ACTUATED CONTROL PARAMETERS TO REDUCE VEHICLE EMISSIONS AND FUEL CONSUMPTION AT ISOLATED INTERSECTIONS

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ABSTRACT

While isolated intersections in small to medium sized cities do not typically experience the high traffic volumes of heavily populated urban areas, the amount of tailpipe emissions and gas consumed are significant. The purpose of this thesis is to provide practitioners with a guideline for reducing emissions and fuel consumption at fully-actuated isolated intersections, considering vehicle volume levels expected in small urban areas. This study applies an industry-standard engine performance model to verify prior research findings that the number of stops is an adequate measure of effectiveness to reduce the environmental impact of traffic operations at isolated intersections. Microscopic traffic simulation was used to investigate a variety of actuated timing settings, using multiple vehicle detection systems, with the goal of identifying strategies that governing agencies might use to better time isolated intersections with keeping environmental impacts in mind. The results consistently show that the passage time setting carries the most weight, especially on the minor approaches, in limiting environmentally harmful by-products of traffic. The number of stops on the major approaches was less sensitive to the passage time setting on the major approaches, but better performance was observed when a higher value of passage time was used. The minimum green setting was found to have an impact at low vehicle volumes only. Practitioners may use the guidelines presented in this paper to adequately time actuated control parameters to reduce the environmental impact of traffic at isolated intersections.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Overview

The continuous growth in vehicular traffic has led to a large increase in fuel consumption and vehicle emissions, which negatively impacts the environment, public health, and the economy. The optimal traffic flow, from an environmental standpoint, is the one with fewest stops, shortest delays, and constant speeds. Providing traffic signal operations with such characteristics, however, is not an easy task to achieve. For example, in isolated intersections, stops experienced on a major road with a higher operational speed contribute more to fuel consumption than stops on a minor road with a lower speed limit.

At which combination of delay and stops do we achieve the best environmental performance? The research on linking isolated intersection control parameters and performance measures to environmental policy objectives such as carbon emission reduction and fuel efficiency has been very limited. The traditional signal timing modeling and analysis tools either do not consider or fail to provide accurate estimates of consumed fuel or pollutants emitted. With more attention being given to environment-related performance of traffic operations, defining policies and control parameters for signal timing environmental optimization are necessary to achieve the goal of eco-traffic signal systems that offer a reduction in fuel consumption and vehicular emissions.

The primary goal of this thesis is to develop actuated control timing parameters for fully-actuated signalized intersections operating on an isolated or free mode in order to reduce tailpipe emissions and fuel consumption. Engine characteristics representative of a common passenger vehicle are used to accurately estimate engine emissions and fuel consumption at signalized intersection approaches using an advanced engine modeling software tool. Microscopic simulation was used to model the traffic operations at a fully actuated isolated intersection. This analysis considers three major approach speed limits; 25 mph, 35 mph, and 45 mph, whereas the speed limit for the minor approach is kept constant at 25 mph. Stop bar detection is modeled on approaches with a 25 mph posted speed limit. Advance detection is employed on approaches in which the posted speed limits are set to 35 mph and 45 mph. Detection configurations for the experiment used in this study follow the Idaho Transportation Department (ITD) signalized intersection detection guidelines.

1.2 Thesis Goals and Objectives

The intended end result of the research presented in this thesis is to provide practitioners with recommendations of signal timing settings to reduce the number of stops on the major approaches of a fully-actuated signalized intersection. The objectives of the work presented in this thesis are:

1. Document the characteristics of fuel consumption and vehicle emissions at signalized intersection approaches using an advanced engine performance modeling software tool.
2. Investigate the relationship between actuated control parameters and fuel consumption and vehicle emission levels for fully actuated signaled intersections operating on an isolated or free mode of operation.
3. Develop guidelines for actuated control parameters to minimize fuel consumption and vehicle emissions for fully actuated signaled intersections operating on isolated or free mode of operation.

1.3 Thesis Organization

This thesis is organized in seven chapters. After the introduction, chapter 2 documents the characteristics of fuel consumption and vehicle emissions at signalized intersection approaches using the GT-Suite advanced engine performance modeling software. The purpose of this chapter is to investigate the environmental costs of a vehicle-stop at a signalized intersection. Chapter 3 provides a literature review covering previous research efforts in the area of eco-traffic signal control for isolated intersections. Chapter 4 provides a background of actuated control parameters for fully actuated isolated intersections. The technologies and engineering judgment employed during actuated signal timing design are highlighted. Chapter 5 documents the study methodology and experimental design. Chapter 6 summarizes the study analysis and results. Finally, chapter 7 lists the study conclusions and recommendations.

CHAPTER 2: MODELING ENGINE PERFORMANCE AT SIGNALIZED INTERSECTION APPROACHES

2.1 Overview

One of the primary goals of the research is to directly quantify the environmental costs of a vehicle-stop at a signalized intersection. To do so, the study took vehicle trajectories specific to stopping at a signalized intersection into account, focusing on the action of a vehicle accelerating from a stationary position to a desired velocity. The described vehicle trajectory was investigated to conclude if it was the origin of intersection pollution. The engine performance after a green display is shown at an intersection is the focus in order to understand the result of when drivers accelerate to reach their desired speed. To account for different driver behaviors mild, normal, and aggressive acceleration tendencies are modeled. Fuel consumption, nitrogen oxides emissions (NOx), hydrocarbon emissions (HC), and carbon monoxide emissions (CO) were measured. Information regarding the employed engine modeling software, the vehicle characteristics used in the modeling effort, and the corresponding results are explained further.

2.2 GT-Suite Background

GT- Suite is a product of Gamma Technologies (GTI), a specialist software company solely focused on the engine and vehicle industry. Practically all leading engine makers and suppliers have chosen GT- Suite because it comes as an all-inclusive package with many valuable productivity tools. These tools increase user efficiency and offer 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.

In a single software tool, GT- Suite handles a wide variety of vehicle and engine technical applications. It is a versatile multiphasic platform for constructing a wide range of engineering models through a combination of different libraries, providing the ability to execute Integrated Simulations of the entire vehicle and engine system. Such simulations are an industry trend that is gaining in importance and constitute the next frontier in Computer Aided Engineering (CAE) applications.

GT- Suite has long been recognized for its high degree of accuracy in predicting the behavior of complex engine related phenomena. At its core, the solver is based on the 1-D solution of the fully unsteady, nonlinear equations. Additionally, state of the art thermodynamic and phenomenological model solvers capture the effects of combustion, heat transfer, evaporation, in-cylinder motion and turbulence, and engine and tailpipe out emissions. It has been chosen to aid in the research presented in this thesis for its ability to accurately estimate vehicle emissions and fuel consumption.

GT-Suite has been used in several research fields. In (Keller et al. 2010), 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 2013), a design of gas mixer venturi as per IS4477 and simulation of dual fuel (Diesel-CNG) engine for performance parameters to examine the BSFC using GT-suite is presented. In (Almeida et al. 2012), a vehicle simulation of a 4-cylinder diesel internal combustion engine (ICE) coupled with the driveline of the vehicle, including its accessories, was developed utilizing the numerical 1D model, built in GT-Suite, to study the impact of accessory loads in a physically-representative way on the fuel consumption and emissions. In (Yang and Wang 2008), a Nissan SR20DET turbocharged gasoline engine with two charge-air cooling turbocharging systems has been modeled using GT-Suite 6.0 engine simulation code. (Lahuerta and Samuel 2013) presented numerical model of the warm-up characteristics of a 4-cylinder, 1.6 liter, turbocharged and intercooled, Euro IV, gasoline direct-injected engine. Also, GT-Suite was used in (Arunachalam et al. 2013; Birckett et al. 2012; Pohorelsky et al. 2011).

2.3 Vehicle Model for Engine Modeling

Engine characteristics of a common passenger vehicle were used as inputs for the vehicle model and normal atmospheric and roadway conditions were employed. A conventional Internal Combustion Engine (ICE) driven drivetrain equipped with a 3.0L gasoline engine has been modeled as a map-based engine that describes engine performance, power output and friction, fuel consumption, emissions and other characteristics. The engine maps for these quantities are specified as a function of engine speed and load. An ICE controller was used to simulate engine control functions such as idling and fuel cut off, this controller is recommended for applications where maximizing fuel economy and minimizing emissions are important. Torque is applied to the engine crankshaft by means of a look-up map-based accelerator pedal position and engine speed, where a driver module is incorporated to represent the driver actions that control the accelerator pedal, brake pedal, and transmission gear number during driveway and shifting.

An environment module is used to specify the ambient air conditions that affect the aerodynamic force on the vehicle. Several attributes are used to determine the air density including relative humidity, ambient air temperature and pressure. The wind velocity and direction are used to determine the effective vehicle-air velocity. The density and effective air velocity are used in drag and lift force calculations. A road module is used to model the road properties that affect vehicle dynamics including road grade, elevation, curvature radius, and rolling resistance. Table 1 summarizes the engine specifications and physical conditions used in quantifying the environmental costs of a vehicle-stop at a signalized intersection.

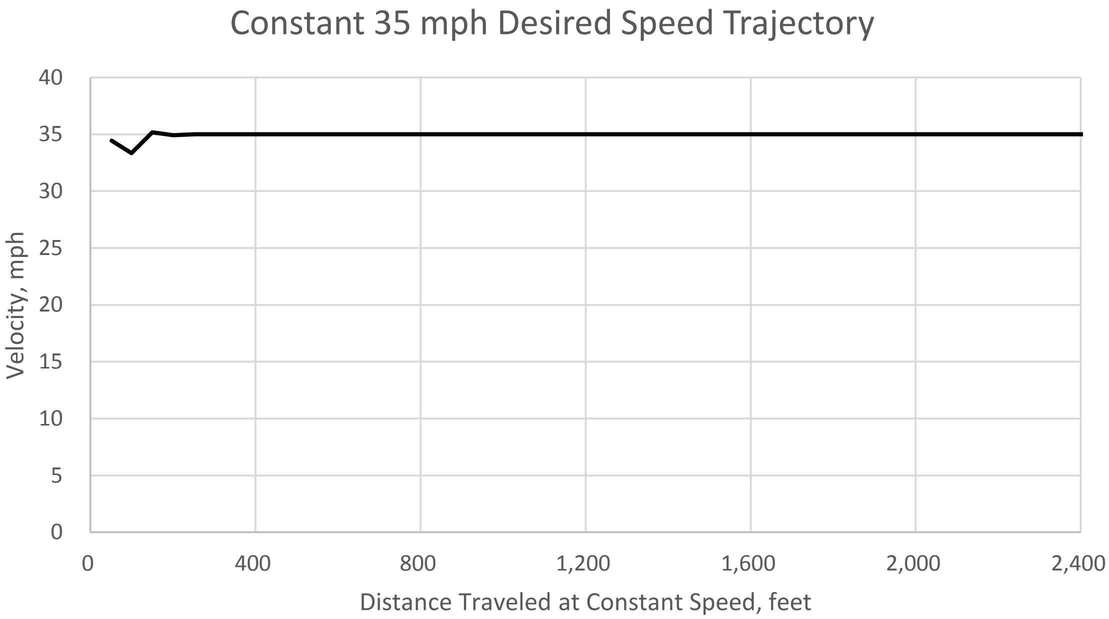
Table 1. Engine and Vehicle Specifications Inputs

Engine Configuration	Naturally Aspirated Four-stroke, Inline Four-cylinder, Direct Injection
Transmission	Automatic
Displacement	3 Liters
Minimum Operating Speed	950 RPM
Fuel Density	756 kg/m^3
Vehicle Weight	1800 kg
Vehicle Rolling Resistance Coefficient	0.01
Vehicle Drag Coefficient	0.32
Vehicle Frontal Area	0.8 m^2

2.4 Fuel Consumption and Emission Trends

Three separate cases of engine performance based on vehicle speed trajectories were simulated and analyzed. Case 1 is that of a vehicle idling with a zero velocity similar to the behavior seen at signalized intersections when a red display is shown. Case 2 describes the behavior of a vehicle accelerating from the idle position to a desired speed at the onset of a green display and as the vehicle travels through the intersection. Lastly, Case 3 shows the behavior of a vehicle traveling at constant speed upstream or downstream of a signalized intersection. Case 3 is significant in that it shows the environmental cost of a vehicle stopping at a signalized intersection compared to being able to clear the intersection without experiencing any delays as a result of the intersection control. The case of a vehicle decreasing its velocity to some speed above zero and avoiding a full stop while approaching a signalized intersection is not taken into account in this research. The environmental impact of speed reduction due to signalized control may be significant, but is difficult to estimate.

Figure 1 summarizes the results of the Case 1 behavior simulation, reaching and traveling at a constant 35 mph speed. The simulated trajectory and the engine performance graphs are paired together. Note that the significant spike in the fuel consumption rate between the times of 0 to 5 seconds is attributed to the end of the acceleration behavior, which was included to show the transition between states. The fuel consumption rate drops to the estimated value after the acceleration behavior and during constant speed trajectory. Figure 2 summarizes the results of the Case 2 behavior simulation, acceleration to a desired speed of 35 mph. Table 2 summarizes the engine performance rate during the idling behavior, in which the vehicle’s velocity is 0 mph. The engine performance was found to be constant as the vehicle idles.



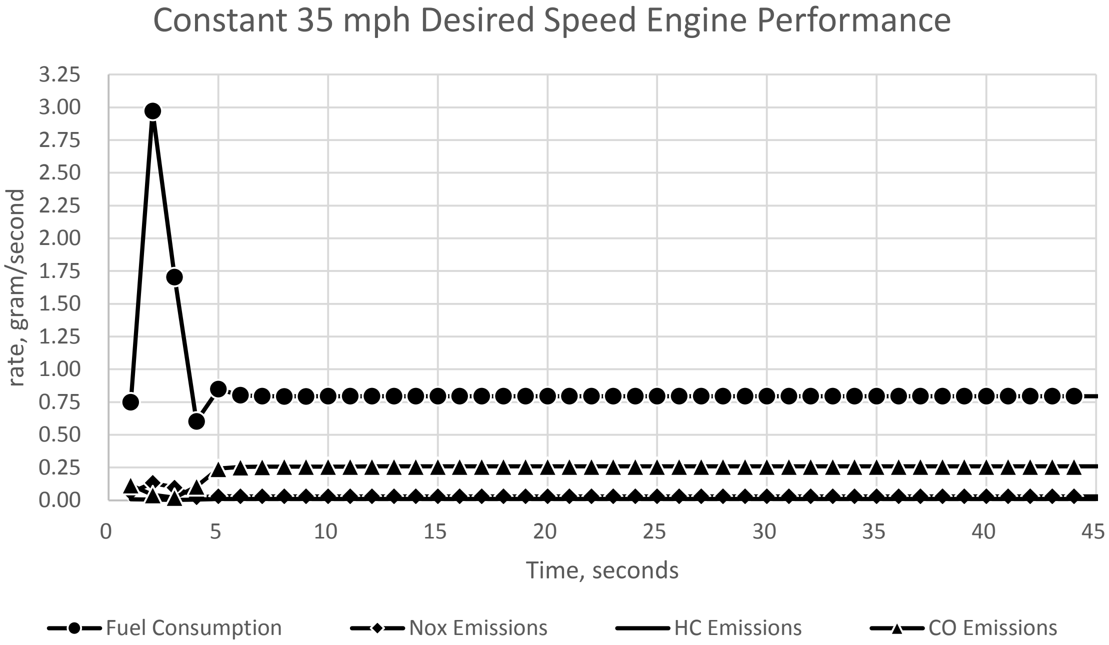


Figure 1. Case 1 Vehicle Trajectory and Engine Performance Results

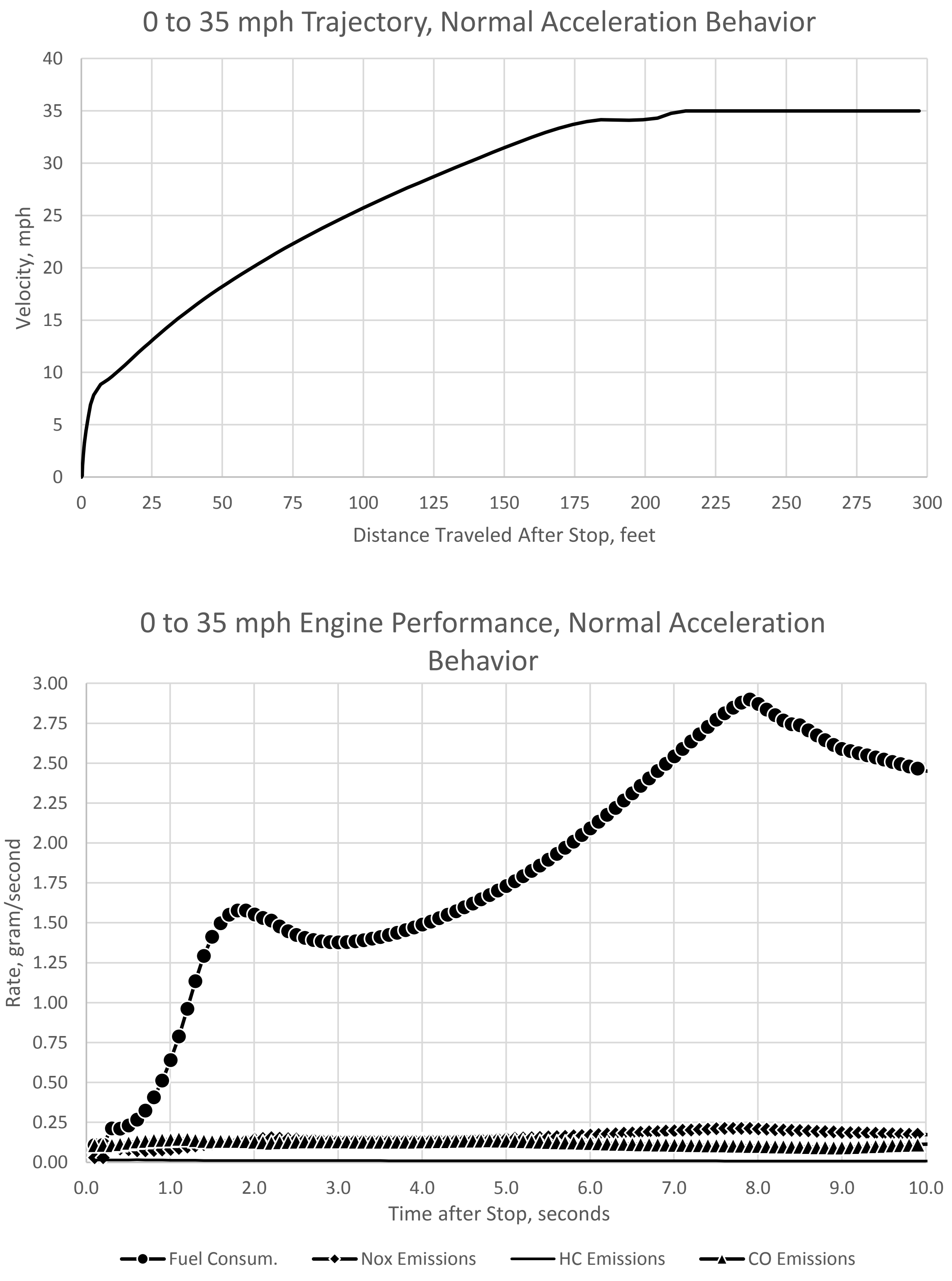


Figure 2. Case 2 Vehicle Trajectory and Engine Performance Results

Table 2. Case 3, Idle Behavior Engine Performance, all units grams/second

Fuel Consumption	**NO_x Emissions**	**HC Emissions**	**CO Emissions**
0.1057	0.0282	0.0131	0.1053

Driver behavior often varies during Case 2 behavior, the acceleration from idle position during a red display to the desired speed. Table 3 summarizes the engine performance results in total values measured over a common distance, which includes the time taken to reach the desired speed with three acceleration behaviors. Note that two engine performance relationships exist. Total Fuel Consumption and Total NO_x emissions increase as maximum acceleration behavior increases in magnitude. However, Total HC and Total CO emissions decrease slightly in most desired speed cases as maximum acceleration behaviors increase. All environmental measures increased as the desired speed increase. This can be seen comparing values based on the 0 to desired speed trajectory categories. The results back previous research conclusions made by others that fuel consumption rates vary the greatest as desired speed is increased rather than with more aggressive acceleration behaviors.

Table 3. Environmental Measures Based on Maximum Acceleration Behavior and Desired Speed

	0 to 25 mph Trajectory			**0 to 35 mph Trajectory**		
	4.7 ft/s^2	**7.1 ft/s^2**	**11.8 ft/s^2**	**4.7 ft/s^2**	**7.1 ft/s^2**	**11.8 ft/s^2**
Total Fuel Consumption (grams)	9.5	11.2	13.2	15.8	18.8	21.9
Total NO$_x$ Emissions (grams)	0.9	1.0	1.6	1.3	1.6	2.3
Total HC Emissions (grams)	0.10	0.08	0.06	0.13	0.10	0.08
Total CO Emissions (grams)	1.25	0.96	1.04	1.69	1.22	1.35
	0 to 45 mph Trajectory			**0 to 55 mph Trajectory**		
	4.7 ft/s^2	**7.1 ft/s^2**	**11.8 ft/s^2**	**4.7 ft/s^2**	**7.1 ft/s^2**	**11.8 ft/s^2**
Total Fuel Consumption (grams)	24.1	28.6	34.2	33.6	40.6	48.6
Total NO$_x$ Emissions (grams)	1.8	2.4	3.2	2.4	3.1	4.0
Total HC Emissions (grams)	0.16	0.12	0.09	0.18	0.14	0.11
Total CO Emissions (grams)	2.09	1.43	1.46	2.42	1.63	1.64

Modeling the three vehicle trajectory cases typical at a signalized intersection, suggests that Case 2 (acceleration from a zero velocity to the desired speed typical to the roadway geometry) is the state that is more harmful to the environment. Although examples of engine performance were displayed for the 35 mph desired speed, the trends do not vary as desired speed deviates. Fuel consumption tends to vary the most as the vehicle shifts through low gears at low velocities. The highest fuel consumption rate is seen at the last instant before the engine shifts gears for the second time. The maximum observed rate for fuel consumption with a desired speed of 35 mph was nearly 3.0 grams per second during the acceleration to desired speed behavior, Case 2. During the constant speed behavior (Case 1) the fuel consumption rate is estimated at approximately 0.75 grams per second. During Case 3 (idle behavior) the fuel consumption rate is slightly higher at approximately 0.11 grams per second. NO_x emission results show similar trends with rates ranging from 0.03 grams per second while idling and constant speed to nearly 0.25 grams per second during acceleration behavior. HC emission rates did not vary during the three vehicle behavior cases, and seemed to remain at approximately 0.01 grams per second. Unlike the other engine emissions, CO emission rates reached an observed maximum during the constant velocity behavior. The CO emission rates during the acceleration behavior reached 0.14 grams per second around a velocity of 20 mph and then decreased as velocity increased until desired speed was reached, in which the CO emission rate increased to the highest observed level of 0.25 grams per second. During the idling behavior CO emission rates were minimal at approximately 0.11 grams per second.

A comparison of the fuel consumed and the pollutants emitted by an engine for the two trajectory scenarios of stopping at an intersection and proceeding at constant speed through an intersection can be seen in Table 4. These estimates are based from the engine performance of a vehicle with a desired speed of 35 mph and normal acceleration behavior, 7.1 ft/s^2. The idling and acceleration trajectories were used to estimate the environmental cost of a single vehicle that stops during 30 seconds of a red display and then proceeds to accelerate to the 35 mph desired speed. The environmental costs of decelerating to a stop were not considered. Likewise, the environmental estimates of a vehicle not having to stop at an intersection were found using the engine performance of a vehicle traveling at a desired speed of 35 mph over roughly 500 feet, which in this case is considered the travel length across the distance of intersection influence. Using 500 feet as the intersection influence leads to 10 seconds as the period used to estimate the fuel consumption and tailpipe emissions for the constant speed behavior.

Table 4. Estimate of Environmental Costs of a Vehicle Stop vs. Traveling at Constant Speed through the Intersection, 35 mph Desired Speed

	Stop at Intersection	**Proceed Through Intersection**
Total Fuel Consumption (grams)	22.0	8.0
Total NO_x Emissions (grams)	2.4	0.3
Total HC Emissions (grams)	0.5	0.1
Total CO Emissions (grams)	4.4	2.6

The results of the engine performance modeling task show that the total number of stops is an adequate measure of effectiveness when analyzing the performance of signalized intersections. Traffic engineers may aim to reduce the number of stops in order to minimize environmental costs of signalized control.

CHAPTER 3: LITERATURE REVIEW

3.1 Overview

Many previous research efforts have aimed to reduce tailpipe emissions and fuel consumed at signalized intersections using various techniques. For instance, researchers have analyzed efficient fixed-time signal timing parameters of coordinated networks consisting of multiple intersections. Other work has focused on various performance measures such as average delay per vehicle to reduce pollution and fuel consumption. The following sections of this chapter will summarize research efforts similar to the methodology and experiments described in this thesis. Due to an abundance of research in the field, reviewed literature has been limited to the 21st century. Research has also been done to investigate the effect of roadway and intersection geometry on emissions, a topic which presents an interesting topic but is not considered in this literature review.

3.2 Fuel Consumption and Emissions at Intersections

Coordinated signal timing typically employs different signal timing logic than the actuated signal timing logic described in the Background section. Multiple intersections in close proximity of each other can be timed based on traffic characteristics as a result of the interaction with each other. A brief overview of research efforts focusing on coordinated arterials will follow with the purpose of showing the wide range of techniques and capabilities of researchers and engineers.

In (Zhang et al. 2009), real time emission data was gathered using portable emissions measurement system (PEMS) for a corridor in Beijing. The authors compared emission factors and emission rates based on driving cycle, and thus speed, in coordinated and uncoordinated signal controlled systems. Microscopic simulation using VISSIM and an emissions model integrating vehicle specific power were used as tools to analyze different corridor management plans. 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. In (Lv and Zhang 2012), a combination of VISSIM and MOVES, the emissions model developed by the U.S. Environmental Protection Agency, was used to investigate the effect of signal coordination on emissions at signalized intersections. Results showed that the earlier a platoon of vehicles arrived at a red indication, an increase in emissions can be expected due to idling and additional stops at an intersection.

In (Den Braven et al. 2012), microscopic vehicle emissions models and microscopic traffic simulation models are stated to be methods of choice for providing professional-grade environmental modeling investigation. The authors suggest using vehicle on-board diagnostics (OBD) for the purpose of recording a large number of vehicle operating parameters. This option seems more accurate than the incorporate kinematic components of motion only and without regards to kinematic components. In (De Coensel et al. 2012), the microscopic simulation software Paramics and the noise and pollutant emissions model VERSIT+ were used as tools to estimate the pollutant emissions CO_2, NO_x, and PM_{10}. Results showed that traffic intensity and green split duration had the largest influence on the reduction of emissions and that when perfect major arterial coordination, also termed green wave in the publication, is achieved a reduction of 10%-40% is seen across the estimated pollutants. In (Li et al. 2004), the authors took the approach of utilizing the optimization method to efficiently time isolated intersections with the goal of reducing tailpipe emissions and fuel consumption. An empirical calculation of a performance index function utilizing measures average delay per vehicle and the intersection, amount of fuel consumption of vehicles, and the amount of exhaust emissions is used to produce an optimal length of green phase and signal cycle length. A case study was conducted for a facility in Nanjing City, China with collected traffic flows, and results showed that average reductions of average delay per vehicle, HC, CO, and NO_x were 4.1 seconds per vehicle, 243.5 grams/hour, 2197.7 grams/hour, and 55.9 grams/hour, respectively.

3.3 Vehicle Trajectory Considerations

In (Ahn et al. 2002), instantaneous speed and acceleration behaviors are utilized to estimate fuel consumption and emissions. Data used to develop the estimation models were collected at the Oak Ridge National Laboratory and 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. Using a Mercury Villager as a test vehicle, emission rates were found to be the highest at high acceleration rates, traveling at speeds around 25 mph and 40 mph. In (Rakha and Ding 2003), the impact of vehicle-stops on fuel consumption and emissions are investigated. The authors find that fuel consumption rates are more sensitive to cruise-speed levels compared to vehicle stops. Another result shows that acceleration and deceleration rates employed during a stopping maneuver have a significant effect on emission rates. VT-Micro, a microscopic traffic simulation model, and data collected at the Oak Ridge National Laboratory were used in the analysis. A vehicle-stop, especially one interrupting high cruise-speeds, causes 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 emissions, CO emissions, and NO_x emissions may increase 60%, 80%, and 40%, respectively. Lastly an extensive effort by (Pandian et al. 2009), summarizes an ample amount of research effort towards understanding traffic, road, and vehicle characteristics that play a role in emissions at signalized intersections. The authors make the conclusion that emission and flow models may be combined to ensure more realistic estimates for all location features and environmental differences.

CHAPTER 4: BACKGROUND

4.1 Actuated Signal Timing Parameters

Actuated signal control is commonly employed when arrivals at the intersection are considered random, which may occur when no upstream intersections or traffic control affects the traffic characteristics leading up to the intersection. Actuated signal timing parameters give engineers a dynamic method of controlling traffic based on anticipated traffic volumes, which correspond to the distance and time between subsequent vehicles (i.e. time and space headways). Engineers are given the task of estimating maximum allowable headways based on traffic characteristics before a green signal phase is terminated, thus causing vehicles to queue at a red display. The main actuated signal timing parameters investigated in this thesis are the minimum green setting and passage time setting, and will be explained further. The maximum green parameter is also explained, but was not considered in the experimental design.

The minimum green setting, if set correctly, allows for the dissipation of queued vehicles at the onset of a green display. A minimum green settings that is too low would allow for the possibility of a premature signal change, resulting in vehicles resuming an idle state waiting for the next green indication.

The passage time setting uses the maximum allowable headway estimation to extend the green display as additional vehicles travel towards the intersection. This parameter is the workhorse of the dynamic aspect of the actuated signal timing method. The duration of green is greatly affected by this parameter.

The maximum green time setting is the max amount of time that a green display may be active. This setting ensures that minor approach traffic does not experience excessive delays due to high traffic volumes on the major approaches.

Each of the timing parameters previously described act as a timer, starting at their respective values and reducing to 0 seconds. The minimum green timer does not start until a conflicting movement call is placed, that is, when a vehicle arrives on another approach to the intersection. A green phase is terminated when either the maximum green timer expires or both the minimum green timer and passage timer expires. The former scenario is known as a max out and the latter a gap out. Figure 3 visually represents the workings of each parameter (Kyte and Urbanik 2012).

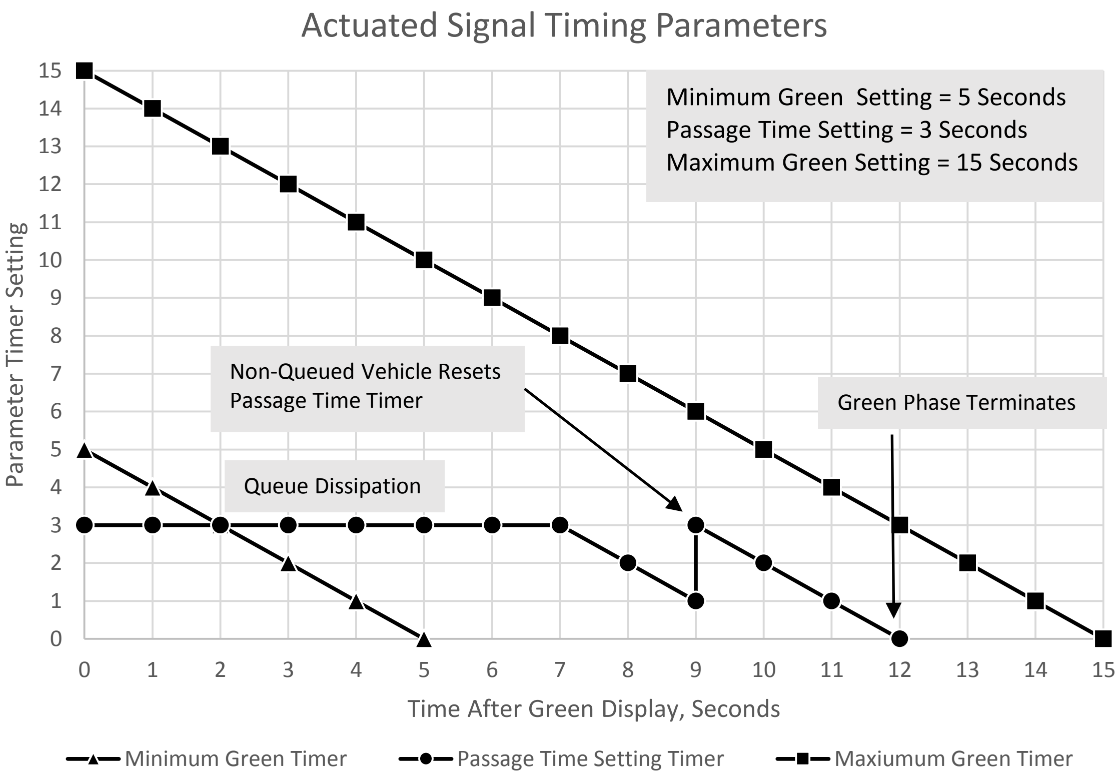


Figure 3. Example of Actuated Signal Timing Parameter Logic

4.2 Inductive-Loop Detection Systems at Signalized Intersections

Many different detector technologies have been used to track traffic movement at signalized intersections including loop detection, video detection, magnetic sensors, microwave radar, and microwave radar. Inductive-loop detection systems are widely used due to their low cost and long useful life duration. Inductive loop detectors, along with video detection, are primarily used in the state of Idaho. The research at hand employs inductive-loop detection, which can then be modeled in microscopic traffic simulation experiments. The Idaho Department of Transportation's documentation of common detector loop spacing plans can be found in the Methodology Section.

Inductive-loop detectors are convenient due to their flexibility of design for many applications since they are placed directly in the pavement, which is referred to an intrusive sensor type. However, placement within the roadway infrastructure can cause premature degradation due to traffic loads, and lane closure is needed to remediate malfunctioning detectors. Inductive-loop detectors operate as a region in the pavement that collects information based on the state of traffic at that location. An electrical current produces a magnetic flux along the employed wire. When a vehicle passes over the loop detector the inductance, the electrical property prompted by the magnetic flux, decreases as a result and that information is relayed to the traffic signal controller (U.S. Department of Transportation 2006).

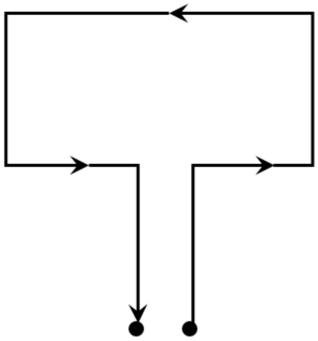


Figure 4. Magnetic Flux around Inductive-Loop Detector

CHAPTER 5: EXPERIMENT METHODOLOGY

Microscopic simulation was chosen as the main research tool used to investigate traffic operations for signalized intersections. To ensure accurate and meaningful experiment results, simplified intersection models were built and driver behavior settings were controlled. This section summarizes the simulation modeling efforts and appropriate inputs.

5.1 Intersection Modeling

The vehicle fleet utilized in the experiments consists entirely of passenger vehicles. The scope of this research does not including heavy vehicles such as trucks, busses, and recreational vehicles and the engine modeling was performed for an average vehicle as summarized in an earlier chapter. Including these vehicle types in the traffic simulation experiments might have altered the results of the experiments due to the inclusion of longer vehicle lengths. Typically driver populations in small to medium sized cities do not include a significant amount of heavy vehicles.

To represent the wide range of vehicle volumes that any isolated signalized intersection may experience, different flow rates were tested during microscopic simulation. A low volume case considered 400 vehicles per hour (vph) on the major approaches and 200 vph on the minor approaches. A medium volume case considered 600 vph on the major approaches and 300 vph on the minor approaches. Lastly, a high volume case considered 800 vph on the major approaches and 600 vph on the minor approaches. Table 5 summarizes the vehicle volumes in the experiments performed per major approach speed limit.

Table 5. Traffic Flow Combinations Implemented in Simulation Efforts

	Low Case	**Medium Case**	**High Case**
Major Approach Flow, vph	400	600	800
Minor Approach Flow, vph	200	300	600

The fully-actuated signalized intersection was developed using ring barrier controller logic, one of multiple controller capabilities of VISSIM, and a common controller type employed in the field. When modeling traffic movements, a ring barrier diagram consisting of through movements only was modeled. Incorporating right turns and protected or permitted left turn movements in the experiments may skew the results beyond the point of being able to observe the effects of different signal timing plans. Additional signal timing parameters beyond the minimum green and passage time settings were held constant for each major approach speed limit. These settings are summarized in Table 6. Suggestions from the Signal Timing Plans were considered for actuated signal timing settings (U.S. Department of Transportation 2008).

Table 6. Actuated Signal Timing Parameters Held Constant per Experiment

	Speed Limit on Major Approach		
	25 mph	**35 mph**	**45 mph**
Maximum Green Setting, Seconds	50	60	60
Yellow Change Interval, Seconds	3.0	3.6	4.2
All Red Interval, Seconds	3.0	2.0	2.0

5.2 Driver Behavior Modeling

Although users of a roadway are given a suggested speed in the form of a posted speed limit, many drivers choose to travel at a speed that best fits their behavior. Therefore, as observed in the field, the driver population employed in the Microscopic simulation efforts utilize a range of speeds. Table 7 summarizes the range of desired speeds modeled based on the posted speed limits used in the research experiments. Desired acceleration behavior was left as the default in VISSIM simulation, which the developers have formulated.

Table 7. Desired Speed Ranges based on Posted Speed Limits

Posted Speed Limit	***25 mph***	***35 mph***	***45 mph***
Desired Speed Ranges	22-28 mph	32-38 mph	42-48 mph

A period of startup time was employed before collecting microscopic traffic characteristics during the simulation experiments. This is a common practice in the industry as it allows the network model to reach a state of equilibrium. The size of the tested network is relatively small in size with a single intersection, and thus an equilibrium period may not be needed but was included nonetheless. A startup period of 300 seconds was implemented followed by 3600 seconds of data collection during the simulation. It is important to run each simulation for one hour to accurately characterize the model outputs as a per hour measure, such as the number of stops per hour (Kyte and Urbanik 2012).

5.3 Vehicle Detection Systems Modeling

Two vehicle detection systems commonly used at actuated-controlled signalized intersections were modeled in VISSIM. Stop bar detection is commonly used on approaches in which vehicle speeds are low, typically 25 mph. Advance detection systems are beneficial for intersections in which vehicle speeds are higher than 25 mph. At higher speeds, the earlier a vehicle is detected on an approach of the intersection and a call is placed to the controller, the earlier the actuated signal timing logic may account for effective phase durations. To do so, numerous inductive loop detectors are placed along each lane at each approach of an intersection. To model actuated signal timing operations as accurately as possible, the Idaho Transportation Department’s (ITD’s) standard drawing I-5 titled “Loop Detectors” was referenced. The standard drawing was updated in 2006 and describes how loop detectors shall be installed on roadways in Idaho, assuming a 10 ft/second^2 deceleration rate. Figure 5 summarizes the detection layouts for approach speed limits as detailed by ITD.

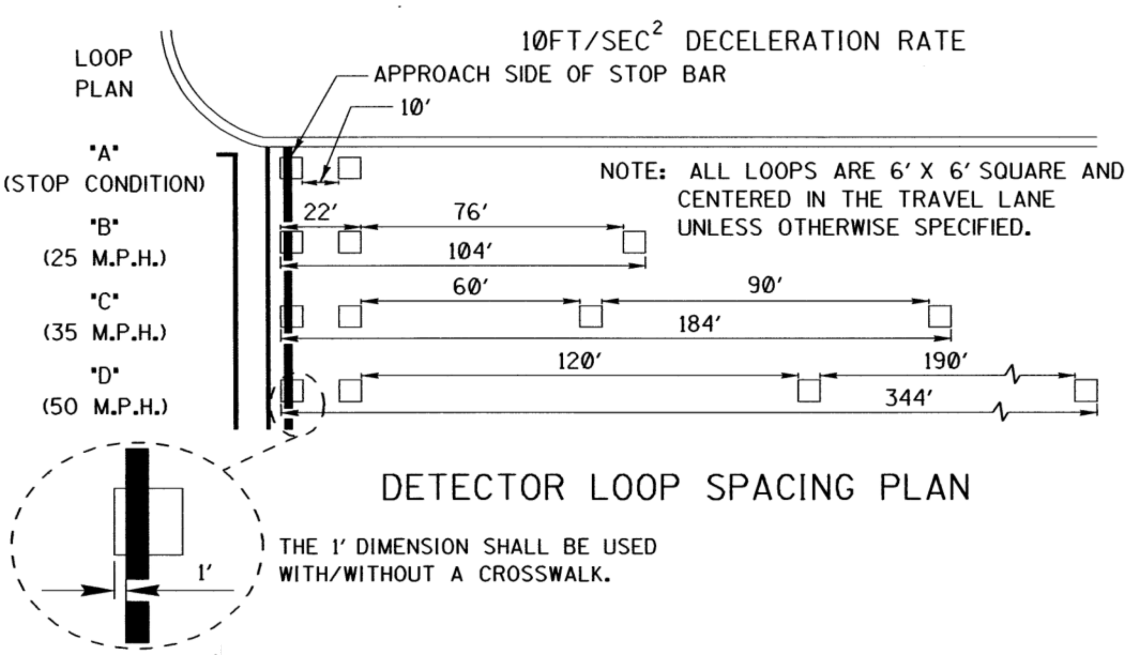


Figure 5. Idaho Transportation Department Standard Drawing I-5

Stop bar detection implemented in the field, described by “Loop Plan A”, requires two 6 feet by 6 feet induction loop detectors at or near the stop bar of each lane at all approaches of the intersection for fully actuated systems. The two loops are spaced 10 feet apart giving the system an effective length of 22 feet. For modeling purposes, induction loop detectors are represented by one 22 foot presence detector. Figure 6 shows how this detection system was modeled in the VISSIM simulation. All intersection approaches were assigned 25 mph speed limits when utilizing stop bar detection.

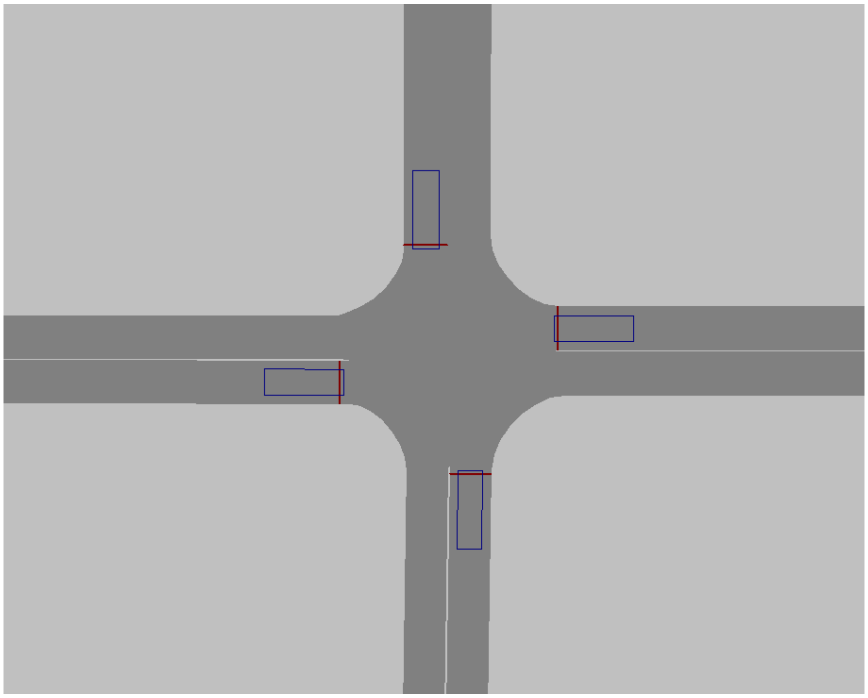


Figure 6. Stop Bar Detection System as Modeled in VISSIM

Advance detection systems vary depending on the posted speed limit per approach. For the purposes of the research presented in this paper, “Loop Plan C” was used for 35 mph and 45 mph posted speed limits. A posted speed limit of 50 mph and above may warrant “Loop Plan D”, which was not considered. “Loop Plan C” includes two 6 feet by 6 feet induction detection loops spaced identical to the stop bar detection system with additional loops spaced 60 feet upstream. To create the same system, two presence detection zones were modeled in VISSIM, as seen in Figure 7, on the major approaches. The larger detection zones are spaced 60 feet upstream of the 22 feet detector zone and span 102 feet in length. The minor approaches, which are modeled with a posted speed limit of 25 mph still employ the stop bar detection layout.

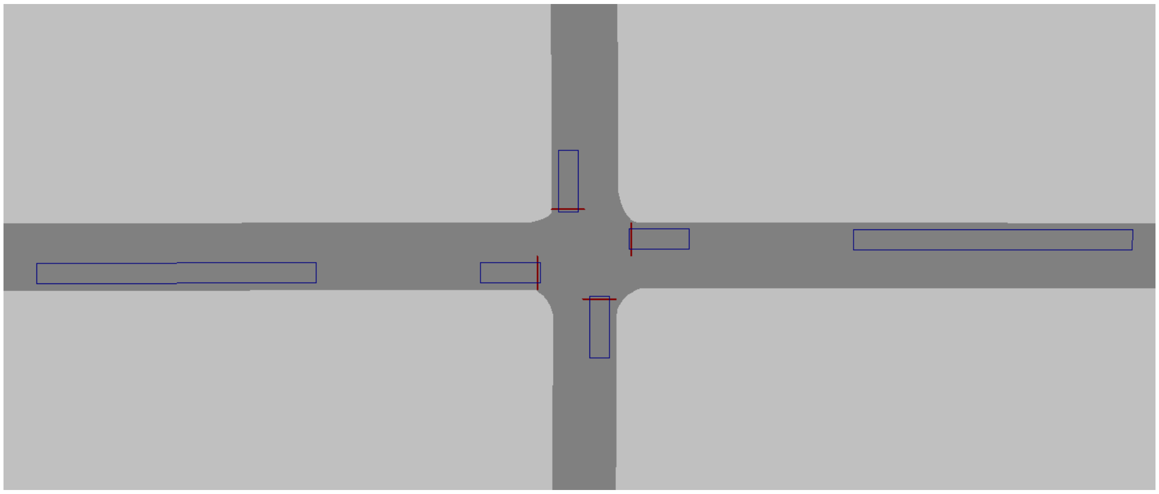


Figure 7. Advance Stop Bar Detection System as Modeled in VISSIM

The previous signalized intersection and driver behavior modeling techniques were employed to most accurately represent typical driver populations of small urban areas. Some aspects of intersection traffic operations were simplified to ensure significant simulation results were observed. Many microscopic behavioral models utilized by VISSIM were relied on to produce realistic traffic flow characteristics, and several behavioral settings were controlled to fit the traffic flow experiments at hand.

CHAPTER 6: RESULTS

Microscopic simulation was utilized to measure traffic performance measures for intersections considering a range of major approach speed limits and signal timing settings. Two common signalized intersection detection systems were modeled. See the Methodology section for the details behind the two separate detection layouts used and additional microscopic simulation modeling techniques.

The average number of stops per vehicle was collected on the major approaches when considering a range of vehicle demand cases and varying the passage time and minimum green settings for all approaches. To account for variability of random behavior of traffic at isolated intersections 10 simulation runs were conducted per actuated signal timing setting. The average number of stops per vehicle was computed using the results from the 10 simulation runs. A simple conversion taking into account the average number of stops per vehicle for both major approaches and the appropriate major approach vehicle volume was done to produce the total number of stops for one approach only. The standard deviation of the 10 simulation results for the average number of stops on the major approach was calculated to report the 95% confidence interval (CI).

The following passage time experiment results are organized by major approach speed limit and the appropriate detector system used per speed limit. Each speed limit was tested using three vehicle volume scenarios; low, medium, and high. The passage time setting was found to have the most significance in varying the number of stops on the major approached and thus the next several sections will focus on the passage time setting effects. Graphs of passage time averages and 95% CI results are displayed with the same vertical axis scales to show the results of the experiments from an unbiased standpoint. The results of holding passage time settings constant on the minor approach was used to represent the variability of the data. Graphing all minor approach passage time settings would create an unreadable graph. An additional section on the minimum green setting effects can be found later in the document.

Figures 8, 10, 12, 14, 16, 18, 20, 22, and 24 give a visual representation of the total number of stops per hour, as estimated using 10 Microscopic simulation runs. Figures 8, 10, and 12 are for an intersection with 25 mph speed limits on all approaches and the three tested traffic volumes. Figures 14, 16, and 18 summarize the results for an intersection with a 35 mph speed limit on the major approaches over the tested vehicle volumes. Figures 20, 22, and 24 summarize the results for an intersection with a 45 mph speed limit on the major approaches over the tested vehicle volumes. Figures 9, 11, 13, 15, 17, 19, 21, 23, and 25 summarize the 95% CI for each accompanying speed limit and vehicle volume. The 95% confidence intervals were only visually represented for the case of a 1.4 second passage time setting on the minor approaches and the rest of the data can be found in Tables 8 through 16, which summarize all the collected data for the passage time experiment.

6.1 Stop Bar Detection and 25 mph Speed Limit on Major Approaches

6.1.1 Low Traffic Volume

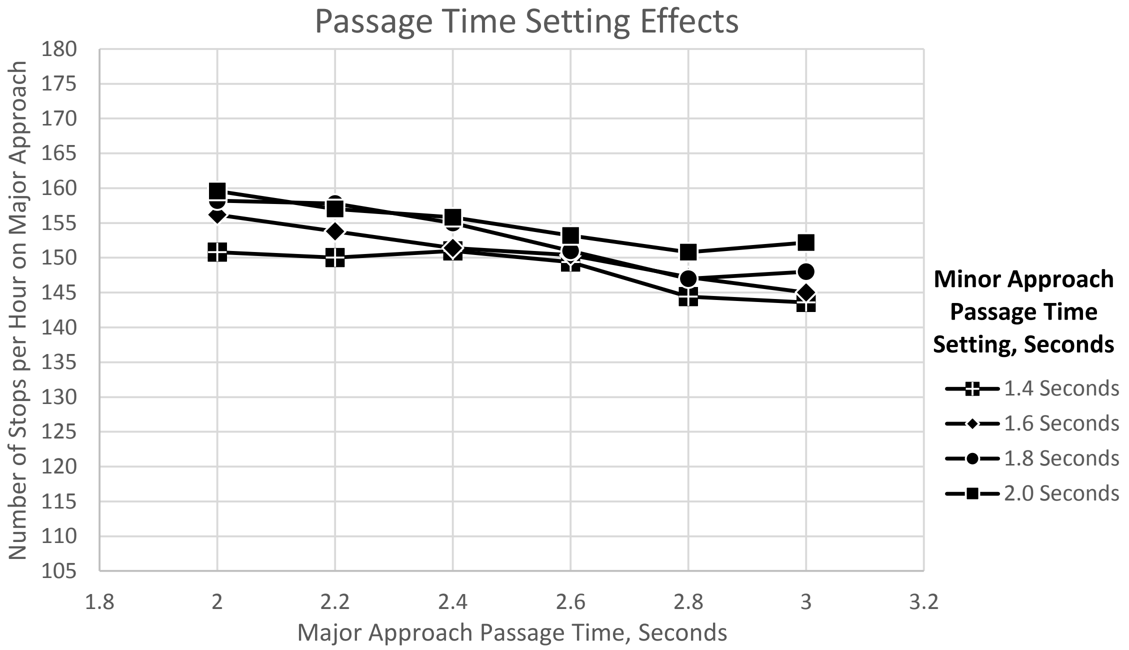


Figure 8. Number of Stops per Hour on 25 mph Major Approach, Low Volume

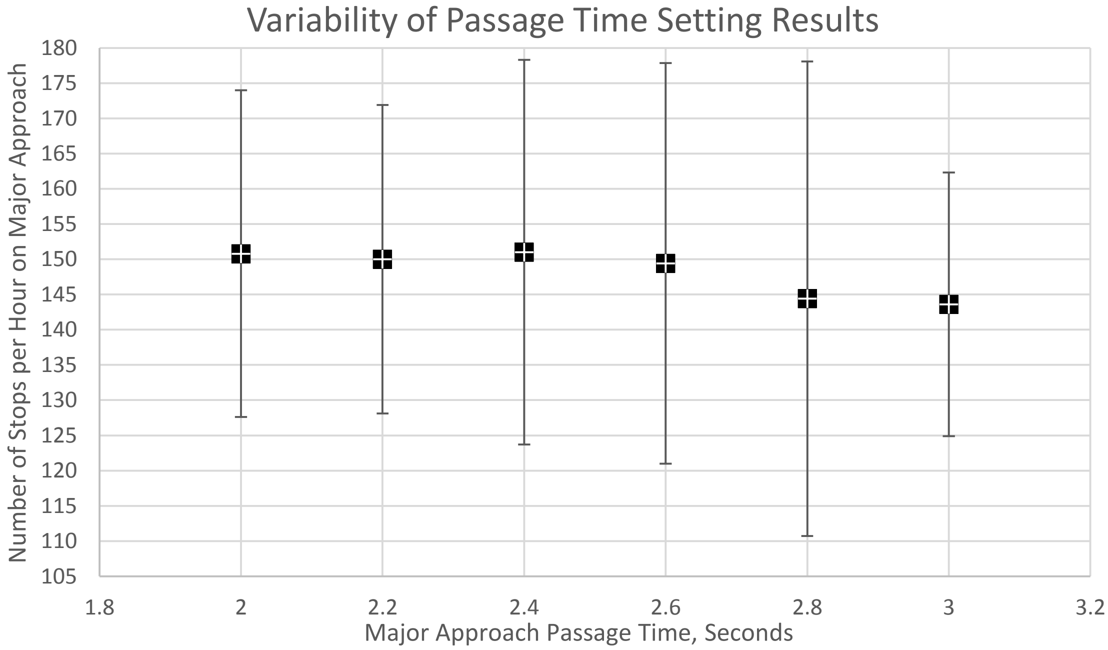


Figure 9. 95% CI for 1.4 Second Minor Approach Setting

Table 8. Low Traffic Volume on 25 mph Major Approach Experiment Results

				95% Confidence Interval	
Minor Passage Time Setting	**Major Passage Time Setting**	**Average Number of Stops**	**Std. Deviation of Average Stops**	**High Range**	**Low Range**
1.4	2.0	**150.8**	11.6	**174.0**	**127.6**
1.4	2.2	**150.0**	11.0	**171.9**	**128.1**
1.4	2.4	**151.0**	13.7	**178.3**	**123.7**
1.4	2.6	**149.4**	14.2	**177.8**	**121.0**
1.4	2.8	**144.4**	16.8	**178.1**	**110.7**
1.4	3.0	**143.6**	9.4	**162.3**	**124.9**
1.6	2.0	**156.2**	14.8	**185.8**	**126.6**
1.6	2.2	**153.8**	10.0	**173.9**	**133.7**
1.6	2.4	**151.4**	15.0	**181.5**	**121.3**
1.6	2.6	**150.4**	15.8	**182.0**	**118.8**
1.6	2.8	**147.2**	15.8	**178.7**	**115.7**
1.6	3.0	**145.0**	6.7	**158.3**	**131.7**
1.8	2.0	**158.2**	13.0	**184.2**	**132.2**
1.8	2.2	**157.8**	12.4	**182.5**	**133.1**
1.8	2.4	**155.0**	13.7	**182.3**	**127.7**
1.8	2.6	**151.0**	11.1	**173.1**	**128.9**
1.8	2.8	**147.0**	8.7	**164.5**	**129.5**
1.8	3.0	**148.0**	8.6	**165.2**	**130.8**
2.0	2.0	**159.6**	14.5	**188.7**	**130.5**
2.0	2.2	**157.0**	13.0	**183.0**	**131.0**
2.0	2.4	**155.8**	9.8	**175.5**	**136.1**
2.0	2.6	**153.2**	11.1	**175.3**	**131.1**
2.0	2.8	**150.8**	11.4	**173.6**	**128.0**
2.0	3.0	**152.2**	9.7	**171.7**	**132.7**

6.1.2 Medium Traffic Volume

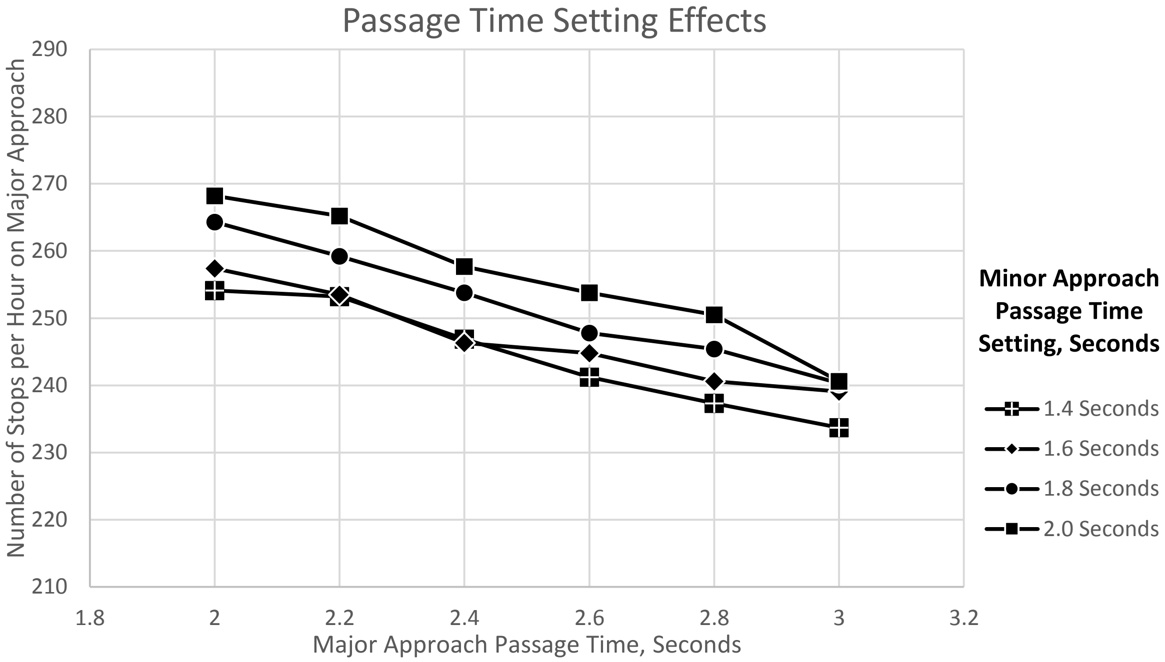


Figure 10. Number of Stops per Hour on 25 mph Major Approach, Medium Volume

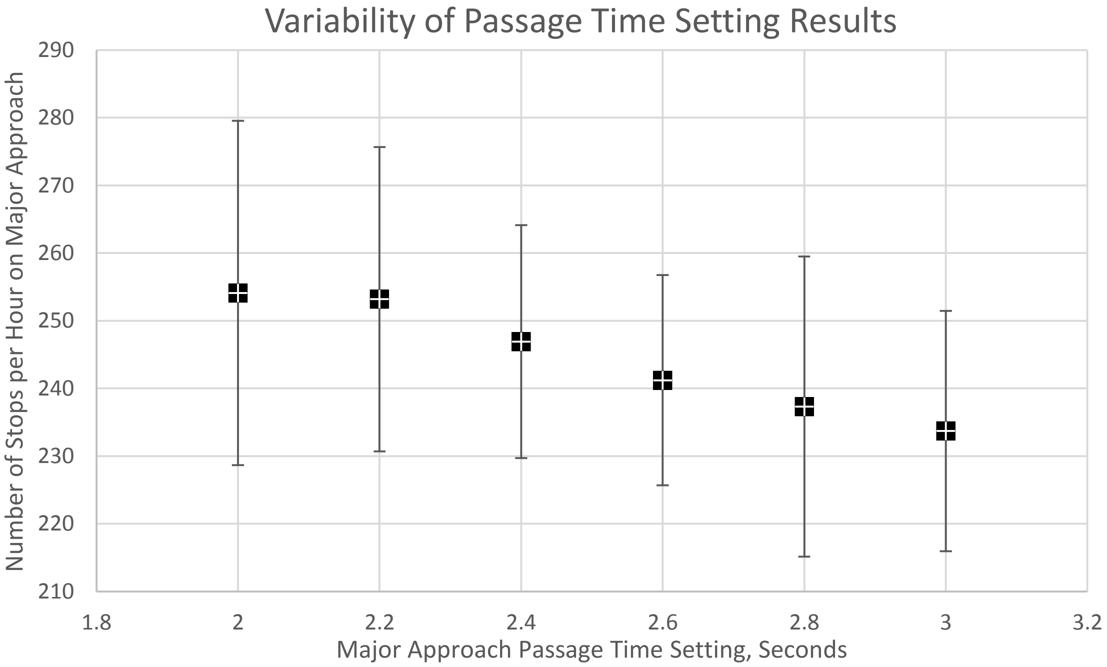


Figure 11. 95% CI for 1.4 sec Minor Approach Setting

Table 9. Medium Traffic Volume on 25 mph Major Approach Experiment Results

				95% Confidence Interval	
Minor Passage Time Setting	**Major Passage Time Setting**	**Average Number of Stops**	**Std. Deviation of Average Stops**	**High Range**	**Low Range**
1.4	2.0	**254.1**	12.7	**279.6**	**228.6**
1.4	2.2	**253.2**	11.2	**275.7**	**230.7**
1.4	2.4	**246.9**	8.6	**264.1**	**229.7**
1.4	2.6	**241.2**	7.8	**256.7**	**225.7**
1.4	2.8	**237.3**	11.1	**259.5**	**215.1**
1.4	3.0	**233.7**	8.9	**251.5**	**215.9**
1.6	2.0	**257.4**	12.1	**281.5**	**233.3**
1.6	2.2	**253.5**	11.9	**277.4**	**229.6**
1.6	2.4	**246.3**	9.6	**265.6**	**227.0**
1.6	2.6	**244.8**	9.3	**263.4**	**226.2**
1.6	2.8	**240.6**	11.6	**263.7**	**217.5**
1.6	3.0	**239.1**	11.2	**261.6**	**216.6**
1.8	2.0	**264.3**	9.4	**283.2**	**245.4**
1.8	2.2	**259.2**	8.1	**275.5**	**242.9**
1.8	2.4	**253.8**	12.3	**278.3**	**229.3**
1.8	2.6	**247.8**	6.0	**259.9**	**235.7**
1.8	2.8	**245.4**	8.6	**262.6**	**228.2**
1.8	3.0	**240.3**	8.9	**258.1**	**222.5**
2.0	2.0	**268.2**	8.3	**284.7**	**251.7**
2.0	2.2	**265.2**	11.0	**287.1**	**243.3**
2.0	2.4	**257.7**	18.6	**294.8**	**220.6**
2.0	2.6	**253.8**	9.5	**272.8**	**234.8**
2.0	2.8	**250.5**	6.8	**264.1**	**236.9**
2.0	3.0	**240.6**	8.6	**257.8**	**223.4**

6.1.3 High Traffic Volume

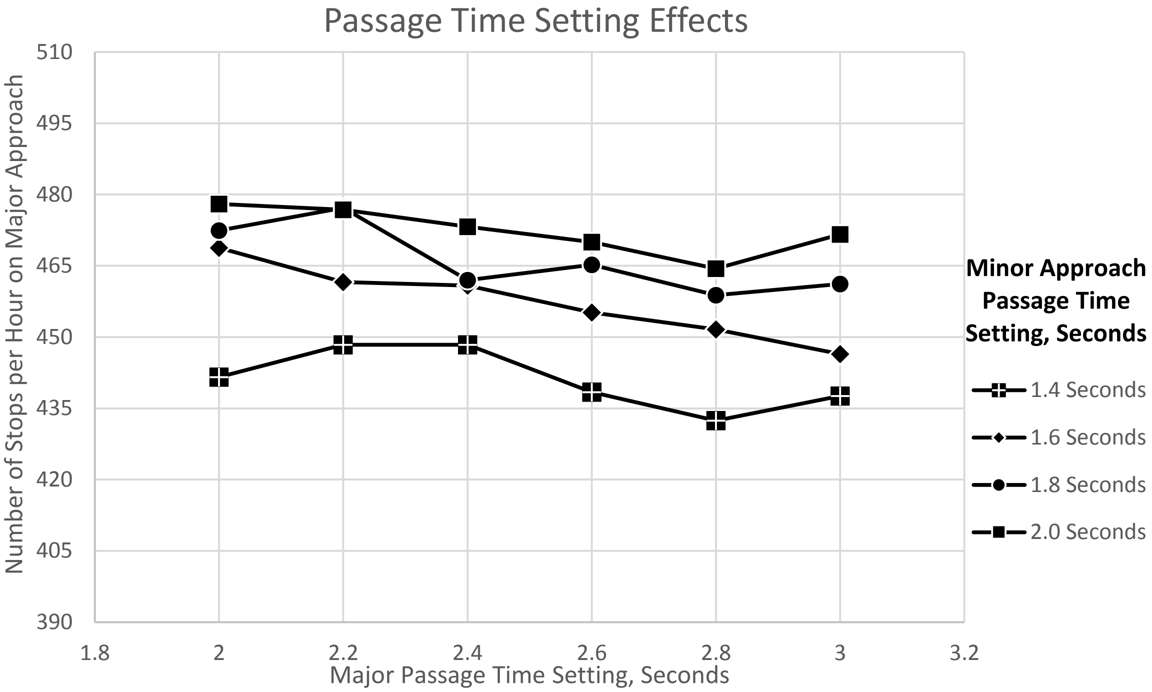


Figure 12. Number of Stops per Hour on 25 mph Major Approach, High volume

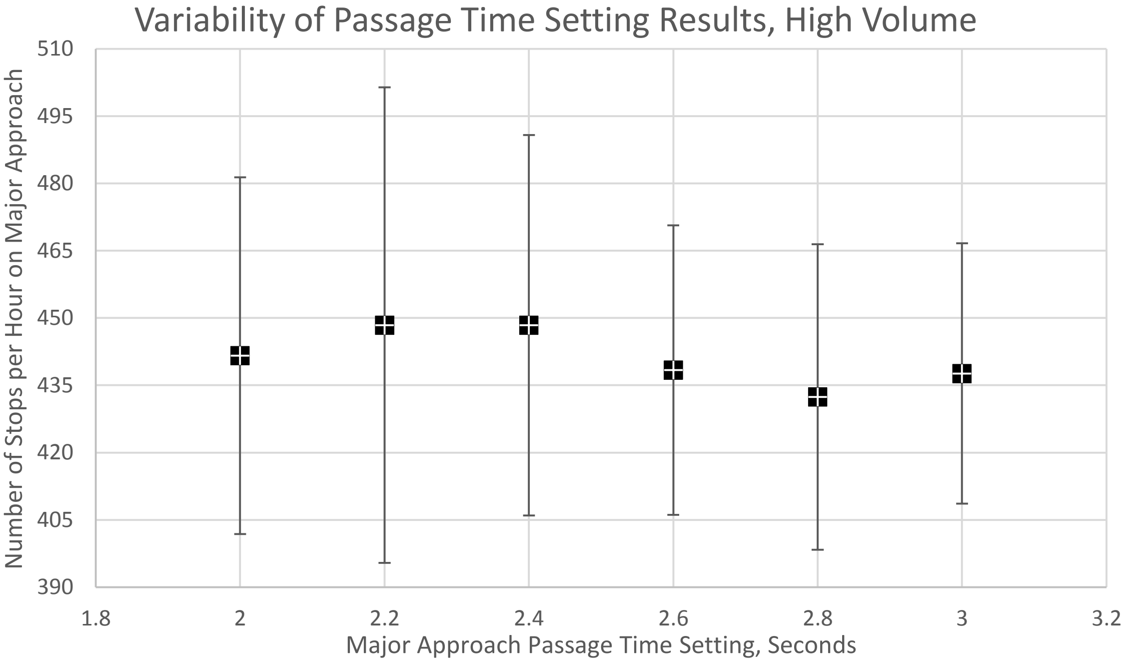


Figure 13. 95% CI for 1.4 Second Minor Approach Setting

Table 10. High Traffic Volume on 25 mph Major Approach Experiment Results

				95% Confidence Interval	
Minor Passage Time Setting	**Major Passage Time Setting**	**Average Number of Stops**	**Std. Deviation of Average Stops**	**High Range**	**Low Range**
1.4	2.0	**441.6**	19.9	**481.4**	**401.8**
1.4	2.2	**448.4**	26.5	**501.4**	**395.4**
1.4	2.4	**448.4**	21.2	**490.8**	**406.0**
1.4	2.6	**438.4**	16.1	**470.7**	**406.1**
1.4	2.8	**432.4**	17.0	**466.4**	**398.4**
1.4	3.0	**437.6**	14.5	**466.6**	**408.6**
1.6	2.0	**468.8**	16.3	**501.4**	**436.2**
1.6	2.2	**461.6**	14.4	**490.4**	**432.8**
1.6	2.4	**460.8**	20.8	**502.4**	**419.2**
1.6	2.6	**455.2**	19.0	**493.3**	**417.1**
1.6	2.8	**451.6**	15.3	**482.1**	**421.1**
1.6	3.0	**446.4**	18.4	**483.2**	**409.6**
1.8	2.0	**472.4**	18.4	**509.2**	**435.6**
1.8	2.2	**477.2**	21.8	**520.7**	**433.7**
1.8	2.4	**462.0**	21.5	**505.0**	**419.0**
1.8	2.6	**465.2**	20.6	**506.3**	**424.1**
1.8	2.8	**458.8**	14.5	**487.8**	**429.8**
1.8	3.0	**461.2**	27.9	**517.0**	**405.4**
2.0	2.0	**478.0**	19.3	**516.5**	**439.5**
2.0	2.2	**476.8**	27.1	**531.0**	**422.6**
2.0	2.4	**473.2**	20.9	**515.0**	**431.4**
2.0	2.6	**470.0**	24.7	**519.5**	**420.5**
2.0	2.8	**464.4**	23.3	**511.0**	**417.8**
2.0	3.0	**471.6**	21.9	**515.5**	**427.7**

6.2 Advance Detection and 35 mph Speed Limit on Major Approaches

6.2.1 Low Traffic Volume

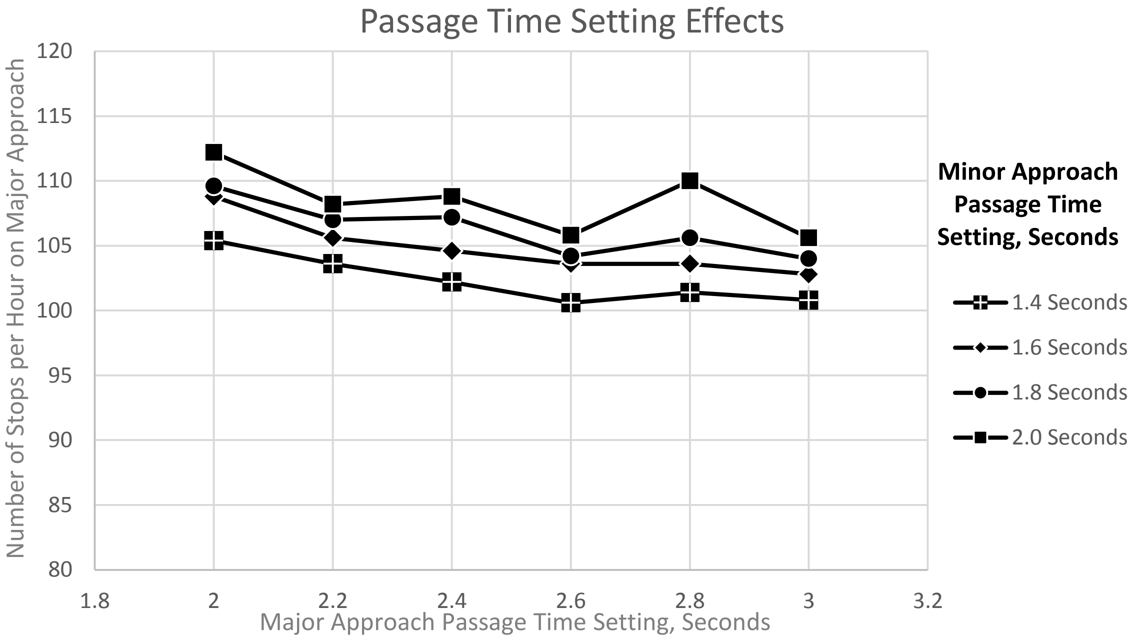


Figure 14. Number of Stops per Hour on 35 mph major Approach, Low Volume

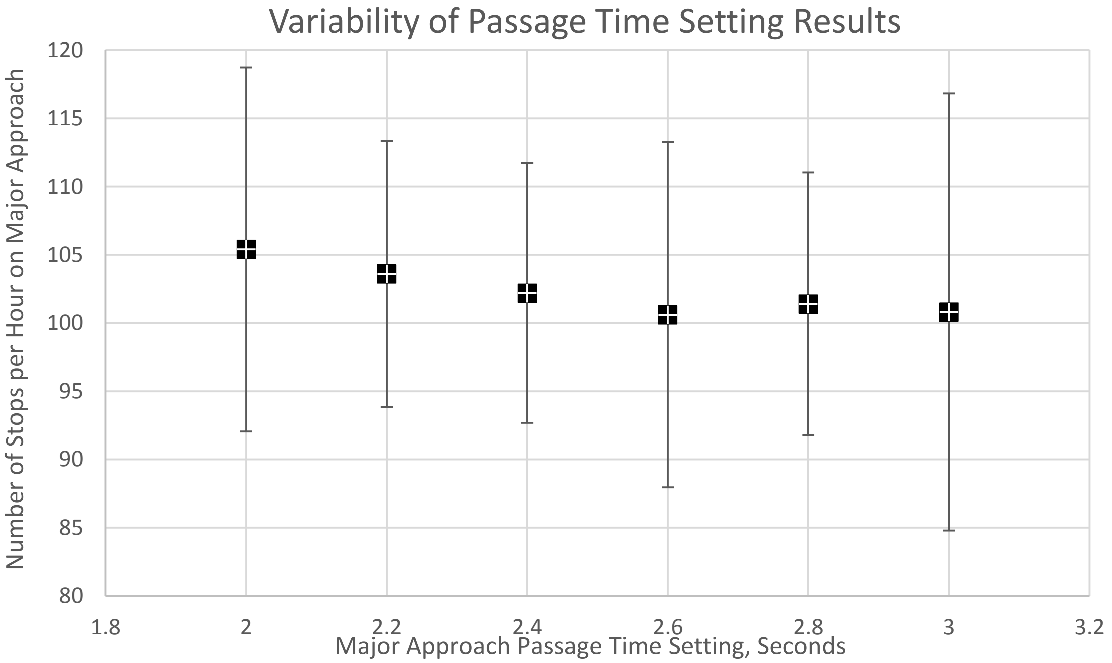


Figure 15. 95 % CI for 1.4 Second Minor Approach Setting

Table 11. Low Traffic Volume on 35 mph Major Approach Experiment Results

				95% Confidence Interval	
Minor Passage Time Setting	**Major Passage Time Setting**	**Average Number of Stops**	**Std. Deviation of Average Stops**	**High Range**	**Low Range**
1.4	2.0	**105.4**	6.7	**118.7**	**92.1**
1.4	2.2	**103.6**	4.9	**113.4**	**93.8**
1.4	2.4	**102.2**	4.8	**111.7**	**92.7**
1.4	2.6	**100.6**	6.3	**113.3**	**87.9**
1.4	2.8	**101.4**	4.8	**111.0**	**91.8**
1.4	3.0	**100.8**	8.0	**116.8**	**84.8**
1.6	2.0	**108.8**	6.3	**121.5**	**96.1**
1.6	2.2	**105.6**	6.1	**117.8**	**93.4**
1.6	2.4	**104.6**	4.1	**112.8**	**96.4**
1.6	2.6	**103.6**	5.1	**113.9**	**93.3**
1.6	2.8	**103.6**	5.9	**115.5**	**91.7**
1.6	3.0	**102.8**	7.7	**118.1**	**87.5**
1.8	2.0	**109.6**	7.0	**123.7**	**95.5**
1.8	2.2	**107.0**	5.9	**118.8**	**95.2**
1.8	2.4	**107.2**	4.8	**116.9**	**97.5**
1.8	2.6	**104.2**	4.9	**114.1**	**94.3**
1.8	2.8	**105.6**	5.5	**116.6**	**94.6**
1.8	3.0	**104.0**	6.8	**117.6**	**90.4**
2.0	2.0	**112.2**	7.4	**127.0**	**97.4**
2.0	2.2	**108.2**	3.8	**115.8**	**100.6**
2.0	2.4	**108.8**	5.4	**119.7**	**97.9**
2.0	2.6	**105.8**	4.4	**114.5**	**97.1**
2.0	2.8	**110.0**	5.2	**120.5**	**99.5**
2.0	3.0	**105.6**	6.1	**117.8**	**93.4**

6.2.2 Medium Traffic Volume

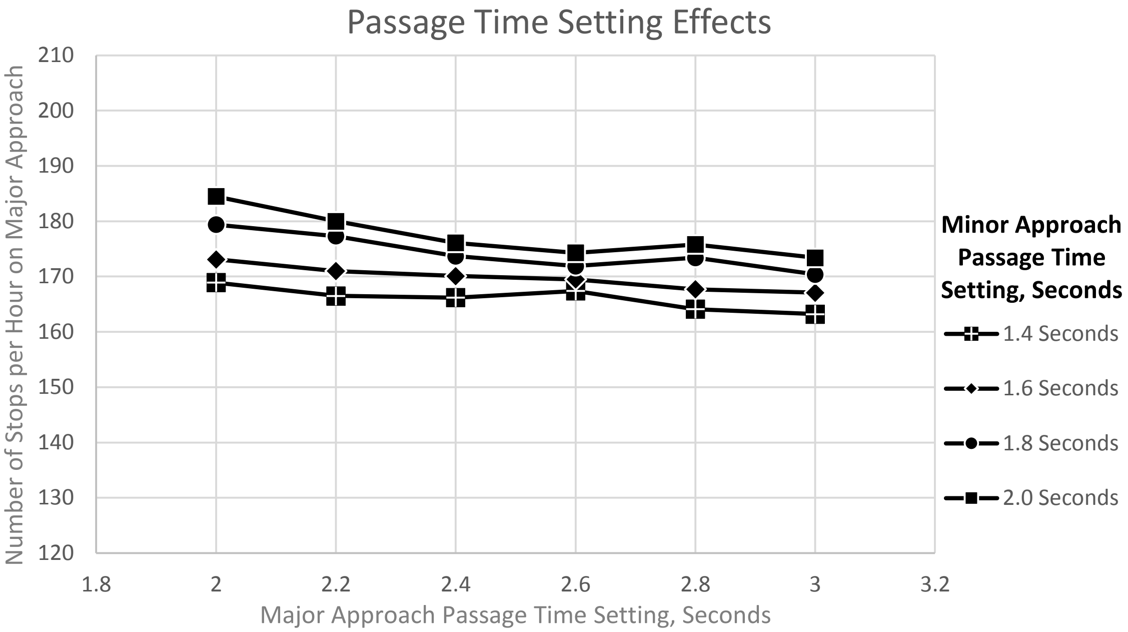


Figure 16. Number of Stops per Hour on 35 mph Major Approach, Medium Volume

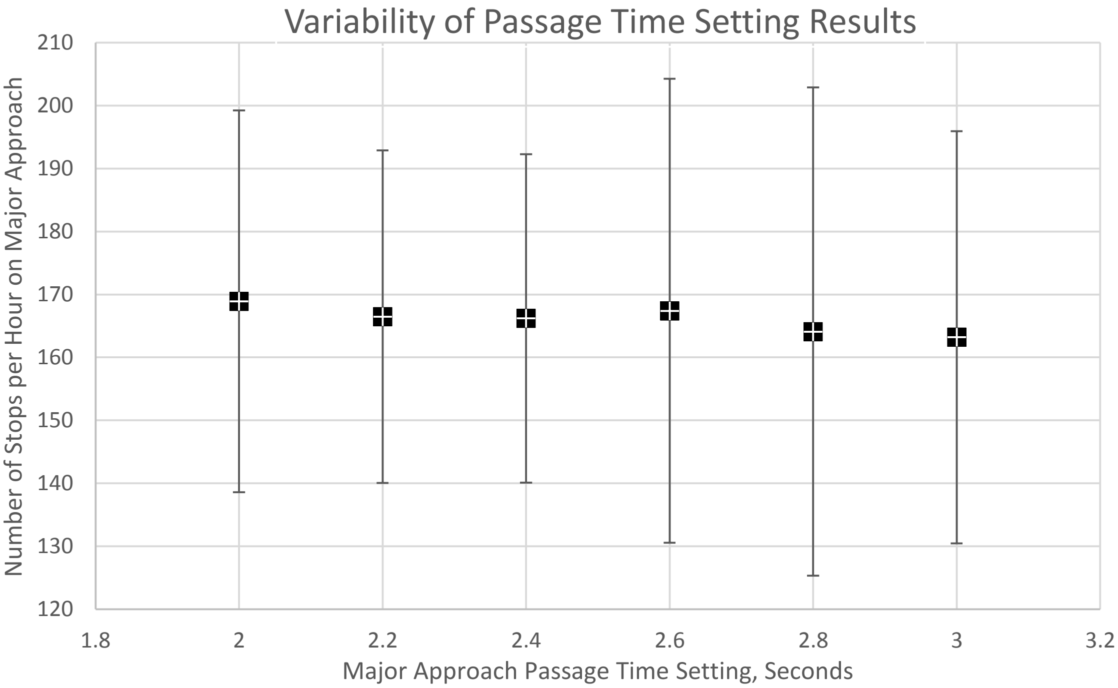


Figure 17. 95% CI for 1.4 Second Minor Approach Setting

Table 12. Medium Traffic Volume on 35 mph Major Approach Experiment Results

				95% Confidence Interval	
Minor Passage Time Setting	**Major Passage Time Setting**	**Average Number of Stops**	**Std. Deviation of Average Stops**	**High Range**	**Low Range**
1.4	2.0	**168.9**	15.2	**199.2**	**138.6**
1.4	2.2	**166.5**	13.2	**192.9**	**140.1**
1.4	2.4	**166.2**	13.1	**192.3**	**140.1**
1.4	2.6	**167.4**	18.4	**204.3**	**130.5**
1.4	2.8	**164.1**	19.4	**202.9**	**125.3**
1.4	3.0	**163.2**	16.4	**196.0**	**130.4**
1.6	2.0	**173.1**	14.9	**202.9**	**143.3**
1.6	2.2	**171.0**	13.5	**198.0**	**144.0**
1.6	2.4	**170.1**	14.8	**199.8**	**140.4**
1.6	2.6	**169.5**	19.8	**209.0**	**130.0**
1.6	2.8	**167.7**	19.2	**206.1**	**129.3**
1.6	3.0	**167.1**	18.3	**203.8**	**130.4**
1.8	2.0	**179.4**	14.4	**208.2**	**150.6**
1.8	2.2	**177.3**	13.8	**204.9**	**149.7**
1.8	2.4	**173.7**	21.7	**217.0**	**130.4**
1.8	2.6	**171.9**	19.4	**210.8**	**133.0**
1.8	2.8	**173.4**	20.4	**214.2**	**132.6**
1.8	3.0	**170.4**	18.5	**207.4**	**133.4**
2.0	2.0	**184.5**	11.9	**208.2**	**160.8**
2.0	2.2	**180.0**	17.1	**214.3**	**145.7**
2.0	2.4	**176.1**	19.9	**215.8**	**136.4**
2.0	2.6	**174.3**	21.4	**217.1**	**131.5**
2.0	2.8	**175.8**	21.5	**218.7**	**132.9**
2.0	3.0	**173.4**	21.2	**215.8**	**131.0**

6.2.3 High Volume

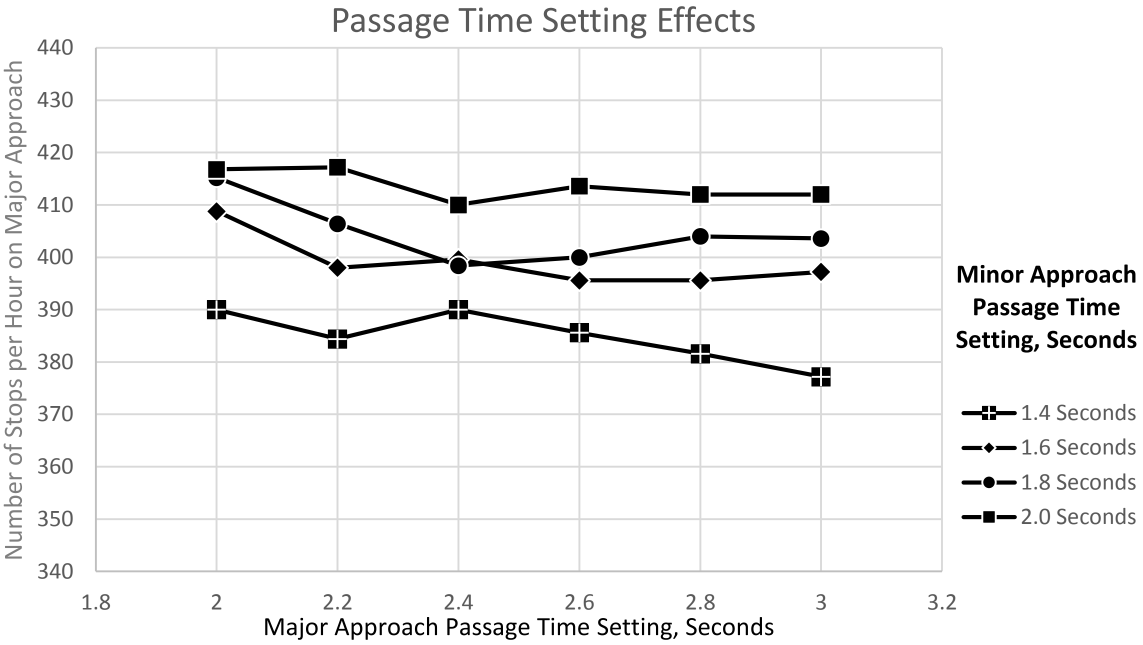


Figure 18. Number of Stops per Hour on 35 mph Major Approach, High Volume

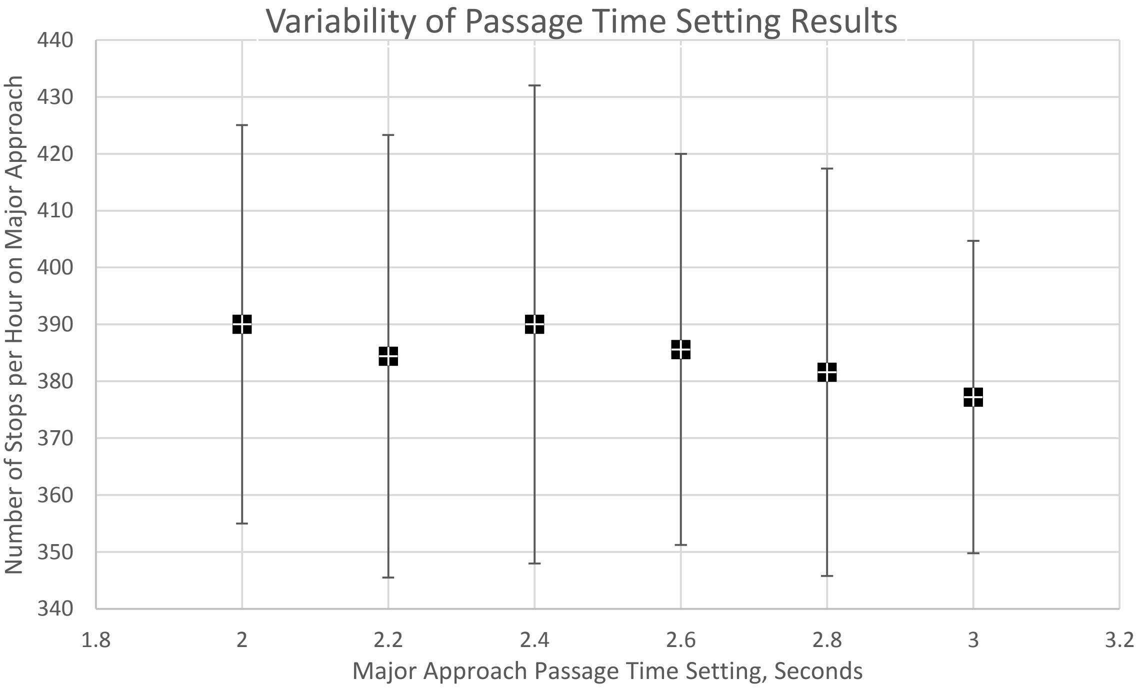


Figure 19. 95% CI for 1.4 Second Minor Approach Setting

Table 13. High Traffic Volume on 35 mph Major Approach Experiment Results

				95% Confidence Interval	
Minor Passage Time Setting	**Major Passage Time Setting**	**Average Number of Stops**	**Std. Deviation of Average Stops**	**High Range**	**Low Range**
1.4	2.0	**390.0**	17.5	**425.0**	**355.0**
1.4	2.2	**384.4**	19.5	**423.3**	**345.5**
1.4	2.4	**390.0**	21.0	**432.0**	**348.0**
1.4	2.6	**385.6**	17.2	**420.0**	**351.2**
1.4	2.8	**381.6**	17.9	**417.4**	**345.8**
1.4	3.0	**377.2**	13.7	**404.7**	**349.7**
1.6	2.0	**408.8**	21.0	**450.8**	**366.8**
1.6	2.2	**398.0**	22.3	**442.5**	**353.5**
1.6	2.4	**399.6**	21.5	**442.7**	**356.5**
1.6	2.6	**395.6**	24.6	**444.8**	**346.4**
1.6	2.8	**395.6**	22.3	**440.1**	**351.1**
1.6	3.0	**397.2**	19.4	**436.0**	**358.4**
1.8	2.0	**415.2**	21.8	**458.8**	**371.6**
1.8	2.2	**406.4**	18.7	**443.8**	**369.0**
1.8	2.4	**398.4**	18.7	**435.8**	**361.0**
1.8	2.6	**400.0**	19.7	**439.4**	**360.6**
1.8	2.8	**404.0**	23.5	**451.0**	**357.0**
1.8	3.0	**403.6**	19.6	**442.9**	**364.3**
2.0	2.0	**416.8**	20.4	**457.6**	**376.0**
2.0	2.2	**417.2**	20.2	**457.7**	**376.7**
2.0	2.4	**410.0**	16.8	**443.6**	**376.4**
2.0	2.6	**413.6**	15.8	**445.2**	**382.0**
2.0	2.8	**412.0**	16.8	**445.5**	**378.5**
2.0	3.0	**412.0**	16.1	**444.2**	**379.8**

6.3 Advance Detection and 45 mph Speed Limit on Major Approaches

6.3.1 Low Traffic Volume

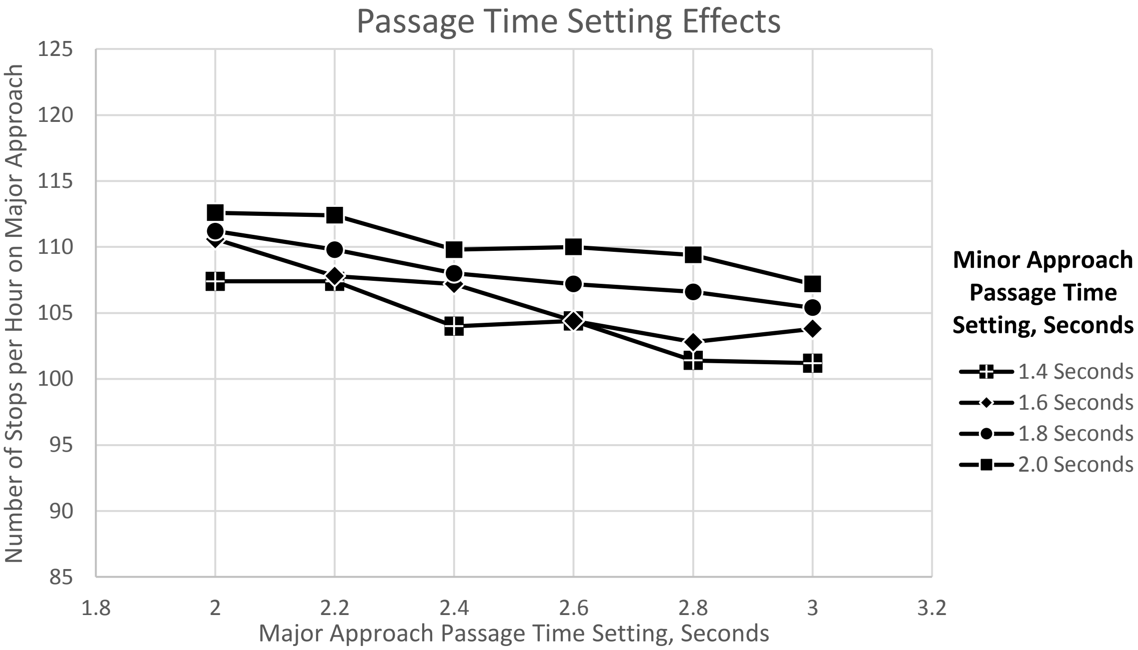


Figure 20. Number of Stops per Hour on 45 mph Major Approach, Low Volume

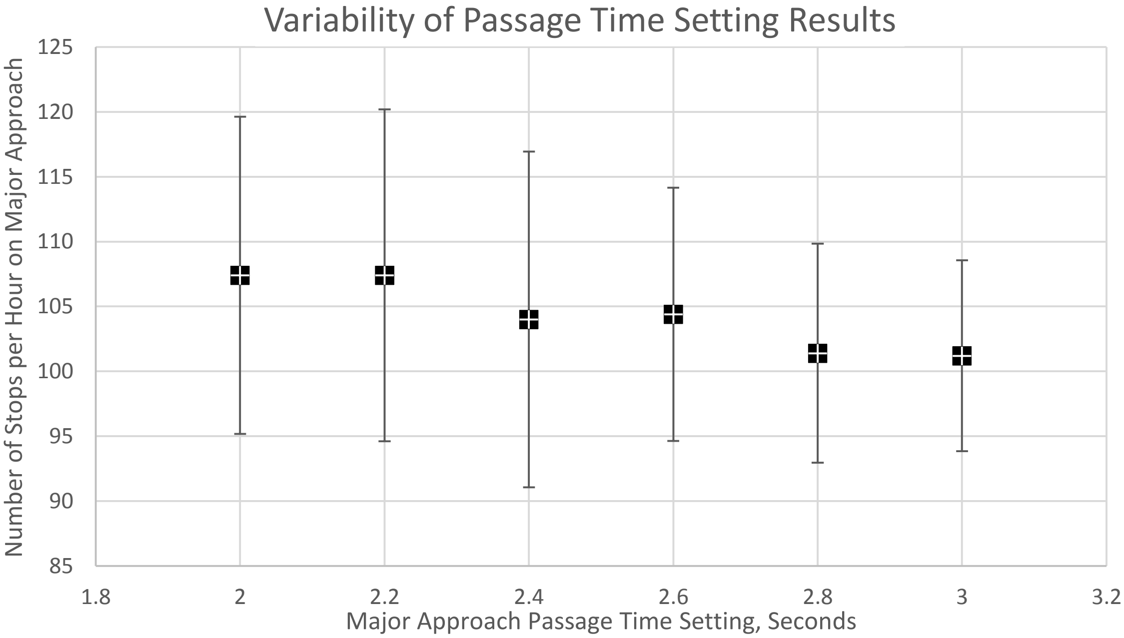


Figure 21. 95% CI for 1.4 Second Minor Approach Setting

Table 14. Low Traffic Volume on 45 mph Major Approach Experiment Results

				95% Confidence Interval	
Minor Passage Time Setting	**Major Passage Time Setting**	**Average Number of Stops**	**Std. Deviation of Average Stops**	**High Range**	**Low Range**
1.4	2.0	**107.4**	6.1	**119.6**	**95.2**
1.4	2.2	**107.4**	6.4	**120.2**	**94.6**
1.4	2.4	**104.0**	6.4	**116.9**	**91.1**
1.4	2.6	**104.4**	4.8	**114.2**	**94.6**
1.4	2.8	**101.4**	4.2	**109.8**	**93.0**
1.4	3.0	**101.2**	3.6	**108.6**	**93.8**
1.6	2.0	**110.6**	6.1	**123.0**	**98.2**
1.6	2.2	**107.8**	6.3	**120.5**	**95.1**
1.6	2.4	**107.2**	5.0	**117.4**	**97.0**
1.6	2.6	**104.4**	4.9	**114.3**	**94.5**
1.6	2.8	**102.8**	3.9	**110.6**	**95.0**
1.6	3.0	**103.8**	4.0	**111.9**	**95.7**
1.8	2.0	**111.2**	7.1	**125.6**	**96.8**
1.8	2.2	**109.8**	5.9	**121.6**	**98.0**
1.8	2.4	**108.0**	5.5	**119.2**	**96.8**
1.8	2.6	**107.2**	5.6	**118.5**	**95.9**
1.8	2.8	**106.6**	3.6	**113.9**	**99.3**
1.8	3.0	**105.4**	3.4	**112.2**	**98.6**
2.0	2.0	**112.6**	7.0	**126.7**	**98.5**
2.0	2.2	**112.4**	7.1	**126.6**	**98.2**
2.0	2.4	**109.8**	5.6	**121.0**	**98.6**
2.0	2.6	**110.0**	5.0	**120.2**	**99.8**
2.0	2.8	**109.4**	3.6	**116.7**	**102.1**
2.0	3.0	**107.2**	3.9	**115.0**	**99.4**

6.3.2 Medium Volume

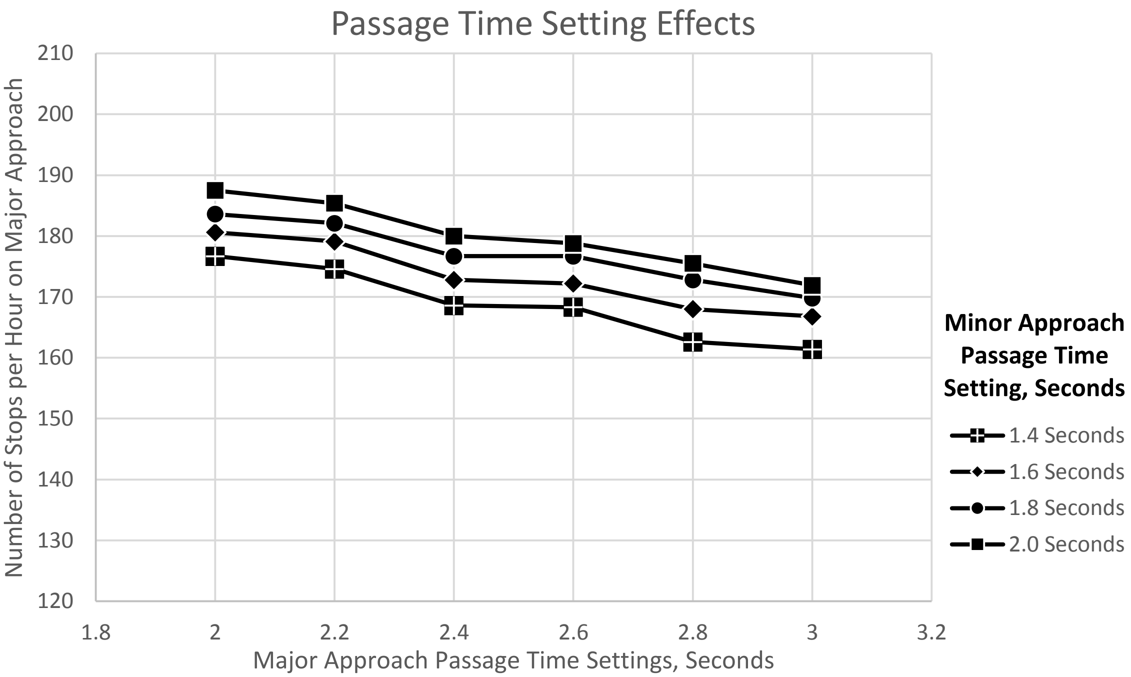


Figure 22. Number of Stops per Hour on 45 mph Major Approach, Medium Volume

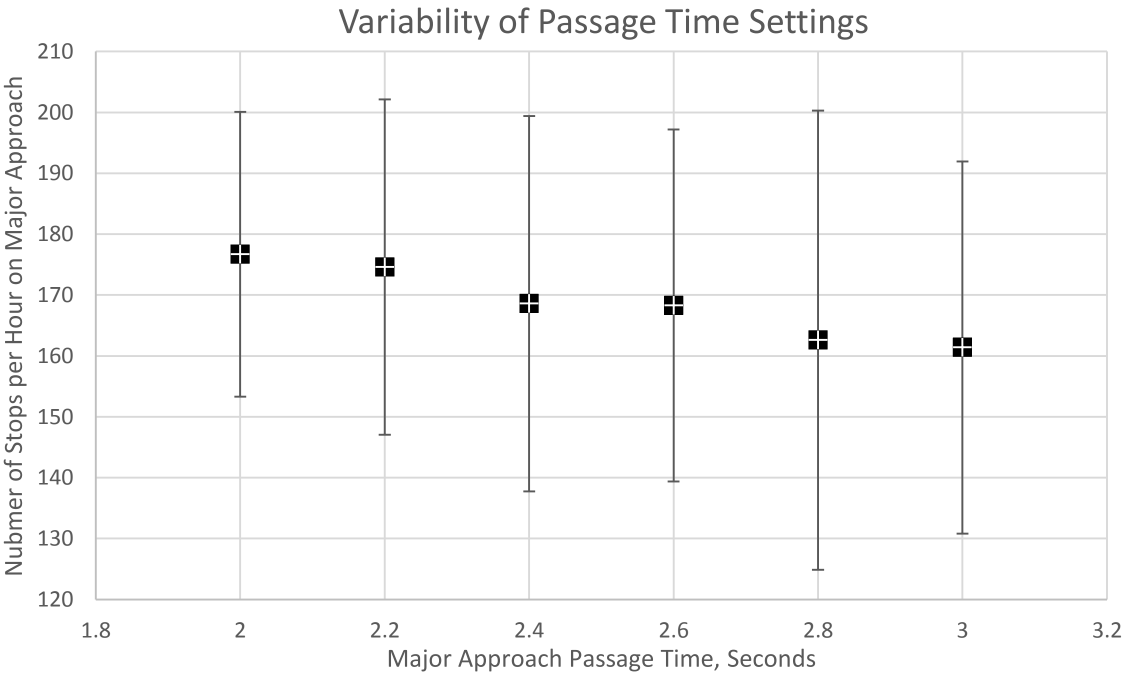


Figure 23. 95% CI for 1.4 Second Minor Approach Setting

Table 15. Medium Volume on 45 mph Major Approach Experiment Results

				95% Confidence Interval	
Minor Passage Time Setting	**Major Passage Time Setting**	**Average Number of Stops**	**Std. Deviation of Average Stops**	**High Range**	**Low Range**
1.4	2.0	**176.7**	11.7	**200.1**	**153.3**
1.4	2.2	**174.6**	13.7	**202.1**	**147.1**
1.4	2.4	**168.6**	15.4	**199.4**	**137.8**
1.4	2.6	**168.3**	14.4	**197.2**	**139.4**
1.4	2.8	**162.6**	18.8	**200.3**	**124.9**
1.4	3.0	**161.4**	15.2	**192.0**	**130.8**
1.6	2.0	**180.6**	13.9	**208.4**	**152.8**
1.6	2.2	**179.1**	12.3	**203.8**	**154.4**
1.6	2.4	**172.8**	14.4	**201.7**	**143.9**
1.6	2.6	**172.2**	15.2	**202.7**	**141.7**
1.6	2.8	**168.0**	17.7	**203.6**	**132.4**
1.6	3.0	**166.8**	12.8	**192.6**	**141.0**
1.8	2.0	**183.6**	15.5	**214.7**	**152.5**
1.8	2.2	**182.1**	13.7	**209.5**	**154.7**
1.8	2.4	**176.7**	16.1	**209.0**	**144.4**
1.8	2.6	**176.7**	16.2	**209.1**	**144.3**
1.8	2.8	**172.8**	16.1	**205.1**	**140.5**
1.8	3.0	**169.8**	13.9	**197.7**	**141.9**
2.0	2.0	**187.5**	17.5	**222.5**	**152.5**
2.0	2.2	**185.4**	12.7	**211.0**	**159.8**
2.0	2.4	**180.0**	16.6	**213.3**	**146.7**
2.0	2.6	**178.8**	13.5	**206.0**	**151.6**
2.0	2.8	**175.5**	17.7	**211.0**	**140.0**
2.0	3.0	**171.9**	11.3	**194.5**	**149.3**

6.3.3 High Traffic Volume

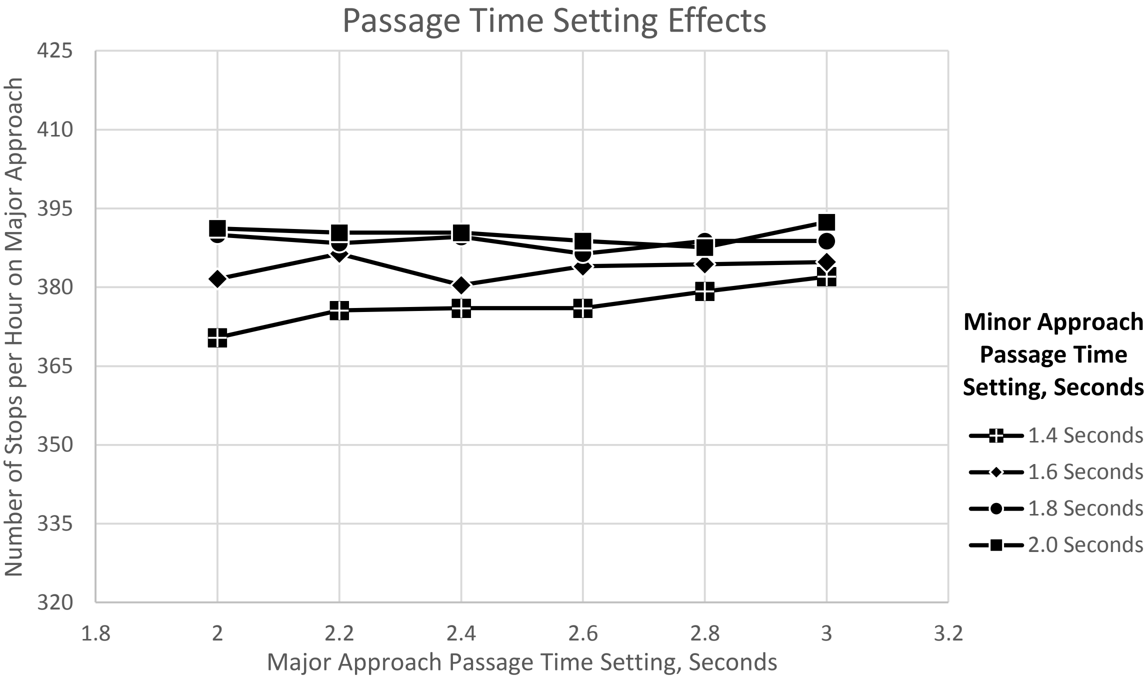


Figure 24. Number of Stops on 45 mph Major Approach, High Volume

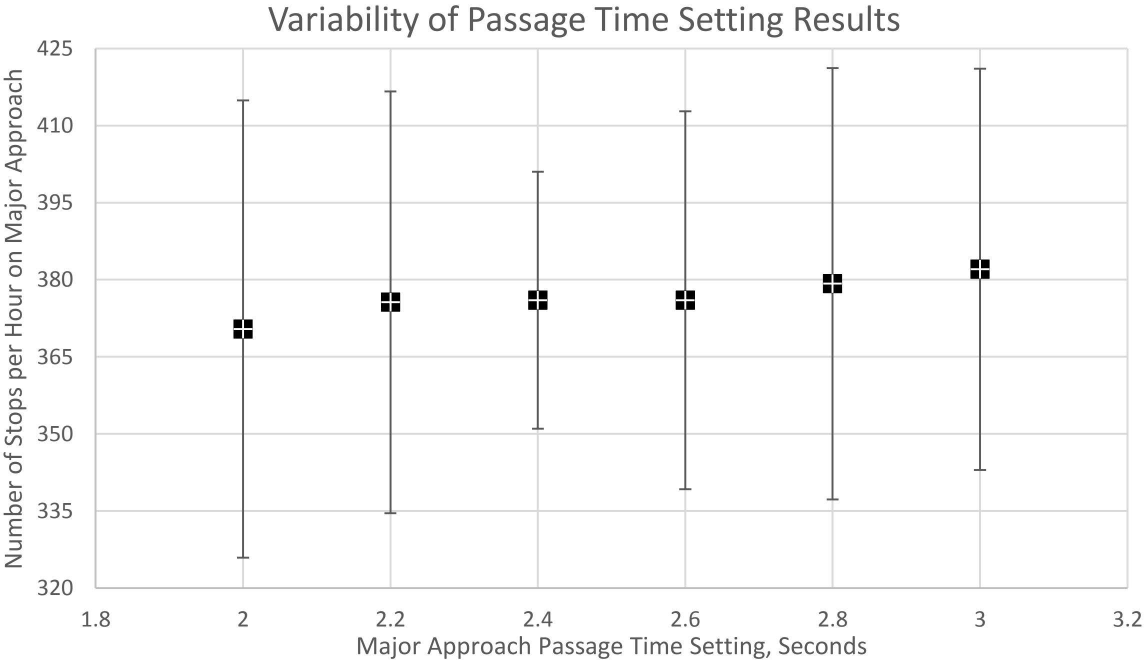


Figure 25. 95% CI for 1.4 Second Minor Approach Setting

Table 16. High Traffic Volume on 45 mph Major Approach Experiment Results

				95% Confidence Interval	
Minor Passage Time Setting	**Major Passage Time Setting**	**Average Number of Stops**	**Std. Deviation of Average Stops**	**High Range**	**Low Range**
1.4	2.0	**370.4**	22.2	**414.9**	**325.9**
1.4	2.2	**375.6**	20.5	**416.6**	**334.6**
1.4	2.4	**376.0**	12.5	**401.0**	**351.0**
1.4	2.6	**376.0**	18.4	**412.8**	**339.2**
1.4	2.8	**379.2**	21.0	**421.2**	**337.2**
1.4	3.0	**382.0**	19.5	**421.1**	**342.9**
1.6	2.0	**381.6**	19.3	**420.3**	**342.9**
1.6	2.2	**386.4**	17.9	**422.2**	**350.6**
1.6	2.4	**380.4**	16.4	**413.2**	**347.6**
1.6	2.6	**384.0**	23.5	**431.0**	**337.0**
1.6	2.8	**384.4**	25.7	**435.8**	**333.0**
1.6	3.0	**384.8**	20.6	**426.1**	**343.5**
1.8	2.0	**390.0**	18.2	**426.4**	**353.6**
1.8	2.2	**388.4**	20.6	**429.6**	**347.2**
1.8	2.4	**389.6**	21.1	**431.8**	**347.4**
1.8	2.6	**386.4**	21.7	**429.8**	**343.0**
1.8	2.8	**388.8**	22.8	**434.5**	**343.1**
1.8	3.0	**388.8**	19.7	**428.1**	**349.5**
2.0	2.0	**391.2**	18.7	**428.7**	**353.7**
2.0	2.2	**390.4**	19.8	**430.0**	**350.8**
2.0	2.4	**390.4**	16.4	**423.1**	**357.7**
2.0	2.6	**388.8**	19.2	**427.2**	**350.4**
2.0	2.8	**387.6**	18.7	**425.0**	**350.2**
2.0	3.0	**392.4**	19.5	**431.3**	**353.5**

6.4 Effect of Minimum Green Setting

Minimum green settings for both the minor and major approaches were varied while all other timing parameters were kept constant to show the effect on the number of stops on the major approaches. For the case in which both the major and minor approaches experience low volumes, the appropriate minimum green settings for the major and minor approaches may play a significant role in reducing the number of stops on the major approaches. For intersections experiencing low volumes the minimum green settings did affect the number of stops on the major approaches. Typically, giving the minor approaches a low minimum green time setting while assigning the major approach a low minimum green time setting will produce favorable results. At high and medium volumes, the minimum green setting does show significant trends in the reductions of the number of stops on the major approach, because the time for queued vehicles to clear the intersection is typically larger than the minimum green setting. The passage time setting tends to carry the most weight for medium and high volume cases in extending the green time to allow vehicles approaching the intersection to travel through without stopping. Insignificant reductions in the number of stops on a major approach were seen in a case of medium and high vehicle volumes as seen in Tables 15, 16, and 17. Therefore, regardless of the vehicle demand at the intersection, using a high minimum green time for the major approach and a low minimum green time for the minor approach may minimize the number of stops on the major approach.

Table 17. Number of Stops for Range of Minimum Green Settings, 25 mph

		Low Volume		***Medium Volume***		***High Volume***	
		Minor Approach Minimum Green Setting, Seconds					
		3	***5***	***3***	***5***	***3***	***5***
Major Approach Minimum Green Setting, Seconds	***5***	156	157	237	238	440	441
	7	150	152	236	235	438	439
	10	141	145	236	233	436	436

Table 18. Number of Stops for Range of Minimum Green Settings, 35 mph

		Low Volume		***Medium Volume***		***High Volume***	
		Minor Approach Minimum Green Setting, Seconds					
		3	***5***	***3***	***5***	***3***	***5***
Major Approach Minimum Green Setting, Seconds	***5***	100	105	164	163	381	382
	7	101	104	163	163	377	383
	10	96	100	161	161	385	384

Table 19. Number of Stops for Range of Minimum Green Settings, 45 mph

		Low Volume		***Medium Volume***		***High Volume***	
		Minor Approach Minimum Green Setting, Seconds					
		3	***5***	***3***	***5***	***3***	***5***
Major Approach Minimum Green Setting, Seconds	***5***	104	108	167	167	379	383
	7	103	107	164	165	385	384
	10	101	104	164	163	382	383

CHAPTER 7: CONCLUSION

The research presented in this thesis gives traffic engineers recommendations for fully-actuated signal timing parameters that were found to reduce fuel consumption and tailpipe emissions. The process included estimating the fuel consumption and tailpipe emission rates for vehicle trajectories typically executed by drivers in response to signalized intersections. Engine modeling was conducted for a typical passenger vehicle and resulting environmental measures were collected. This step of the research showed that fuel consumption and emission rates are high during the vehicle acceleration behavior typical to a vehicle stop at a signalized intersection. Microscopic traffic simulation was then used to identify actuated timing parameter settings that may reduce the number of stops on the major approaches of signalized intersections while sustaining an acceptable cost to the users of the minor approaches.

Experiments were conducted for three major approach speed limit considerations. To show the range of expected number of stops per signal timing setting the standard deviation was computed using the 10 simulation runs. 95% confidence intervals show a relatively large range in the number of stops which make choosing a suggested signal timing plan difficult. The variation in the results was expected due to the random nature of traffic. Overall, the results showed that the passage time setting on the minor approaches tended to affect the number of stops on the major approaches the greatest. A low passage time setting, such as 1.4 seconds, on the minor approach and a high passage time setting, such as 3.0 seconds, on the major approach produced favorable results, although lower settings showed similar results. The outcomes of the tested signal timing settings were most clear when a greater differential in vehicle volumes occur between the major and minor approaches, as seen in the medium volume settings. The effects of minimum green time settings were only observed during periods of low volumes on all approaches. Recommendations to practitioners and the expected traffic flow measures are located in the following section.

7.1 Signal Timing Setting Recommendations

With a better understanding of the effects of the minimum green time and passage time settings, both of the actuated signal timing parameters may be taken into account together to suggest the signal timing setting combinations that will control traffic in the most eco-friendly way. Along with the average number of stops, it is important to consider the cost to the users of the minor approaches for scenarios in which the major approaches are given greater weight in setting the signal timing settings. It is important to note that only values of minimum green time and passage time settings that are widely thought in the profession to be appropriate were tested. For example, a minimum green time setting of less than three seconds may not be used in practice. Each recommendation, which is based on the lowest average number of stops on the major approaches, includes an estimate of the percentage of vehicles stopping on the major approaches, average delay per vehicle on the minor approaches, and a level of service designation using the Highway Capacity Manual 2010 criteria (Transportation Research Board 2010). Tables 20, 21, and 22 summarize the minimum green and passage time settings that may reduce the number of stops on the major approaches.

These recommendations are the final step in the presented research concerning actuated control parameters to reduce vehicle emissions and fuel consumption at isolated intersections.

Table 20. Recommended Timing Plans for 25 mph Major Approach Speed Limit

		Low Volume	**Medium Volume**	**High Volume**
		Stop Bar Detection System		
Signal Timing Settings	*Major Approach Min Green*	10 seconds	10 seconds	10 seconds
	Minor Approach Min Green	3 seconds	5 seconds	5 seconds
	Major Approach Passage Time	3.0 seconds	3.0 seconds	3.0 seconds
	Minor Approach Passage Time	1.4 seconds	1.4 seconds	1.4 seconds
Measures of Effectiveness	*Number of Stops on Major Approach per hour*	141	233	436
	Percent of Vehicles Stopping on Major Approach	35%	39%	54%
	Average Delay per Vehicle on Minor Approach, seconds	12	16	25
	Level of Service on Minor Approach	B	B	C

Table 21. Recommended Timing Plans for 35 mph Major Approach Speed Limit

		Low Volume	**Medium Volume**	**High Volume**
		Advance Detection System		
Signal Timing Settings	*Major Approach Min Green*	10 seconds	10 seconds	10 seconds
	Minor Approach Min Green	3 seconds	3 seconds	3 seconds
	Major Approach Passage Time	3.0 seconds	3.0 seconds	3.0 seconds
	Minor Approach Passage Time	1.4 seconds	1.4 seconds	1.4 seconds
Measures of Effectiveness	*Number of Stops on Major Approach per hour*	96	161	377
	Percent of Vehicles Stopping on Major Approach	24%	27%	47%
	Average Delay per Vehicle on Minor Approach, seconds	18	26	33
	Level of Service on Minor Approach	B	C	C

Table 22. Recommended Timing Plans for 45 mph Major Approach Speed Limit

		Low Volume	**Medium Volume**	**High Volume**
		Advance Detection System		
Signal Timing Settings	*Major Approach Min Green*	10 seconds	10 seconds	10 seconds
	Minor Approach Min Green	3 seconds	3 seconds	5 seconds
	Major Approach Passage Time	3.0 seconds	3.0 seconds	3.0 seconds
	Minor Approach Passage Time	1.4 seconds	1.4 seconds	1.4 seconds
Measures of Effectiveness	*Number of Stops on Major Approach per hour*	101	161	382
	Percent of Vehicles Stopping on Major Approach	25%	27%	48%
	Average Delay per Vehicle on Minor Approach, seconds	16	23	31
	Level of Service on Minor Approach	B	B	C

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