 2012d. MOVES2010b User Guide.

EPA, 2012e. Related Programs, TTN, Support Center for Regulatory Atmospheric Modeling [WWW Document]. URL http://www.epa.gov/scram001/dispersion_related.htm#ems-hap

EPA, 2012f. Technology Transfer Network Clearinghouse for Inventories & Emissions Factors [WWW Document]. URL http://www.epa.gov/ttnchie1/eiinformation.html

EPA, 2011a. Development of Emission Rates for Heavy-Duty Vehicles in the Motor Vehicle Emissions Simulator MOVES2010 Final Report.

EPA, 2011b. Development of Emission Rates for Light-Duty Vehicles in the Motor Vehicle Emissions Simulator (MOVES2010) Final Report.

Evans, L., Herman, R., 1978. Automobile Fuel Economy on Fixed Urban Driving Schedules. Transportation Science 12, 137–152. doi:10.2307/25767904

FHWA, 2010. Introduction to CORSIM Theory [WWW Document]. Appendix A: Introduction to CORSIM Theory. URL http://ops.fhwa.dot.gov/trafficanalysistools/tat_vol4/app_a.htm

FHWA, 1999. Development and Validation of Light-Duty Vehicle Modal Emissions and Fuel Consumption Values for Traffic Models (No. FHWA-RD-99-068).

Gomes, G., May, A., Horowitz, R., 2004. A Microsimulation Model of a Congested Freeway Using VISSIM, in: Transportation Research Board Conference.

Hallmark, S., Mudgal, A., 2012. Comparison of VSP Profiles for Three Types of Intersection Control and Implications for Emissions, in: 2012 15th International IEEE Conference on Intelligent Transportation Systems (ITSC). Presented at the 2012 15th International IEEE Conference on Intelligent Transportation Systems (ITSC), pp. 415 – 420. doi:10.1109/ITSC.2012.6338862

ISSRC, 2012. The International Vehicle Emissions (IVE) Model [WWW Document]. URL http://www.issrc.org/ive/

Kosman, K., Hallmark, S., Poska, S., 2003. Evaluation of Simulation Models for Project-Level Emissions Modeling, in: Transportation Research Board, Annual Meeting.

Lieberman, E., Rathi, A., 1997. Traffic Simulation. Traffic flow theory.

Mehta, T., Kottapalli, A., Mahmassani, H., Bhat, C., 2003. Assessing The Environmental Benifits of intelligent Transportation Systems Measures: Methodologies and Applications. Work 4197, 3.

Minnesota Department of Transportation, 2008. Advanced CORSIM Training Manual- Final Corsim Manual (No. SEH No. A-MNDOT0318.00).

MSU, 2014. Introduction to Synthesis [WWW Document]. Introduction to Synthesis. URL https://www.msu.edu/~jdowell/135/Synthesis.html

Office of Air Quality Planning and Standards, U.E., 2012. Emissions Factors & AP 42 [WWW Document]. URL http://www.epa.gov/ttnchie1/ap42/

Park, B., Yun, I., Choi, K., 2004. Evaluation of Microscopic Simulation Tools for Coordinated Signal System Deployment. KSCE Journal of Civil Engineering, Transportation Engineering 8, 239–248.

PTV Group, 2012. VISSIM and Enviver [WWW Document]. Common Add-ons - EnViVer. URL http://www.ptv-vision.com/en-uk/products/vision-traffic-suite/ptv-vissim/modules/

Qiao, F., Wang, J., Wang, X., Jia, J., Yu, L., 2012. A RFID Based E-STOP Sign and its Impacts to Vehicle Emissions, in: 2012 15th International IEEE Conference on Intelligent Transportation Systems (ITSC). Presented at the 2012 15th International IEEE Conference on Intelligent Transportation Systems (ITSC), pp. 206 –211. doi:10.1109/ITSC.2012.6338899

Quadstone, 2012. Quadstone Paramics | Traffic and Pedestrian Simulation, Analysis and Design Software [WWW Document]. URL http://www.paramics-online.com/

Quadstone UGM, 2009. Paramics North American Update 2009.

Rakha, H., 2013. INTEGRATION © Release 2.40 for Windows: User's Guide – Volume I: Fundamental Model Features. Virginia Tech.

Rakha, H., Ahn, K., 2004. Integration Modeling Framework for Estimating Mobile Source Emissions. Journal of transportation engineering 130, 183–193.

Rakha, H., Ahn, K., Trani, A., 2004a. Development of VT-Micro Model for Estimating Hot Stabilized Light Duty Vehicle and Truck Emissions. Transportation Research Part D: Transport and Environment 9, 49–74.

Rakha, H., Lucic, I., Demarchi, S., Setti, J., Van Aerde, M., 2001. Vehicle Dynamics Model for Predicting Maximum Truck Acceleration Levels. Journal of transportation engineering 127, 418–425.

Rakha, H., Snare, M., Dion, F., 2004b. Vehicle Dynamics Model for Estimating Maximum
Light-Duty Vehicle Acceleration Levels. Transportation Research Record: Journal of
the Transportation Research Board 1883, 40–49.

Rakha, H., Van Aerde, M., Ahn, K., Trani, A., 2000. Requirements for Evaluating Traffic
Signal Control Impacts on Energy and Emissions Based on Instantaneous Speed and
Acceleration Measurements. Presented at the Transportation Research Board 79th
Annual Meeting, Washington D.C.

SAIS, 2012. SIAS Transport Planners [WWW Document]. Paramics Microsimulation. URL
http://www.sias.co.uk/ng/sparamicshome/sparamicshome.htm

SMOKE version 3.1, 2012.

Speirs, E., Braidwood, R., 2004. Quadstone Paramics V5.0 Technical Notes 15.

TFEIP, 2012. Task Force on Emission Inventories and Projections (TFEIP) [WWW
Document]. URL http://tfeip-secretariat.org/

Umedu, T., Togashi, Y., Higashino, T., 2012. A Self-Learning Traffic Signal Control
Method for CO2 Reduction using Prediction of Vehicle Arrivals, in: Intelligent
Transportation Systems (ITSC), 2012 15th International IEEE Conference on. IEEE,
pp. 421–426.

United Nations Economic Commission for Europe, 2012. TF Emission Inventories and
Projections [WWW Document]. URL
http://www.unece.org/env/lrtap/taskforce/tfeip/welcome.html

Watson, H., 1979. A Simplified Method for Quantifying Fuel Consumption of Vehicles in
Urban Traffic. Presented at the Automotive Engineering Conference, 4th, 1979,
Melbourne, Australia.

West, B., McGill, R., Hodgson, J., Sluder, S., Smith, D., 1997. Development of Data-Based Light-Duty Modal Emissions and Fuel Consumption Models (No. 972910). SAE International, Warrendale, PA.

Xia, H., Boriboonsomsin, K., Schweizer, F., Winckler, A., Zhou, K., Zhang, W.-B., Barth, M., 2012. Field Operational Testing of ECO-Approach Technology at a Fixed-Time Signalized Intersection, in: 2012 15th International IEEE Conference on Intelligent Transportation Systems (ITSC). Presented at the 2012 15th International IEEE Conference on Intelligent Transportation Systems (ITSC), pp. 188 –193. doi:10.1109/ITSC.2012.6338888

Yue, H., 2008. Mesoscopic Fuel Consumption and Emission Modeling. Virginia Polytechnic Institute and State University.

CHAPTER 4: ENGINE PERFORMANCE MODELING - AN EFFORT TOWARDS MINIMIZING THE ENVIRONMENTAL IMPACT OF CORRIDOR TRAFFIC OPERATIONS

Abstract

The main objective of this work is to quantify the fuel consumption and environmental cost of vehicle operations at signalized intersection approaches using advanced engine modeling software (GT-Suite). Specifically, fuel consumption and environmental impact comparison for vehicles in four different driving modes were compared. These modes are: 1) idling, 2) cruising speed, 3) accelerating from a stopped condition to a target speed, and 4) accelerating from a non-zero speed to a target speed.

The results of this modeling show that fuel consumption and the environmental cost of stops are highly dependent on the corridor operating speeds and increase as vehicle speed increases. Another factor that impacts the fuel consumption and environmental cost of the stops is the drivers' acceleration patterns. Aggressive driving with high acceleration rates yields negative impacts on fuel consumption and emission rates because of the high and rich fuel/air ratio needed for this kind of aggressive accelerations. Fuel consumption rates increased by increasing the acceleration rate. NOx emissions increased in the mild to normal acceleration range and decreased in the aggressive acceleration range. HC and CO emissions increased by increasing the acceleration rates.

Introduction and significance of this work

The main objective of this work is to quantify the fuel consumption and environmental cost of vehicle operations at signalized intersection approaches using advanced engine modeling software (GT-Suite). This study used the following pollutants: Nitrogen Oxides (NO_x), HydroCarbon emissions (HC), and Carbon Monoxide (CO). Four different vehicle modes of operations were considered:

- Vehicles in idle mode (stopped at the intersection),
- Vehicles cruising at constant speed (non-stopped vehicles),

- Vehicles accelerating from a stopped position to a target speed (accelerating from a stopped position at the onset of the green display),

- Vehicles accelerating from a non-zero speed to a target speed (delayed at the intersection approach).

To account for different driver behaviors, three different acceleration modes are considered in the analysis:

- Mild acceleration (4.7 ft./sec.^{2}),

- Normal acceleratoin (7.1 ft./sec.^{2}), and

- Aggressive acceleration (11.8 ft./sec.^{2}).

The acceleration values were obtained from previous literature, (Larsson and Ericsson, 2009) and (Rakha et al., 2004a), which specified mild, normal, and aggressive acceleration values as the 40 %, 60 %, and 100% of the maximum vehicle acceleration envelope. This chapter is organized into the following sections. After the introduction, section two documents a brief literature review of related studies. After that, the reasons of why the GT-Suite software is needed for this study and an introduction about the GT-Suite software will be shown. The following section provides the analysis procedure of the work. The next section documents the analysis results. Finally, the conclusions and recommendations for this work will be discussed.

Literature Review

Ahn et al. used instantaneous speed and acceleration behaviors to estimate fuel consumption and emissions (Ahn et al., 2002d). Test vehicles were used to verify the range of estimated values. Emission and fuel consumption rates were estimated along a range of accelerations at corresponding speeds and regression models were formalized. Emission rates were found to be the highest at high acceleration rates, traveling at speeds around 25 mph and 40 mph. Rakha and Ding studied the impact of vehicle-stops on fuel consumption and emissions (Rakha and Ding, 2003). The authors found that fuel consumption rates are more sensitive to cruise-speed levels compared to vehicle stops. Another result showed that acceleration and

deceleration rates employed during a stopping maneuver had a significant effect on emission rates. The authors used VT-Micro, a microscopic traffic simulation model, and data collected at the Oak Ridge National Laboratory in the analysis. A vehicle-stop, especially one interrupting high cruise-speeds, was shown to cause a considerable increase in fuel consumption and emission rates. The authors presented the scenario that if the speed limit along an arterial is increased from 55 mph to 65 mph, and a stop maneuver is executed, HC, CO, and NO_x emissions may increase by 60 %, 80 %, and 40 %, respectively.

Finally, Pandian et al. studied the role of traffic, road, and vehicle characteristics that affect emissions at signalized intersections (Pandian et al., 2009). The authors concluded that combining emission and flow models ensures a more realistic estimate for all location features and environmental parameters.

Why GT-Suite is Needed?

After performing the literature review part, it was noticed that none of the research work used advanced modeling tools (like GT-Suite). GT- Suite is an engine modeling tool produced by Gamma Technologies (GTI) (Gamma Technologies (GTI), 2014). It offers versatile simulation of vehicles with conventional, Hybrid-Electric (HEV), or Electric-only (EV) drivelines, as well as the control systems and strategies key to the operation of these vehicles.

Using GT-Suite will facilitate making a full understanding of emissions and transportation operations. It will also show how fuel consumption and emissions are varying under different driving conditions. As can be seen in Figure 6, while many of standard driving cycles include several stoppage and acceleration scenarios, none of them exclusively and thoroughly covers all parameters of vehicle operations at signalized intersection approaches such as the wide ranges of initial and target speeds and acceleration modes.
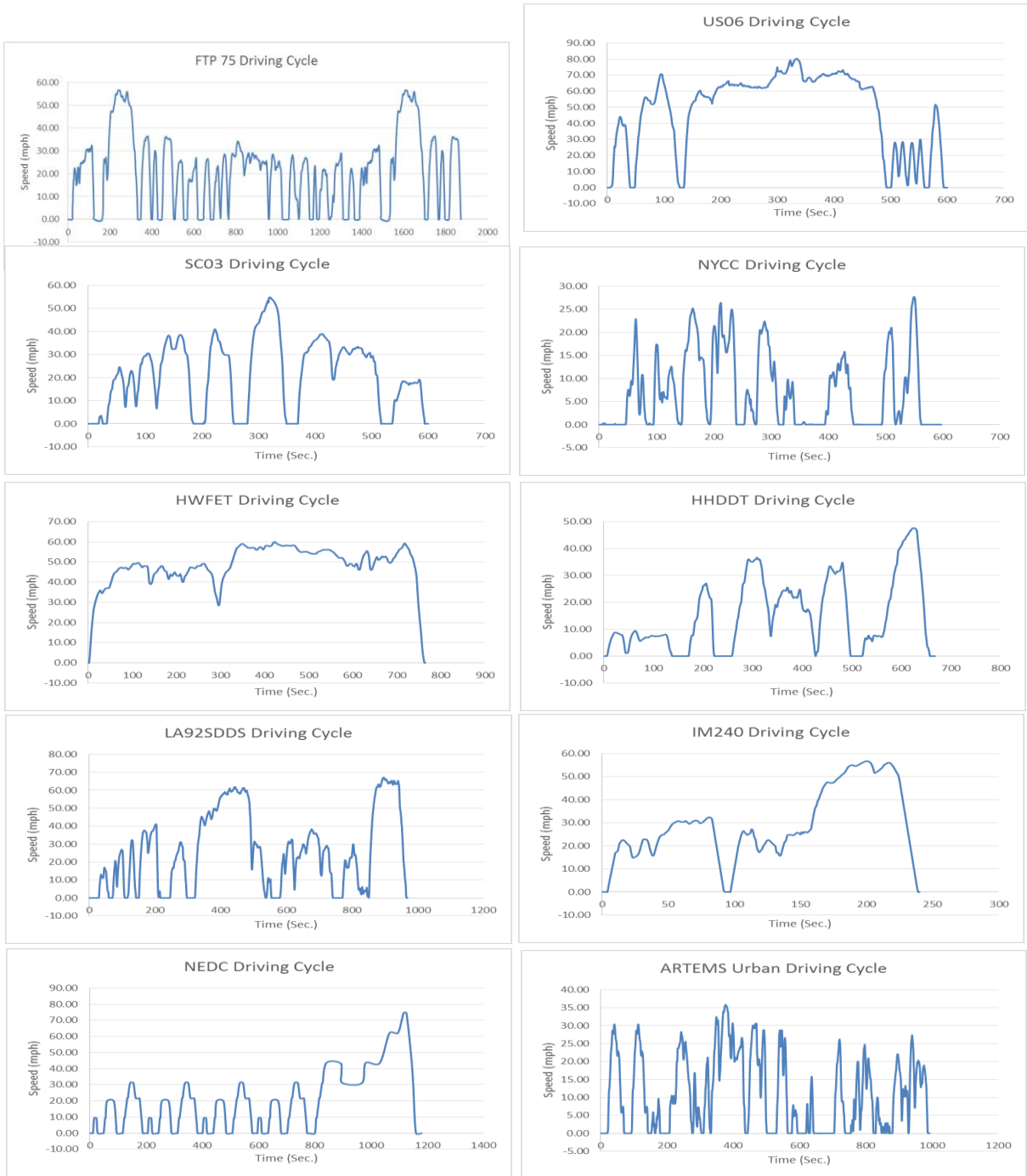
Figure 6 Different American and European driving cycles initially studied.

Sources: (DieselNet, 2014), (EPA, 2014), (The United Nations Environment Programme (UNEP), 2014), and (Virtual-Car, 2014)

Examples of some of the standard driving cycles presented in Figure 6 include:

- FTP 75: The Federal Test Procedure. This cycle was designed in the late 1960s to ensure that newly manufactured light duty vehicles comply with emission standards and then are eligible for certification. There are three main components of the FTP cycle. These components are the cold-start, stabilized, and a hot start components.

- US06 - Supplemental FTP: high acceleration aggressive driving schedule. This cycle is covering the high-acceleration, the high-speed, or both of these driving styles. It covers the aggressive driving styles, and it deals with some of the limitations in the original FTP driving cycle.

- SC03: Supplemental Federal Test Procedure (SFTP) with Air Conditioning.

- NYCC: The New York City Cycle. This cycle deals mainly with frequent stops, low speeds, and general congested urban driving conditions.

- HWFET: Highway Fuel Economy Test Cycle.

- HHDDT: Heavy Heavy-Duty Diesel Truck Driving Cycle.

- LA92SDDS & LA92DDS: Unified Dynamometer Driving Schedule.

- IM240: EPA Inspection & Maintenance Driving Cycle / the shorten FTP driving cycle. Its main use is to check whether the light duty vehicles fulfill the emission standards.

- NEDC: The New European Driving Cycle.

- ARTEMS Motorway, ARTEMS Motorway 130, ARTEMIS_Road, Artemis_Urban: Driving Cycles developed within the (Assessment and Reliability of Transport Emission Models and Inventory Systems) project.

A full documentation and description of these standard driving cycles are documented in several references like (DieselNet, 2014), (EPA, 2014), (The United Nations Environment Programme (UNEP), 2014), and (Virtual-Car, 2014).

The GT-Suite analysis presented in the next section is intended to provide an analysis of the fuel consumption and environmental cost of vehicle operations at signalized intersection

approaches. While all the fuel consumption and emissions data presented in this work are for an average four-cylinder gasoline engine, the result trends can be generalized to cover the six-cylinder and eight-cylinder gasoline engines with a different engine size capacity.

GT-Suite

GT- Suite is an engine modeling tool produced by Gamma Technologies (GTI) (Gamma Technologies (GTI), 2014). It offers versatile simulation of vehicles with conventional, Hybrid-Electric (HEV), or Electric-only (EV) drivelines, as well as the control systems and strategies key to the operation of these vehicles. GT-Suite has been used in several research fields. In (Keller et al., 2010a), a fully integrated model is presented utilizing the GT-Suite commercial code containing a diesel engine system model that evaluates different system and component concepts regarding their influence on fuel consumption and emissions. In (Chougule et al., 2013), a design of gas mixer and a simulation of dual fuel (Diesel-Compressed Natural Gas (CNG)) engine for performance parameters to examine the Brake Specific Fuel Consumption (BSFC) using GT-suite is presented. GT-Suite is also used in (Arunachalam et al., 2013), (Birckett et al., 2012), and (Pohorelsky et al., 2011).

In order to investigate the effect of idling and cruising speed, specifications matching the characteristics of an average four-cylinder vehicle similar to those used in many urban and suburban areas were used. Specifically, the engine and vehicle specification inputs for the GT-Suite model were: engine configuration: naturally aspirated four-stroke with inline four-cylinder and direct injection; transmission: automatic; displacement: two liters; minimum operating speed: 950 revolutions per minute (RPM); fuel density: 756 kg/m^3; vehicle weight: 1800 kg; vehicle rolling resistance coefficient: 0.01; vehicle drag coefficient: 0.32; and final vehicle frontal area: 0.8 m^2.

Analysis Procedure

Because standardized driving cycles do not cover all parameters of vehicle operations such as the wide ranges of initial and target speeds and acceleration modes, four different operation modes were considered to be used in the GT - Suite:

- Idling: representing the case of a vehicle stopped at an intersection approach. Idling time for this case is 90 seconds (Figure 7-a).

- Cruising speed: representing the case of a non-stopped vehicle traveling through the intersection approach at constant speeds. Four cruising speeds are modeled in this analysis: 25 mph, 35 mph, 45 mph, and 55 mph. Cruising time for all of these cases is 90 seconds (Figure 7-b).

- Accelerating from zero mph to a target speed: representing the case of a vehicle stopped at an intersection approach and accelerating back to its target driving speed. Four target speeds are modeled in this analysis: 25 mph, 35 mph, 45 mph, and 55 mph with three different acceleration values for each one (Figure 7-c).

- Accelerating from a speed different from zero speed to a target speed: representing a delayed vehicle at an intersection approach by the presence of a queue at the intersection approach accelerating back to its target speed. Four different initial speed values are used in the analysis five mph, 10 mph, 15 mph, and 20 mph,) with target speeds of 25, 35, 45, and 55 mph, with three different acceleration values for each one (Figure 7-d).

Three different acceleration values were used in the analysis to account for different driver behaviors. These three acceleration values are: mild acceleration (4.7 ft. /sec.^{2}), normal acceleration (7.1 ft. /sec.^{2}), and aggressive acceleration (11.8 ft. /sec.^{2}).
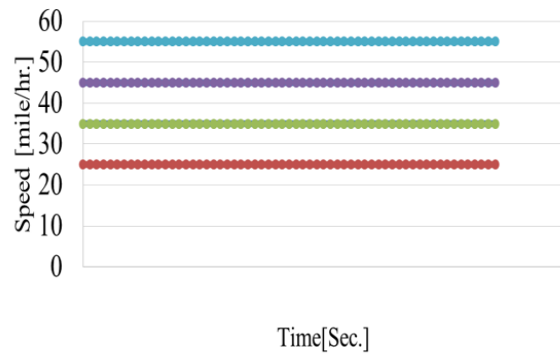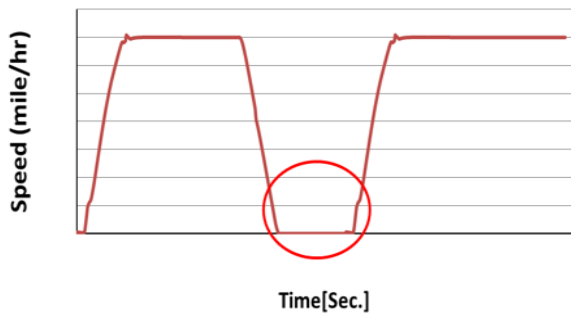
a: Case 1: Idling (stopping at an intersection)

b: Case 2: Cruising at 25, 35, 45, and 55 mph
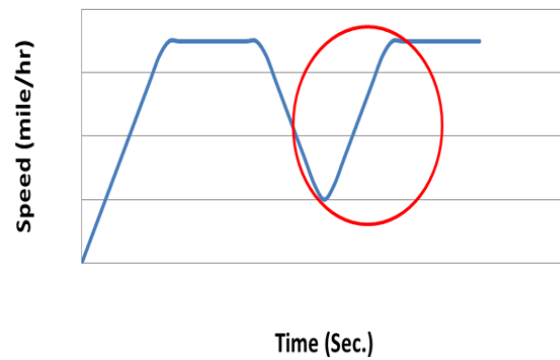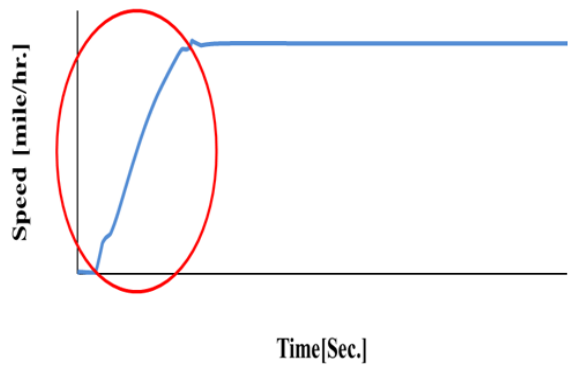
C: Case 3: Accelerate from zero mph to (25, 35, 45, and 55 mph) with three different acceleration values for each one (12 different sub-cases)

d: Case 4: Accelerate from (five, 10, 15, and 20 mph) to (25, 35, 45, and 55 mph) while driving on normal acceleration mode. (16 different sub-cases)

Figure 7 Different Speed Profile Categories

Results of Quantifying Fuel Consumptions and Emission Models in Depth

Cases one and two: The Impact of Idling and Cruising Speeds on Fuel Consumption and Emissions:

The GT-Suite model simulated the idling and cruising for a period of 90 seconds. The idling speed was zero mph while the cruising speeds were 25, 35, 45, and 55 mph. Figure 8 and Figure 9 present the fuel consumption and emission rates and total amounts of the fuel consumption and emissions of cases one and two (idling and cruising). Figure 8 and Figure 9 show that:

- Fuel consumption rates stay constant during the 90 seconds modelling times.

- Cruising speeds of 35 mph result in less fuel consumption and fewer emissions compared to cruising at 25 mph and 45 mph, so the optimum fuel consumption rate is occurs at a cruising speed of 35 mph. This is because the used engine is a typical passenger car engine that has a small engine displacement which is intend to create this kind of behavior for vehicles used mostly in city driving modes. These city driving modes are when the normal driving speeds are around 35 mph to improve fuel economy and reduce emissions. The results of running the GT-Suite found that at 35 mph the engine ran at a higher gear than at 25 mph, and this higher gear caused the engine to perform on lower Revolutions Per Minute (RPM.) These lower engine loads at 35 mph resulted in a fuel consumption rate to be lower than the 25 mph cruising speeds.

- This result is widely recognized and was noticed in the literature (Rakha et al., 2003) and (El-Shawarby et al., 2005). As could be seen in Figure 8, increasing the running speed from 35 mph to 45 mph would result in increasing the fuel consumption rate with a percentage of 54.74, while increasing the running speed from 35 mph to 55 mph would increase the fuel consumption rate by 65.80%.

- The NOx emission rates behaved in a similar way to the fuel consumption rates with lower values for idling and at 35 mph cruising speed compared to other cruising speeds. Increasing the running speed from 35 mph to 45 mph would result in a NOx

emission rate increase of 54.92%, while increasing the running speed from 35 mph to 55 mph would increase the NOx emission rate by 65.84%.
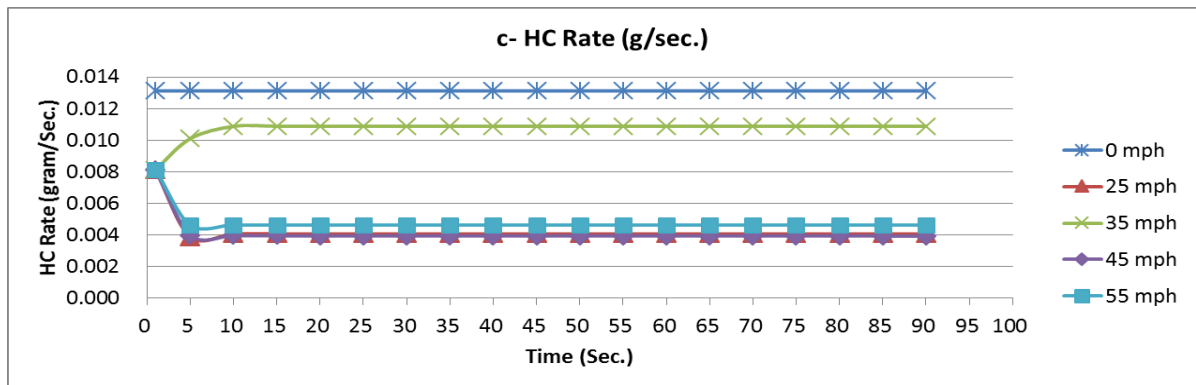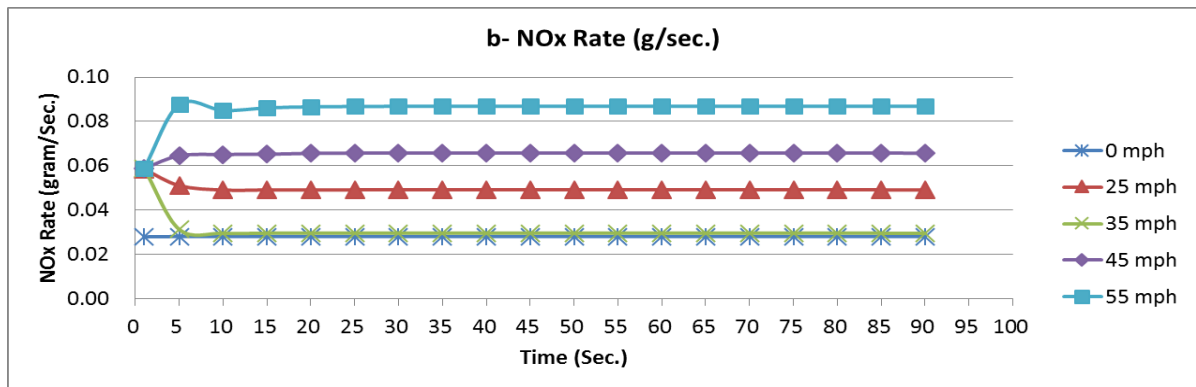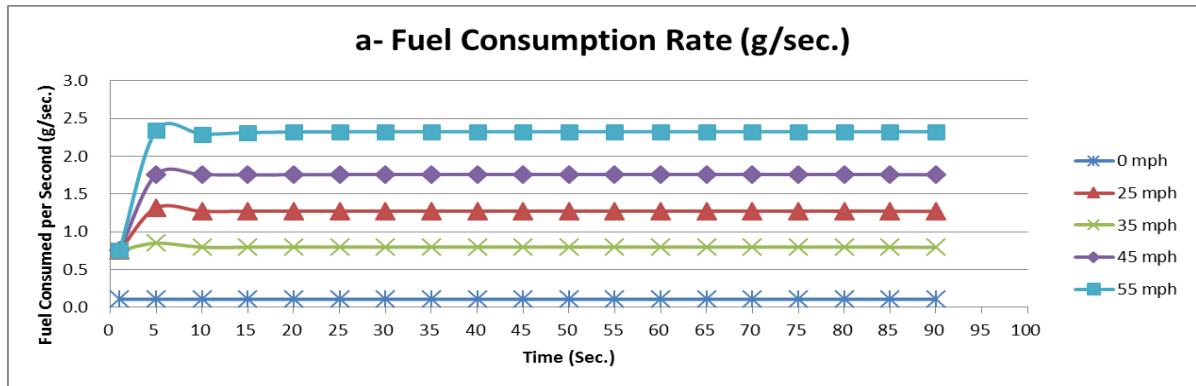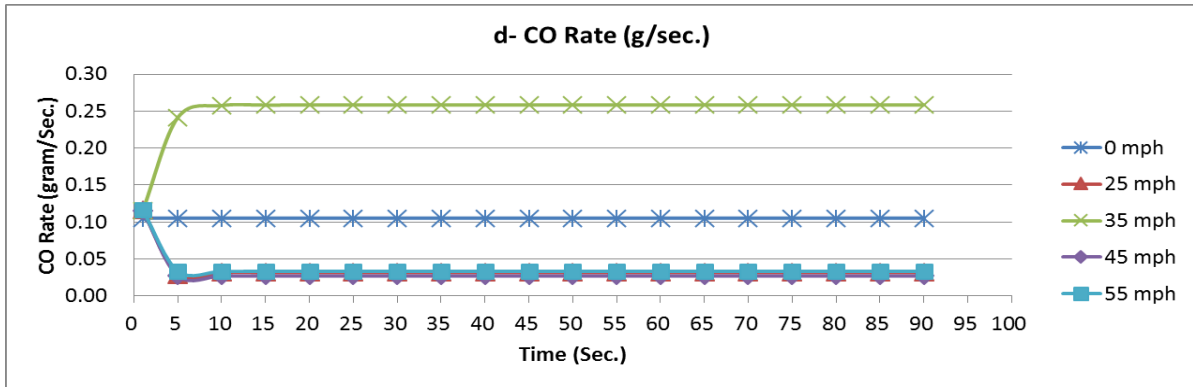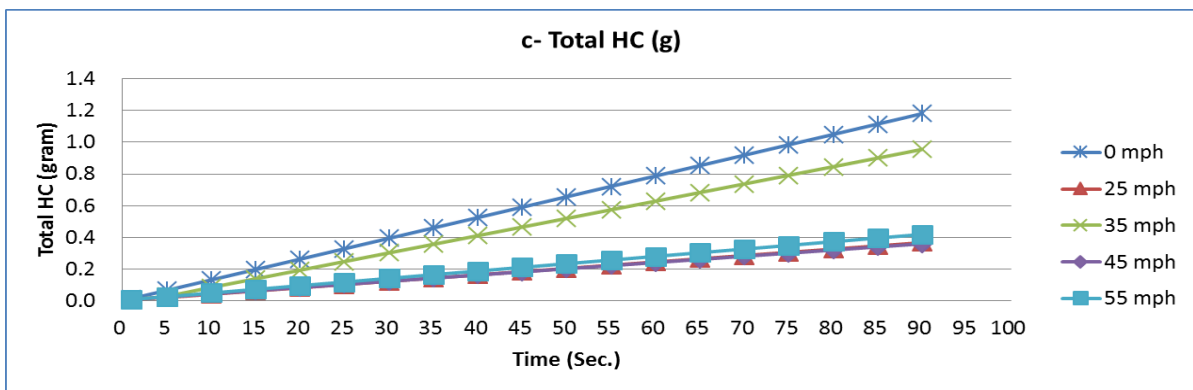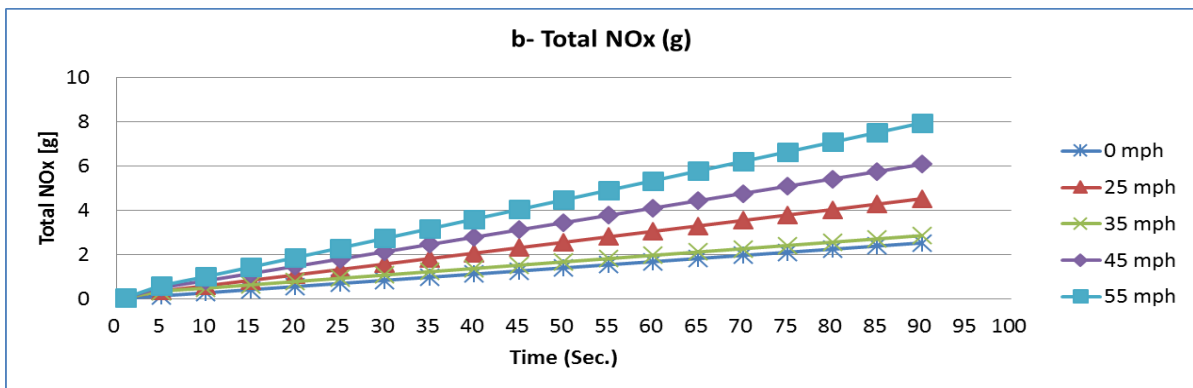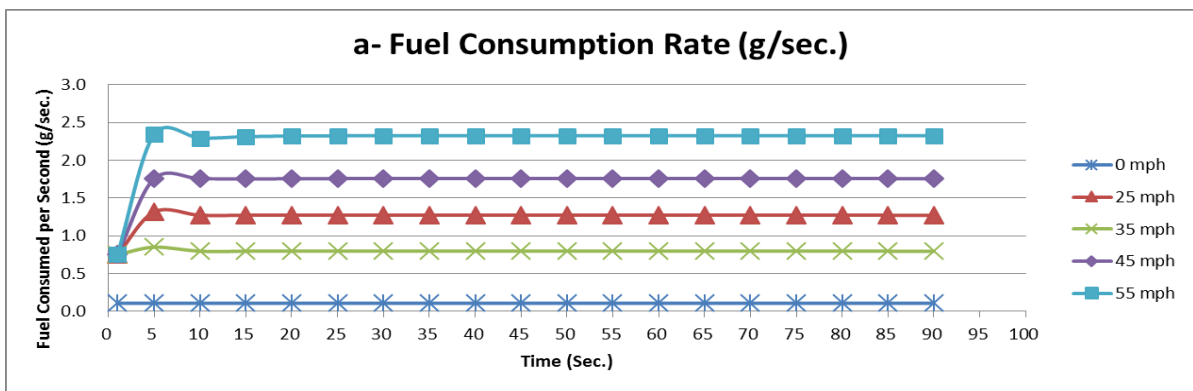
Figure 8 Fuel consumption and emission rates for the cases of idling and cruising
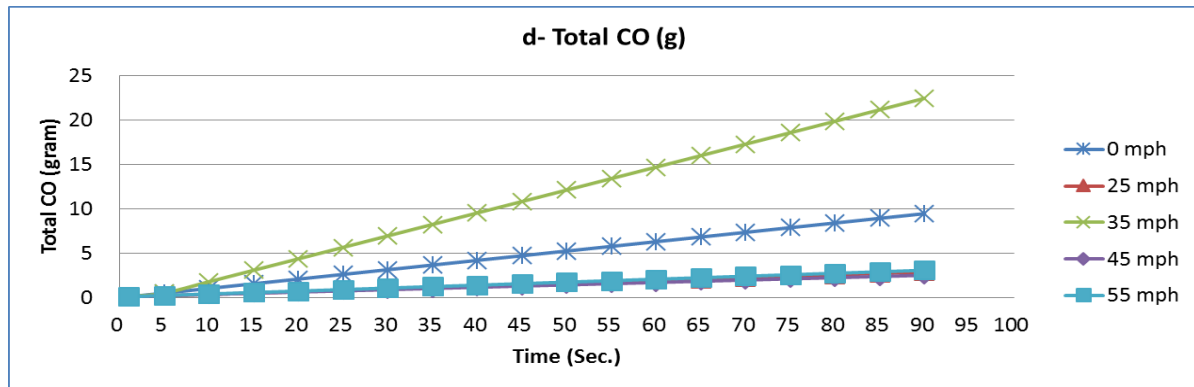
Figure 9 Total Fuel consumption and emissions for the cases of idling and cruising

- The HC and CO emissions reported lower rates in the case of 45 and 55 mph cruising speeds compared to idling and the 35 mph cruising speed. This is because of the influence of the air / fuel ratio on the levels of emissions of pollutants discussed in details in (Stone, 1999). This kind of variation in different emission types was mentioned in (Rakha and Ding, 2003). These authors also discussed the effect of engine loads and stoichiometric (enough air to completely burn the available fuel) engine conditions on this emission behavior.

Case Three: The impact of accelerating and driving behavior and different target speeds:

Case three represents a vehicle stopped at an intersection approach and accelerating back to its target and desired driving speed. In this analysis, four different target speeds were modeled using the GT-Suite: 25 mph, 35 mph, 45 mph, and 55 mph (Figure 7-c). The acceleration happened from zero mph to each one of these target speeds using three different acceleration values. These acceleration values are mild acceleration (4.7 ft./sec.^{2}), normal acceleration (7.1 ft./sec.^{2}), and aggressive acceleration (11.8 ft./sec.^{2}). These four target speeds with the three acceleration values for each one of these target speeds formed a total of 12 different subcases. These 12 subcases show the effect of different acceleration values and driver aggressiveness on fuel consumption and emissions.
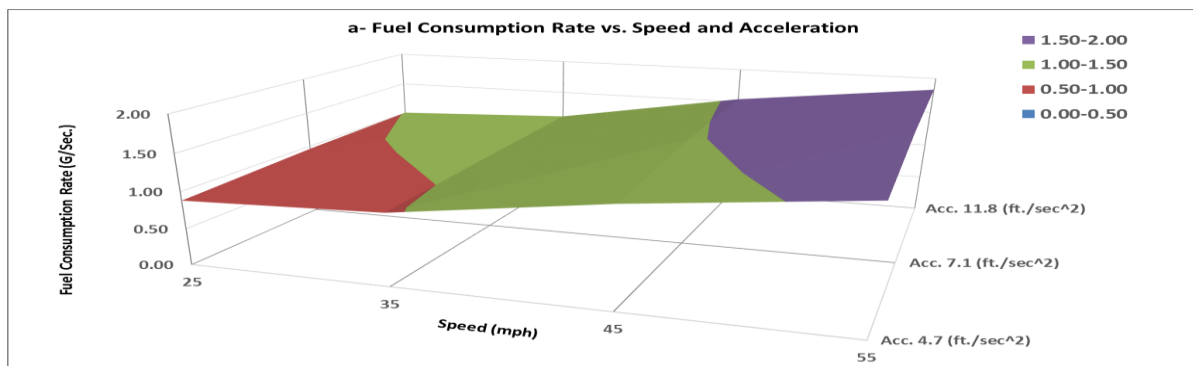
Because of the different acceleration values, the modeled engine reached each target speed over different times and distances. For example, it would take the modeled engine in GT-Suite a time of 18.3 seconds to go from a speed of zero mph to a target speed of 55 mph in

the mild acceleration mode (4.7 ft./sec.^{2}), while it would take the same engine a time of 13.68 seconds to reach the same target speed of 55 mph from a zero mph starting speed in the aggressive acceleration mode (11.8 ft./sec.^{2}). To make a fair comparison between the 12 different cases, all of these 12 different cases were modeled in the GT-Suite to cover a same distance of 720 ft. If the vehicle reached the target speed before the 720 ft., the vehicle would simply cruise on the target speed till it covers the 720 ft.

Table 5 summarizes the total amounts of fuel consumption and emissions for the different target and acceleration cases over a distance of 720 ft. To show the data from a different perspective, Figure 10 shows the fuel consumption and emission rates and total amounts for the case of accelerating from a zero mph using three different acceleration values (mild, normal, and aggressive).

Table 5 Fuel Consumption and Emissions rates for the case of accelerating from zero mph to different target speeds using different acceleration values over a distance of 720 ft.

|	Fuel Cons. Rate (g./sec.)	NOx Rate (g./sec.)	HC Rate (g./sec.)	CO Rate (g./sec.)
4.7 ft./ sec.^{2}	0.881	0.068	0.0069	0.064
7.1 ft./ sec.^{2}	0.961	0.100	0.0068	0.064
11.8 ft./ sec.^{2}	1.002	0.099	0.0070	0.091
4.7 ft./ sec.^{2}	0.967	0.079	0.0078	0.106
7.1 ft./ sec.^{2}	1.039	0.105	0.0079	0.114
11.8 ft./ sec.^{2}	1.103	0.099	0.0080	0.136
4.7 ft./ sec.^{2}	1.322	0.104	0.0062	0.056
7.1 ft./ sec.^{2}	1.473	0.128	0.0061	0.056
11.8 ft./ sec.^{2}	1.541	0.126	0.0063	0.080
4.7 ft./ sec.^{2}	1.599	0.111	0.0059	0.053
7.1 ft./ sec.^{2}	1.773	0.131	0.0058	0.053
11.8 ft./ sec.^{2}	1.835	0.129	0.0059	0.076
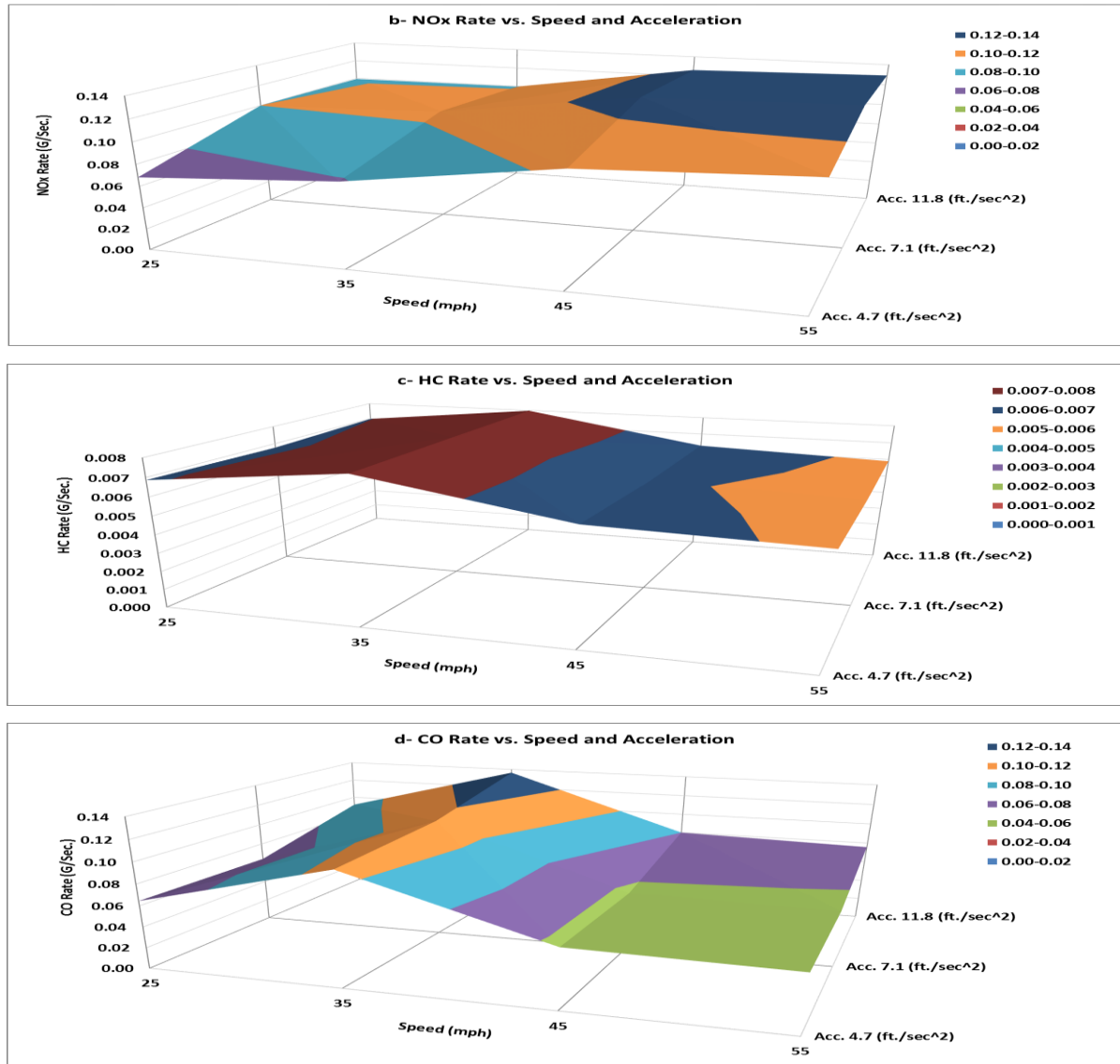
Figure 10 Fuel consumption and emission rates for the cases of accelerating from zero to 55 mph using different acceleration values (gram/sec.)

Table 5 and Figure 10 show that:

- **Regarding the Fuel Consumption:** mild acceleration behavior causes lower fuel consumption rates (gram / second) compared to the normal acceleration case. The same result is valid for normal acceleration that causes less fuel consumption rates compared to the aggressive acceleration. The average fuel consumption rate increase in the case of normal acceleration is 9.69% compared to the mild acceleration case, while the average fuel consumption rate increase in the case of aggressive acceleration is 14.76% compared to the mild acceleration case.

- On the other hand, mild acceleration is typically causing higher amounts of accumulated fuel consumption (grams) until the point of reaching a target speed compared to the other two cases of normal and aggressive acceleration. This occurs because, in the case of mild acceleration, the vehicle will typically take more acceleration time to get to the target speed, causing an increase in the accumulated fuel consumption.

- **Regarding the NO_x emissions:** The relation between the NO_x emission rates and fuel consumption rates is nonlinear. NO_x emission rates increase in the normal acceleration case (7.1 ft./s^2) compared to the mild acceleration case (4.7 ft./s^2) with a percentage of 23.44%. The aggressive acceleration case has a 21.6% higher NO_x rate compared to the mild acceleration case, but this increase is lower than the normal acceleration case. This behavior is consistent with other studies (Stone, 1999), (Rakha and Ding, 2003), and (El-Shawarby et al., 2005) and can be attributed to two reasons. First, NO_x emissions are very high at the stoichiometric engine conditions as opposed to high engine loads. Second, in the case of mild acceleration, the vehicle takes a longer time to reach the desired target speeds compared to the mild and aggressive accelerations, causing the emission rates to be higher. When comparing the effect of cruising speeds and acceleration levels, it should be noted that cruising speeds have much higher effects on the NO_x emission rates compared to the different acceleration levels.

- **Regarding the HC and CO emissions:** HC and CO emission rates revealed similar behavior to the fuel consumption rates. The more aggressive the acceleration is, the more the engine operates in a higher fuel to air ratio mode, which is required to prevent engine knocking, thus bypassing the catalytic converter, and so the higher HC and CO emission rates. In the case of CO, the average CO emission in the case of normal acceleration is slightly higher than the mild acceleration mode, but the CO emission rate in the case of aggressive acceleration is 38.77% higher than the CO emission rates in the case of mild acceleration. This general behavior is consistent with other studies (Rakha and Ding, 2003) and (El-Shawarby et al., 2005).

This part of the study revealed higher level of acceleration resulting in higher fuel consumption and emission rates because of the high and rich fuel/air ration needed for aggressive accelerations to prevent engine knocking, thus bypassing the catalytic converter and increasing vehicle emissions. Fuel consumption rates increased by increasing the acceleration rate. NO_x emissions increased in the mild to normal acceleration range and decreased in the aggressive acceleration range. HC and CO emissions increased by increasing the acceleration rates.

<div align="center">Case Four: Accelerating from Non-Zero Speeds:</div>

Table 6 summarizes the total amounts of fuel consumption and emissions for accelerating from non-zero values. Although the fuel consumption and environmental cost of vehicles delayed at the intersection approach because of a queue are lower than that for stopped vehicles, the data reveals these vehicles still constitute a significant portion of the fuel consumed and pollutants emitted as a result of the corridor operations. In addition, these costs increase when the operating speed of the corridor increases.

Table 6 Total Fuel Cons. and Emissions for the of Accelerating from Non-Zero Values

	Fuel (g)	NO_x (g)	HC (g)	CO (g)
5-25 mph	28.294	1.841	0.083	0.711
10-25 mph	27.575	1.56	0.08	0.701
15-25 mph	26.38	1.284	0.077	0.656
20-25 mph	24.841	1.026	0.074	0.576
5-35 mph	24.69	1.816	0.115	2.405
10-35 mph	23.921	1.58	0.113	2.398
15-35 mph	22.289	1.289	0.113	2.442
20-35 mph	20.724	1.077	0.112	2.449
5-45 mph	36.784	2.66	0.052	0.398
10-45 mph	35.821	2.421	0.052	0.436
15-45 mph	34.496	2.15	0.048	0.385
20-45 mph	33.306	1.942	0.045	0.316
5-55 mph	46.301	2.901	0.045	0.351
10-55 mph	45.41	2.693	0.045	0.396
15-55 mph	43.958	2.418	0.04	0.332
20-55 mph	42.671	2.197	0.037	0.268

The Fuel Consumption and Emissions Cost of Stopping:

The data presented in Table 5,

Table 7, Figure 9, and Figure 10 document the fuel consumption and environmental cost of vehicles stopping at signalized intersection approaches. For example, a vehicle accelerating back from a stopped position to a speed of 45 mph using a normal acceleration will consume 38.59 grams of fuel. A non-stopped vehicle cruising through the intersection approach for the same distance would consume 20.27 grams of fuel. This demonstrates that the cost of a single stop for an average 4-cylinder vehicle is approximately 18.32 grams. Such quantitative-based comparison could be used to provide transportation professionals with a more accurate fuel consumption and environmental cost of stops and delay to assist them in making decisions about optimizing different intersections and corridors.

Table 7-a shows that the cost of stopping can be calculated at each driving speed for vehicles running for the same distance (720 ft. in this example). This could be performed by making a comparison between vehicles cruising at 720 ft., and other vehicles starting from zero mph and accelerating normally (7.1 ft/s^2) to different driving speeds (25, 35, 45, and 55 mph). A similar table,

Table 7-b, is provided for the case of accelerating normally from non-zero values (for example 10 mph).

Table 7 shows the negative effects of stopping at signalized intersections could be easily seen especially at higher driving speeds. The table also shows the cost of stopping from a speed of 55 mph is 26.28 grams of fuel compared to 4.82 grams in the case of 25 mph. Previous tables and graphs also show that the fuel consumption cost in the case of 25 mph (4.82 g) is equivalent to idling at a signalized intersection for a period of 46 seconds. The 4.8 grams of fuel could be obtained by going vertically up at the 46 seconds location on the horizontal axis.

Table 7 Cost of Stopping (units in grams)

7-a- Accelerating from zero mph

	0-25 mph	25 mph cruise	Cost	0-35 mph	35 mph cruise	Cost	0-45 mph	45 mph cruise	Cost	0-55 mph	55 mph cruise	Cost
Fuel	30.72	25.89	4.82	26.28	14.03	12.25	38.59	20.27	18.31	47.94	21.66	26.28
NOx	2.29	1.09	1.20	2.27	0.61	1.66	3.11	0.89	2.22	3.35	0.93	2.42
HC	0.09	0.08	0.01	0.13	0.13	0.00	0.06	0.05	0.01	0.06	0.04	0.01
CO	0.88	0.69	0.19	2.73	2.84	-0.11	0.61	0.40	0.21	0.57	0.39	0.18

7-b- Accelerating from non-zero speed

	10-25 mph	25 mph cruise	Cost	10-35 mph	35 mph cruise	Cost	10-45 mph	45 mph cruise	Cost	10-55 mph	55 mph cruise	Cost
Fuel	27.575	25.89	1.68	23.921	14.03	9.89	35.821	20.27	15.55	45.41	21.66	23.75
NOx	1.56	1.09	0.47	1.58	0.61	0.97	2.421	0.89	1.53	2.693	0.93	1.76
HC	0.08	0.08	0.00	0.113	0.13	-0.01	0.052	0.05	0.00	0.045	0.04	0.00
CO	0.701	0.69	0.01	2.398	2.84	-0.44	0.436	0.40	0.04	0.396	0.39	0.01

Several conclusions can be drawn from the presented data. First, fuel consumption and environmental cost of stops are highly dependent on the corridor operating speeds and increases as the speed increases. Second, drivers' acceleration patterns significantly affect the fuel consumption and environmental cost of stops. Aggressive driving with high acceleration rates yields a much higher fuel consumption and environmental costs. The numbers shown in previous tables and figures could be used in public awareness campaigns to show how aggressive driving practices can affect significantly the fuel consumption and environmental cost.

Conclusion and Recommendations

While corridor traffic in small and medium size cities does not experience the high levels of congestion typically present in large urban areas, it generates a considerable amount of emissions and vehicle pollutants that has a negative impact on the environment. The main objective of this work is to quantify fuel consumptions and emissions in more depth for vehicles operating at signalized intersection approaches.

The results presented in this chapter show that the fuel consumption and environmental cost of stops are highly dependent on the corridor operating speeds and increases as the speed increases. Another factor that impact the fuel consumption and environmental cost of the stops is the drivers' acceleration patterns. Aggressive driving with high acceleration rates, yields much higher fuel consumption cost. As a summary of this part, it could be concluded that higher level of acceleration resulted in higher fuel consumption and emission rates. This is because of the high and rich fuel/air ration needed for this kind of aggressive accelerations which is required to prevent engine knocking, thus bypassing the catalytic converter and increasing vehicle emissions. Fuel consumption rates increased by increasing the acceleration rate. NO_x emissions increased in the mild to normal acceleration range and decreased in the aggressive acceleration range. HC and CO emissions increased by increasing the acceleration rates. Public awareness campaigns about the high cost of aggressive driving practices can contribute significantly to the reduction of corridor fuel consumption and environmental cost.

References

Ahn, K., Rakha, H., Trani, A., Van Aerde, M., 2002. Estimating Vehicle Fuel Consumption and Emissions Based on Instantaneous Speed and Acceleration Levels. Journal of Transportation Engineering 128, 182–190.

Arunachalam, P.N., Tuner, M., Tunestal, P., Johansson, B., Thern, M., 2013. System Simulations to Evaluate the Potential Efficiency of Humid Air Motors (SAE Technical Paper No. 2013-01-2646). SAE International, Warrendale, PA.

Birckett, A., Tomazic, D., Bowyer, S., Bevan, K., Wetzel, P., Keidel, S., Biller, B., 2012. Transient Drive Cycle Modeling of Supercharged Powertrains for Medium and Heavy Duty On-Highway Diesel Applications (SAE Technical Paper No. 2012-01-1962). SAE International, Warrendale, PA.

Chougule, V.P., Vora, K.C., Suryavanshi, Y., gunjegaonkar, D., 2013. Design and Simulation of 2.5 L Dual Fuel (Diesel-CNG) Engine for Performance Parameters (SAE Technical Paper No. 2013-01-2885). SAE International, Warrendale, PA.

DieselNet, 2014. Emission Standards [WWW Document]. URL https://www.dieselnet.com/standards/ (accessed 7.27.14).

El-Shawarby, I., Ahn, K., Rakha, H., 2005. Comparative Field Evaluation of Vehicle Cruise Speed and Acceleration Level Impacts on Hot Stabilized Emissions. Transportation Research Part D: Transport and Environment 10, 13–30. doi:10.1016/j.trd.2004.09.002

EPA, 2014. Dynamometer Drive Schedules | Testing and Measuring Emissions | US EPA [WWW Document]. URL http://www.epa.gov/nvfel/testing/dynamometer.htm (accessed 7.27.14).

Gamma Technologies (GTI), 2014. GT-SUITE Overview [WWW Document]. URL http://www.gtisoft.com/products/p_GT_SUITE.php (accessed 1.15.14).

Keller, P., Wenzel, W., Becker, M., Roby, J., 2010. Coupled Thermal-Engine Simulation for a Light Duty Application (SAE Technical Paper No. 2010-01-0806). SAE International, Warrendale, PA.

Larsson, H., Ericsson, E., 2009. The Effects of an Acceleration Advisory Tool in Vehicles for Reduced Fuel Consumption and Emissions. Transportation Research Part D: Transport and Environment 14, 141–146. doi:10.1016/j.trd.2008.11.004

Pandian, S., Gokhale, S., Ghoshal, A.K., 2009. Evaluating Effects of Traffic and Vehicle Characteristics on Vehicular Emissions Near Traffic Intersections. Transportation Research Part D: Transport and Environment 14, 180–196. doi:10.1016/j.trd.2008.12.001

Pohorelsky, L., Zak, Z., Macek, J., Vitek, O., 2011. Study of Pressure Wave Supercharger Potential using a 1-D and a 0-D Approach (SAE Technical Paper No. 2011-01-1143). SAE International, Warrendale, PA.

Rakha, H., Ahn, K., El-Shawarby, I., Jang, S., 2004. Emission Model Development Using In-Vehicle On-Road Emission Measurements, in: Annual Meeting of the Transportation Research Board, Washington, DC.

Rakha, H., Ahn, K., Trani, A., 2003. Comparison of MOBILE5a, MOBILE6, VT-MICRO, and CMEM Models for Estimating Hot-Stabilized Light-Duty Gasoline Vehicle Emissions. Canadian Journal of Civil Engineering 30, 1010–1021. doi:10.1139/l03-017

Rakha, H., Ding, Y., 2003. Impact of Stops on Vehicle Fuel Consumption and Emissions. Journal of Transportation Engineering 129, 23–32. doi:10.1061/(ASCE)0733-947X(2003)129:1(23)

Stone, R., 1999. Introduction to Internal Combustion Engines, 3 edition. ed. Society of Automotive Engineers Inc, Warrendale, Pa.

The United Nations Environment Programme (UNEP), 2014. International Test Cycles for Emissions and Fuel Economy [WWW Document]. URL http://www.unep.org/transport/gfei/autotool/approaches/information/test_cycles.asp#US (accessed 7.27.14).

Virtual-Car, 2014. Driving Cycles for Use with Wheels [WWW Document]. URL http://www.virtual-car.org/wheels/cycles.html (accessed 7.27.14).

CHAPTER 5: GUIDELINES FOR MINIMIZING THE ENVIRONMENTAL IMPACT OF CORRIDOR TRAFFIC OPERATIONS

Introduction and significance of this work

The motivation for this work came after knowing that more than a quarter of the total U.S. gas consumption and greenhouse gas emissions come from the transportation sector, making transportation the second largest source of greenhouse gas emissions in the United States after the electric power sector (EPA, 2012a) and (U.S. Energy Information Administration, 2015).

This chapter presents the results from studying the effectiveness of reducing fuel consumption emissions using different corridor signal timing plans optimized for different objective functions. These functions were combinations of minimizing control delay; minimizing stops; maximize the corridor throughput; maximize progression opportunities; and minimizing fuel consumption and emissions.

Two signal timing optimization software tools, TRANSYT-7F (McTrans Center, 2014) and PTV VISTRO (PTV, 2014), were used to develop different corridor signal timing plans using 14 different combinations of objective functions. A microscopic simulation tool, INTEGRATION (Rakha and Ahn, 2004b) is used to model the corridor operations under different signal control plans. The microscopic modeling tool, INTEGRATION, is used in this work rather than macroscopic modeling tools like MOVES or EMFAC for two main reasons. First, emission models in both MOVES and EMFAC are based on average running speed. Second, these models show low levels of certainty in estimating the different emission rates (Board, 1995). INTEGRATION is also used because it more accurately estimates emissions and fuel consumption factoring vehicle kinetics elements such as roadway grade and rolling resistance.

Literature Review

The results of some studies examining the environmental impact of corridor signal control plans will be described here. Zhang et al. used a portable emissions measurement system

(PEMS) to collect real-time data for a corridor in Beijing (Zhang et al., 2009). The authors compared emission factors and rates based on a driving cycle in coordinated and uncoordinated signal controlled systems. The analysis of different corridor management plans was done using a microscopic simulation model (VISSIM) and an emissions model that integrates vehicle specific power. Results showed that efficiently optimizing a corridor could produce a decrease in HC and CO emissions by 50 % and 30%, respectively. As a counter effect, the authors noted an increase in NO_x pollution by 10 % when the timing strategies were used.

Lv and Zhang in (Lv and Zhang, 2012) used a combination of VISSIM and MOVES, the emission model developed by the U.S. Environmental Protection Agency (EPA) to study the effect of signal coordination on emissions at signalized intersections. Results showed that an increase in emissions can be expected when a platoon of vehicles arrives early on a red indication. This increase in emissions is attributed to the idling and additional stops happening at the intersection.

De Coensel et al. used the Paramics microscopic simulation software and the VERSIT+ emissions model to estimate three pollutant emissions CO_2, NO_x, and PM_{10} that result from corridor operations (De Coensel et al., 2012). Results showed that traffic intensity, and green split duration had the largest influence on the reduction of emissions. The authors documented 10% to 40% reduction in pollutants when an optimized signal timing plan is implemented in a major arterial.

Analysis Procedure

Two signal timing optimization software tools, TRANSYT-7F (McTrans Center, 2014) and PTV VISTRO (PTV, 2014), were used to develop different corridor signal timing plans using 14 different combinations of objective functions. A microscopic simulation tool, INTEGRATION (Rakha and Ahn, 2004b) is used to model the corridor operations under different signal control plans. The microscopic modeling tool, INTEGRATION, is used in this work rather than macroscopic modeling tools like MOVES or EMFAC for two main reasons. First, emission models in both MOVES and EMFAC are based on average running

speed. Second, these models show low levels of certainty in estimating the different emission rates (Board, 1995). INTEGRATION is also used because it more accurately estimates emissions and fuel consumption factoring vehicle kinetics elements such as roadway grade and rolling resistance.

The objective functions generated from PTV Vistro and TRANSYT-7F are:
- Case 1: 0.0 delay 1.0 stops (PTV VISTRO) (Reducing the number of stops),
- Case 2: 0.1 delay 0.9 stops (PTV VISTRO),
- Case 3: 0.2 delay 0.8 stops (PTV VISTRO),
- Case 4: 0.3 delay 0.7 stops (PTV VISTRO),
- Case 5: 0.4 delay 0.6 stops (PTV VISTRO),
- Case 6: 0.5 delay 0.5 stops (PTV VISTRO),
- Case 7: 0.6 delay 0.4 stops (PTV VISTRO),
- Case 8: 0.7 delay 0.3 stops (PTV VISTRO),
- Case 9: 0.8 delay 0.2 stops (PTV VISTRO),
- Case 10: 0.9 delay 0.1 stops (PTV VISTRO),
- Case 11: 1.0 delay 0.0 stops (PTV VISTRO) (Reducing the delay),
- Case 12: Progression and Control Delay (TRANSYT-7F),
- Case 13: Fuel Consumption Only (TRANSYT-7F),
- Case 14: Progression and Fuel Consumption (TRANSYT-7F).

Background for Used Software

PTV VISTRO

PTV VISTRO is a traffic analysis software used for timing traffic signals and optimizing individual intersections, corridors, and networks, and assessing their impact. It can also estimate an intersection's Level of Service (LOS). PTV VISTRO can handle different types of intersection control, including signalized, two-way stops, all-way stops, and roundabouts. VISTRO also allows the user to apply different standard methodologies like HCM 2010, HCM 2000, Circular 212, Intersection Capacity Utilization (ICU), and Kimber methods. VISTRO can test different mitigation options for failing or poorly timed intersections. It can

also compare the various options to each other and the base network. One useful aspect of VISTRO is that users can visualize and analyze the existence of queues and spill back by exporting their networks to the PTV VISSIM microscopic simulation model (PTV VISTRO, 2014).

PTV VISTRO is one of two optimization tools used in my study to produce sets of optimum timing plans with different objective functions. The optimization process I used focused on minimizing one of these three objective functions: 1) minimizing control delay only, 2) minimizing the number of stops only, and 3) minimizing a combination of control delay and number of stops. PTV VISTRO is an addition to the widely used PTV traffic modeling software Suite.

TRANSYT-7F

TRANSYT-7F is a signal timing optimization program. It has the capability of utilizing the Hill-Climb and Genetic Algorithm optimization techniques. Signal timing settings available for optimization include cycle length, phase splits, offsets, and phase order. The user has the option of specifying the low and high bound for cycle length optimization, time increment the optimization process uses, and original cycle length (McTrans, 2010).

TRANSYT-7F has been used in numerous traffic studies and researches, including the recent research work described in (Birckett et al., 2012). In the research, Ratrout and Abu Olba evaluated the adequacy of TRANSYT-7F release 10.1 under traffic conditions on a major arterial in Saudi Arabia (Ratrout and Abu Olba, 2009). The model was calibrated by producing similar queue length trends using field conditions. The study evaluated traffic signal timing plans produced by TRANSYT-7F's optimization process. Results showed adequate timing plans as compared to the timing plan obtained through the SYNCHRO optimization model. Transyt-7F can optimize based on different objective functions. These objective functions are: maximizing progression and minimizing control delay; minimizing the fuel consumption; and maximizing the progression and minimizing the fuel Consumption.

INTEGRATION

INTEGRATION is a trip-based microscopic traffic and emissions simulation model. Vehicle operations in INTEGRATION are governed by proprietary car following, lane changing and gap acceptance models. The traffic simulator in INTEGRATION uses a traffic assignment tool based on origin-destination matrices defined by the user. INTEGRATION represents acceleration and velocity accurately at high temporal resolution by using a vehicle operation dynamics (Rakha, 2013).

INTEGRATION has been used in several fuel consumption and emission-related research projects. Rakha and Ahn discussed the validation of the energy and emission model used in the INTEGRATION framework for Intelligent Transportation System (ITS) and non-ITS alternatives (Rakha and Ahn, 2004b). INTEGRATION was validated using four evaluation scenarios (Rakha and Ahn, 2004b), and (Rakha, 2013). These scenarios were: a constant speed scenario, a variable speed scenario, a stop sign scenario, and signal coordination scenario. The study concluded that for a steady state condition, INTEGRATION's energy and emissions models were consistent with the Oak Ridge National Laboratory's field data. It also showed that the fuel consumption and emissions are sensitive to a combination of vehicle acceleration and speed during steady state conditions. The study also showed that the effect of traffic signal control on energy was only marginally dependent on the vehicle acceleration while the environmental impacts were highly dependent on acceleration.

INTEGRATION would be the main microscopic tool in this chapter because the VT-Micro model used in INTEGRATION showed the validity for both light-duty normal and absolute hot stabilized vehicle tailpipe emissions. VT-Micro also reflects all the differences in drive cycles to give accurate estimations for fuel consumption and emission rates very close to the field observations (Rakha et al., 2003).

Studied Network and the process of Calibration and Validation

The SH8 corridor used in this study is approximately 2 kilometers (1.25 miles) in length and is located in the City of Moscow, Idaho. The corridor has four intersections as seen in Figure 11. Three of the four intersections, (Farm Rd. & SH8, Peterson Dr. & SH8, and Line St. &

SH8) are standard four-approach eight-phase signalized intersections. US 95 is a one-way street in the south direction with three lanes and a right turn lane. A lane drop along SH8 from two to one lane occurs between Line Street and US 95 with a single lane extending to US 95.

Figure 11 VISTRO model of SH8 and used volumes

Field data used to calibrate and validate the models in the micro-simulation and optimization tools included:

- Turning movement counts for all intersections during the P.M. peak hours and vehicle types;
- Collecting the signal timing data for all the traffic signals;
- Corridor travel times while driving over the studied segment;
- Stopped delay for all the movements of the studied intersections;
- Geometric measurements for the right and left turn pockets, lane widths, etc.

Some of the collected field data (link speed and turning movement counts) were used in building the traffic simulation models, while other data (like point-to-point travel time and queue lengths at different approaches) were used in calibrating the model. Figure 12 shows an example in the maximum queue length distribution in the southbound direction of US95 for the simulation runs. The figure shows that field collected queue length data are within the distribution obtained through the simulation model. During and after the calibration

processes, all the simulations were visualized to make sure that field conditions are well represented in the microscopic simulations and that the animations are realistic.
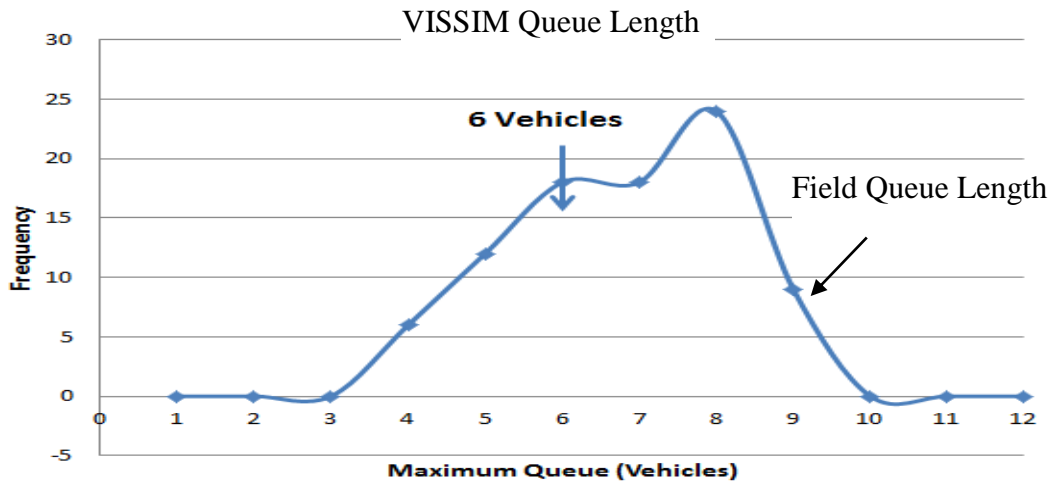
VISSIM Queue Length

Figure 12 VISSIM vs. Field queue distribution in the SB direction of US95

Results of Investigating Different Corridor Traffic Management Plans and Objective Functions

INTEGRATION was used to simulate and get the fuel consumption and emissions of the 14 different timing plans resulting from the 11 PTV VISTRO, and three TRANSYT-7F objective functions previously mentioned.

Table 8 shows the results for the two extreme cases, in PTV VISTRO: (100% delay & 0% stops,) and (0% delay & 100% stops). To make the task of the differentiation between the two objective functions easier to follow in Table 8, text in some cells is underlined. Underlined text represents better values compared to other text. As can be seen in Table 8, the plan resulting from using the objective function of (1.0 delay & 0.0 stops), or giving the priority to reducing the delay produced the following outputs:

1- Smaller cycle length, 60 seconds, compared to the 290 seconds produced by the 0.0 delay & 1.0 stops plan.

2- A higher percentage of bandwidth time /cycle length, 29%, compared to 21% for the 0.0 delay & 1.0 stops plan.

3- Better travel time for the whole corridor, 176 seconds, compared to 223 seconds for the 0.0 delay & 1.0 stops plan.

4- Higher travel speed, 28.5 mph, compared to 23.2 mph for the 0.0 delay & 1.0 stops plan.

5- Worse average number of stops, 1.98 stops/corridor, compared to 1.43 stops/corridor for the 0.0 delay & 1.0 stops plan.

6- Less delay, 43.74 seconds, compared to 90.96 seconds for the 0.0 delay & 1.0 stops plan.

7- Worse fuel consumption rate, 1.43 gram/second, compared to 1.16 gram/second for the 0.0 delay & 1.0 stops plan.

8- Worse HC emission rate, $2.47*10^{-3}$ gram/second, compared to $1.82*10^{-3}$ gram/second for the 0.0 delay & 1.0 stops plan.

9- Worse CO and NO_x emission rates, 0.06 and $3.26*10^{-3}$ gram/second consequently, compared to 0.04 and $2.26*10^{-3}$ gram/second consequently for the 0.0 delay & 1.0 stops plan.

10- Worse CO2 emission rate, 3.24 gram/second, compared to 2.65 gram/second for the 0.0 delay & 1.0 stops plan.

All of these results reinforce what was mentioned before in the results part of Chapter three about the negative impacts of introducing a stop in the signalized intersection corridors. As could be seen in Table 8, the case which has the highest number of stops, produced worse fuel consumption, NO_x, HC, and CO emissions. The in-between nine objective functions, (0.1 delay 0.9 stops) to (0.9 delay 0.1 stops), produced in-between Measure of Effectiveness, fuel consumption, and emissions, and this is why the focus is towards the two extreme cases (1.0D 0.0S) and (0.0D 1.0S).

Table 8 Fuel consumptions, emissions, delay, and number of stops for the best and worst PTV Vistro Cases

	Cycle Len. (sec.)	% Band / Cycle	Travel Time (sec.)	Speed (mph)	No. of Stops	Delay (sec.)	Fuel, (g/sec.)	HC 10^{-3} (g/sec)	CO, (g/sec.)	NOx 10^{-3} (g/sec.)	CO$_2$, (g/sec.)
1.0D 0.0S	60	.29	175.99	28.45	1.98	43.74	1.43	2.47	.06	3.26	3.24
0.0D 1.0S	180	.21	223.24	23.21	1.43	90.96	1.16	1.82	.04	2.26	2.65

After considering that more than 4000 vehicles are running over the studied network during the peak times, the values mentioned in Table 8 show the possibility of achieving significant reductions in fuel consumption and emissions on signalized intersection corridors.

INTEGRATION was used to simulate the three different TRANSYT-7F timing plans resulting from the three different objective functions: Progression and Control Delay; Fuel Consumption; and Progression and Fuel Consumption. Table 9 shows INTEGRATION outputs for these three timing plans. To show the differentiation between the three TRANSYT-7F objective functions and their INTEGRATION outputs more clearly in Table 9, the table is color coded in green and red. Green cells represent better values compared to red cells. The case of "Progression and Fuel Consumption" produced the best combination of pretty good Measure of Effectiveness and Environmental Impact compared to the other two objective functions. Table 9 shows the inconsistency of results of TRANSYT-7F compared to PTV VISTRO, but the values show that in a general way, introducing more stops is going to negatively impact emissions and Measure of Effectiveness.

The outputs of the analysis of this second part support the findings of the first part about the negative effects of stops.

Table 9 Fuel Cons., Emissions, Delay, and No. of Stops for the TRANSYT-7F Cases

	Cycle Len.(sec.)	Travel Time (sec.)	Speed (mph)	No. of Stops	Delay (sec.)	Fuel, (g/sec.)	HC 10^{-3} (g/sec.)	CO, (g/sec.)	$NO_x 10^{-3}$ (g/sec.)	CO_2, (g/sec.)
Progression and Control Delay	110	181.63	27.83	**1.64**	49.36	1.35	2.07	.047	**2.82**	3.07
Fuel Consumption Only	110	217.28	23.33	2.46	84.98	**1.29**	2.14	.050	2.86	**2.92**
Progression and Fuel Consumption	110	**177.17**	**28.59**	1.73	**44.88**	1.37	**2.05**	**.047**	2.90	3.13

Conclusion

Inefficient signal timing plans in urban and suburban corridors can cause an abundance of vehicle emission pollution. Prolonged idling times for vehicles queued at signalized intersection approaches can decrease fuel efficiency for users. The main objective of this work is to investigate the effectiveness of different corridor signal timing plans optimized using different objective functions in reducing fuel consumption and emissions. These objective functions included in this study are combinations of: minimizing control delay; minimizing the number of stops; maximizing the progression; and minimizing the fuel consumption.

Two signal timing optimization software tools, TRANSYT-7F (McTrans Center, 2014) and PTV VISTRO (PTV, 2014), are used to develop different corridor signal timing plans using 14 different combinations of objective functions. A microscopic simulation tool, INTEGRATION (Rakha and Ahn, 2004b) is used to model the corridor operations under different signal control plans.

The results presented in this chapter in Table 8 and Table 9 reinforce previous findings mentioned in Chapter Three about the negative impacts of introducing a stop in the signalized intersections corridors. In a general way, objective functions that have a higher number of stops are associated with worse fuel consumption, NO_x, HC, and CO emission rates.

References

Birckett, A., Tomazic, D., Bowyer, S., Bevan, K., Wetzel, P., Keidel, S., Biller, B., 2012. Transient Drive Cycle Modeling of Supercharged Powertrains for Medium and Heavy Duty On-Highway Diesel Applications (SAE Technical Paper No. 2012-01-1962). SAE International, Warrendale, PA.

De Coensel, B., Can, A., Degraeuwe, B., De Vlieger, I., Botteldooren, D., 2012. Effects of Traffic Signal Coordination on Noise and Air Pollutant Emissions. Environ. Model. Softw. 35, 74–83. doi:10.1016/j.envsoft.2012.02.009

EPA, 2012. EPA - Air Quality Management (AQM) - Emissions Inventory [WWW Document]. EPA - Air Quality Management (AQM) - Emissions Inventory. URL http://www.epa.gov/air/aqmportal/management/emissions_inventory/

Lv, J., Zhang, Y., 2012. Effect of Signal Coordination on Traffic Emission. Transportation Research Part D: Transport and Environment 17.

McTrans, 2010. TRANSYT-7F Users Guide. University of Florida.

McTrans Center, 2014. TRANSYT-7F- Traffic Network Study Tool [WWW Document]. URL http://mctrans.ce.ufl.edu/featured/transyt-7f/ (accessed 1.15.14).

PTV, 2014. PTV Vistro - the Traffic Engineering Tool [WWW Document]. URL http://vision-traffic.ptvgroup.com/en-us/products/ptv-vistro/ (accessed 1.15.14).

PTV VISTRO, 2014. PTV VISTRO User Manual. AG, Karlsruhe.

Rakha, H., 2013. INTEGRATION © Release 2.40 for Windows: User's Guide – Volume I: Fundamental Model Features. Virginia Tech.

Rakha, H., Ahn, K., 2004. Integration Modeling Framework for Estimating Mobile Source Emissions. Journal of Transportation Engineering 130, 183–193. doi:10.1061/(ASCE)0733-947X(2004)130:2(183)

Rakha, H., Ahn, K., Trani, A., 2003. Comparison of MOBILE5a, MOBILE6, VT-MICRO, and CMEM Models for Estimating Hot-Stabilized Light-Duty Gasoline Vehicle Emissions. Canadian Journal of Civil Engineering 30, 1010–1021. doi:10.1139/l03-017

Ratrout, N., Abu Olba, M.A., 2009. Adequacy of TRANSYT-7F and Synchro Models Along a Major Arterial in Saudi Arabia. Canadian Journal of Civil Engineering 36, 95–102. doi:10.1139/L08-120

U.S. Energy Information Administration, 2015. Short-Term Energy Outlook (STEO) [WWW Document]. Short-Term Energy Outlook (STEO). URL http://www.eia.gov/forecasts/steo/

Zhang, Y., Chen, X., Zhang, X., Song, G., Hao, Y., Yu, L., 2009. Assessing Effect of Traffic Signal Control Strategies on Vehicle Emissions. Journal of Transportation Systems Engineering and Information Technology 9, 150–155. doi:10.1016/S1570-6672(08)60050-1

CHAPTER 6: DEVELOP SIGNAL CONTROL PARAMETERS GUIDELINES FOR ISOLATED INTERSECTIONS FOCUSING ON ADVANCED CONTROLLER SETTINGS

Overview

In this chapter, seven different traffic controller settings were tested to investigate their environmental impact. The significance of this work is that agencies with limited funds could reduce the environmental impact of vehicles at isolated intersections without any added cost or equipment by simply using the traffic signal controller settings as demonstrated in this chapter.

Used Settings

Fixed time using recommended Synchro timings.

In this setting, a standard NEMA (National Electrical Manufacturers Association) phasing was used. In this standard phasing, a leading left for the major street will start the cycle, followed by a green for the through movement of the major street. After that, a barrier will come to start the leading left for the minor street, followed by the green for the minor street. This standard NEMA phasing could be seen in Figure 13.

Figure 13 Synchro timings and a NEMA standard phasing

Source: http://ops.fhwa.dot.gov/trafficanalysistools/tat_vol4/app_f.htm

Green-rest for the major direction and red-rest for the minor street

In this setting, when there are no calls in the minor street, the green-rest mode would be enabled for the major street. The controller will also enable a red rest for the minor street as far as there are no calls are present. Once this call arrives, the signal will switch to yellow followed by red for the major street.

Green-rest for the last movement (major or minor) and red-rest for the other direction

This scenario is activating the green rest mode for the direction which got the last vehicle. For example, if the East Bound direction got a vehicle, the EB signal head will rest on green where the other directions (northbound and southbound) will rest on red. After that, if a vehicle came from the northbound direction, it will rest on green for this northbound direction and rest on red for the eastbound and westbound directions. This scenario is helpful for intersections with platooned vehicle arrivals.

Delayed detection for the minor street.

In this delayed detection setting, the detector electronics are giving few seconds of delay from the start of a continuous presence of a vehicle on the minor street until an output signal begins. If the vehicle on the minor street is turning right on red and leaves the detection area before the delay time has expired, no output signal is generated. This setting will help in reducing unneeded stops in the major street if the minor street vehicle already turned right on red. If this delayed detection setting was used, the general code of practice is to set this value for a time period of (10 to 15 seconds). In this analysis, the value of delayed detection is set for 10 seconds.

Right turn on red for both major and minor streets

This setting allows right-turn vehicles to turn right, if they have a safe gap, even if the traffic signal is red.

Combination between delayed detection for the Minor Street and right turn on red for both major and Minor Street

This case is basically maximizing the probability that vehicles on the major street will not face a red signal. If a vehicle came from the minor street and it is turning right, it can make the right-turn movement in a period not exceeding the delayed detection period (10 seconds in this case). If the right-turning vehicle from the minor street exceeded the delayed detection period (the 10 seconds in this case), the minor street direction would be granted a green signal. From watching the simulation files, it was noticed that most of the minor street right-turn vehicles were able to complete their right-turn movement while the minor street signal is still on red.

Flashing red for both major and minor streets

This case is basically making the intersection to act as an all-way stop control intersection. All vehicles coming from the major and minor streets will make a full stop before completing their movement through the intersection.

VISSIM Intersection

Figure 14 shows the typical four-leg studied intersection. The major street (eastbound and westbound) consists of two through lanes, one right-turn pocket, and one left-turn pocket. The minor street (northbound and southbound) consists of one shared through and right lane, and one left-turn pocket lane. Lane lengths are set to a length of 400 feet from the start of the link to the traffic signal in all the directions.

Signal timings for the default case were obtained by optimizing the intersection on the traffic signal optimization tool (Trafficware Synchro.) Synchro timings were used as inputs to the traffic simulation software (PTV VISSIM). The PTV VISSIM model was adjusted according to the different requirement of each case. For each case of the studied seven cases, ten different simulation runs were conducted in VISSIM with ten different random seeds. The average for each ten VISSIM runs was calculated. The measure of effectiveness, fuel

consumption, and emissions were obtained from VISSIM by selecting the appropriate "Evaluation" settings.

For all the VISSIM runs, a 900 seconds (15 minutes) seeding period was used, followed by a 3600 seconds (60 minutes) simulation period. Only the results of the (60 minutes) simulation period were used for the analysis. Only one vehicle type was used (General Purpose vehicle) to eliminate any bias in the results. Low volumes were also used to exclude any congestion, lane changing, or vehicle to vehicle interaction. Simply, the VSSIM network is set so that it only reflects the effect of changing the signal timing setting with no other variables.
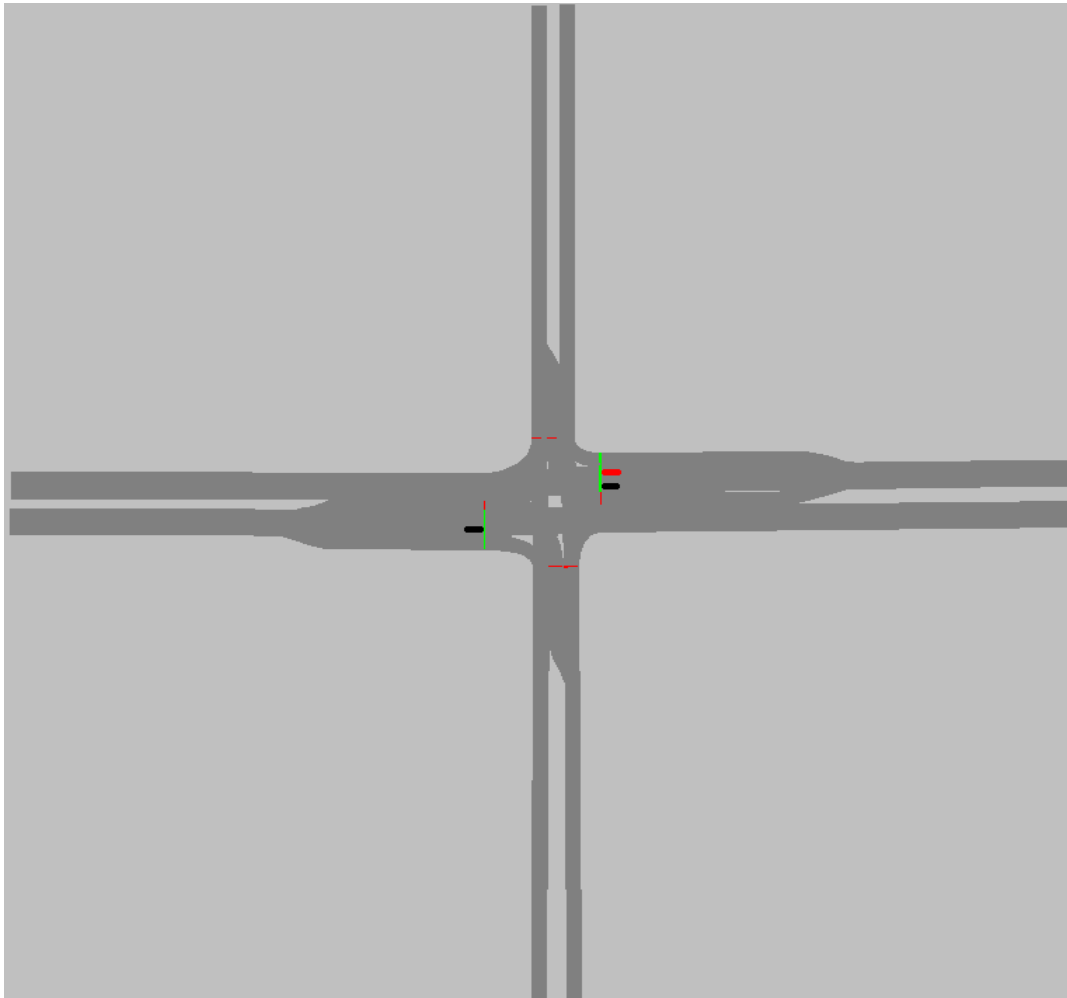

Figure 14 VISSIM Intersection

VISSIM Results

PTV VISSIM outputs included Measures of Effectiveness (MOE), fuel consumption, and emissions. These different outputs are listed in the following tables. For the sake of space, column heads are titled as Case 1 to 7 instead of writing down the full description for each one of these cases where different cases in the tables are as follows:

- Case 1: Default case with Synchro timings,
- Case 2: Green-rest for the major direction and red-rest for the minor street,
- Case 3: Green-rest for the last movement (major or minor) and red-rest for the other direction,
- Case 4: Delayed detection for the minor street,
- Case 5: Right turn on red for both major and minor streets,
- Case 6: Combination between delayed detection for the minor street and right turn on red for both major and minor street,
- Case 7: Flashing red for both major and minor streets.

In all the following tables, these abbreviations were included in the first column:

- Mov: Movement,
- W: West,
- E: East,
- N: North,
- S: South.

Table 10 Average Delay per Vehicle [s]

Mov.	Average Delay Per Vehicle [s]									
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Min	Max	Avg.
W-E	21.08	**<u>2.45</u>**	5.15	2.51	2.52	2.50	7.32	2.45	21.08	6.22
W-S	23.07	2.97	5.27	**<u>2.19</u>**	3.10	2.66	7.24	2.19	23.07	6.64
E-S	38.20	9.37	8.56	9.28	9.35	9.29	**<u>7.54</u>**	7.54	38.20	13.08
S-E	21.73	10.66	8.19	20.95	10.66	20.84	**<u>7.23</u>**	7.23	21.73	14.32
S-N	26.65	10.64	8.45	18.95	10.11	19.11	**<u>7.51</u>**	7.51	26.65	14.49
S-W	38.14	10.98	9.42	10.53	11.07	10.41	**<u>7.33</u>**	7.33	38.14	13.98
N-W	20.41	11.53	8.65	7.96	**<u>7.28</u>**	7.96	7.44	7.28	20.41	10.18
N-S	25.38	11.67	8.67	21.51	11.37	21.55	**<u>7.54</u>**	7.54	25.38	15.38
N-E	36.23	10.84	8.92	11.82	10.92	11.74	**<u>7.31</u>**	7.31	36.23	13.97
W-N	39.58	9.88	9.08	9.33	9.13	9.37	**<u>7.56</u>**	7.56	39.58	13.42
E-N	20.51	2.73	4.77	2.69	**<u>2.64</u>**	2.89	7.29	2.64	20.51	6.22
E-W	22.80	2.93	5.69	2.33	2.82	**<u>2.25</u>**	7.28	2.25	22.80	6.59
All	27.82	7.01	7.16	8.16	**<u>6.69</u>**	8.24	7.38	6.69	27.82	10.35

Table 11 Average Stopped Delay per Vehicle [s]

Mov.	Average Stopped Delay Per Vehicle [s]									
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Min	Max	Avg.
W-E	16.40	0.72	1.41	0.76	0.71	0.76	**<u>0.10</u>**	0.10	16.40	2.98
W-S	18.21	0.96	1.31	0.66	0.88	0.86	**<u>0.11</u>**	0.11	18.21	3.28
E-S	32.10	2.84	2.40	2.69	2.73	2.69	**<u>0.10</u>**	0.10	32.10	6.51
S-E	17.04	3.92	2.24	13.86	3.82	13.75	**<u>0.10</u>**	0.10	17.04	7.82
S-N	21.39	3.93	2.39	12.18	3.44	12.35	**<u>0.10</u>**	0.10	21.39	7.97
S-W	32.40	4.31	3.21	3.88	4.39	3.79	**<u>0.10</u>**	0.10	32.40	7.44
N-W	15.71	4.36	2.60	0.30	0.15	0.30	**<u>0.10</u>**	0.10	15.71	3.36
N-S	20.24	4.61	2.67	14.05	4.42	14.11	**<u>0.10</u>**	0.10	20.24	8.60
N-E	30.10	3.90	2.42	4.63	4.01	4.55	**<u>0.10</u>**	0.10	30.10	7.10
W-N	33.35	3.29	2.63	2.62	2.53	2.65	**<u>0.10</u>**	0.10	33.35	6.74
E-N	16.23	0.86	1.22	0.96	0.70	1.02	**<u>0.10</u>**	0.10	16.23	3.01
E-W	17.96	0.99	1.69	0.70	0.97	0.66	**<u>0.11</u>**	0.11	17.96	3.30
All	22.64	2.44	2.05	3.61	2.09	3.63	**<u>0.10</u>**	0.10	22.64	5.22

Table 12 Average Number of Stops per Vehicles

Mov.	Average Number of Stops Per Vehicles							Min	Max	Avg.
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7			
W-E	0.58	0.16	0.46	**0.15**	0.17	**0.15**	1.00	0.15	1.00	0.38
W-S	0.62	0.19	0.48	**0.13**	0.22	0.17	1.00	0.13	1.00	0.40
E-S	**0.80**	0.87	0.81	0.90	0.87	0.90	1.00	0.80	1.00	0.88
S-E	**0.61**	0.90	0.74	1.00	0.92	1.00	1.00	0.61	1.00	0.88
S-N	**0.71**	0.86	0.74	0.91	0.85	0.91	1.00	0.71	1.00	0.85
S-W	0.76	0.86	**0.74**	0.85	0.86	0.84	1.00	0.74	1.00	0.84
N-W	0.56	0.88	0.71	0.98	**0.43**	0.98	1.00	0.43	1.00	0.79
N-S	**0.64**	0.86	0.67	0.97	0.87	0.97	1.00	0.64	1.00	0.85
N-E	**0.79**	0.84	0.81	0.93	0.87	0.93	1.00	0.79	1.00	0.88
W-N	**0.79**	0.86	0.81	0.89	0.84	0.89	1.00	0.79	1.00	0.87
E-N	0.54	0.19	0.43	**0.18**	0.21	0.20	1.00	0.18	1.00	0.39
E-W	0.63	0.19	0.51	**0.12**	0.17	**0.12**	1.00	0.12	1.00	0.39
All	0.66	0.55	0.63	0.57	**0.54**	0.58	1.00	0.54	1.00	0.65

Table 13 Average Queue Length [ft.]

Mov.	Average Queue Length [ft.]							Min	Max	Avg.
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7			
W-E	2.41	0.14	0.35	0.16	0.14	0.15	**0.00**	0.00	2.41	0.48
W-S	2.91	0.23	0.36	0.15	0.21	0.17	**0.00**	0.00	2.91	0.58
E-S	4.60	0.72	0.61	0.74	0.73	0.75	**0.00**	0.00	4.60	1.16
S-E	2.90	0.84	0.62	2.10	0.82	2.11	**0.00**	0.00	2.90	1.34
S-N	2.90	0.84	0.62	2.10	0.82	2.11	**0.00**	0.00	2.90	1.34
S-W	2.71	0.50	0.38	0.46	0.50	0.45	**0.00**	0.00	2.71	0.71
N-W	2.56	0.88	0.56	0.00	0.00	0.00	**0.00**	0.00	2.56	0.57
N-S	2.56	0.88	0.56	1.11	0.46	1.12	**0.00**	0.00	2.56	0.96
N-E	2.59	0.48	0.32	0.53	0.47	0.53	**0.00**	0.00	2.59	0.70
W-N	5.29	0.79	0.71	0.72	0.69	0.71	**0.00**	0.00	5.29	1.27
E-N	2.70	0.18	0.33	0.19	0.15	0.19	**0.00**	0.00	2.70	0.53
E-W	2.61	0.18	0.41	0.15	0.18	0.14	**0.00**	0.00	2.61	0.52
All	3.07	0.58	0.48	0.70	0.43	0.71	**0.00**	0.00	3.07	0.85

Table 14 Maximum Queue Length [ft.]

Mov.	Maximum Queue Length [ft.]							Min	Max	Avg.
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Min	Max	Avg.
W-E	38.35	21.36	23.82	21.54	23.19	21.51	**0.00**	0.00	38.35	21.40
W-S	52.52	26.27	30.08	25.46	24.21	25.46	**0.00**	0.00	52.52	26.29
E-S	60.71	35.67	39.86	37.29	37.55	37.29	**0.00**	0.00	60.71	35.48
S-E	51.73	37.20	35.24	44.26	39.15	44.26	**3.28**	3.28	51.73	36.45
S-N	51.73	37.20	35.24	44.26	39.15	44.26	**3.28**	3.28	51.73	36.45
S-W	44.09	27.89	27.51	29.82	25.94	29.82	**0.00**	0.00	44.09	26.44
N-W	49.16	41.68	33.52	0.00	0.00	0.00	**0.00**	0.00	49.16	17.77
N-S	49.16	41.68	33.52	36.73	32.83	36.73	**0.00**	0.00	49.16	32.95
N-E	36.53	30.01	24.06	32.34	30.12	32.34	**0.00**	0.00	36.53	26.49
W-N	59.29	34.34	41.22	32.29	32.84	32.29	**0.00**	0.00	59.29	33.18
E-N	44.66	24.32	28.08	27.26	24.34	27.31	**0.00**	0.00	44.66	25.14
E-W	41.75	23.46	24.08	19.21	23.43	19.20	**0.00**	0.00	41.75	21.59
All	73.24	46.16	48.49	47.53	45.72	47.53	**3.28**	3.28	73.24	44.56

Table 15 Number of Vehicles

Mov.	Number of Vehicles							Min	Max	Avg.
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Min	Max	Avg.
W-E	28.6	**27.5**	27.6	28.0	27.7	28.0	28.3	27.50	28.60	27.96
W-S	28.2	28.8	28.4	28.9	28.5	28.9	**27.6**	27.60	28.90	28.47
E-S	**26.0**	27.9	26.1	28.7	28.4	28.8	29.2	26.00	29.20	27.87
S-E	**13.2**	13.4	13.3	13.7	13.3	13.7	13.3	13.20	13.70	13.41
S-N	**13.6**	13.7	13.7	13.8	13.7	13.8	13.7	13.60	13.80	13.71
S-W	**15.0**	15.1	15.1	15.1	15.1	15.1	15.1	15.00	15.10	15.09
N-W	**12.3**	12.4	12.4	12.4	**12.3**	12.4	12.4	12.30	12.40	12.37
N-S	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.90	12.90	12.90
N-E	**15.4**	**15.4**	15.5	15.5	**15.4**	15.5	**15.4**	15.40	15.50	15.44
W-N	29.4	29.1	29.2	**28.2**	29.1	**28.2**	29.3	28.20	29.40	28.93
E-N	29.8	28.4	29.0	27.5	27.9	**27.4**	**27.4**	27.40	29.80	28.20
E-W	28.5	27.4	28.6	27.8	27.5	27.8	**27.2**	27.20	28.60	27.83
All	252.9	252.0	251.8	252.5	251.8	252.5	**251.8**	251.80	252.90	252.19

Table 16 Fuel Consumption [gal]

Mov.	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Min	Max	Avg.
				Fuel Consumption [gal]						
W-E	0.339	**0.149**	0.221	0.150	0.152	0.149	0.340	0.149	0.340	0.214
W-S	0.348	0.155	0.222	**0.139**	0.158	0.151	0.320	0.139	0.348	0.213
E-S	0.439	0.315	**0.280**	0.328	0.324	0.330	0.346	0.280	0.439	0.337
S-E	0.158	0.153	**0.131**	0.195	0.154	0.193	0.152	0.131	0.195	0.162
S-N	0.191	0.161	**0.146**	0.190	0.159	0.191	0.167	0.146	0.191	0.172
S-W	0.250	0.177	**0.161**	0.174	0.178	0.172	0.181	0.161	0.250	0.185
N-W	0.142	0.148	0.126	0.147	**0.099**	0.147	0.148	0.099	0.148	0.137
N-S	0.172	0.154	**0.131**	0.191	0.155	0.191	0.157	0.131	0.191	0.164
N-E	0.255	0.179	**0.169**	0.192	0.181	0.192	0.184	0.169	0.255	0.193
W-N	0.507	0.337	**0.323**	0.330	0.331	0.331	0.357	0.323	0.507	0.359
E-N	0.334	0.147	0.209	**0.141**	0.149	0.145	0.315	0.141	0.334	0.206
E-W	0.360	0.156	0.242	0.143	0.152	**0.142**	0.328	0.142	0.360	0.218
All	3.493	2.230	2.361	2.326	**2.185**	2.341	2.994	2.185	3.493	2.561

Table 17 Emissions CO [g]

Mov.	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Min	Max	Avg.
				Emissions CO [g]						
W-E	23.75	**10.38**	15.40	10.46	10.58	10.41	23.81	10.38	23.81	14.97
W-S	24.34	10.80	15.52	**9.72**	11.01	10.49	22.38	9.72	24.34	14.89
E-S	30.63	22.08	**19.54**	23.00	22.57	23.12	24.27	19.54	30.63	23.60
S-E	11.00	10.67	**9.22**	13.57	10.75	13.54	10.66	9.22	13.57	11.34
S-N	13.28	11.32	**10.19**	13.36	11.12	13.45	11.58	10.19	13.45	12.04
S-W	17.42	12.41	**11.19**	12.25	12.42	12.11	12.63	11.19	17.42	12.92
N-W	9.98	10.29	8.90	10.31	**6.92**	10.31	10.31	6.92	10.31	9.57
N-S	12.01	10.79	**9.16**	13.38	10.81	13.38	10.97	9.16	13.38	11.50
N-E	17.83	12.42	**11.77**	13.40	12.61	13.39	12.86	11.77	17.83	13.47
W-N	35.39	23.56	**22.69**	23.12	23.11	23.13	24.87	22.69	35.39	25.13
E-N	23.31	10.32	14.63	**9.87**	10.32	10.18	22.15	9.87	23.31	14.40
E-W	25.24	10.91	16.89	10.09	10.61	**10.02**	22.83	10.02	25.24	15.23
All	244.17	155.92	165.04	162.51	**152.75**	163.56	209.27	152.75	244.17	179.03

Table 18 Emissions NO$_x$ [g]

Mov.	Emissions NOx [g]									
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Min	Max	Avg.
W-E	4.62	**2.02**	3.00	2.04	2.06	2.03	4.63	2.02	4.63	2.91
W-S	4.74	2.10	3.02	**1.89**	2.14	2.04	4.35	1.89	4.74	2.90
E-S	5.96	4.30	**3.80**	4.48	4.39	4.50	4.72	3.80	5.96	4.59
S-E	2.14	2.08	**1.79**	2.64	2.09	2.64	2.07	1.79	2.64	2.21
S-N	2.58	2.20	**1.98**	2.60	2.16	2.62	2.25	1.98	2.62	2.34
S-W	3.39	2.41	**2.18**	2.39	2.42	2.36	2.46	2.18	3.39	2.51
N-W	1.94	2.00	1.73	2.01	**1.35**	2.01	2.00	1.35	2.01	1.86
N-S	2.34	2.10	**1.78**	2.60	2.10	2.60	2.13	1.78	2.60	2.24
N-E	3.47	2.42	**2.29**	2.61	2.46	2.61	2.50	2.29	3.47	2.62
W-N	6.89	4.58	**4.41**	4.50	4.50	4.50	4.84	4.41	6.89	4.89
E-N	4.53	2.01	2.85	**1.92**	2.01	1.98	4.31	1.92	4.53	2.80
E-W	4.91	2.12	3.29	1.96	2.06	**1.95**	4.44	1.95	4.91	2.96
All	47.51	30.34	32.11	31.62	**29.72**	31.82	40.72	29.72	47.51	34.83

Discussion of Results and Conclusion

After analyzing the different PTV VISSIM outputs listed in the previous tables, and looking at how the whole intersection performs, the last row "All" in the previous tables, it could be noticed that:

- The Trafficware Synchro 9 optimized case, case one, resulted in the worst delay per vehicle, stopped delay per vehicles, average queue lengths, maximum queue lengths, fuel consumption, CO emission, and NO$_x$ emission. The number of stops is the lowest in most of movements in this case, but this did not cause the measure of effectiveness, fuel consumption, and emissions to go down because once a stop in happening, it happens for long times compared to other cases. This shows the need for fine tuning all the timings obtained from different optimization tools.

- Case five, right turn on red for both major and minor streets, showed lowest values for average number of stops per vehicle, the average delay per vehicle, fuel consumption, CO emissions, and NO$_x$ emissions for the whole intersection. This also reinforces all the prior findings about the negative impact of vehicle stops on the measure of effectiveness, fuel consumption, and emissions.

- Case three, green rest for the last movement (major or minor) and red rest for the other direction, helped the turning movements in reducing their fuel consumption, CO emission, and NO_x emissions because it eliminated the unnecessary stops, delays, and speed variations for platooned (following) vehicles. Since numbers of these turning vehicles are not controlling the behavior of the intersection, this case, case three, did not result in improving the overall behavior of the whole intersection.

- When comparing the behavior of cases one and seven, the default case and the flashing red case, it could be noticed that:

    1- Average number of stops in case seven is the worst (one full stop for all the vehicles) and case one earned the lowest average number of stops in most of the movements.

    2- The behavior of average delay per vehicle, average stopped delay, average queue length, and maximum queue length is completely the opposite for these two cases. This occurs because in case seven, flashing red, even if all the vehicles made a full stop, they did not wait for long times at the intersection compared to case one.

    3- The rlatively long stopping times in the case one, the default case, affected the overall behavior of the intersection and resulted in the worst fuel consumption, CO emission, and NOx emissions.

References

Appendix F: Actuated Signal Control (FHWA Office of Operations,

http://ops.fhwa.dot.gov/trafficanalysistools/tat_vol4/app_f.htm . Accessed 12/2014

CHAPTER 7: Study CONCLUSIONS

Throughout this chapter summarizes the report's key findings and conclusions from research into fuel consumption and the environmental impact of corridor traffic.

Fuel Consumption and Emission Models, Tools, and Data Sources

Chapter three is directed to researchers and transportation engineers who would like to get one organized, thorough, and concise document about transportation emissions sources and modeling tools. The main goal and contribution of this work is to synthesize and document the state-of-the-art-practices in modeling fuel consumption and emissions in a synthesis format.

In the first part of this work, details about the definition, importance, and methods of calculation of emission inventories, emission factors, and some of the currently available emission inventories were provided. In the second part, the available fuel consumption and emission models suitable for modeling traffic operations were reviewed. The review in this second part included three different analysis levels: microscopic, mesoscopic, and macroscopic models. This section's structure covered techniques that utilize mathematical models, simulation packages, and in-the-field systems.

A concise summary of all the previous work can be seen in the following four tables.

Table 19 Summary of the Emission Inventories and Factors

Sources of Vehicle Emissions and Fuel Consumption Data	
Emission Inventories	The emission inventories are a database that lists, by source, the amount of air pollutants discharged into the atmosphere during a given period from a certain activity. Two emission inventories examples are the National Emission Inventory (NEI), and the Biogenic Emissions Inventory System (BEIS).
Emission Factors	The emission factor is a value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. Emission factors are typically expressed as the weight of a specific pollutant divided by the unit weight, volume, distance, or duration of the activity emitting the pollutant

Table 20 Summary of Microscopic Models

Microscopic Models	
VISSIM	VISSIM is a stochastic, microscopic, time step, and behavior based traffic simulation tool, which is based mainly on the psychophysical driver behavior model of R. Wiedemann. VISSIM is supporting an add-on called EnViVer, which can calculate different types of emissions like CO2, NO_x, and PM10
CORSIM	CORSIM is a microscopic simulation tool developed by the (FHWA). CORSIM adopts the VeTESS software for the process of calculating fuel consumption and emissions.
CMEM	The Comprehensive Modal Emissions Model (CMEM) is based on a deterministic physical power demand model, which is based on a parameterized analytical representation of emissions product. Emission rates depend on causal variables such as fuel delivery system, inspection, maintenance effects, and vehicle age
INTEGRATION	INTEGRATION is a trip-based microscopic traffic and emissions simulation model. The emissions model incorporated into INTEGRATION is the VT-Micro model. Integration is used in lots of research work since it takes into consideration the vehicle kinetics.
PARAMICS	PARAMICS is a microscopic traffic simulation software package published by Quadstone in Edinburgh Scotland. PARAMICS incorporates the "Monitor" tool that utilizes tables that contain vehicle exhaust emissions and fuel consumption rates as a function of vehicle type, speed, and acceleration

Table 21 Summary of the Mesoscopic Models

Mesoscopic Models	
The MEASURE Model	MEASURE is a GIS-based emissions model. It can calculate estimates of HC, CO, and NO_x. Two major modules are included in MEASURE. The first one is the start emissions module while the second one is the on-road emission module
DYNASMART-P	DYNASMART is currently supported by the FHWA through McTrans. The used emission models in DYNASMART-P are adapted from the lookup tables for fuel consumption and emissions developed at Oak Ridge National Laboratory (ORNL) in the mid-1990s (ORNL models)

Table 22 Summary of Macroscopic Models

Mesoscopic Models	
Moves Model	MOVES is supported by the EPA. In macro scale, MOVES computes vehicle activity based on nationwide vehicle miles traveled data, which is not precise enough for mesoscopic and microscopic scale analysis. Emissions data for light-duty passenger vehicles is based largely on inspection maintenance test data. This data dates from 1995 to 2005 and was collected from approximately 62,500 vehicles
Watson Model	WATSON is a fuel consumption model developed by Watson et al. (1979) using average speed data. The changes in the positive kinetic energy during acceleration was used as a predictor variable in this model, But the effects of speed changes during the deceleration phase are not included

This synthesis work provides a foundation for those who are interested in a comprehensive introduction to the research done on the fuel consumption and emission fields. This work of modeling fuel consumption and emission model has been awarded to be published in the 54th Annual Transportation Research Forum and was published in its procedure. This could be downloaded from here

http://www.trforum.org/forum/downloads/2013_program.pdf?i=03190818 (Elbassuoni, 2013)

Modeling Engine Performance at Signalized Intersection Approaches

Chapter four provided an introduction of the GT-Suite advanced engine performance model and how it was used to document vehicle performance at signalized intersection approaches. The results presented in chapter four demonstrate that the fuel consumption and environmental cost of stops are highly dependent on the corridor operating speeds and this cost increases as the speed increases. Another factor that impact the fuel consumption and environmental cost of the stops is the drivers' acceleration patterns. Aggressive driving with high acceleration rates, yields much higher fuel consumption cost.

It could be concluded from these results that a higher level of acceleration resulted in higher fuel consumption and emission rates because aggressive accelerations need high and rich fuel/air ration to prevent engine knocking, thus bypassing the catalytic converter and increasing vehicle emissions. NO_x emissions increased in the mild to normal acceleration range and decreased in the aggressive acceleration range. HC and CO emissions increased by increasing the acceleration rates.

Minimizing the Fuel Consumption and Environmental Impacts of Corridor Traffic Operations

This work investigated the effectiveness of different corridor signal timing plans optimized by using different objective functions in reducing fuel consumption and emissions. The objective functions included in this work were combinations of minimizing control delay, minimizing stops, maximize the corridor throughput, maximize progression opportunities, and minimizing fuel consumption and emissions.

Two signal timing optimization software tools, TRANSYT-7F (McTrans Center, 2014) and PTV VISTRO (PTV, 2014), were used to develop different corridor signal timing plans using 14 different combinations of objective functions. A microscopic simulation tool, INTEGRATION (Rakha and Ahn, 2004b) was used to model the corridor operations under different signal control plans.

The results presented in Table 8, and Table 9 of chapter four reinforce previous findings mentioned in chapter three about the negative impacts of introducing a stop in the signalized intersections corridors. In a general way, objective functions that have a higher number of stops are associated with worse fuel consumption, NO_x, HC, and CO emission rates.

Actuated Control Parameters to Minimize Fuel Consumption and Emissions at Isolated Intersections

In this chapter, seven different traffic controller settings were tested to investigate their fuel consumption and environmental impact on intersection operations. The significance of this

work is to provide agencies with guidance on actuated controller settings to reduce stops, fuel consumption, and emissions at signalized intersections operating in isolated actuated mode. After analyzing delay, stops, fuel consumption, and emission values for different cases examined as part of this report, the following observations can be made:

- Case one, the Trafficware Synchro 9 optimized case, resulted in the worst delay per vehicle, stopped delay per vehicles, average queue lengths, maximum queue lengths, fuel consumption, CO emission, and NO_x emission. The number of stops is the lowest in this case, but this did not cause the measure of effectiveness, fuel consumption, and emissions to go down because once a stop in happening, it happens for longer times compared to other cases. This shows the need for fine tuning all the timings obtained from different optimization tools.

- Case three, green rest for the last movement (major or minor) and red rest for the other direction, helped the turning movements in reducing their fuel consumption, CO emission, and NO_x emissions because it eliminated the unnecessary stops, delays, and speed variations for platooned (following) vehicles. Since numbers of these turning vehicles are not controlling the behavior of the intersection, this case, case three, did not result in improving the overall behavior of the whole intersection.

- Case five, right turn on red for both major and minor streets, showed lowest values for average number of stops per vehicle, the average delay per vehicle, fuel consumption, CO emissions, and NO_x emissions for the whole intersection. This result also reinforces all the findings in previous chapters about the negative impact of vehicle stops on the measure of effectiveness, fuel consumption, and emissions.

- Comparing the behavior of the default case and the flashing red case (cases one and seven), it could be noticed that:

  1. Average number of stops in case seven is the worst (one full stop for all the vehicles) and case one got the lowest average number of stops in most of the movements.

  2. The behavior of average delay per vehicle, average stopped delay, average queue length, and maximum queue length is completely the opposite for these two cases. This occurs because in case seven, flashing red, even if all

the vehicles made a full stop, they did not wait for long time at the intersection compared to case one.

3. The high value of stopping times in case one, the default case, affected the overall behavior of the intersection and resulted in the worst fuel consumption, CO emission, and NO_x emissions.

Conclusions and Recommendations

- Traffic simulation and optimization models use different methods and data sets to estimate the fuel consumption and emissions that result from vehicular traffic. Chapter three of this report provides an extensive review of the fuel consumption and emission modeling approaches, and the source of fuel consumption and emission data used in different traffic simulation and optimizations models currently available. Analysts are encouraged to carefully examine this documentation and similar reviews before selecting the model suitable for the environmental analysis they are conducting.

- Microscopic traffic simulation models that take into consideration the vehicle kinetics (drag force, wind resistance, grade effect, etc.) estimate fuel consumption and emissions more accurately than models that do not take into consideration this aspect of vehicle motion. To improve the accuracy of the model estimates, the mathematical models that relate the engine VSP to fuel consumption and emission rates should be calibrated and validated to reflect field conditions at different sites.

- The results of the advanced engine modeling analysis presented in this report demonstrate that the fuel consumption and environmental costs of stops and delay at signalized intersection approaches are highly dependent on the vehicle's acceleration rate.

- The fuel consumption and environmental costs of stops at signalized intersection approaches are also highly dependent on the corridor operating speeds and increases as the speed increases. When optimizing corridors to minimize the environmental impacts of vehicular traffic, priorities should be given to minimizing stops for approaches with operating speed of 40 mph and higher. Eco traffic signal system

operations for such corridors can be achieved through minimizing stops and maximizing throughput for the major approach traffic.

- There is no significant difference in the fuel consumption and environmental costs of stops for vehicles operating with speeds of 25 mph and 35 mph, respectively. For corridors where the operating speed is equal or less than 35 mph, eco traffic signal system operations can be achieved through minimizing network wide stops.

- The fuel consumption and emission results presented in this report are based on modeling an average 2000 cubic centimeter gasoline engine. The analysis should be expanded to include vehicles with other engine capacity and for different fuel types.

- When optimizing corridors to minimize the negative environmental impacts of traffic, the choice of which objective function to apply should be based on the major road operating speed and the origin-destination distribution of the corridor traffic. For a typical corridor in small and medium size cities, where the operating speeds are 35 mph or less and the percentage of major road-through traffic is approximately 60 percent, optimizing the corridor to minimize network wide stops or to minimize fuel consumption should provide the best eco traffic system operations for the corridor. Moderate Cycles lengths (90 seconds to 120 seconds) should be used in the corridor.

- For isolated actuated intersections in small and medium size cities with operating speeds of 35 mph or lower, minimizing intersection stops should result in the best eco-traffic operations at the intersection. The use of some advanced controller features, such as rest-on-green and delayed detector calls on right turn lanes, can also lead to a considerable reduction in the number of stops at the intersection.