MICROSCOPIC SIMULATION MODEL OF TRAFFIC OPERATIONS AT INTERSECTIONS IN MALFUNCTION FLASH MODE

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MICROSCOPIC SIMULATION MODEL OF TRAFFIC OPERATIONS AT INTERSECTIONS IN MALFUNCTION FLASH MODE

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SUMMARY

In the United States, when intersection traffic signals go into flash mode, motorists are presented with one of the following two scenarios: flashing yellow for the main road and flashing red for the minor road, or flashing red for all approaches. Drivers facing a flashing yellow signal do not have to stop, while drivers facing a flashing red signal are required by law to come to a full stop before crossing the intersection. In the event of an intersection in yellow/red mode, drivers on the minor road have to wait for an adequate gap before crossing the main street; while in the case of a red/red mode the right-of-way is assigned in a first-in first-out fashion. At this time there are no laws regulating the circumstances under which flash is invoked or the selection of the mode of flash.

Chapter two of this thesis presents past studies that have been conducted to provide general guidelines for the implementation of flashing operation; however, transportation agencies still have minimum guidance upon which to base their engineering judgment. Additionally, previous studies that have analyzed intersection performance under flashing signal control have all started with the basic assumption that all drivers abide by the traffic control devices. Findings by Bansen [1] and Jenior [2] based on field data collection show this assumption to be overly optimistic, with up to 70% of the vehicles facing a flashing yellow stopping under certain conditions. Jenior [2] further analyzed this behavior with logit models of the stopping rate of the vehicles facing a flashing yellow. This thesis further supports the initial findings of Bansen, by developing a microscopic network simulation, which implements the stopping rate

forecasted by Jenior's logit model. General guidelines on how to recreate drivers' behavior at a simulated intersection in flashing mode are provided in chapter three. VISSIM was the simulation program used to create a basic four leg intersection with one lane in each direction. After undergoing a calibration and validation process, the simulation is used to recreate the potential flashing scenarios, along with operation under normal signalized control. A comparison with HCS predictions is made and the results are presented in chapter four. Based on the simulation findings, the Red/Red scenario is suggested to be the primary mode of malfunction flash, while the Yellow/Red scenario should be utilized under special conditions. This recommendation is incorporated into chapter five, which also presents the limitations of the simulation model and other items worthy of further investigation.

CHAPTER 1

INTRODUCTION

In the United States, when intersection traffic signals go in flash mode, motorists are presented with one of the following two distinct patterns:

1) Flashing yellow on the major road and flashing red on the minor road
2) Flashing red on all intersection approaches

Drivers facing a flashing yellow signal do not have to stop, while drivers facing a flashing red signal are required by law to come to a full stop before proceeding through the intersection. In the event of an intersection in yellow/red mode, drivers on the minor road have to wait for an adequate gap before crossing the main street; while in the case of a red/red mode the right-of-way is assigned in a first-in first-out fashion.

A traffic signal can be placed in flashing mode by either a random event or a programmed one. The former typically happens when the conflict monitor unit inside the controller cabinet detects either an electrical power surge (i.e. during thunderstorms or black-outs) or a potential conflict displayed by the traffic signal heads. No matter the reason, every road users has probably experienced a traffic signal in flashing mode at least once in their lifetime. Unfortunately not all motorists are aware of the proper way to approach an intersection in malfunction mode, often behaving differently according to traffic condition.

1.1 Study Need

At this time there are no laws regulating the circumstances under which flash is invoked or the selection of the mode of flash. Past studies have been conducted to provide general guidelines on the subject; however, transportation agencies still have minimum guidance upon which to base their engineering judgment. Additionally, previous studies that have analyzed the performance at flashing signals, have all started with the basic assumption that all drivers abide by the traffic control devices. As part of the overarching study of which this report is a portion, Bansen [1] and Jenior [2] collected data at intersections in malfunction flash and observed that a significant number of drivers facing a flashing yellow signal do come to a full stop. The main observation of Bansen and Jenior was that at high traffic volumes or high minor to major volume ratios, traffic movements at a Yellow/Red flashing signal deteriorates to those similar to All-Way-Stop-Control. Jenior [2] further analyzed this behavior with logit models of the stopping rate of the vehicles on the major road facing the flashing yellow based on the presence of minor street vehicles and the volume ratio between the minor and major street traffic demand.

1.2 Study Objective

This research further supports the initial findings of Bansen [1], by developing a microscopic network simulation, which will test several scenarios (Ideal Yellow/Red, Actual Yellow/Red, Red/Red, and Signalized) and implementing the stopping rate forecasted by Jenior's logit model [2]. General guidelines on how to recreate drivers' behavior at a simulated intersection in flashing mode will be provided. Recommendations on selecting a malfunction flash will also be made.

CHAPTER 2

LITERATURE REVIEW

This chapter presents an overview of previous work relating to malfunctioning flash traffic signals and unsignalized intersections, with a specific focus on how these problems were analyzed from a simulation point of view.

2.1 Background

This thesis is the third part of a three part research project conducted at the Georgia Institute of Technology on malfunction flash modes. The two previous theses were: *Evaluation of Traffic Operations at Intersections in Malfunction Flash Mode* by Bansen [1] and *Observation and Modeling of Traffic Operations at Intersections in Malfunction Mode* by Jenior [2].

Bansen was the initial investigator of the Georgia Tech research project. He identified the lack of research regarding flashing operations and was unable to find any clear guidelines regarding the selection of flashing Red/Red or Yellow/Red in case of a malfunctioning traffic signal. He developed the initial field data collection procedure and the Excel spreadsheet utilized to perform the video-reduction of traffic movements. He collected and analyzed 13 intersections in malfunction flash mode (11 Yellow/Red and 2 Red/Red) in Atlanta (GA). Bansen observed significant confusion among drivers approaching an intersection in malfunction flash mode. At high volumes, intersections operating under Yellow/Red malfunction flash conditions, which are assumed to operate similarly to a Two-Way-Stop-Control (TWSC), were instead observed to have traffic behavior resembling Red/Red flash, i.e. All-Way-Stop-Control (AWSC). A significant number of vehicles on the major road facing the yellow flash stopped, and allowed the minor road drivers at the stop bar facing the flashing red to proceed. This was not the expected behavior; the mainline vehicles should have proceeded through the intersection without stopping. According to Georgia Law, Section 40-6-23 of the Unannotated Georgia Code [3]:

> "When a red lens is illuminated with rapid intermittent flashes, drivers of vehicles shall stop at a clearly marked stop sign… …When a Yellow lens is illuminated with rapid intermittent flashes, drivers of vehicles may proceed through the intersection or past such signal only with caution."

Bansen identified several direct violations of these guidelines by observing the tendency of vehicles to cross a flashing red intersection in a platoon style, with one or more vehicles following a lead vehicle. This action is sometimes referred as "piggybacking", and the field data analysis showed that this behavior was common for both the major and minor street vehicles.

Bansen assumed that the main factor influencing the behavior of a vehicle on the major road facing a flashing yellow was the presence or absence of a minor street vehicle. Other variables correlated to the major road stopping rate were functional classification and the minor street to major street volume ratio. Bansen recommended providing one consistent mode of flashing operation, specifically Red/Red. This mode would provide a safer environment for all road-users and eliminate the potential driver expectancy problem experienced by drivers facing a flashing red who do not know what signal indication is being flashed (red or yellow) to drivers on the intersecting road.

Jenior expanded the project beyond the original 13 intersections. He continued the field data collection task by studying over 40 intersections (including Bansen's original

13) in malfunction flash mode, along with several newly installed signals and intersection flashing beacons. This significant data set allowed Jenior to create logit models, which predicted the stopping rate of vehicles approaching a yellow traffic signal during a malfunction flash event. Jenior determined that along with the presence or absence of a vehicle on the side street, the relative difference between functional classes of the intersecting streets also seemed to influence the observed stopping behavior. Two utility equations were created according to the presence (Equation 1) or the absence (Equation 2) of a vehicle on the minor street [2]:

Equation 1: $$P_{Stopping} = \left[\exp(-7 + 25 * VR) \big/ \exp(-7 + 25 * VR) + 1 \right] * 0.62$$

Equation 2: $$P_{Stopping} = \left[\exp(-7 + 25 * VR) \big/ \exp(-7 + 25 * VR) + 1 \right] * 0.31$$

In both equations the only independent variable is the volume ratio (VR), which acts as a surrogate for functional classification. For a complete explanation of the utility functions please refer to Jenior's paper [2]. The stopping rates modeled by Jenior are implemented in the microscopic simulation of Yellow/Red malfunction flash that is covered in this thesis. Figures 1 and 2 show the stopping rate models when vehicles are present and absent, respectively.

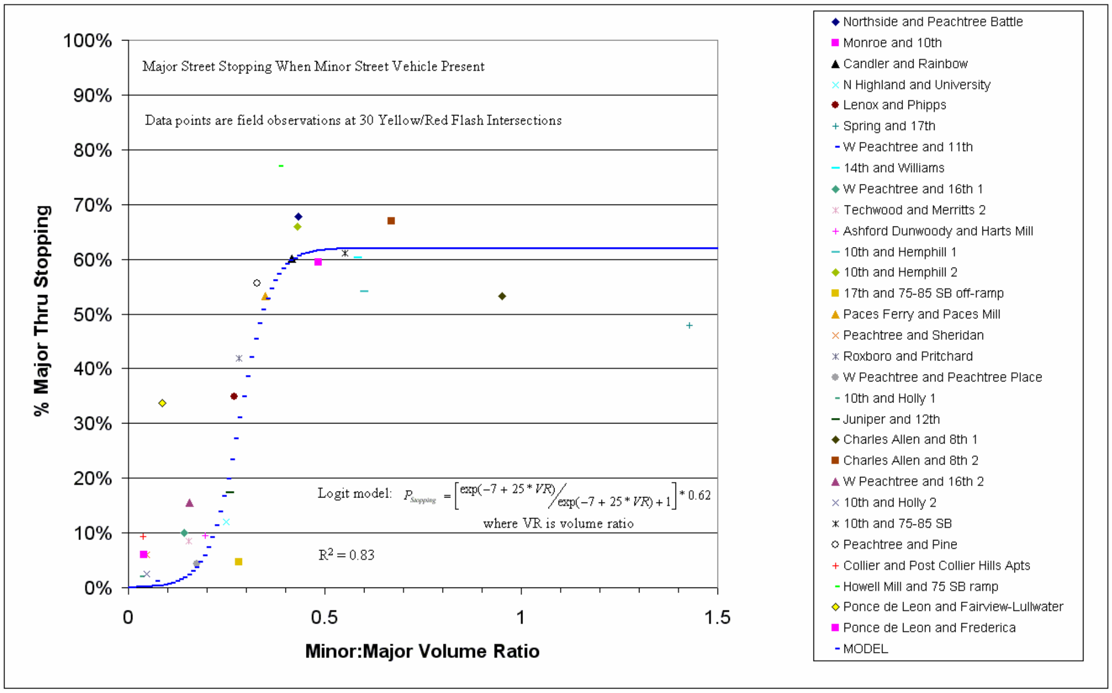

Figure 1. Logit model 1 – percent major through stopping during Y/R with minor street vehicle present. *Source:* Jenior [2]

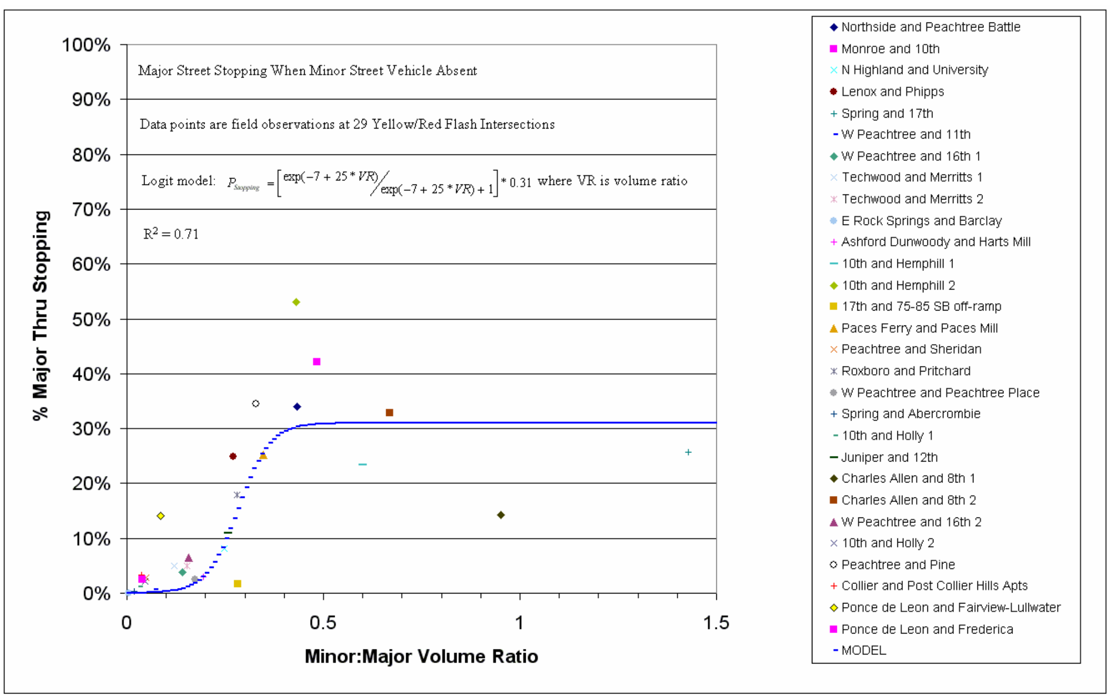

Figure 2. Logit model 2 – percent major through stopping during Y/R with minor street vehicle absent. *Source:* Jenior [2]

In order to give an assessment of the state of practice of malfunction flash traffic signals, Jenior also conducted a survey at the state and national level. The aim of the survey was to analyze policies and procedures in use with regard to flashing operation and prevention of malfunction flash. The result of the survey showed that in Georgia, most traffic signals in malfunction flash operate in Yellow/Red mode, with Red/Red used only in special circumstances. This flash mode selection is similar in most other areas surveyed, with a few exceptions that did limit malfunction flash to Red/Red.

Jenior's final remarks [2] were similar to Bansen's:

> "if one flash mode to be used at all intersections had to be selected, that mode should be Red/Red……if Yellow/Red is to be used at all, the most appropriate location would be at intersections of local and arterial roads where the minor street to major street volume ratio is approximately 0.20 or less (during all time periods as malfunction flash may occur any time of day) and AASHTO intersection sight distance requirements are met"

2.2 Previous Work

Previous studies have attempted to analyze and compare various signal operations, but have tended to analyze the Y/R scenario under the assumption that vehicles did not stop when approaching a yellow flash indication (henceforth this assumption is referred to as ideal conditions). Some of the studies also conducted only a limited number of simulation runs due to hardware and software constraints. The primary focus of these studies tended to be programmed flash, where the signal control is set to go into flashing operations only during very low demand periods. This implies that the flashing signal operation was studied during off-peak hours or for intersections with relatively low total volumes. However, the malfunction flash event is a random event that can happen at any time, during any traffic demand. Therefore, it becomes necessary to investigate flashing operation under traffic demands well beyond where programmed flash is allowed.

Bansen [1] and Jenior [2] conducted an extensive literature review about flashing operation. Their main focus was analyzing malfunction flash operation from a qualitative point of view, finding policies and procedures on the implementation of malfunction flash, and previous literature regarding empirical delay and/or stopping rate estimation. They found no papers regarding microsimulation of an intersection in flash mode under high volume conditions (either Red/Red or Yellow/Red). Where simulation of intersections in flash mode was performed, none addressed the issue of the high stopping rate of vehicles facing a flashing yellow, particularly under heavy traffic conditions.

This chapter presents the literature review, focused on microscopic simulation and unsignalized intersection operation and performance studies. The papers are presented in chronological order. For a more extensive literature review on general operation and analysis of flashing signal, please refer to Bansen [1] and Jenior [2].

2.2.1 Federal Highway Administration (1980)

Between August 1975 and May 1978 a study on flashing traffic signal operation commissioned by the FHWA was performed by TJKM. The objective of the study was to answer the following two questions [4]:

1) “Under what circumstances should traffic signals be operated in a flashing mode?”

2) "Where flashing operation is used, when should it have yellow/red pattern and when should it have a red/red pattern?"

As part of this study the authors conducted a detailed review of relevant literature and applicable state laws, surveyed state and local traffic engineers, surveyed drivers regarding their understanding of flashing operations, conducted field studies, and analyzed and modeled the intersection operations. Flashing signal operations data was collected at 94 intersections (all in programmed flash) from around the country, and five types of studies were performed, specifically: accidents, conflicts, violations, spot speed, and stopped time delay. Of these studies, the violations, spot speed, and stopped time delay data are used for calibration and results comparisons with the simulation model that will be discussed in chapter 3. Each of these is briefly described below:

I) A violation was recorded during the study if a vehicle did not come to a full stop when faced with a flashing red signal. Findings showed that vehicles on the side streets had a tendency to run a flashing red at a rate of 6 for every 100.

II) Spot speed data was collected using radar speed meters for each major approach. Flashing Y/R speeds had a mean of 46.5 kph (28.9 mph) and a 4.3 kph (7 mph) standard deviation, while flashing R/R had mean and standard deviation speeds of 41.5 kph (25.8 mph) and 5.2 kph (3.2 mph)

III) Stopped delay was measured by means of digital stop watches. The observers recorded the time of stopping and the time of departure from the stop bar of approaching vehicles. For the flashing Y/R scenario, no delay data was collected for the main street. The study assumed that no vehicles on the major road would stop at a flashing yellow, which at the low volumes experienced during programmed flash is likely correct. Moreover, only intersections with low minor street volumes (less than 36 vph) were analyzed. Also, the flashing R/R analysis was conducted under low volume scenarios; the study found that mean delay for the major street was significantly less than that of the minor street. The authors inferred that major street drivers tend to be more aggressive than minor street ones when faced with a flashing red.

No simulations were performed for this study; the field data collected was used for validation of mathematical models predicting stopped time delay.

2.2.2 Federal Highway Administration (1982)

Another study on flashing operation was commissioned by the FHWA, in collaboration with the Virginia Department of Highways and Transportation, and the study was conducted by the University of Virginia [5]. This study includes an attempt to simulate flashing operations. The location selected for the study was the U.S. Route 29 north corridor in the Charlottesville-Albemarle metropolitan area. The network simulated consisted of an arterial road with three out of thirty intersections flashing yellow/red. Again, this study was limited to programmed flash conditions.

The main problems encountered by the authors were software and hardware limitations. The program used for the study was NETSIM. At the time, it was the only traffic simulator capable of implementing stop and yield control at intersections. The authors assumed that flashing operation would act like a two-way stop (i.e. vehicles approaching the flashing yellow do not stop) when the signals flash yellow/red or a four-way stop sign when signals flash red/red [5]. The simulation runs represented only 5 minutes of real time, due to the high computing cost. Each run cost an average of six hundred dollars!

The intention of the authors was to study the implementation of flashing signal operations during the peak hour and analyze volume variations up to 200% the original value; unfortunately NETSIM was limited to a network capacity of a maximum of 1600 vehicles. The authors stated [5]:

> “When the afternoon peak-hour volume was doubled, the maximum occupancy was attained after 51 seconds of simulation, and then simulation was aborted. When the volume was tripled, simulation aborted before starting”

Due to these limitations the results presented in the study were not used as an input or comparative data source for this current effort. It is notable that this effort appears to be the first published attempt at the simulation of a flashing signal. Moreover, their concept of simulating a R/R and Y/R flashing signal as four and two-way stop control, respectively, is included in the operational scenarios considered in this current effort.

2.2.3 Salter and Ismail (1991)

In issue No. 1320 of the Transportation Research Record, Salter and Ismail published their paper titled: *Simulation of Two- and Four-Way Stop Control* [6]. The authors developed a simulation model for each unsignalized scenarios: TWISSIM for two-way stop and FWSSIM for four-way stop. “The main simulation models, together with other sub-models used in the simulations, were built into a general and modular computer program, SIMPHINT” [6]. The main inputs for drivers’ behavior in their model were: critical acceptable gaps, the headways between vehicles, and the turning movement's distributions. The intersection analyzed had four legs with one lane for each approach. Each approach had volumes varying from 100 to 800 veh/hr, with turning proportions of 15, 70, and 15 percent, for left, straight, and right movements, respectively. The results of the simulation showed that at low traffic volumes there is no significant difference between the two control methods, whereas, at flow higher than 250 veh/hr per approach, the four-way stop intersection yields lower delay values than the two-way one [6].

2.2.4 Federal Highway Administration (1993)

Ten years after the first major study [4] on flashing signal operation, FHWA commissioned the Texas Transportation Institute to conduct a flashing operations study [7]. Again, the aim of the study was to develop a series of guidelines for deciding which conditions are appropriate for flashing signal operation, and the selection of the flash mode [7]. For this effort computer-based traffic simulations were performed as part of the operational analysis. Total delay per vehicle, calculated using the difference between desired and actual travel time through the intersections, was used exclusively as the measure-of-effectiveness (MOE) [7]. Two simulation programs were used: TEXAS and TRAF-NETSIM. Both programs were capable of modeling the yellow/red flashing scenario (with the assumption of no vehicles stopping on the flashing yellow), but only TEXAS was able to model the red/red scenario. The simulation experimental design adopted was very detailed, including various intersection geometric configurations (4), approach volumes (45), and multiple runs (5). Unfortunately, the study did not take into account volumes higher than 500 veh/hr/approach, and more importantly the simulation analysis assumed perfect compliance to traffic control devices. That is, all drivers abide by the traffic control devices [7], an assumption directly challenged by the field data collected by Bansen [1] and Jenior [2].

2.2.5 National Cooperative Highway Research Program 3-46 Report (1996)

"In January 1993, the University of Idaho, in cooperation with Kittelson and Associates, Ruhr University, and Queensland University of Technology, initiated work on NCHRP 3-46 to develop new capacity and level of service analysis procedures for unsignalized intersections" [8]. One of the objectives of the study was to create a new and comprehensive data base for traffic operations related to four-way stop intersections. "Thirty unique sites were videotaped during 41 different time periods… …totaling 151.67 hours of usable data" [8]. Two parameters were used to guide the process of sampling of this data: traffic flow and intersection geometry. Some of the major characteristics of the data set include [8]:

1) "54% of the flow rate data range from 12 vph to 200 vph; 15% of the data points are above 600 vph"
2) "77% of the total delay data are less than 10 sec/veh; 7% of the data are above 30 sec/veh"
3) "42% of the service time data are between 2 and 4 seconds; 45% of the data are between 4 and 6 seconds"

Based on this data set the authors determined that saturation headway, which is the basic parameter to compute intersection capacity, depends on the following [8]:

1) “Degree of conflict faced by the driver of the subject approach as measured by presence of vehicles on the opposing and conflicting approaches”
2) Intersection geometry
3) “Directional movements of the interacting vehicles”
4) “Vehicle type”

This paper proved to be a seminal one. The authors selected, analyzed, and approved the two models for estimation of intersection capacity and delay implemented in the current Highway Capacity Manual (2000).

2.2.6 Tian, Urbanik, Engelbrecht, and Balke (2002)

Tian et. al. examined and compared some of the most popular microscopic traffic simulation models, namely: CORSIM, SimTraffic, and VISSIM. The authors investigated the variations of performance measures, such as capacity and delay, generated by these models and the conditions affecting the variability between models [9]. The comparison was performed for two cases: (1) a single-lane approach at a signalized intersection with 100% through traffic and (2) a single-lane approach at a signalized intersection with a right turn pocket (20% right and 80% through traffic). The results showed that the highest variations happen when traffic demand is close to the capacity condition. Factors such as link length and travel speed distribution also affect the delay results, where lower delays are obtained with shorter links or higher speeds [9].

A section of this study is dedicated to the comparison of simulation models versus analytical models, such as the ones incorporated in the HCM. The HCM methodology under scrutiny was related to delay estimation. Tian et. al. found [9]:

1) “HCM reports average control delay, which includes the deceleration, queue moving time, stopped time, and the acceleration. However, the length and speed of an approach, which may contribute to the acceleration and deceleration portions of control delay, is not specifically considered”
2) HCM does not take into account delays generated by car following behavior (non-control delay)
3) “HCM reports delay for vehicles arriving during the analysis period, while simulation models take into account vehicles departing during the analysis period”
4) “Simulation models automatically take into account residuals queue from previous time period”, while analytical models do not

In its final remarks, the study recommended using long simulation durations to reduce variations, to conduct at least 2 simulation runs for low to medium traffic demand level, and at least 20 runs for near and over capacity conditions.

2.3 Literature Review Summary

Several studies have analyzed flashing signal operations, but most of them were either performed under low volume conditions (ideal for programmed flash) or with the assumption that few violations would occur.

Simulations programs did not, or could not, produce reliable analysis until the beginning of the 1990’s. Even if the algorithms behind these programs were based on proven analytical models, hardware capabilities were limiting the researchers.

The theory behind unsignalized intersection operation and performance has been covered by many researchers and studies, but the NCHRP document can be considered the most in-depth study: no other research in the past 10 years had such an extensive field data collection and depth of analysis.

Unfortunately, no last-generation microsimulation programs such as VISSIM have been used for modeling either a four-way-stop or flashing signals scenarios.

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CHAPTER 3

SIMULATION

As noted in the literature review, previously developed models of operations at intersections in flash mode, either programmed or due to malfunction, have assumed that vehicles approaching a flashing red indication will always stop and vehicles approaching a flashing yellow indication will proceed through the intersection without stopping [7]. These efforts predicted queuing and delay for various geometric layouts and demand conditions given these assumed driving behaviors. Bansen [1] and Jenior [2] have clearly shown these assumptions to be false. Of particular significance is observed operations on approaches under flashing yellow control, where vehicle stopping rates from zero to over 70% were observed. The likelihood is that previous models utilizing a zero stopping percentage for vehicles approaching a flashing yellow significantly underestimated delay, and overestimated capacity, during yellow/red malfunction flash operations. To allow for an adequate comparison of operations under red/red and yellow/red malfunction flash it is important to measure operational performances that reflect realistic driving behaviors.

Field measurement of operational performance metrics (i.e. delay, queues, capacity, etc.), while the intersection is in malfunction flash, is impractical. In order to adequately conduct field data collection of operational parameters significant forewarning of the flashing event is necessary. This implies the intersection must intentionally be place in flash, creating a safety risk to the road users that simply cannot be justified. However, simulation modeling provides an opportunity to analyze various geometric and traffic volume conditions without incurring any safety hazards.

Thus, to estimate performance metrics under malfunction flash operation a hypothetical intersection is modeled. Simulation models are created in order to make a comparison of three signal operation scenarios: flashing Yellow/Red (*Y/R*), flashing Red/Red (*R/R*) and *Signalized* (S). The Yellow/Red scenario is further broken down in two cases: *Ideal* and *Actual*; the former assumes that no vehicle stops on the approach facing a flashing yellow light (the assumption of previous studies), while the latter implements the stopping behaviors observed by Bansen [1] and Jenior [2]. Average delay per vehicle on the major and minor road is used as the primary comparative measure-of-effectiveness (MOE). The delays obtained through the microsimulation runs are also compared with the values predicted by the Highway Capacity Manual (HCM 2000) methodology, as implemented in the Highway Capacity Software (HCS 2000), specifically the Two-Way-Stop-Control (TWSC), All-Way-Stop-Control (AWSC) and Normal signal operation.

3.1 Simulation Software

All intersection simulations are undertaken using VISSIM. VISSIM is a microscopic, time step and behavior-based multi-purpose traffic simulation model developed to model urban traffic. VISSIM was developed by PTV (Planung Transport Verkehr) AG of Karlsruhe, Germany. During the runtime execution the simulation generates a graphical visualization of traffic operations. Statistical data such as travel times, delays, and queue lengths are also gathered that may be analyzed later, once the simulation runs are completed [10]. VISSIM version 4.10-12 was used for the study described herein.

This project requires extensive post-processing and numerous scenarios to be investigated, thus efficiency demanded process automation. The software used for this task is VISSIM COM. Access to model data and simulation components is provided through a Component Object Model (COM) interface, which allows VISSIM to work as an Automation Server (i.e. tasks that a user may implement through menu pull downs may be automated through COM) and to export objects, methods and properties. The VISSIM COM interface supports Microsoft Automation, allowing for the use of any Rapid Application Development (RAD) tools, ranging from scripting language like Visual Basic (VB) Script or Java Script to programming environments like Visual C++ or Visual J++ [11]. For this study Visual Basic for Applications 6.3 embedded in Microsoft Excel is utilized.

3.2 Simulation Hardware

The simulation runs are performed with a 3.4 GHz DELL Precision PWS380, Pentium(R) 4 with 2.00 GB of RAM. A defrag of the hard drive and a computer reboot is suggested after a set of 2,000 or more simulation runs in order to avoid possible system failures.

3.3 Simulation Model

This section covers the characteristics of the intersection model and the procedures adopted to implement the drivers' behavior outlined in Bansen [1] and Jenior [2].

3.3.1 Base Data for Simulation

The following are the basic characteristics and settings of the model.

3.3.1.1 Intersection Characteristics

Figure 3 shows the general characteristics of the VISSIM intersection. The major road is oriented east/west and the minor road north/south.

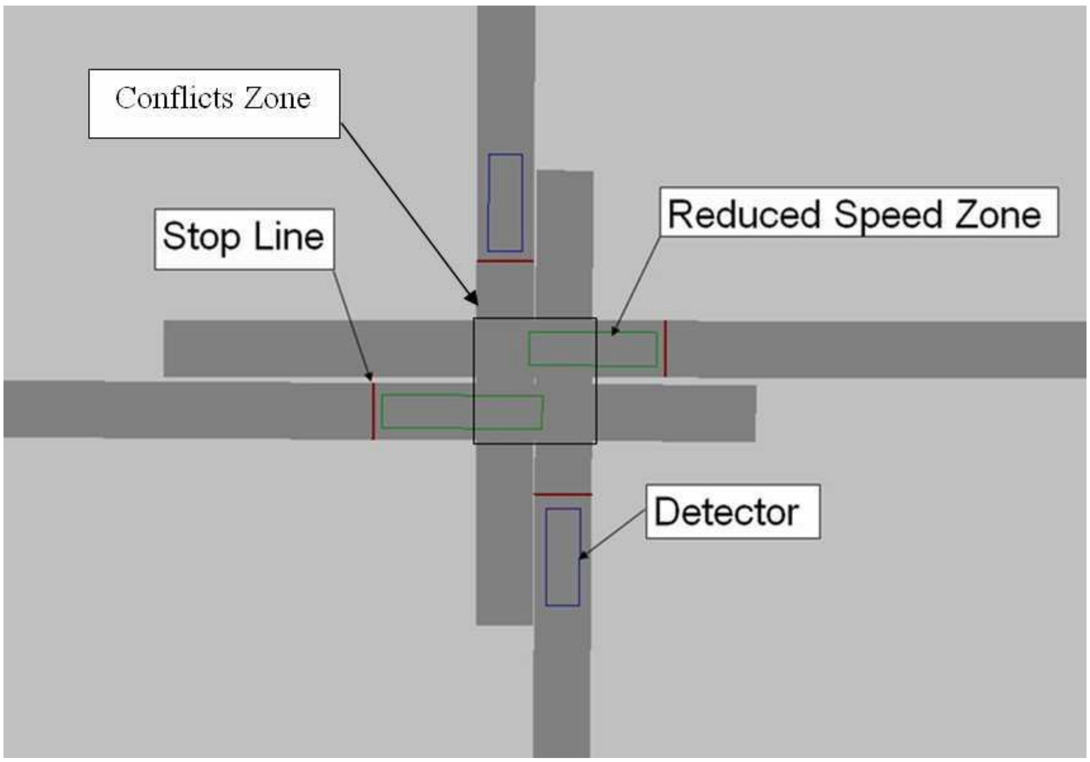

Figure 3. Intersection Layout

The simulated intersection has the following features:

- Geometric Characteristics
    - Four legs with length equal to 800 meters (half-mile), one lane for each direction, with lane width equal to 3.5 meters (11.5 ft).

- The conflicts zone (intersection proper bounded by the extension of the curb lines) is contained in a squared area with side length of 9 meters (30 ft).
- Set back of the stop bar from the extension of the curb line is 4.5 meters (15 ft) for the major road, and 3 meters (10 ft) for the minor road.

- Detectors on the minor approaches with length equal to 4 meters (13 feet). This feature is used to detect the presence or absence of a vehicle and plays an important role in the Type-Changing algorithm discussed in section 3.3.3.2.
- Speed zones to reduce vehicles speeds while crossing the intersection. The speed distribution in these zones has a mean of 40 kph (25 mph) and standard deviation of 8 kph (5 mph). These speed zones are intended to reflect field observations. It was noted that even where vehicle did not stop at a flashing yellow indication they did tend to reduce their speed or “proceed with caution”. The speed is based on field observations and literature findings [4].
- A stop bar dwell time distribution set to zero seconds. The dwell time (also defined as the service time) is the time that a vehicle occupies the first position in queue [8]. The selection of a null value for the dwell time is motivated by the fact that the priority rules (discussed later in the chapter) will generate the delay experienced by motorists while sitting at the stop bar waiting for either their turn to cross the road (*Red/Red*

scenario case), or for an acceptable gap (relevant for vehicle on the minor road in the *Yellow/Red Ideal* and *Actual* scenarios).

- Routing was not implemented; all vehicles simulated went straight, meaning the model does not simulate left and right turn movements.

3.3.1.2 Simulation Duration and Delay Measurement

Simulation data regarding malfunction flash is collected for a period of one hour. There is no warm up period, thus data is collected from time zero to 3600 seconds. The intent of the analysis is to begin the data collection at the moment the intersection begins flashing operations and to capture the impact over the first hour of flashing operations. This will allow for future analysis that considers the impact throughout the malfunction flash episode, from normal signal operations, to malfunction flash, and back to normal operations. It is noted however that this data collection approach does not incorporate the assumption that the simulation reaches a steady state. To the contrary, it is highly likely that under some higher volume conditions a steady state will not be reached at any time during the simulated hour. It will be seen in the presented results that under some demand scenarios a steady state condition is not reached and the measured delays are a function of the simulation time and link lengths.

Delay is measured through the use of travel time sections. A vehicle's travel time is measured from the upstream start of the link until the vehicle enters the intersection. Delay is calculated as the difference between the measured travel time and the ideal travel time assuming the vehicle travels at its desired speed. A vehicles desired speed is defined when the vehicle enters the network. Also, when crossing a reduced speed zone the desired speed is taken to be that of the reduced speed zone. Based on this feature, the delay experienced by a vehicle to slow down to proceed with caution is not taken into account by VISSIM. Queue counters are also placed at each approach at the stop bar, allowing for a queue measurement of stopped vehicles. During simulation runs, the *Resolution* parameter was set to two, meaning that measurements such as vehicle position, delay, and travel time are calculated twice every second.

3.3.1.3 Traffic Input

Traffic volumes are assigned at the beginning of each intersection's leg. VISSIM loads the assigned traffic in a random manner using the Poisson distribution [10]. Traffic composition is assigned to be 100% passenger cars (i.e. no trucks, bikes, motorcycles, etc.). The VISSIM default average car length ranges between 4.11 and 4.76 meters (13.5 to 15.6 ft), with width of 1.5 meter (5 ft). Each scenario is modeled with different traffic volumes, please refer to Section 3.5 for more details.

3.3.1.4 Vehicle Speed

The selected desired vehicle speed is based on average speed limits from the field data. The major road's speed distribution follows a normal distribution with two tails, with mean of 72 kph (45 mph) and standard deviation of 8 kph (5 mph). The minor road's speed distribution follows a normal distribution with two tails, with mean of 40 kph (25 mph) and standard deviation of 8 kph (5 mph). Figures 4 and 5 shows the settings used in VISSIM.

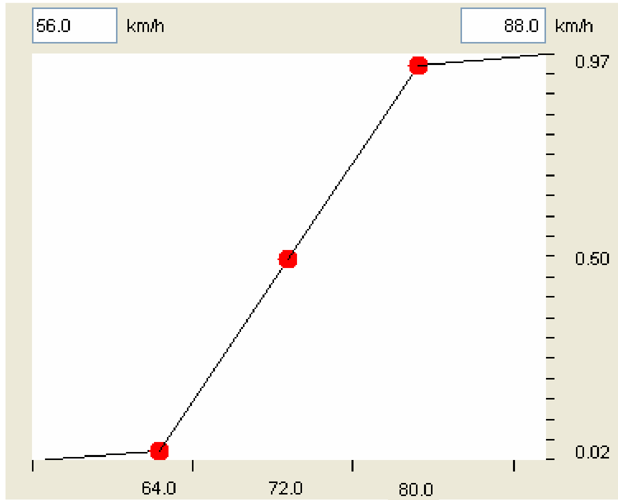

Figure 4. Major road speed distribution

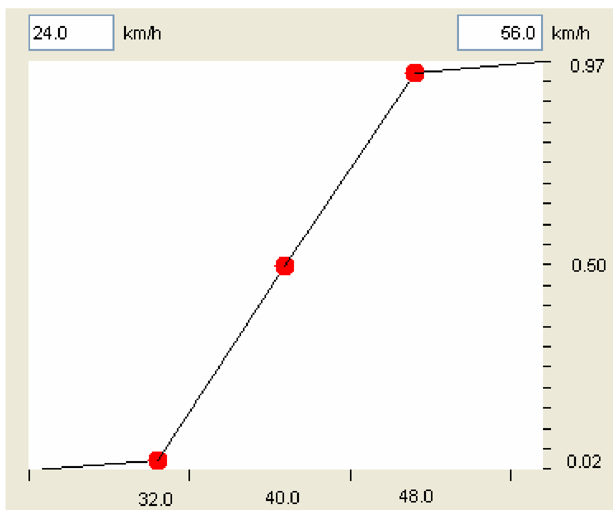

Figure 5. Minor road speed distribution

3.3.1.5 Driver Behavior

The car following and lane changing logic in VISSIM is based on the psycho-physical driver behavior model developed by R. Wiedermann in 1974 [10]. There are several parameters that can be adjusted for the creation of a customized driver behavior.

The simulation default settings were initially utilized; however, after the first round of calibration the *Average Standstill Distance*, which defines the average desired distance between stopped cars, was changed from 2 meters (6.6 ft) to 1 meter (3.2 ft). This adjustment was made based on observations of vehicular behavior in the video recording. Vehicles queuing in the field were observed to either maintain a shorter gap between each other or had a smaller move-up time when compared to the vehicles in the simulation. The move-up time is defined as the time between the departure of one vehicle from the stop line and the time for the next vehicle in line to move up to the first position in the queue [8]. Thus, to better reflect observed conditions it was necessary to either modify the standstill distance or the acceleration parameters of the simulation. The former proved to be an easier variable to adjust and calibrate.

3.3.1.6 Car Type

In order to represent the different behavior of drivers at a malfunction signal intersection and to implement the percentage of stopping vehicles on the major road under Y/R condition the following type of drivers are created in VISSIM:

- Type 1 (green colored) – vehicle on major road that never stops
- Type 2 (red color) – vehicle on major road that always stops
- Type 3 (yellow color) – left turning vehicle (for future implementation)
- Type 4 (gray color) – initial major road vehicle type. In the *Actual Y/R* scenario it is converted to either Type 1 or Type 2 as the vehicle approaches the intersection
- Type 5 (blue color) – vehicle input in the minor street (always stop)

Not all vehicle types are used for each simulation scenario:

- *R/R* simulations have Type 2 and Type 5 vehicles only

- *Actual Y/R* simulations have all vehicle Types (excluding Type 3)
- *Ideal Y/R* simulations have Type 1 and Type 5 vehicles only
- *Signalized* scenarios have Type 4 and Type 5 vehicles only

3.3.2 Priority Rules

For collision avoidance and right-of-way, VISSIM priority rules are utilized. Figure 6 provides an example of how priority rules work.

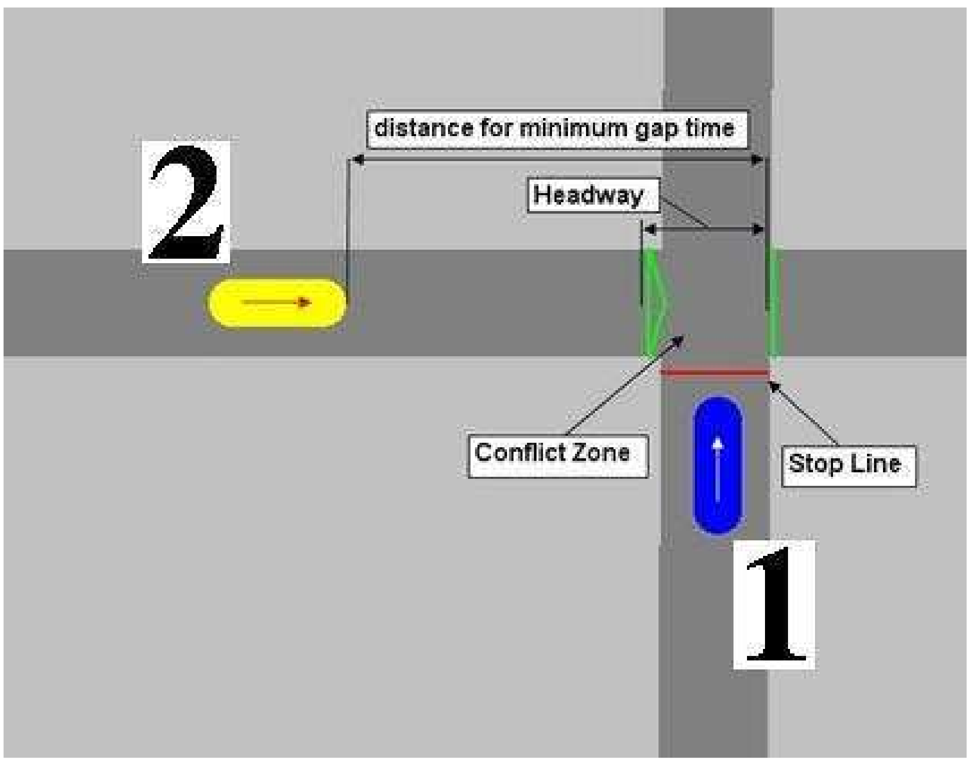

Figure 6. Priority rule example

A priority rule governs the assignment of vehicles to a roadway location when the two vehicles would be in conflict if they both proceeded unabated. For example, at a two-way stop controlled intersection a vehicle stopped at a stop bar should not enter the intersection unless a sufficient gap exists in the cross street traffic. In defining gap acceptance using priority rules VISSIM considers both the distance and time between conflicting vehicles. In Figure 6 the priority rule consists of one stop line (red bar) and one or more conflict markers (green bar) associated with the stop line. After placing stop line and conflict markers, the user specifies the headway which delimits the distance between the conflict markers. If a cross street vehicle is present between the conflict markers, the stopped vehicle will not depart the stop bar. The user also defines the minimum gap time, which sets the minimum allowable travel time from the conflict marker to the nearest conflicting cross street vehicle. If a cross street vehicle would reach the conflict marker in the travel time defined by the minimum gap, the stopped vehicle will again not depart. For example, vehicle number 1 in Figure 6 will come to a halt at the stop line (red bar) if the vehicle number 2 is either inside the conflict zone (between the green lines) or if it will reach the second green bar (the conflict marker) within a time less than the minimum gap time, otherwise the blue vehicle will cross the intersection without stopping.

Priority rules may be specific to vehicle types, that is, a priority rule may be set such that only certain vehicle types will observe the rule. Figure 7 shows VISSIM priority rule interface for the northbound approach; the left side of the priority window represents the car type that will come to a halt at the stop bar (*Type 5* in this case), while the right side of the interface specifies the vehicles which have the right-of-way (*All Vehicle Types*) on the intersecting road.

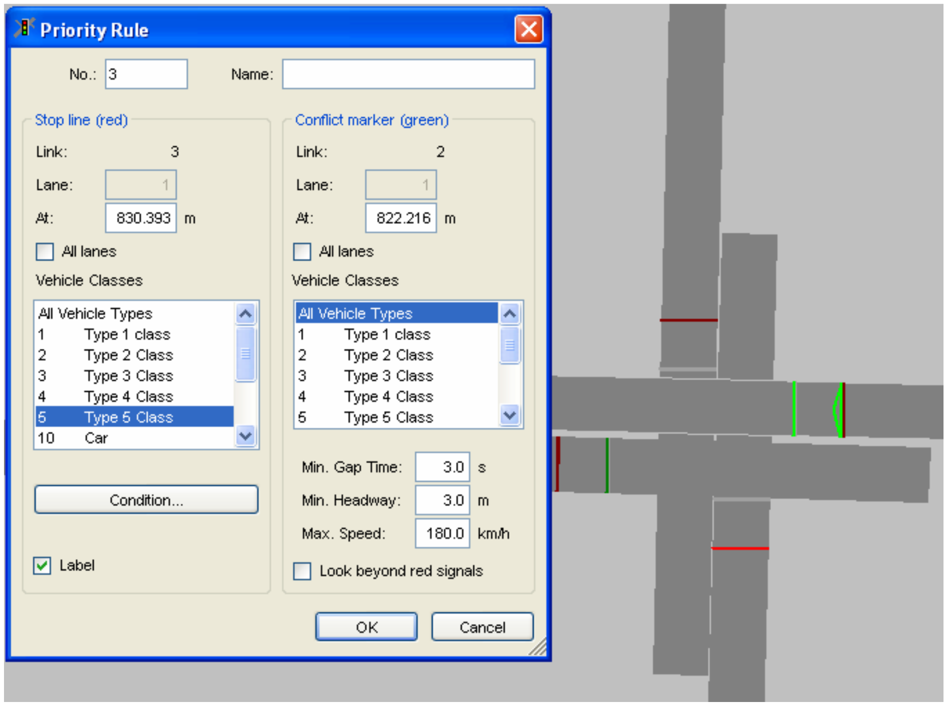

Figure 7. VISSIM priority rule interface.

The simulated intersection used for this malfunction flash study contains several priority rules. Both Type 2 (red, major road only) and Type 5 (blue, minor road only) vehicles obey these rules and may be required to stop for collision avoidance, only Type 1 vehicles (green, major road only) are not influenced by them. Following is a qualitative description of the car types:

- Red, Type 2 – in the *Actual Y/*R scenario he/she can be depicted as the cautious driver that, even if not required to, will come to a full stop for sake of safety or it might be the gentle driver that gives a chance to the blue (Type 5) car on the minor to cross the road. In the Red/Red scenario it will just be the law-abiding driver

- Green, Type 1 – is the driver that follows the rule of not stopping, but proceeds with caution when faced with a flashing yellow light
- Blue, Type 5 – is the driver of the minor road that waits for either an acceptable gap in the Yellow/Red scenario, or its turn in the Red/Red one
- Grey, Type 4 – is present in the *Actual Y/R* scenario only. He/she is the driver on the major road that has to make up his/her mind. He/she will either stop and go (becomes a red car) or proceed without stopping (becomes a green car)

If a grid lock situation occurs, where multiple vehicles are waiting for each other to depart an area, VISSIM resolves it by releasing the vehicle with the earliest stop arrival. The only scenario not requiring priority rules is the *Signalized* scenario.

The scenario that relies most heavily on priority rules is the red/red flash. This scenario seeks to implement the predefined Highway Capacity Manual all-way-stop control two-phase operation pattern (Figure 8), where drivers from opposing approaches enter the intersection at roughly the same time.

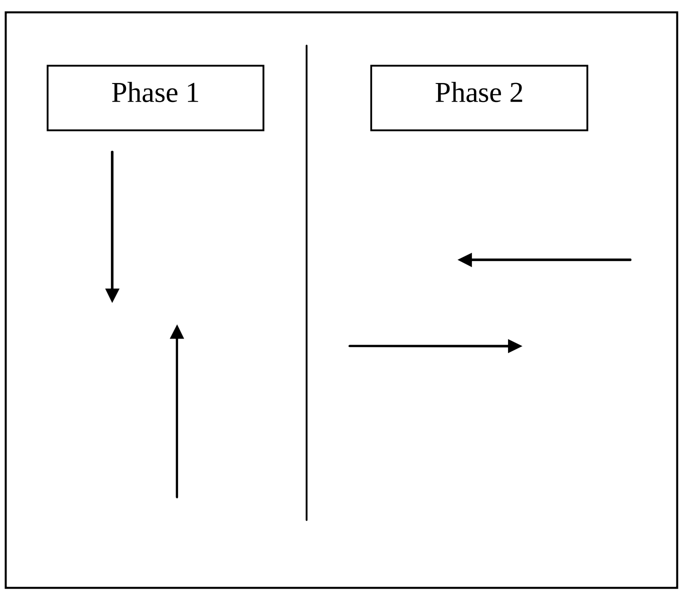

Figure 8. Two-Phase Operation

This general behavior of north-south streams alternating right-of-way with east-west streams is typical of intersections where all approaches are single lane [12].

Priority rules play the dominant role in the modeling and calibration of the service time. As previously mentioned the VISSIM entry for the stop line dwell time is set to zero. The average service time observed in the simulation, as a result of implementing the priority rules, is 4 seconds. This value compares well to service times found in the literature; Figure 9 is taken from the NCHRP Project 3-46 [8], and it shows the comparison of the NCHRP theoretical model versus field measurements recorded at 12 intersections belonging to what the report categorized as Group 1 (4 legs intersection with 1 lane for each approach).

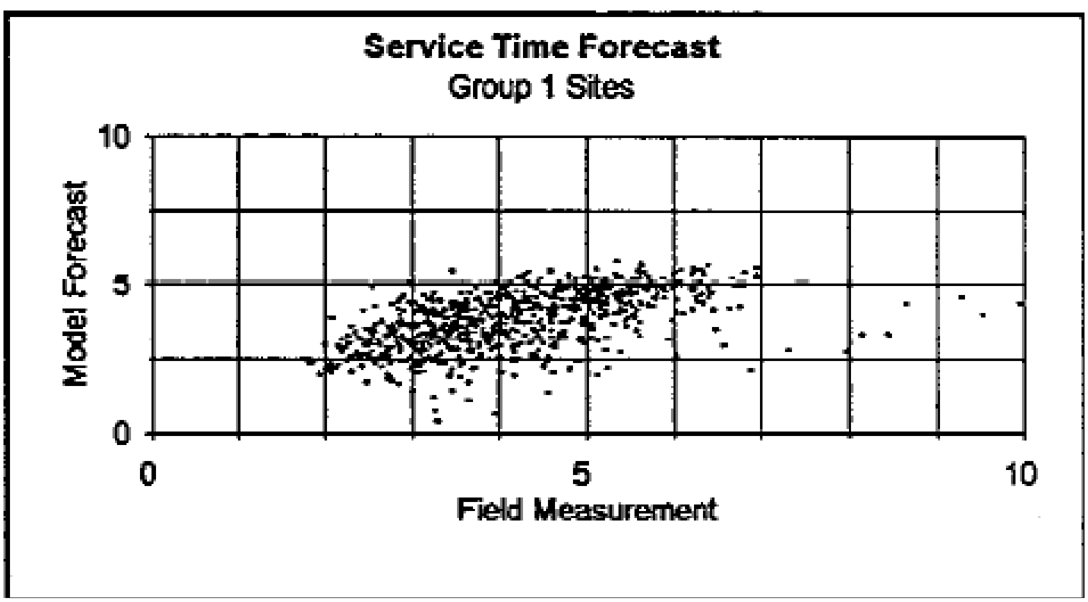

Figure 9. Service time forecast for Group 1 intersection. *Source:* NCHRP 3-46 [8]

3.3.3 Visual Basic Interface (VBCOM)

The COM interface is used for two main aspects of the simulation: first to automate the task of multiple runs and second to implement the vehicle stopping percentages in the *Actual Y/R* scenario. Appendix G presents the full Visual Basic code used to implement the two algorithms explained in this section.

3.3.3.1 Multirun Algorithm

In order to generate delay data for each possible combination of demand volumes and conduct replicate trials (the design of experiment is described in section 3.5), a series of nested visual basic *for* loops are used. The pseudo-code is outlined as follow:

1. Declare the 3 variables
    a. *X1 = major volume*
    b. *X2 = ratio*
    c. *X3 = random number*
2. Code the 3 nested *for* loops
    a. *For X1 = MinimumVolume* to *MaxVolume*
        i. *MajorInput = X1*
    b. *For X2 = MinimumRatio* to *MaxRatio*
        i. *MinorInput = X2 * X1*
    c. *For X3 = 1* to *TotalNumberofRandomSeed*
        i. *SimulationRandomSeed = X3*
3. Open VISSIM and import X1, X2, and X3 as simulation settings
4. Run the simulation
5. Export delay data for offline analysis

6. Repeat until *X1* = *MaxVolume* and *X2* = *MaxRatio* and *X3* = *TotalNumberofRandomSeed*

This code is repeated for each scenario (*R/R*, *Actual Y/R*, *Y/R Ideal*, and *Signalized*). The total number of runs for each scenario varies according to the maximum volume on the major road. For example, if the major road input volumes went from 50 to 500 veh/hr/ln (with an increment of 50), the minor to major volume ratio from 0.1 to 0.5 (with an increment of 0.05), and random seed from 1 to 5 (with increment of 1), there would be: ten × ten × five = 500 simulation runs.

Each time a simulation run is performed, VISSIM stores delay and queue information in special files (*.vlz* extension for delay, *.stz* for queue, and *.rsz* for travel time). Each time VISSIM is restarted these files are overwritten, thus the necessity to implement VB code that retrieves information from these files and exports the data for later analysis.

3.3.3.2 Type Changer Algorithm

As seen in the previous sections, VISSIM allows the user to define numerous parameters regarding car behavior and type. Through the COM interface it is possible to access and change these parameters during the simulation runtime. The Type Changer Algorithm takes advantage of this COM ability.

As described previously, vehicles enter the major street (i.e. yellow flash approach) of the *Actual Y/R* scenario as a Type 4 vehicle. The vehicle will then be changed to a Type 1 (non-stopping vehicle) or Type 2 (stopping vehicle) according to a probabilistic function based on the demand volumes and the presence of minor street vehicles. Jenior [2] developed a set of relationships based on the ratio between the minor and major street demand and the presence of a minor street vehicle when the major street vehicle reached the stop line. The vehicle stopping percentages developed by Jenior [2] are shown in Table 1.

Table 1. Percentage Stopping

Minor/Major Volume Ratio	% Major Stopping	
	minor present	minor absent
0.05	0.2	0.1
0.1	0.68	0.34
0.15	2.31	1.16
0.2	7.39	3.7
0.25	19.89	9.95
0.3	38.59	19.3
0.35	52.82	26.41
0.4	59.06	29.53
0.45	61.13	30.56
0.5	61.75	30.87

The implementation of this probabilistic behavior by the driver is achieved through runtime modifications of the vehicle type and interaction with network elements such as the minor road detector.

The type changer algorithm is implemented as follows:

1. Vehicles on the major road are generated as Type 4 (general type not tied to any priority rules).
2. When a vehicle on the major road reaches a certain position on the network link (near the intersection stop line) :
    a. A uniform random-number generator gives a value between 0 and 100
    b. Detectors calls on the minor road are checked (1 if vehicle present, or 0 if absent).

3. By combining the ratio of the simulation input volumes with the detection call on the minor road, a row and a column of Table 1 are selected giving a stopping percentage value.
4. The value from the table and the random number generated in step 2 are then compared:
    a. If the random number is greater or equal than the table value, the car type of the major is changed from Type 4 to Type 1, and the car will not stop.
    b. Otherwise the car becomes a Type 2 and will come to a halt at the stop line.

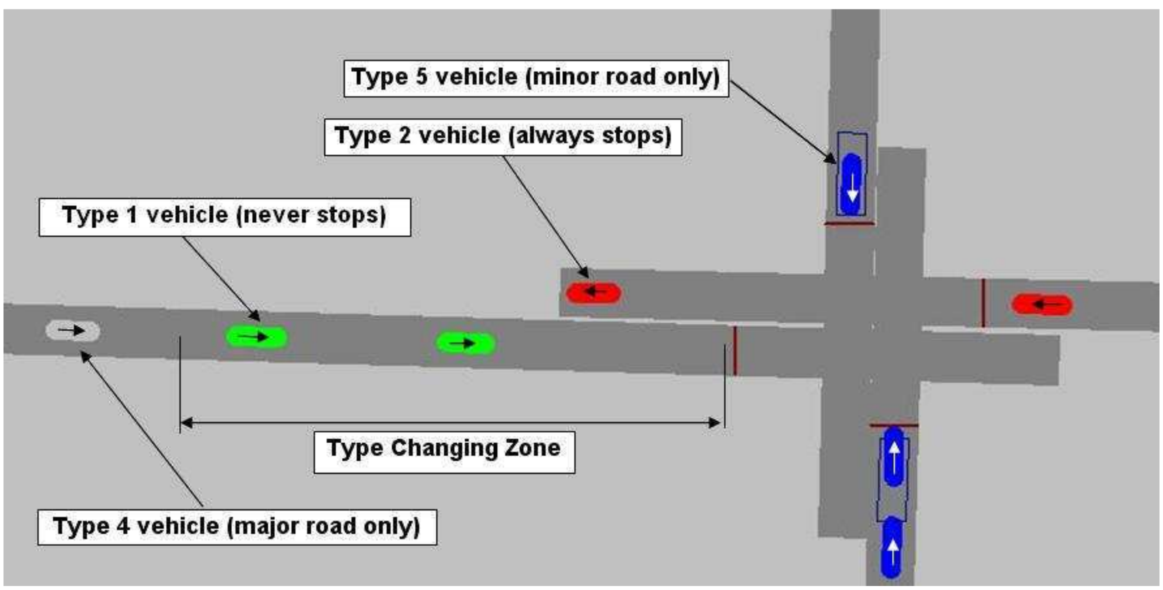

Figure 10. Type changer elements for the *Actual Y/R* scenario

For example, Figure 10 shows a snapshot of an *Actual Y/R* simulation run with all the elements mentioned in the algorithm explanation. The Type 5 (blue) vehicles are on the minor road only and will always stop and wait for an acceptable gap before crossing.

On the major road all vehicles are initially generated as Type 4, once they reach the type changing zone they become either Type 1 (green) or type 2 (red); the former does not stop at the red stop line, while the latter stops and goes if there is no risk of collision with minor road cars.

In this study, the type changing zone ranges from the stop line to 40 meters (130 ft) upstream from the stop line. The zone length was determined to allow sufficient time for a Type 2 car to a come to a full stop. That is, if a Type 4 vehicle is reassigned as a Type 2 vehicle too close to the intersection, it may not have sufficient stopping distance and it would thus drive through the intersection without stopping, regardless of the vehicle type. It is possible that the type changing algorithm might change more than one Type 4 car on the major road for a given car on the minor, but several rounds of model verification showed that the percentage of vehicles stopping (Type 2) was consistent with the values in Table 1. This verification task was achieved by checking the percentage of each vehicle type departing each approach.

3.4 Microsimulation Validation

According to the NCHRP report: "Model validation is the testing of a calibrated model using empirical data that were not used to initially calibrate the model" [8]. For this effort the primary performance metrics of interest are delays and queues. However, the research team involved in this study was not able to directly measure delays at any of the malfunctioning intersections. Thus, to achieve at least a minimal validation and confidence in the model results, delay data was collected at an All-Way-Stop-Control (AWSC) intersection for comparison with the simulated *R/R Scenario*, which is expected to exhibit similar performance under simple geometry configurations. To accomplish this task a new VISSIM intersection was created using the general criteria implemented in the previous sections. The AWSC site traffic volumes were used as inputs into the simulation model, while the field measured queue and delay data were compared to the simulation results.

3.4.1 Site Selection

The data collection site is located approximately 20 miles south-east of Atlanta (GA), at the intersection of SR 155 and SR 138. This intersection is ideal for delay data collection because during peak-hours the vehicle demand is constant on at least three of the four approaches. In the same area there were two more candidate AWSC intersections, specifically the intersection of SR 155 and East Fairview Road, and the one between SR 138 and Union Church Road. The SR 155/SR 138 intersection was selected because it had the same basic geometric configuration of the VISSIM network presented in this paper: 4 legs with one lane for each approach. The other two intersections are good candidates for future study as they both have either left or right turn pockets, and they both have high traffic demand during peak hours.

Because of the rural location of the intersection, there are numerous options for camera and observer positioning, with a clear view of all four approaches (as shown in Figure 11). These features are almost impossible to find in a building-clustered urban environment. This intersection also had a volume nearing or exceeding signal warrants, allowing an analysis under near capacity flow conditions. Moreover, there was no pedestrian crossing activity in the area, which would have further complicated the operational characteristic contributing to vehicle delay.

Figure 11. View of the data collection site.

3.4.2 Data Collection Methodology

After two site visits, recording of some preliminary footage of the intersection from different camera angles, and observation of overall intersection operations, field data collection was performed on June 15, 2007 from 7:17 am till 9:17 am.

3.4.2.1 Equipment and Observer Positioning

Two video cameras and four Jamar boards were used during the study. Figure 12 shows an aerial view of the location and the placement of the cameras (location 1 and 2) and of the hand-held data recording devices (station 1 through 4).

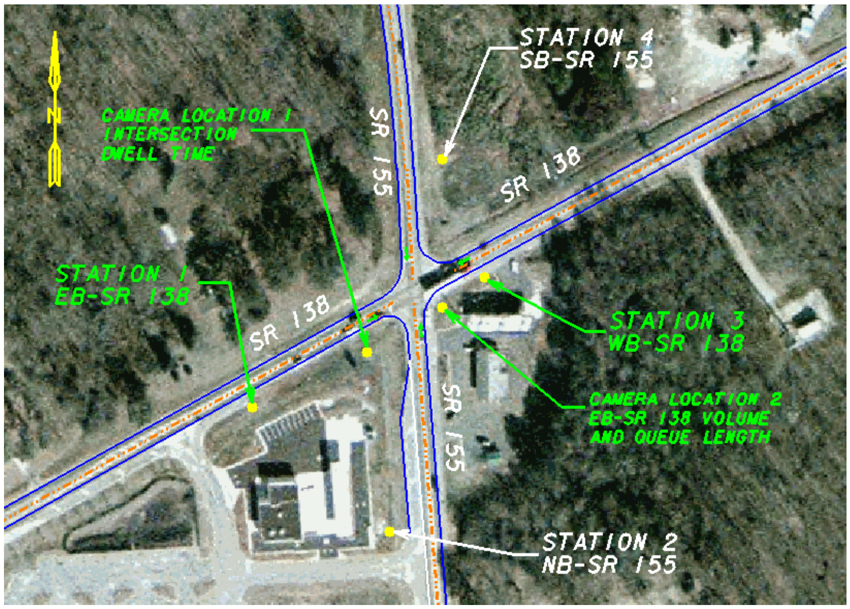

Figure 12. Aerial view plus Cameras and Jamar Boards location

The data collection was performed during morning rush hour, thus the traffic volume was high for the NB and WB, medium-high for the EB, and low for the SB approach. Stations 2 and 3 had each two people assigned, while one person was at station 4. The one person assigned to station 1 also had the support of camera #1 as a backup in case the volume was too difficult to record. Camera #1 was located on an elevated position in order to have a view of all four intersection approaches. Another person was required to control the correct functioning of the cameras during the study. Therefore, the total number of individuals required to accomplish the data collection task was seven. Safety was the primary goal for the delay data collection, thus all analysts wore bright safety vests while in close proximity of the roadway. Once everyone was positioned, the vests were removed in order to not influence the performance of the drivers. Thanks to cell phones and their ability to make conference calls, the delay data collection for all stations began simultaneously; while the video collection was started 7 minutes earlier.

3.4.2.2 Data Collection Procedure

The recording of camera one was used to record vehicle volumes and dwell times for later reduction in the lab. The Jamar Boards were used to gather control delay and queue length in real time. The latter task was accomplished by using the *Stop Sign Delay* mode of the Jamar boards. The methodology is simple: one button on the board was depressed when a car joined the back of the queue, while another button was depressed when the vehicle in front of the queue departed from the stop bar. At the beginning of the data collection the join-the-queue button was depressed as many times as the number of vehicles queued on the observed approach in order to populate the queue reading on the Jamar boards. Based on this data, vehicle arrival and departure curves may be developed, and delay readily derived.

3.4.3 Data Reduction

The data from the videos was reduced by means of the Excel spreadsheet created by Bansen [1]. Unfortunately, due to tape length limitation, the videos had only one and a half hour's worth of data; while the Jamar recording was performed for 2 hours. However, the peak hour was determined to be during the beginning of the taping, thus allowing a crosscheck of the Jamar Board data. The records from the boards were downloaded using the PETRA software. Table 2 on the following page presents the volumes during the peak hour.

Table 2. Peak Hour Volumes

TIME INTERVAL	NB VOLUME	SB VOLUME	EB VOLUME	WB VOLUME	INTERSECTION VOLUME
7:17 - 7:32 AM	105	41	89	90	325
7:32 - 7:47 AM	101	56	87	96	340
7:47 - 8:02 AM	106	45	75	109	335
8:02 - 8:17 AM	90	42	55	86	273
Approach Volume	402	184	306	381	Σ = 1273

The peak hour factor for the intersection was then calculated:

$$PHF = \frac{1273}{4 \times 340} = \frac{1273}{1360} = 0.94$$

This result further proved the high demand experienced by the intersection. The PHF for the single approaches was also calculated and used for the HCS forecast (Table 3)

Table 3. Approaches' PHF

NB	SB	EB	WB
0.95	0.82	0.86	0.87

Figure 13 on the following page shows the output of the video reduction. The average dwell times proved to be consistent with the simulation results and NCHRP findings [8], varying between 4.2 and 6 seconds. Moreover, it is noticeable that the through movement average dwell time is nearly the same, with the largest deviation being only 0.4 seconds, with respect to the overall average dwell time. In general the results show that, with exclusion of the southbound movement, the left turning movement vehicles have higher service time than the through movements, but the right turning movement has the lowest of all.

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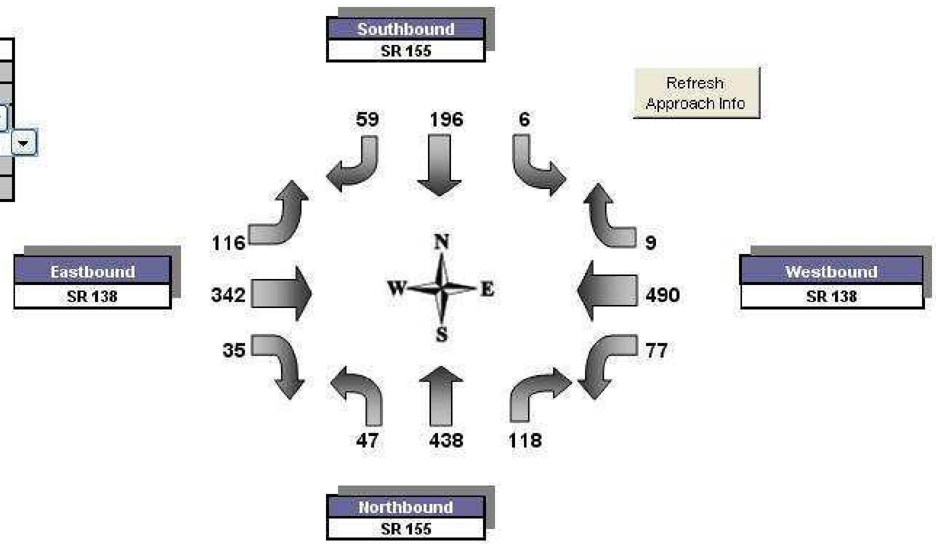
Atlanta, GA 30332

INTERSECTION	**SR 155 and SR 138**
STATUS	**AWSC**
FLASH MODE	**no**

INPUT DATA COLLECTION INFORMATION	
INTERSECTION	Northside and Peachtree Battle
CITY/COUNTY	Atlanta/Fulton
DATE	June 15 2007
DAY	Friday
START TIME	7:10 AM
END TIME	8:40 AM
LIGHT CONDITIONS	Sunrise
WEATHER	Clear

KEY STATISTICS	
Major Volume for Duration of Video	864
Minor Volume for Duration of Video	1069



	155 NB			155 SB			138 EB			138 WB			Total of Entering Vehicles		
	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT
Total # of Stops	47	438	118	6	196	59	116	342	35	77	490	9	246	1466	221
Average Stop Time	00:07.2	00:05.4	00:03.9	00:05.8	00:06.4	00:05.0	00:05.1	00:04.4	00:04.1	00:04.8	00:04.1	00:03.3	00:05.4	00:04.8	00:04.2
	00:05.2			00:06.0			00:04.5			00:04.2			00:04.8		
Max Stop Time	00:18.0	00:15.0	00:09.0	00:09.0	00:21.0	00:11.0	00:20.0	00:17.0	00:07.0	00:14.0	00:12.0	00:09.0	00:20.0	00:21.0	00:11.0
Total Volume (all data)	603			261			493			576			1933		

Figure 13. Video reduction results

3.4.4 Data Comparison

The final step of the validation process was to compare the queue and delay data collected to the results produced by the VISSIM intersection created using the design criteria discussed previously in this chapter. The geometry of the validation network was based on the real world intersection. Table 4 presents the delays in seconds and the number of vehicles present in the queues. HCS analysis results are also included in the comparisons.

Table 4. Data Comparison

	APPROACH	NB	SB	EB	WB
JAMAR	AVG DELAY	88.2	10.5	18.78	49.9
	AVG QUEUE	9.8	0.5	1.6	5.3
	MAX QUEUE	30	4	8	16
HCS	AVG DELAY	59.5	22.7	40.5	76.2
	95th QUEUE	11.4	3.5	8.1	13
VISSIM	AVG DELAY	82.5	14.5	24.9	58.0
	AVG QUEUE	16.9	0.7	2.8	10.0
	MAX QUEUE	50	10	20	38

The PETRA software was able to determine the queue and delay data readily. The analyst had only to highlight the records during the selected time period and all the values were automatically computed. Based on the output of the HCS software, the 95th-percentile queue was calculated using Equation 17-37 of the HCM [12].

The delay data computed by VISSIM proved to be similar to that obtained from the field. With exception of the northbound approach, the VISSIM delays are all slightly higher than the field data, which is as expected since VISSIM also includes delay due to car following. The results for the northbound approach (in particular the much larger simulated queue) may be a result of vehicle behavior during the data collection, where instances of vehicles cutting through a corner parking lot occurred. Many cars coming from south and heading eastbound took a shortcut through the gas station located on the southeast corner of the intersection. This action was disrupting the methodology used to collect the data: the observers could not predict this erratic behavior and registered the vehicle entering the queue, but were not able to record the discharge of the vehicle from the queue. An attempt was made to balance the queue recording by not recording the next vehicle that joined the queue after the cut through vehicle pull out of the queue. Figure 14 shows the location of the gas station and the path taken by the cut through vehicle.

Figure 14. Cut through vehicle path

3.5 Simulation Scenarios

After setting the basic VISSIM intersection characteristics, creating the multirun and type-changing algorithm, and validating the model, four different scenarios were simulated. Every scenario was tested with major road volumes varying from 100 up to 1000 veh/hr/ln, in increments of 100 veh/hr/ln. Ultimately, only the *Ideal Y/R* and *Signalized* scenarios (both VISSIM and HCS) were performed with major road volumes up to 1000 veh/hr/ln, all the other scenarios were conducted until 700 veh/hr/ln because the queues generated were exceeding the link length at that volume level, limiting the demand that could actually be processed, and causing erroneous delay estimations.

In all simulation runs the car type on the minor road was Type 5; the major road had several vehicle types, according to the simulated scenario.

Based on Tian, et. al. [9], as long as the traffic demand is under-capacity, 2 or 5 replicate runs are sufficient to obtain an accurate measure of effectiveness parameters. This rule-of-thumb is true especially with long simulation time (i.e. more than 15 minutes) [9]. For the simulations performed in this paper, each volume condition was repeated 5 times, each time with a different random seed. This means that a typical study set consists of 5 random seeds, 10 ratios, and at least 7 volume changes, for a grand total of 350 simulation runs.

3.5.1 Red/Red

For the R/R case the car-type changing algorithm was not used. Instead the traffic composition was set such that 100% of the cars generated on the major road were Type 2 (red color, always stop). Reduced speed zones and signal heads were also deleted from the model. Figure 15 shows a snapshot of a typical Red/Red simulation run.

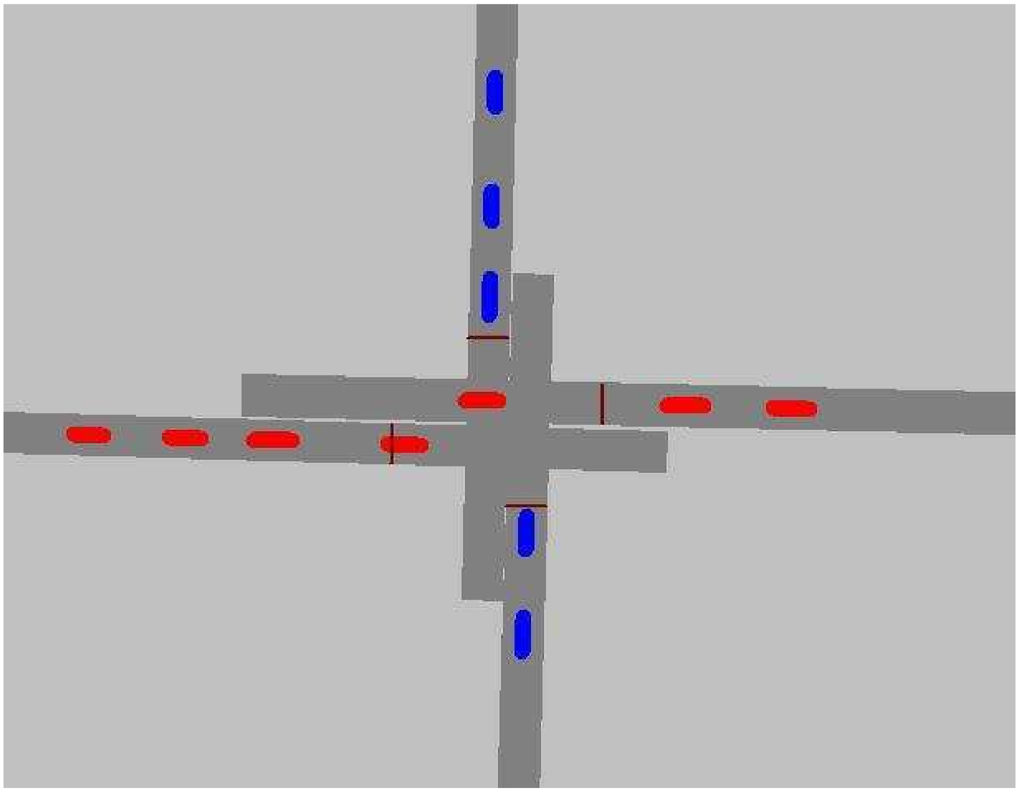


Figure 15. Red/Red simulation snapshot

The Red/Red scenario was simulated with major volume up to 700 veh/hr/ln. At this value and beyond, the queue on the main road exceeded the link length (which has length equal to 800 meters - half mile), thus making all subsequent volume increase useless. This scenario required the second highest processing time.

3.5.2 Yellow/Red Actual

By using the car-type changing algorithm, this scenario proved to be the most computationally demanding. A complete set of all 350 runs on average required approximately 24 hrs. From Figure 16 it is notable that this scenario uses all the available car types (excluding type 3), detectors and reduced speed zones.

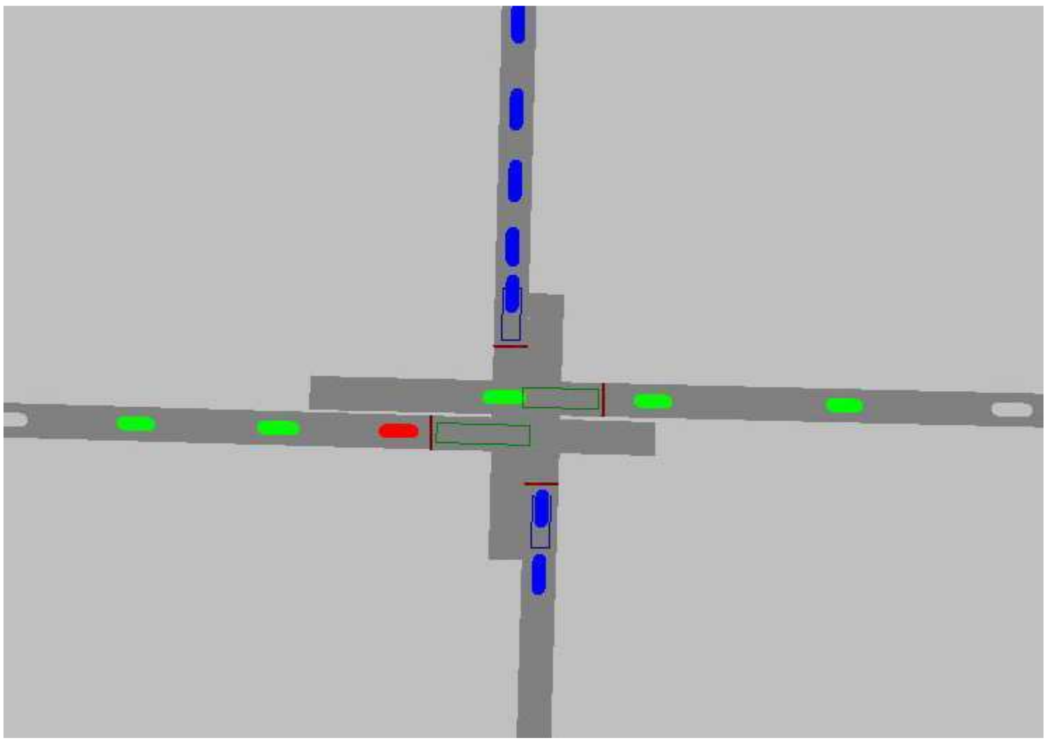


Figure 16. Yellow/Red Actual simulation snapshot

3.5.3 Yellow/Red Ideal

Similar to the *R/R* scenario, the *Ideal Y/R* was simulated by just changing the traffic composition on the major road such that 100% of the vehicles generated are Type 1 (green color, never stop). Even though vehicles do not stop, there is still some minimal delay value due to the car-following behavior. While the major road never experiences any queue, even with vehicles volume at the maximum simulated (approximately 1,000 veh/hr/ln), the performance of the minor street degrades with increasing volume due to the lack of acceptable crossing gaps. When the volume on the minor road exceeds 350 veh/hr/ln the queue exceeds the link length. Figure 17 shows a snapshot of a typical run.

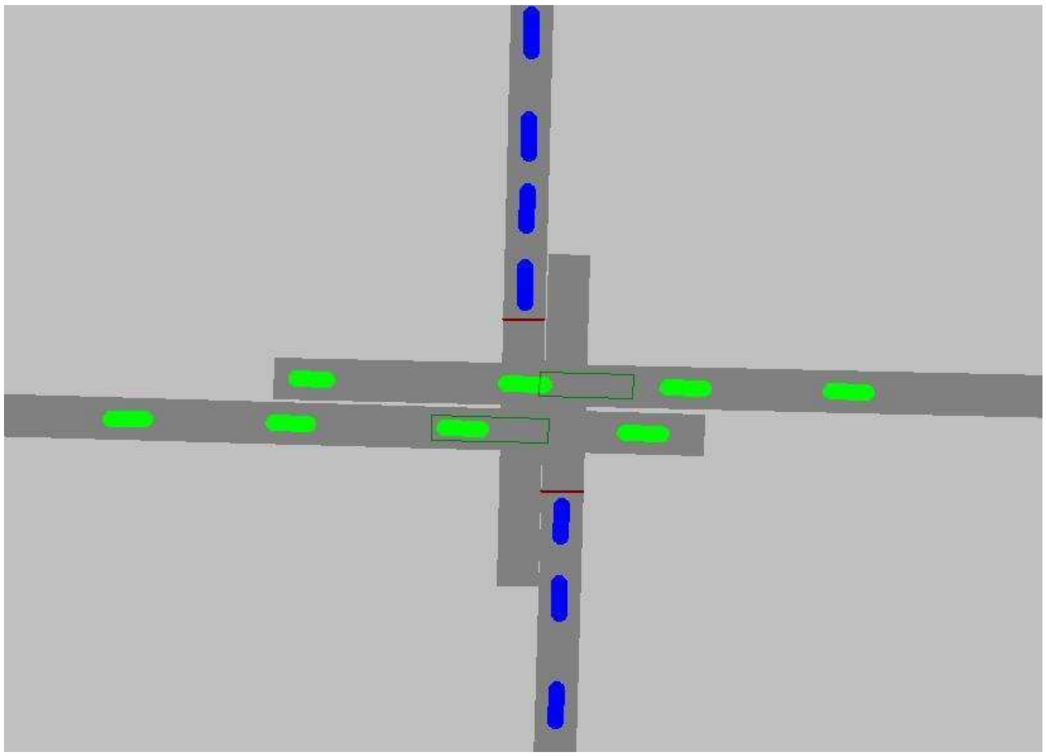


Figure 17. Yellow/Red Ideal simulation snapshot

3.5.4 Signalized

A fixed time signal phasing with a 60-second cycle length, 3-second yellow clearance, 2-second all-red and 30/20 green splits was used for the signalized scenario. The car-type changing algorithm was removed from the VBCOM code and the traffic composition of the main road consisted of 100% Type 5 cars. As shown in Figure 18 all the priority rules, stop bars and reduced speed zones were removed, and signal heads placed for traffic control.

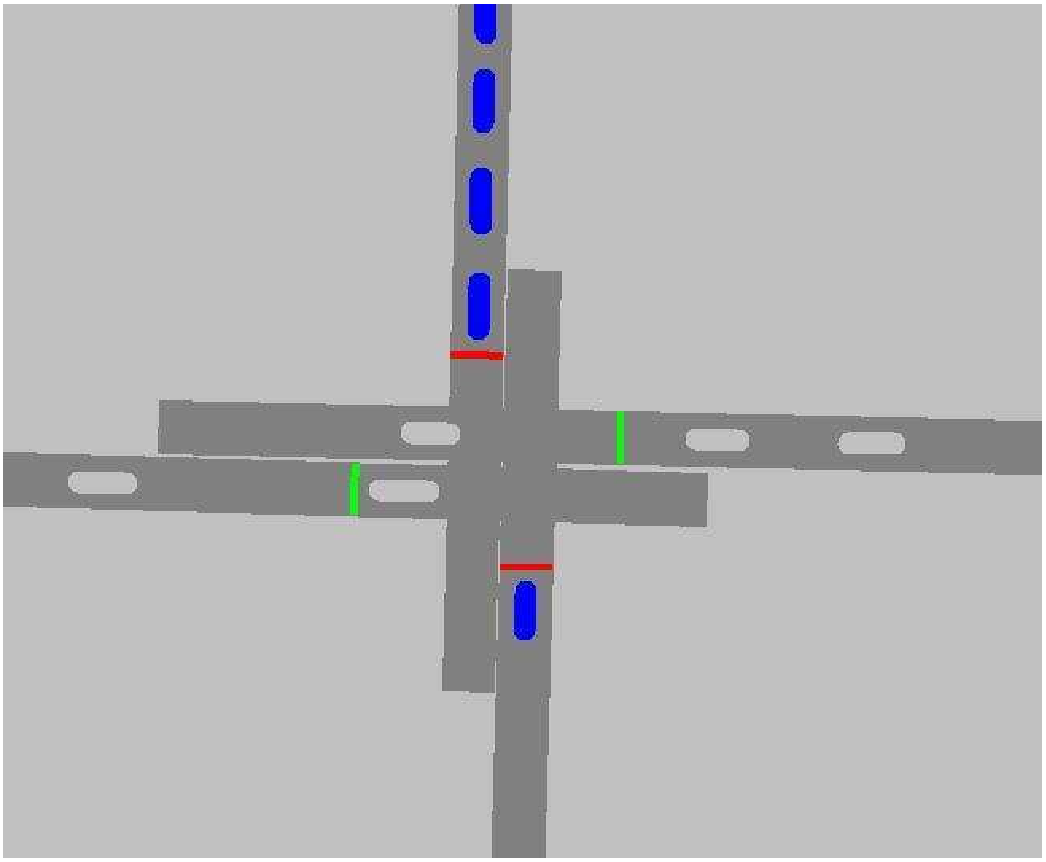


Figure 18. Signalized simulation snapshot

CHAPTER 4

RESULTS AND ANALYSIS

This chapter summarizes the findings from the simulation experiments. The delay data produced by VISSIM was sorted according to two main parameters: total volume on the major road, and minor to major volume ratio. Appendixes A to F present the graphs produced by the simulation runs; average delay per vehicle in seconds (either for minor or major approach) is on the y-axis, while the x-axis has either the major volumes or the volume ratios.

4.1 Comparison Based on Minor/Major Volume Ratio

This analysis is separated into two primary subsections, one for the major road average delay (Appendixes A and B), and another for minor road average delay (Appendix F). The units for volumes mentioned in the following sections are vehicles per hour per lane.

4.1.1 Major Road Average Delay

Figures A1 to A7 in Appendix A present the major road average delay, with each graph representing a major road volume case for all studied operational scenarios (i.e. R/R, Signalized, Actual Y/R, Y/R Ideal, HCS-AWSC, and HCS-signalized). For example, Figure 19 presents the graph for a major road volume of 300 veh/hr/ln (this is the same as Figure A3 in Appendix A).

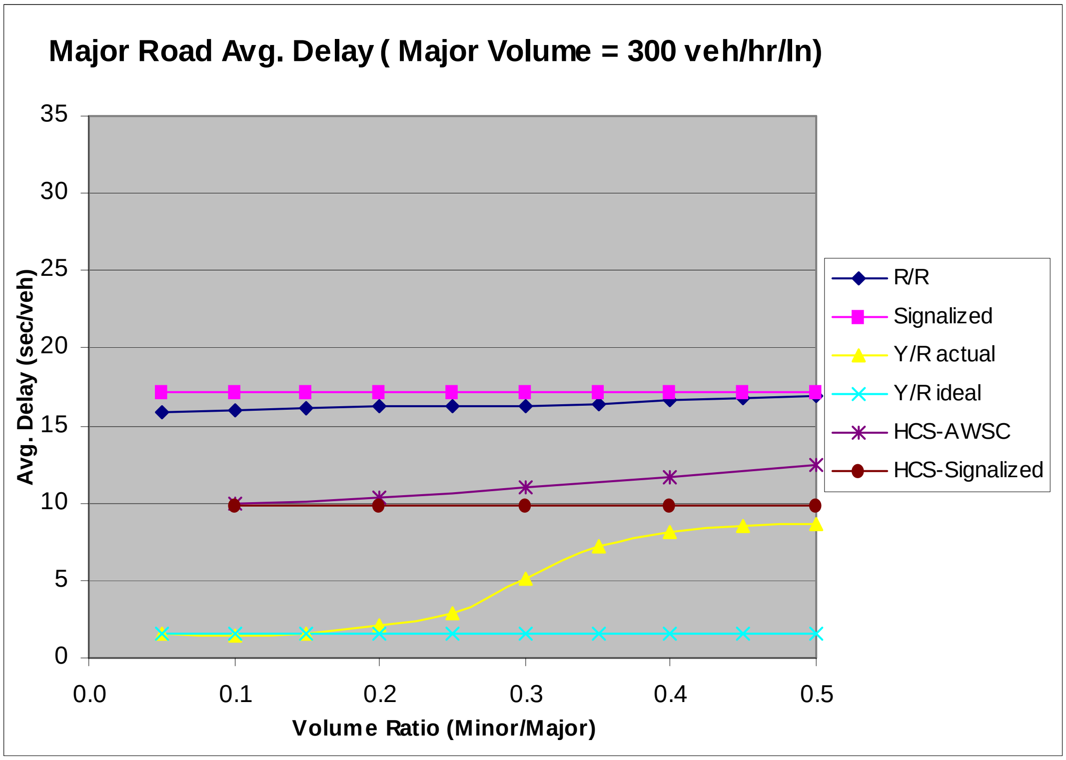


Figure 19. Major road average delay, scenario comparison

The *Ideal Y/R* model, which captures the often assumed performance of Y/R flash mode, proved to be the one producing the least delay on the major road for all major road to minor road volume ratio cases. Even though none of the Type 1 cars stop, there is still some delay as a result of the car-following behavior. Recall from section 3.3.1.2, in these experiments the slowing of the vehicle due to a reduced speed zone is not included in the delay reported by VISSIM. Future efforts will consider the impact of also incorporating this behavior as additional delay. The HCS-TWSC data is not shown as it always yields a value of zero for the major road delay. The R/R scenario produced the highest delay in all cases up to 500 veh/hr/ln; for the 600 veh/hr/ln case it is seen that the HCS-AWSC begins to predict a higher delay at volume ratios exceeding 0.3. The other scenarios showed limited delay differences among them (between 6 and 20 seconds for major volumes up to 400 veh/hr/ln). It is notable that at low volumes the flashing and unsignalized control is predicted to have lower delays than the signalized. Such a result meets expectations, further supporting the model validity. It is first seen in these slides that the R/R flash offers reasonable performance (delay up to 30 sec/veh) for major road volumes up to 400, with high delays (100+ sec/veh) at a major road demand of 500 veh/hr/ln. The *Actual Y/R* scenario performs well (delay consistently under 50sec/veh) with major flow rates up to 500 veh/hr/ln, and does not begin demonstrating high delays until the 600 veh/hr/ln are seen on the major road.

Appendix B presents the results sorted by scenario, with each graph representing a single operational model and containing all tested volume cases for the model. Figures 20 and 21 show VISSIM R/R and HCS-AWSC scenarios respectively.

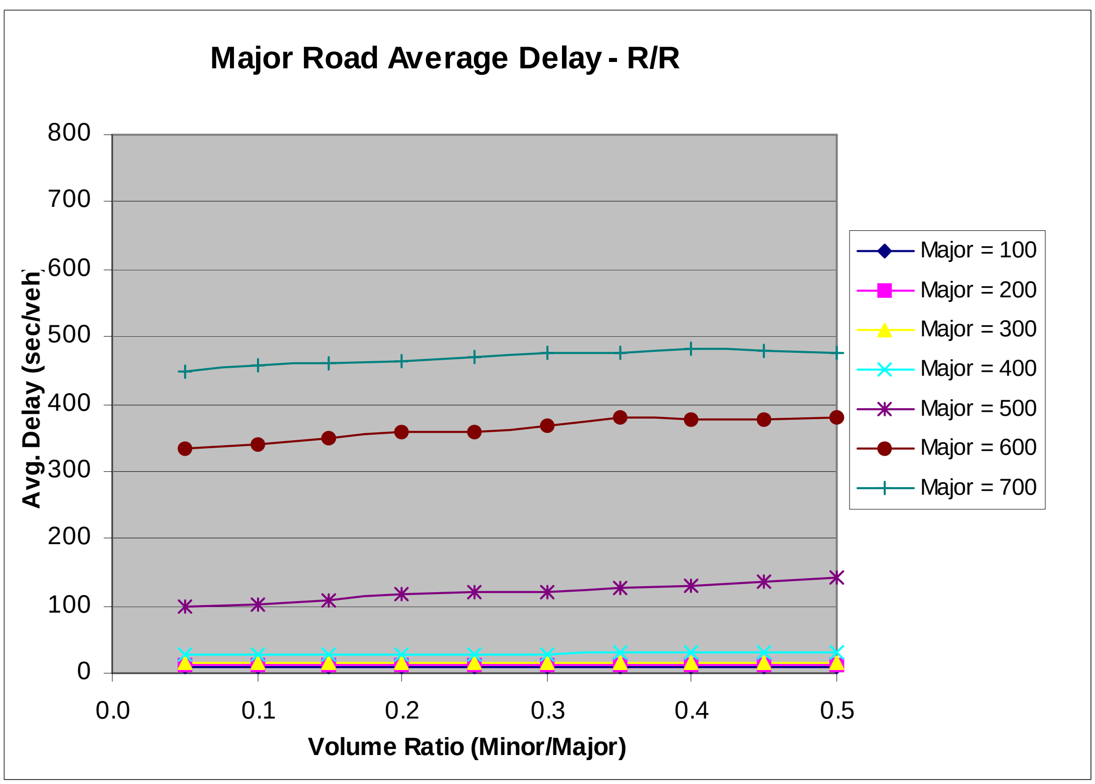


Figure 20. Major road average delay, VISSIM red/red volume comparison

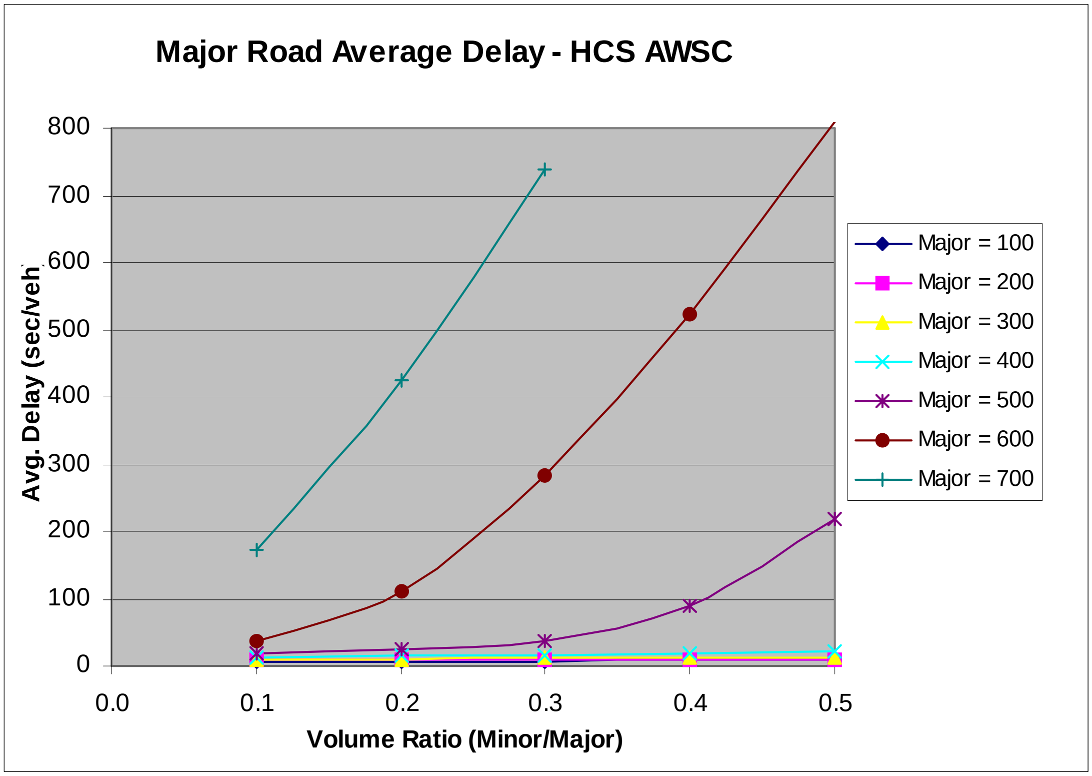


Figure 21. Major road average delay, HCS-AWSC volume comparison

As expected, under low major road volumes (up to 400 veh/hr/ln) the two models produced very similar behavior, again increasing the confidence in the VISSIM results. However, at high volumes the HCS-AWSC delay showed an exponential behavior that is not matched by the VISSIM model. A potential reason VISSIM does not capture this exponential behavior is that beyond an input of 500 veh/hr/ln, the queue generated occupies the entire length of the simulation link (800 meters - half mile), thus blocking the entrance of new vehicles. In this experiment VISSIM is set to calculate delay based on the travel time of vehicles that travel the link length, thus vehicles still queued on the link or that never succeeded in entering the model are not taken into account in the delay calculation. Moreover, at large input volumes (such as 600 and 700 veh/hr/ln) the delays shown in Figure 20 are constant but higher than the delay of lower volumes. The reason is that the intersection is experiencing spillback over the link sooner, thus a greater percentage of the processed vehicles experience the maximum possible delay. This result is one consequence of the simulation not utilizing a warm-up period and not allowing a steady state to be reached. Figures B3 and B4 illustrate the comparison of the signalized scenario for VISSIM and HCS; with major volumes from 100 to 400 the delay estimates are similar in both models, after that the HCS yields significantly greater delays than VISSIM, a behavior similar to the R/R vs. HCS-AWSC scenarios. Figure B5 shows the delay for the *Actual Y/R*; the delays increase with increasing major road volumes and minor to major road volume ratios. This outcome matches expectations based on observations during the field data collection for the Jenior study [2]. This outcome is clearly a result of the increasing percentage of vehicles stopping on the major road, as modeled by Jenior [2]. It is also interesting to not that the major road average delay starts experience exponential growth in delays with major volumes larger than 500 and ratios greater than 0.3. *Ideal Y/R* delay results, shown in Figure B6, do not lead to any major insight. As previously stated, none of the vehicles on the major stop, and minimal non-control delay is produced by the car-following behavior.

4.1.2 Minor Road Average Delay

Figures E1 to E6 present the operational scenario comparisons for minor road average delay. For major road volumes ranging from 100 to 300 veh/hr/ln the average delay differential between scenarios may be considered quite minimal: with a maximum delay variation of 10 seconds. HCS-AWSC predicted the lowest delay, while the signalized scenarios (both VISSIM and HCS) produced the highest delay. However, with major road volumes greater than 500 veh/hr/ln, the HCS-TWSC and the VISSIM *Ideal Y/R* begin to show dramatic increase in delay. The explanation for this result is that at the higher volume levels, when vehicles on the major road do not yield, the vehicles on the minor road are unable to find acceptable gaps to cross the intersection, thus maxing out the queues and sky-rocketing the delay values.

4.2 Comparison Based on Major Road Volume

Again the analysis is separated in two subsections for minor and major road average delay respectively.

4.2.1 Major Road Average Delay

Appendix C clearly shows how for several scenarios, as demand on the major road increases, the intersection capacity is exceeded, resulting in exponential delays. But there are several peculiarities to notice. First the VISSIM R/R scenario critical point occurs when the major volume is equal to 400 veh/hr/ln, independent of the volume ratios. This is partly due to the AWSC two-phase operation pattern performed by the vehicles in the simulation. When vehicles on two opposing movements clear the intersection, the cars on the two conflicting approaches move up to the stop bar; and this pattern is repeated between major and minor road. This result might suggest that in absence of left turning movements (from either opposing or conflicting approach), the major road has a predictable behavior which is independent from the volume on the minor street. On the other hand, the HCS-AWSC scenario critical point (i.e. exponential break point on the graph) is somewhat influenced by the volume ratio, with the critical point ranging from approximately 600 veh/hr/ln to 400 veh/hr/ln on the major road for minor to major road volume ratios ranging 0.1 to 0.5, respectively. Moreover, as seen in figures C1 to C5, as the minor to major volume ratio increases the HCS-AWSC and VISSIM R/R delay curves demonstrate increasing similar results, until they are approximately the same. The *Actual Y/R* has relatively low delays until the volume ratio is greater or equal 0.3, then it shows the exponential behavior, typical at a volume 100 veh/hr/ln to 200 veh/hr/ln greater that the critical point of the R/R scenario.

This last result is the focal point of this research paper: as long as the flow rates are not too high and the minor to major volume ratio is less than 0.3, the average delay experienced by a vehicle on the major road is relatively low under Y/R signal malfunction. But the simulation data proved that when the flow rate of the minor street becomes increasingly significant (minor to major ratio greater than 0.4) the performance of an intersection flashing yellow/red is similar to a red/red one. The only difference is the value of the critical volume that causes average delay to assume exponential behavior. With minor to major ratio equal to 0.5 this difference is approximately 100 veh/hr/ln, as shown in Figure 22. Thus, under many different potential volume demand cases, the actual operational advantages of Y/R flash with respect to R/R flash are potentially minimal**.**

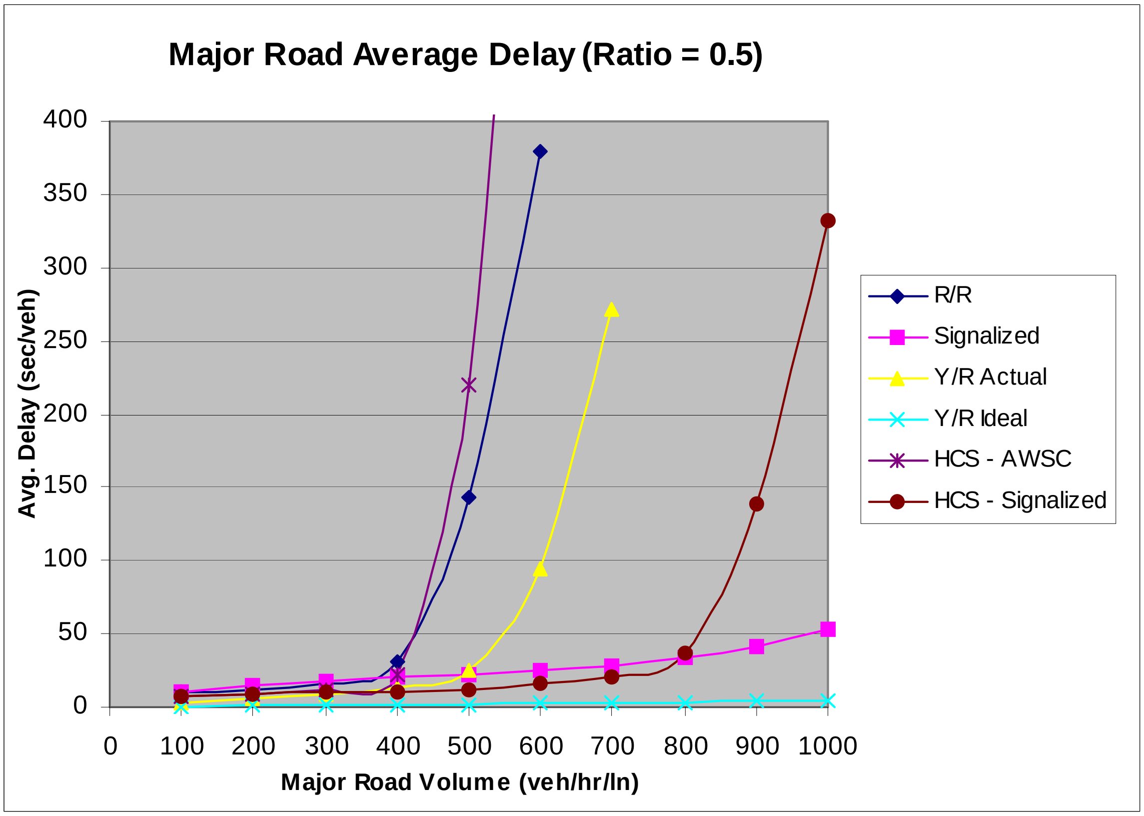


Figure 22. Major road average delay, scenario comparison

Lastly the delay in the VISSIM's signalized scenario never becomes exponential, while HCS does show with major road flow rates greater than 800 veh/hr/ln exceeding intersection capacity; this result can be seen in Appendix C.

Appendix D reinforces the previous findings. Figure D1 shows the independence of the major road delay with respect to the minor volumes for the VISSIM R/R scenario, while figure D2 shows the influence of minor road volumes on major road delay for the HCS-AWSC case. Figure D4 shows the HCS signalized scenario exponential behavior when the major volumes are greater than 800; where figure D5, the microsimulation signalized scenario, maintains a relative low average delay (55 seconds) when the major road flow rate is equal to 1000 veh/hr/ln. Figure D5 shows clearly that the major average delay for *Actual Y/R* demonstrates exponential behavior at minor to major ratios greater or equal 0.3; likely a result of the percentage of vehicles stopping going from an average of 5% up to 30%, reducing the effective capacity of the intersection.

4.2.2 Minor Road Average Delay

Similarly to the findings in section 4.1.2, Appendix F indicates that in both VISSIM Y/R (Ideal and Actual) and HCS-TWSC the lack of gaps in scenarios with high major volumes cause the average delay for the minor road to assume an exponential curvature. In each ratio case the delay predicted by HCS is greater than that of VISSIM.

The R/R scenario produced the least amount of delay for the minor street, and the HCS forecasts are consistent with the VISSIM model.

4.3 Results Summary

The delay estimated by VISSIM confirmed Bansen [1] and Jenior [2] findings regarding the deterioration of the *Actual Y/R* scenario to the operational performance of an AWSC intersection.

As expected, the *Ideal Y/R* scenario produced the least amount of delay for major road vehicles, while at high volumes and minor to major ratios the same scenario proved to be the worst for the minor road approaches. The equation: best scenario for the minor road equal worst scenario for the major road, holds true for the R/R and HCS-AWSC.

The signalized scenarios show similar behavior until the volume on the major road exceeds 800 veh/hr/ln, , after that the HCS delay shows an exponential behavior that is not matched by VISSIM.

CHAPTER 5

CONCLUSIONS

As seen in the literature review, several studies have been conducted to analyze the performance of an intersection under flashing operations. Two questions were driving most of the research in the area [4]:

1) "Under what circumstances should a traffic signal be put in flashing mode?"
2) "If flashing is used, which mode between yellow/red and red/red is more appropriate?"

As discussed, several major studies sponsored and conducted by federal agencies, professional transportation companies, and academic entities, included numerous surveys, models, guidelines and recommendations. However there were a few weaknesses in these studies. The two main flaws were:

1) Assuming ideal conditions under flashing Yellow/Red, specifically: no vehicles on the major road stop when facing the flashing yellow
2) No performance analysis of a flashing intersection when the demand is near, at, or above capacity

Field data collected by Jenior [2] at more than 30 intersections in malfunction Yellow/Red flash in the Atlanta (GA) area showed that approaches under yellow flash control were experiencing stopping rates varying from zero to over 70%. This research paper explored the operational impacts of this behavior through the development of a microscopic simulation network model that captured realistic driving behavior under low, medium, and high intersection traffic demands.

5.1 Microsimulation Model

The microscopic simulation software VISSIM was used for the modeling process. The first core feature of the simulation was the adoption of a Component Object Model (COM) interface. The COM interface allowed for automation of the simulation runs, and access to driver characteristics during simulation runtime, allowing for the implementation of the observed stopping behavior. The second main feature was the modeling and calibration of stop bar dwell time (4 seconds) through priority rules. The characteristics of the model were: a four leg intersection with one lane on each approach, the length of each approach was 800 meters (1/2 mile), the traffic composition was 100% passenger cars, and only through movements were included. An AWSC intersection nearby Atlanta (GA), with high peak hour traffic demand was used to validate the model presented in this study. Once validated, the model was used to perform scenario comparisons with traffic volumes ranging from 100 up to 1000 veh/hr/ln for the major road. The minor road volume was based on minor to major ratio which ranged from 0.1 up to 0.5. The performance measure adopted was vehicle delay. HCM model predictions were considered during the calibration process and included as part of the delay analysis.

5.2 Findings and Recommendations

As part of the simulation effort four primary scenarios were considered:

a. Red/Red flash in which all vehicles stop at the stop bar.
b. Ideal Yellow/Red Flash in which vehicles on the flashing yellow approach are assumed not to stop.

c. Actual Yellow / Red flash in which vehicles on the flashing Yellow approach are model to stop at the rates determine in Jenior [2].

d. Normal Signalized operations.

For comparative purposes each traffic demand scenario was also analyzed using the HCS AWSC and TWSC modules. Results from the simulation runs showed that at flow rates on the major road below 400 veh/hr/ln, the delay differential among all scenarios is at the most 30 seconds. The result holds true for both major and minor road delay, and under all tested minor to major road volume ratios. With volumes greater or equal 500 veh/hr/ln, and minor to major road volume ratios above 0.3, the Red/Red scenario starts showing exponential behavior in both VISSIM and HCS. The *Actual Y/R* also displays exponential increase in delay at a 0.3 minor to major road ratio when the "critical" major road volume, at which the exponential behavior begins, is 700 veh/hr/ln. As the minor to major road ratio increases to 0.5, the difference between critical volumes of Red/Red and *Actual Y/R* scenarios reduces to approximately 100 veh/hr/ln. While not modeled, it can be inferred that at higher minor to major road volume ratios the differential between the critical volumes for these scenarios will likely tend to decrease. In addition major road volumes under 400 veh/hr/ln may experience exponential increase in delay at higher minor to major road volume ratios.

It is clear from this effort that the common assumption of Yellow/Red malfunction flash having operating characteristics similar to a Two-Way Stop controlled intersection is not entirely correct. Under low volume conditions this assumption may hold true, however as the major street and minor street volumes increase, the intersection operation begins to more closely mirror that of All-Way-Stop-Control. Based on these findings this research effort further supports the recommendations proposed by Bansen and Jenior, which is, adopting the Red/Red malfunction flash mode as the default malfunction mode with limited use of Yellow/Red mode. Based on the findings of this paper the specific conditions under which selecting Yellow/Red flash over Red/Red flash is feasible from an operational perspective would be:

1) The highest approach volume should not exceed 400 veh/hr/ln

AND

2) The minor to major volume ratio should be less or equal 0.3

5.3 Model Limitations and Future Research

This research effort provides a reference to learn the procedures and the caveats for developing a simulated intersection operating in flashing mode. However, every intersection has its own peculiarities and many variables need to be taken into account, such as geometry, time of the day, design driver behavior (i.e. an American driver might behave differently from an European or an Atlanta urban driver might behave differently than someone with primarily rural driving experience). Particular items that should be tested in future efforts include:

- Turning movement implementations
- Variable traffic composition
- Pedestrian activity interaction
- Variable geometric configuration
- Driver characteristics in other regions
- Impacts of weather

The simulation model also requires significant validation efforts. While the model was validated against data from the literature and data collected at a single intersection, an extensive calibration and validation effort should be undertaken. This will likely involve the collection of queuing and delay data at numerous stop-controlled intersections, and if possible, intersections in malfunction flash. As part of this effort a sensitivity analysis should be conducted for various model parameters, such as the priority rules, dwell time, speed distribution, delay definitions etc. Another issue meriting study is the discrepancies between VISSIM and HCS under high major road flow rate and low minor to major volume ratio, with respect to AWSC.

APPENDIX A

MAJOR ROAD AVERAGE DELAY

MINOR/MAJOR VOLUME RATIO ON X-AXIS

SCENARIO COMPARISON

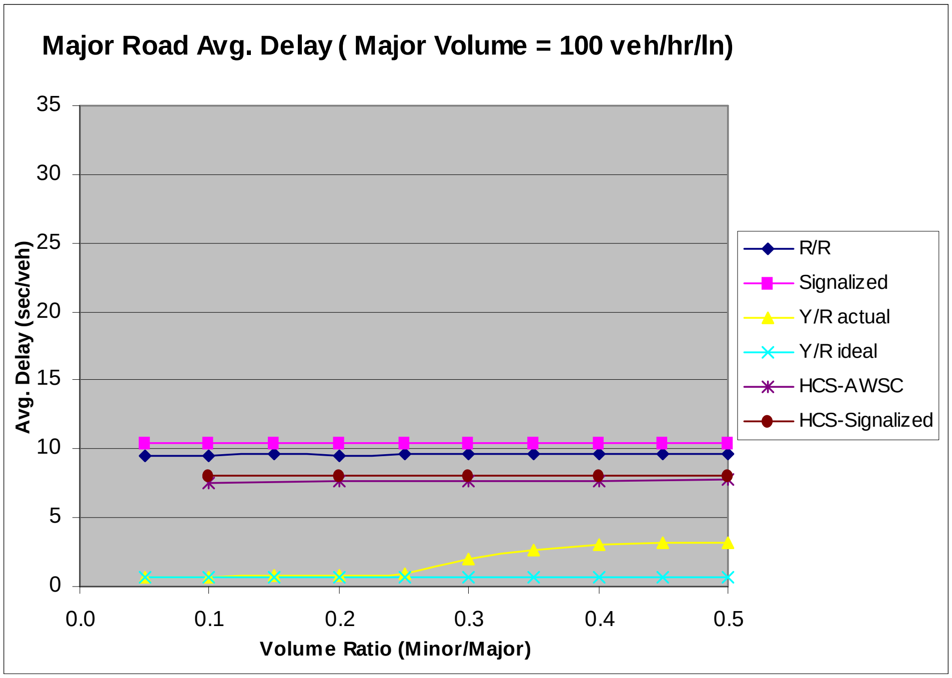


Figure A1. Major road average delay, scenario comparison

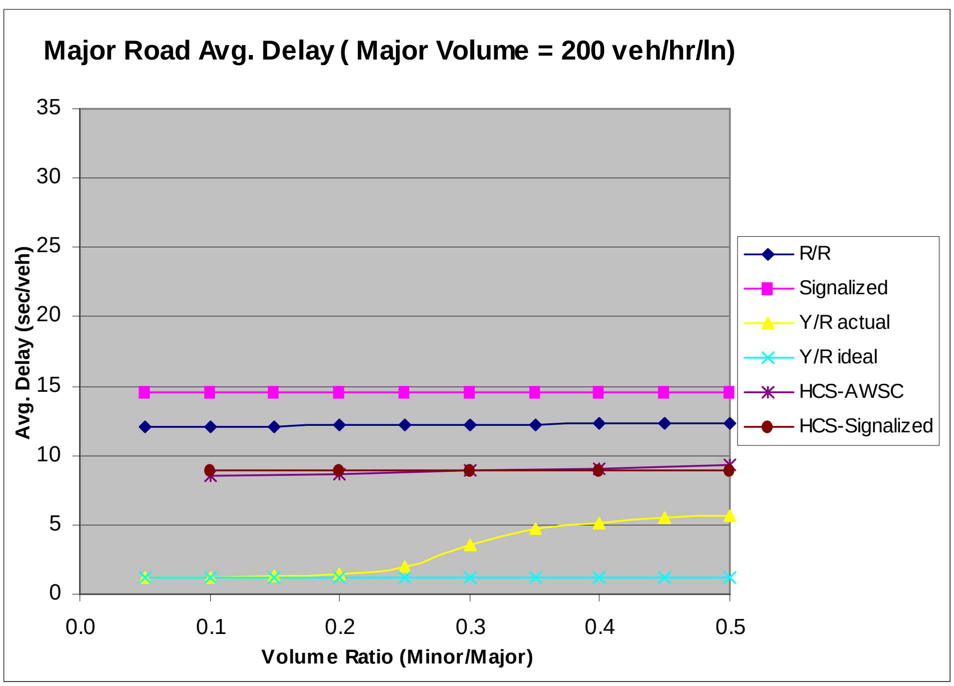


Figure A2. Major road average delay, scenario comparison

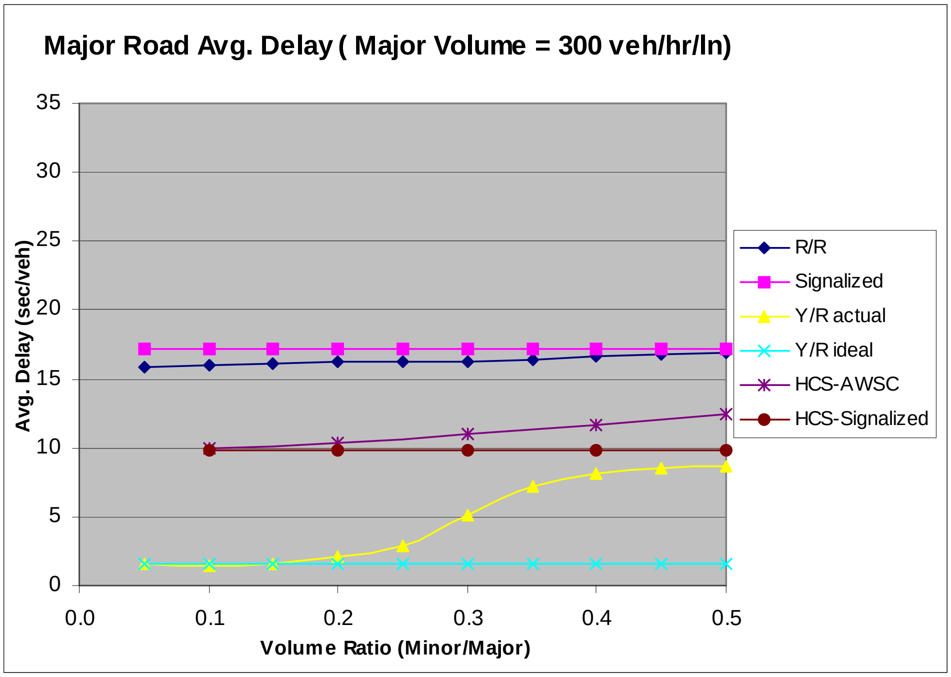


Figure A3. Major road average delay, scenario comparison

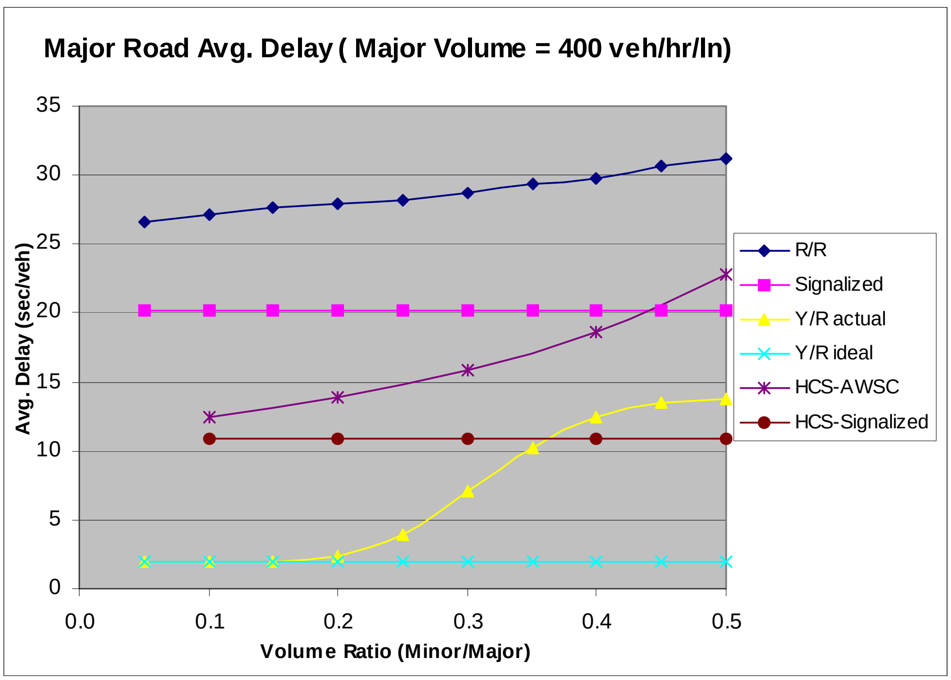


Figure A4. Major road average delay, scenario comparison

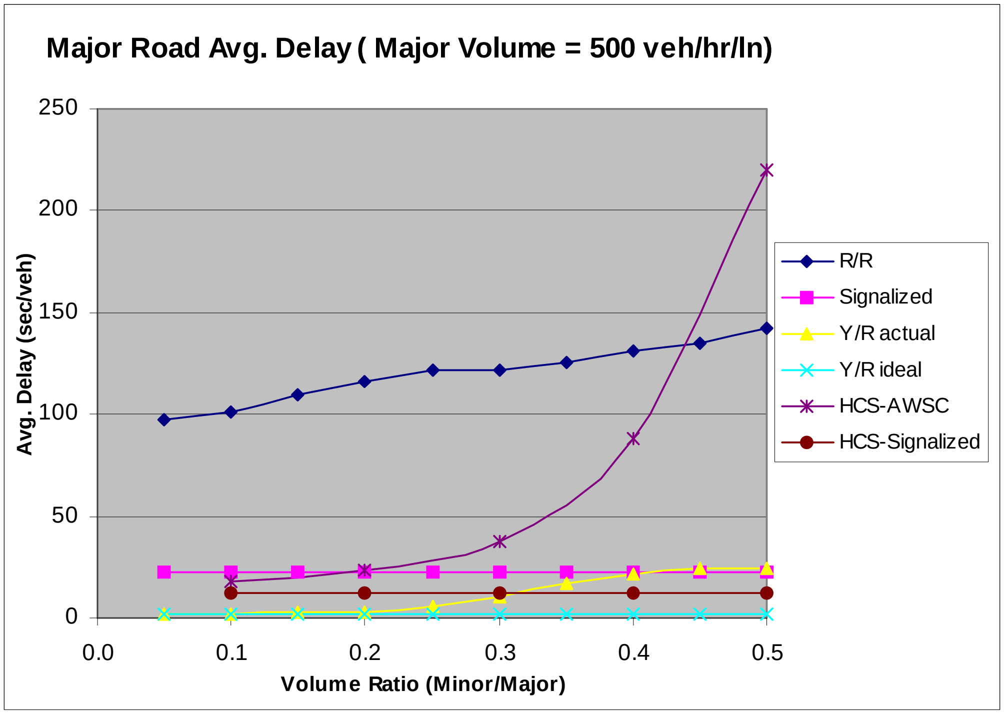


Figure A5. Major road average delay, scenario comparison

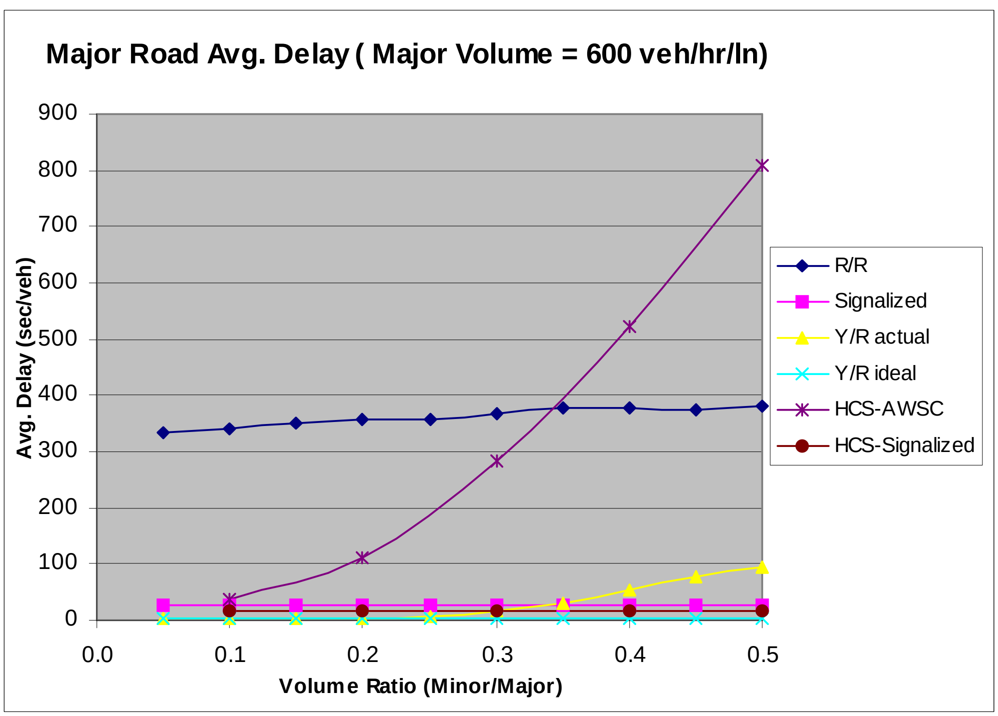


Figure A6. Major road average delay, scenario comparison

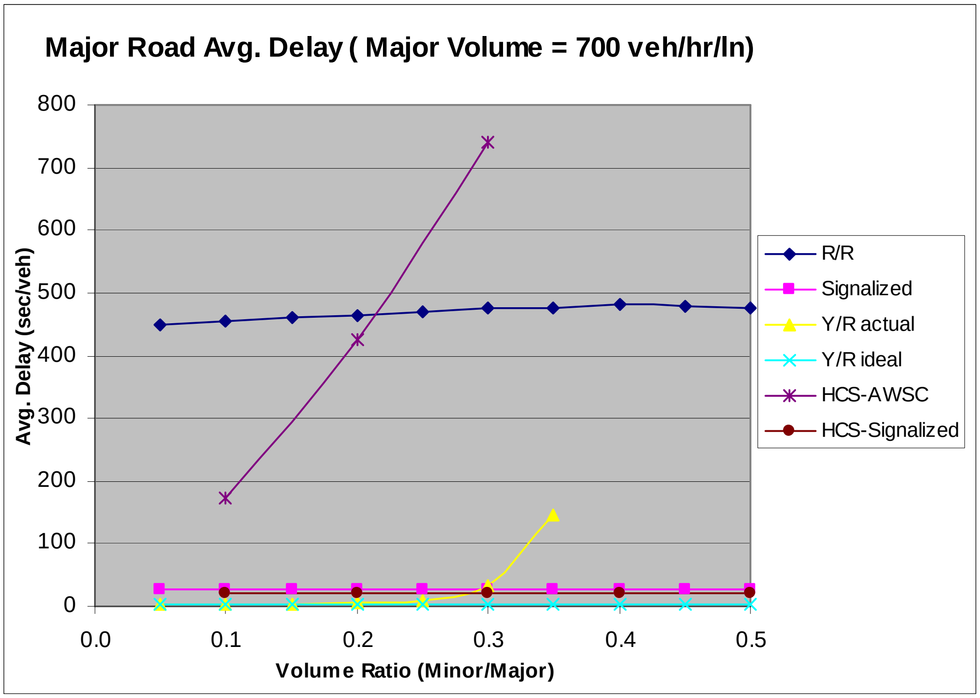


Figure A7. Major road average delay, scenario comparison

APPENDIX B

MAJOR ROAD AVERAGE DELAY

MINOR/MAJOR VOLUME RATIO ON X-AXIS

VOLUME COMPARISON

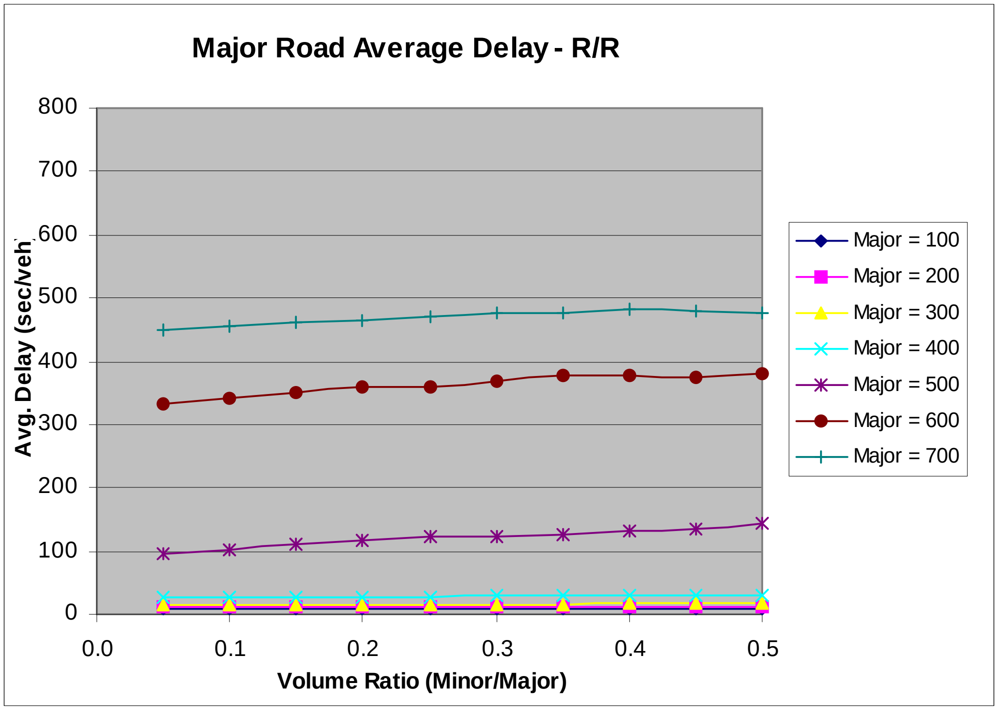


Figure B1. Major road average delay, volume comparison – VISSIM Red/Red

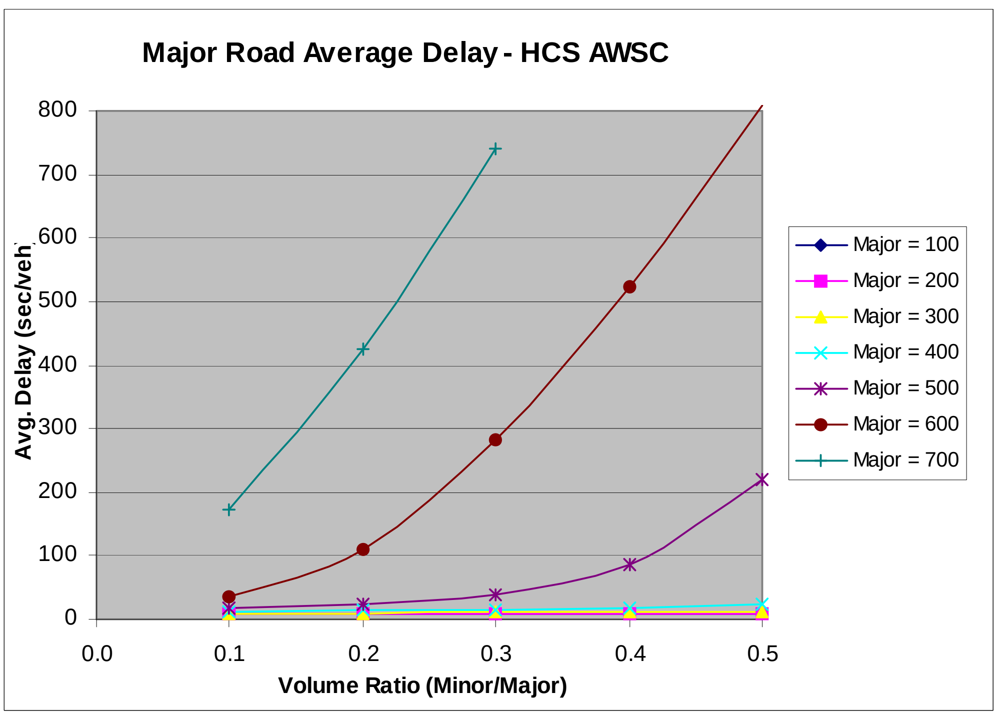


Figure B2. Major road average delay, volume comparison – HCS AWSC

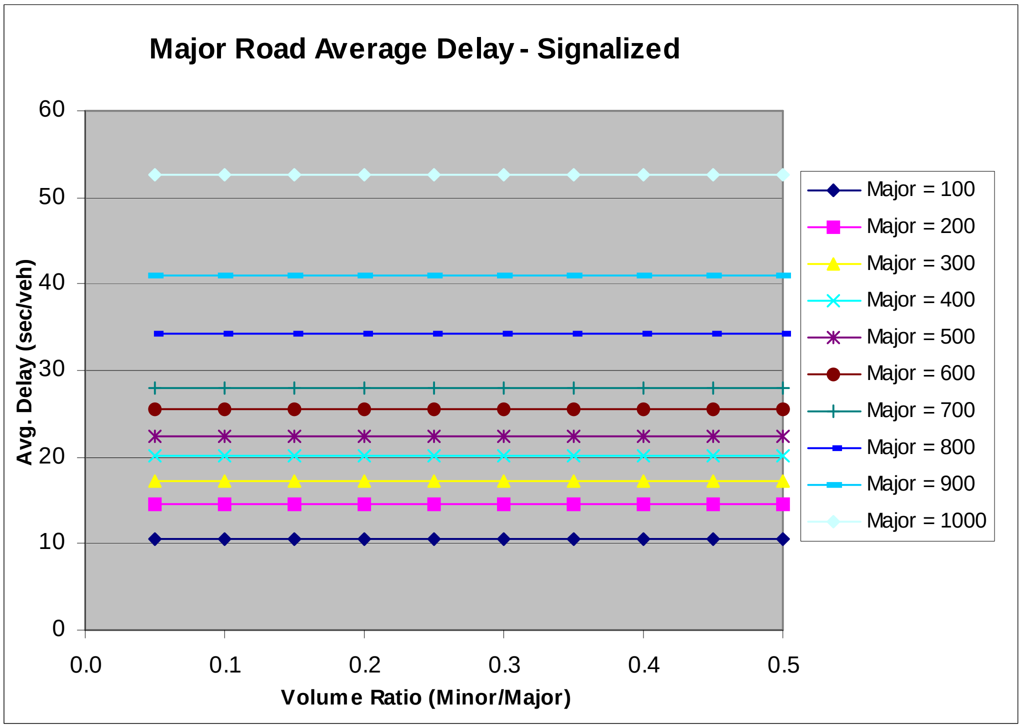


Figure B3. Major road average delay, volume comparison - VISSIM signalized

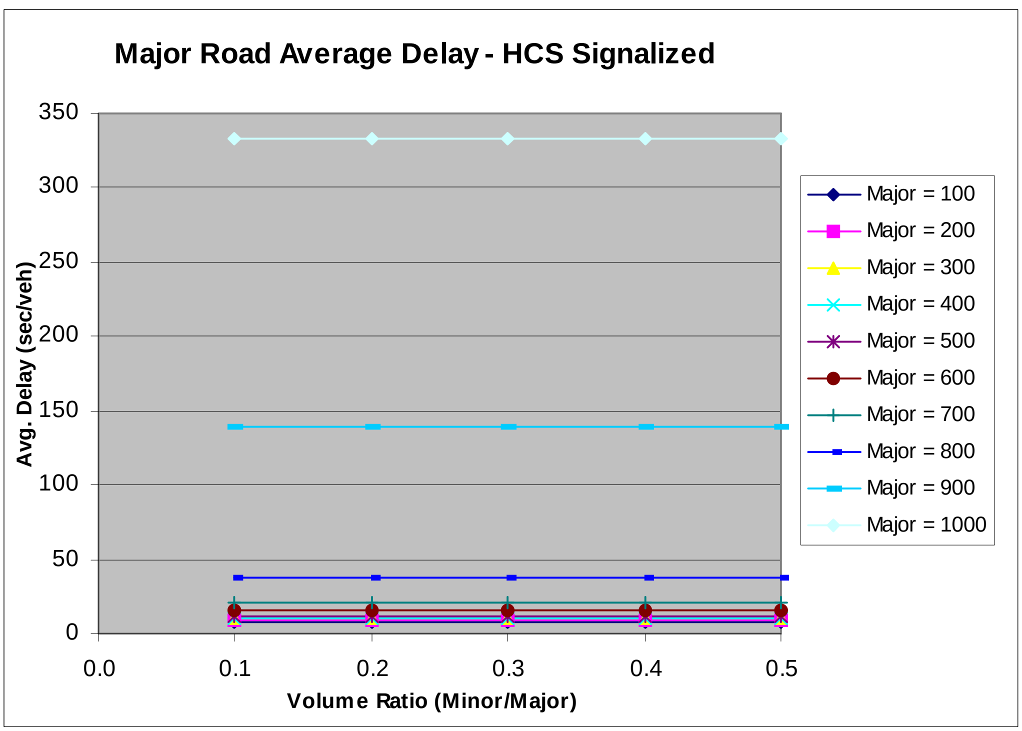


Figure B4. Major road average delay, volume comparison - HCS Signalized

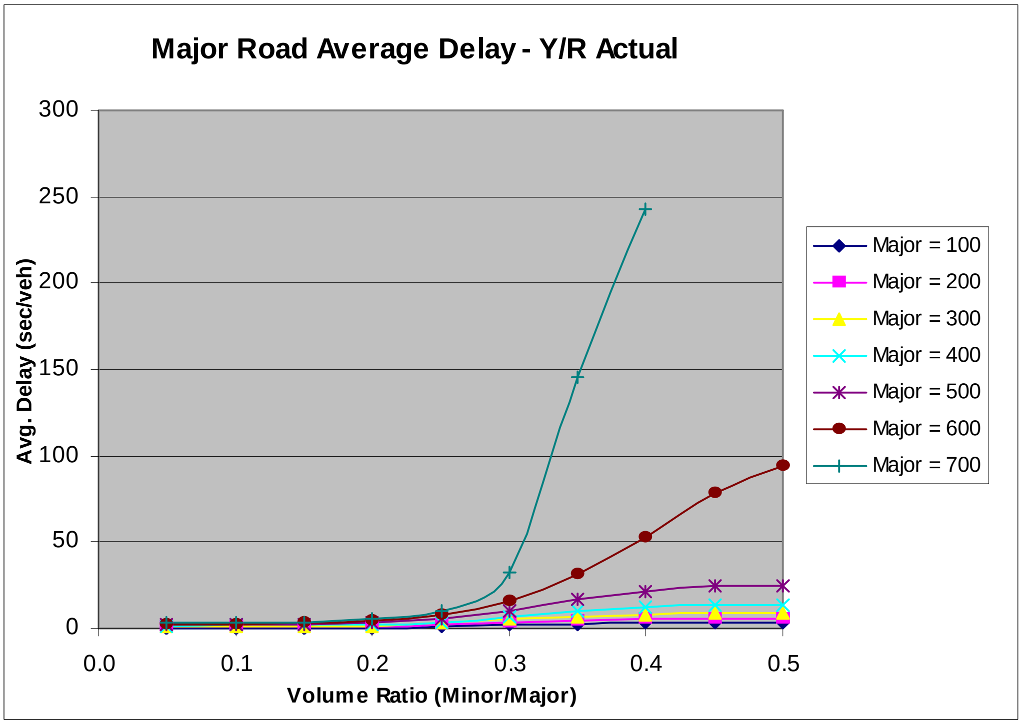


Figure B5. Major road average delay, volume comparison – VISSIM Actual Y/R

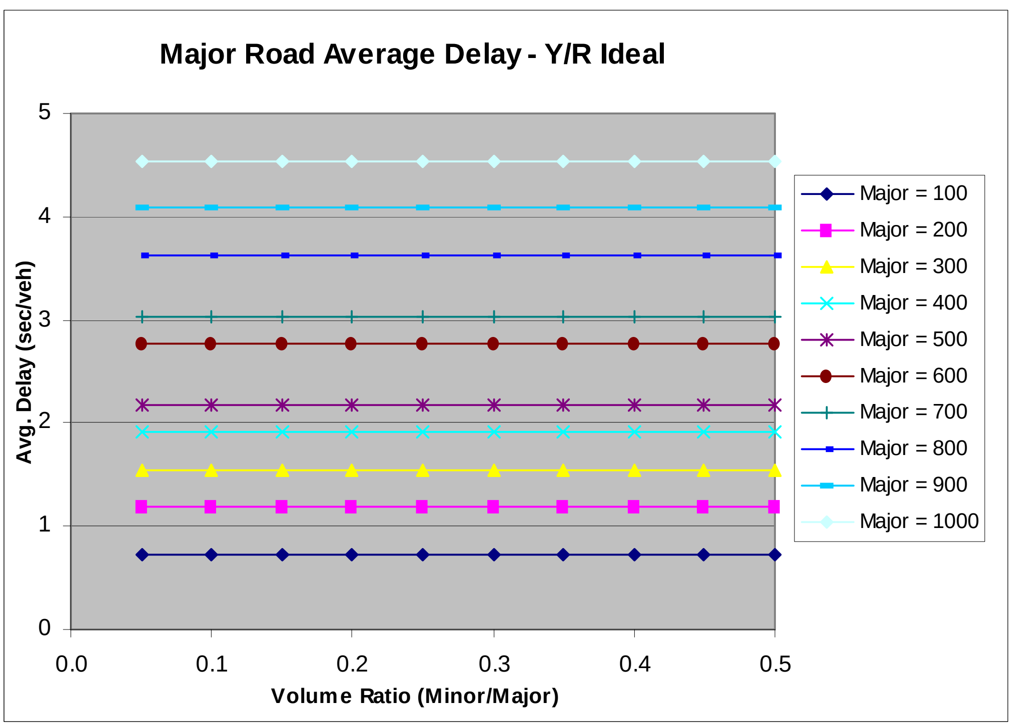


Figure B6. Major road average delay, volume comparison – VISSIM Y/R Ideal

APPENDIX C

MAJOR ROAD AVERAGE DELAY

MAJOR VOLUME ON X-AXIS

SCENARIO COMPARISON

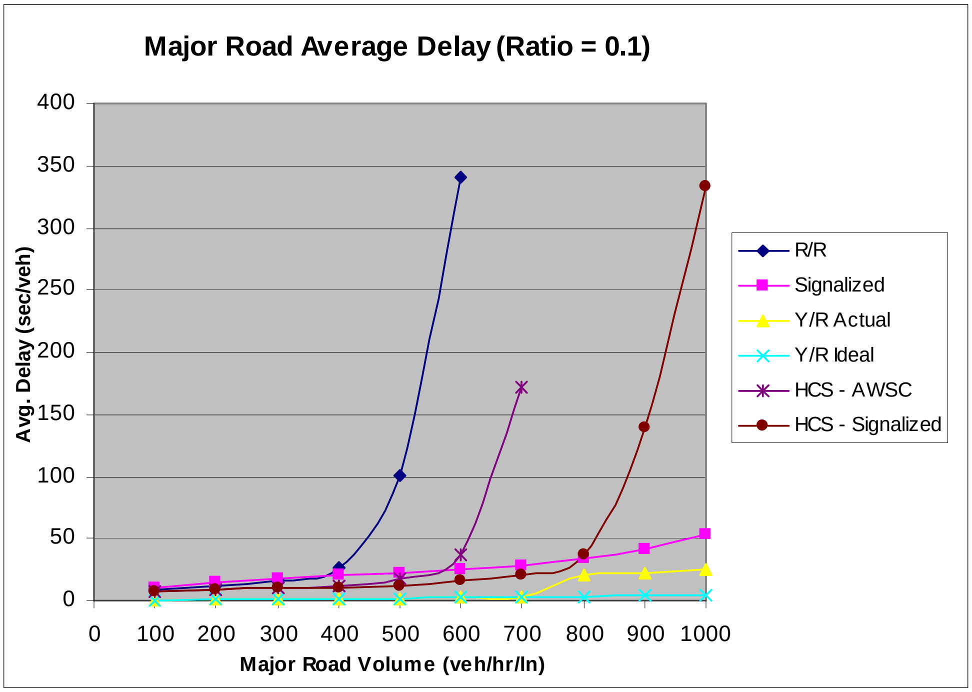


Figure C1. Major road average delay, scenario comparison

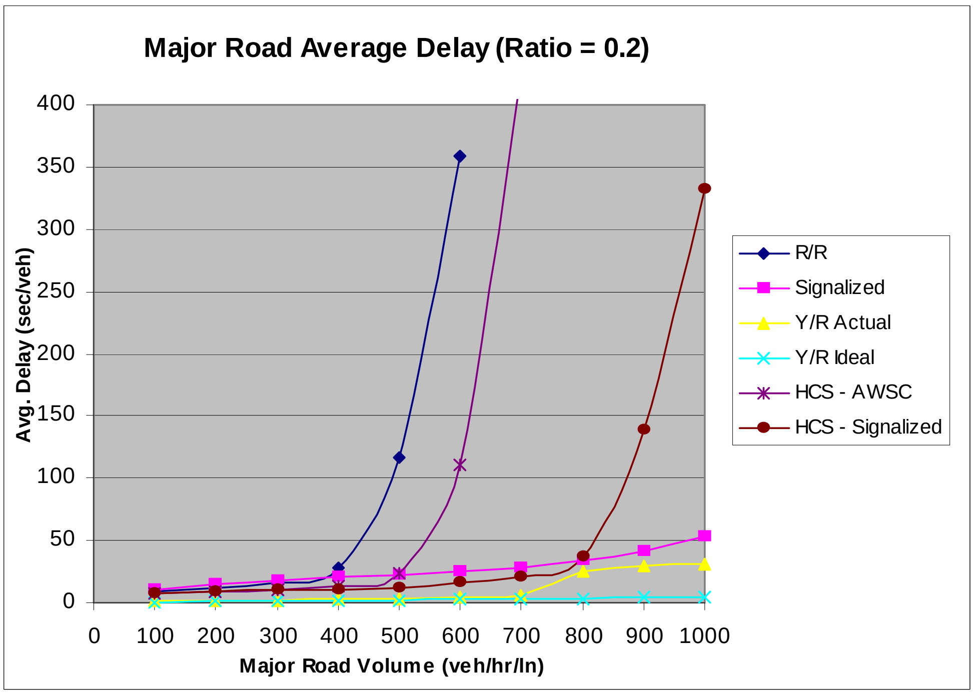


Figure C2. Major road average delay, scenario comparison

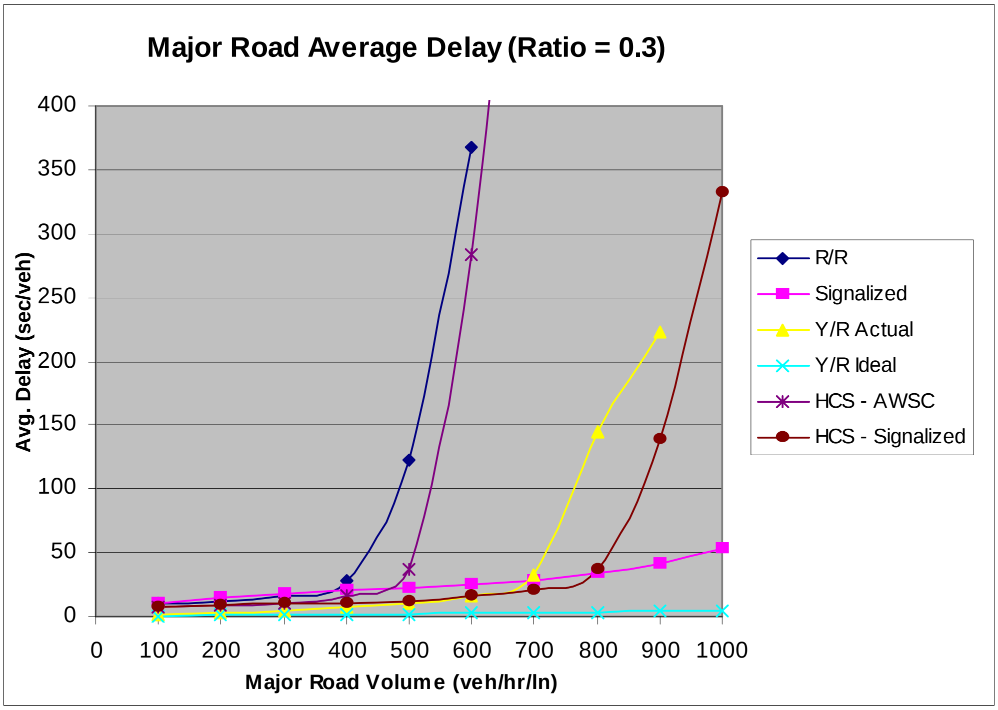


Figure C3. Major road average delay, scenario comparison

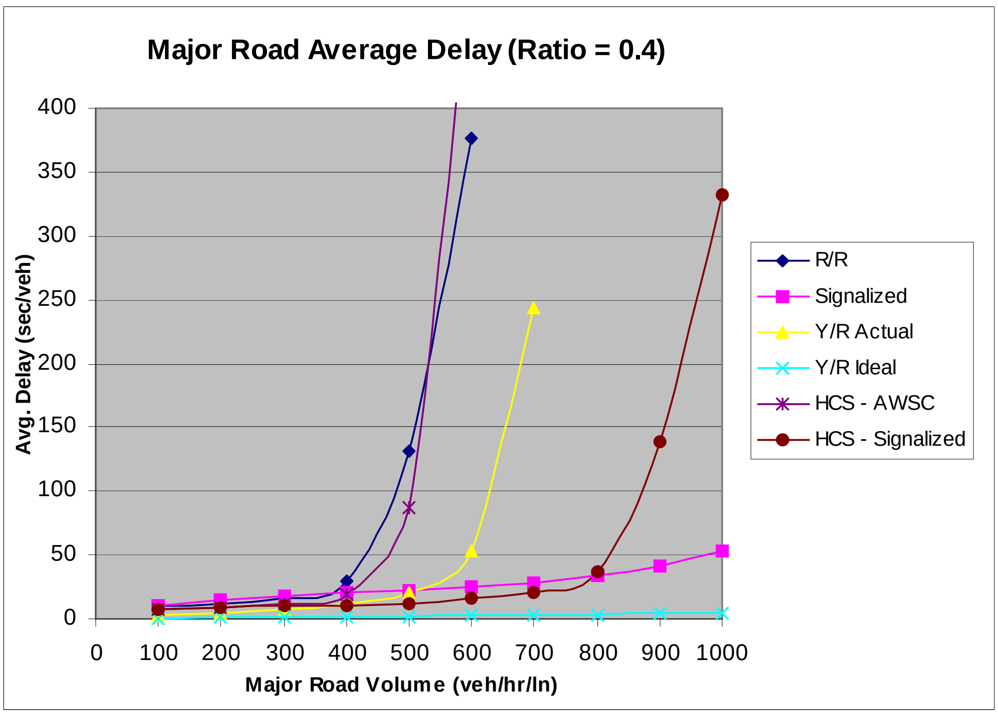


Figure C4. Major road average delay, scenario comparison

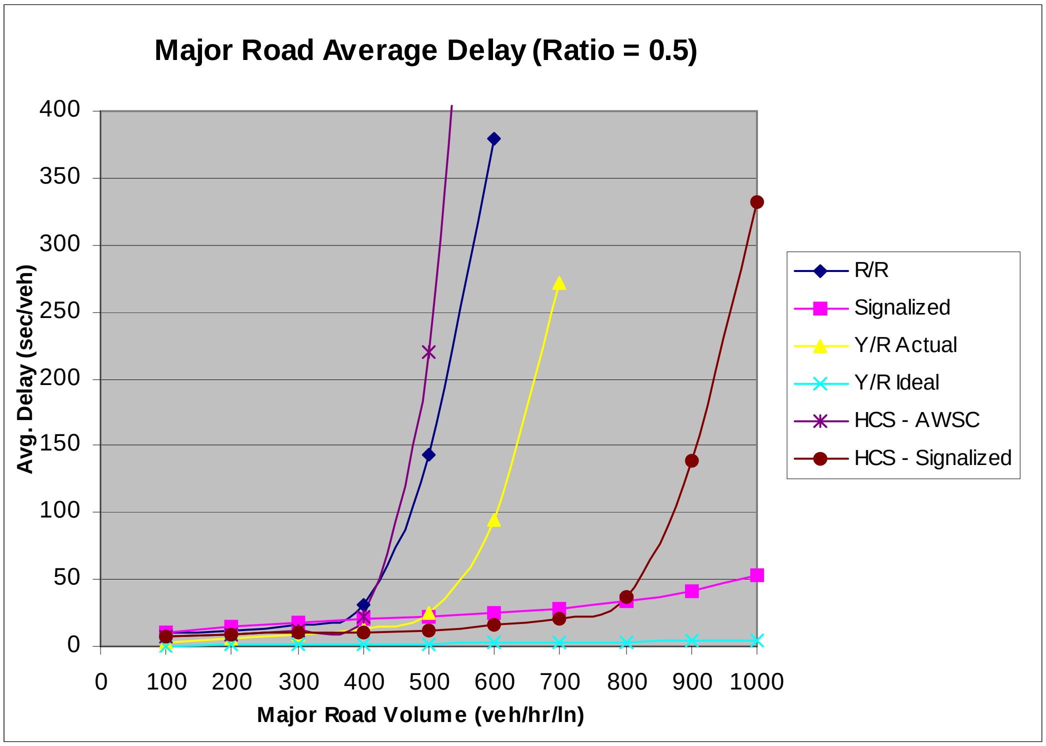


Figure C5. Major road average delay, scenario comparison

APPENDIX D

MAJOR ROAD AVERAGE DELAY

MAJOR VOLUME ON X-AXIS

VOLUME RATIO COMPARISON

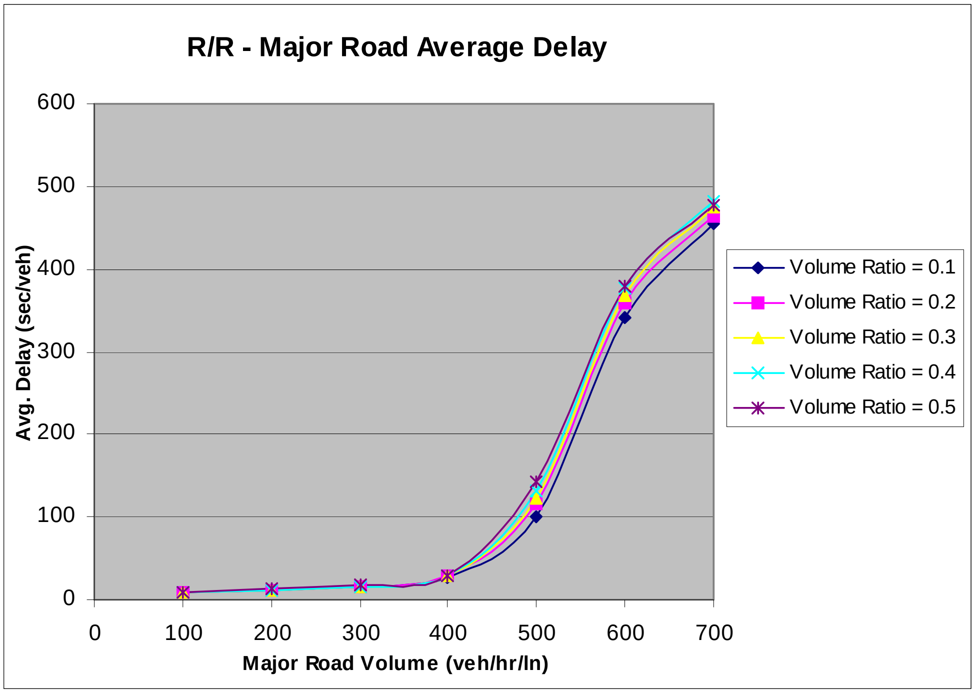


Figure D1. Major road average delay, volume ratio comparison – VISSIM Red/Red

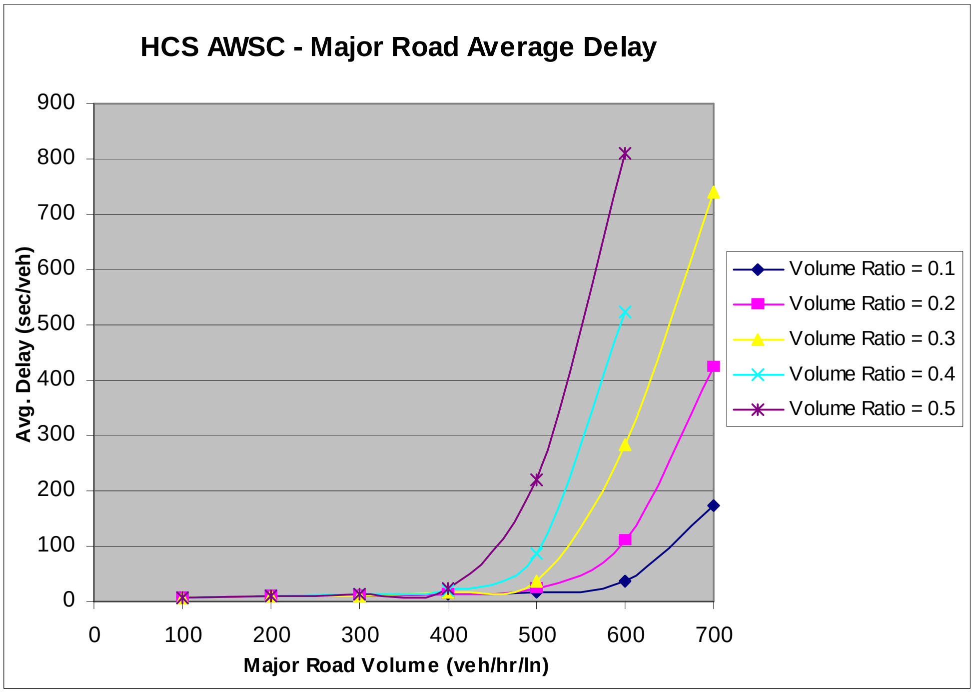


Figure D2. Major road average delay, volume ratio comparison – HCS AWSC

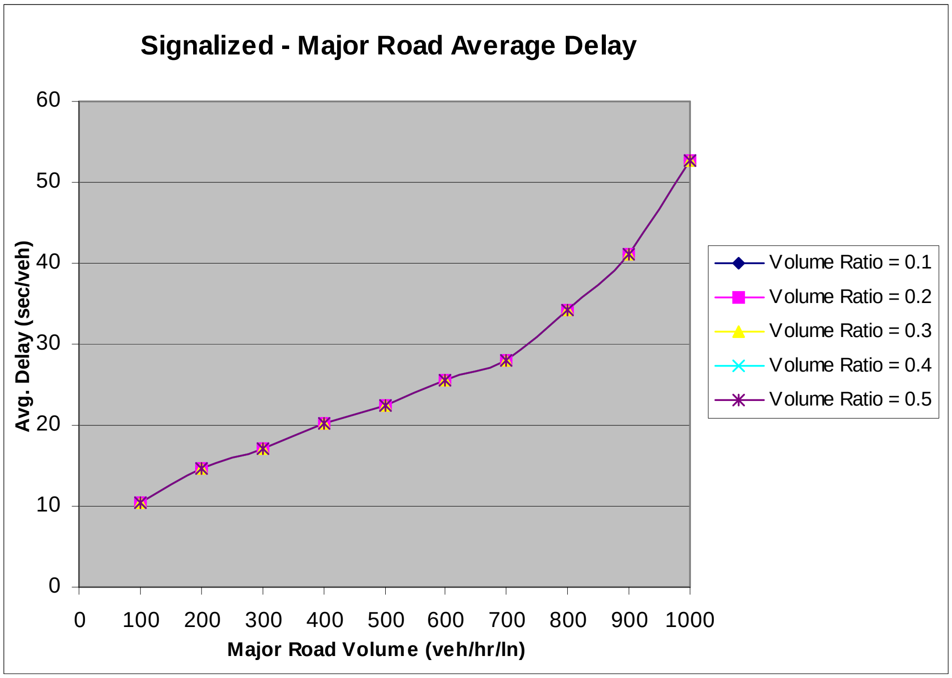


Figure D3. Major road average delay, volume comparison - VISSIM Signalized

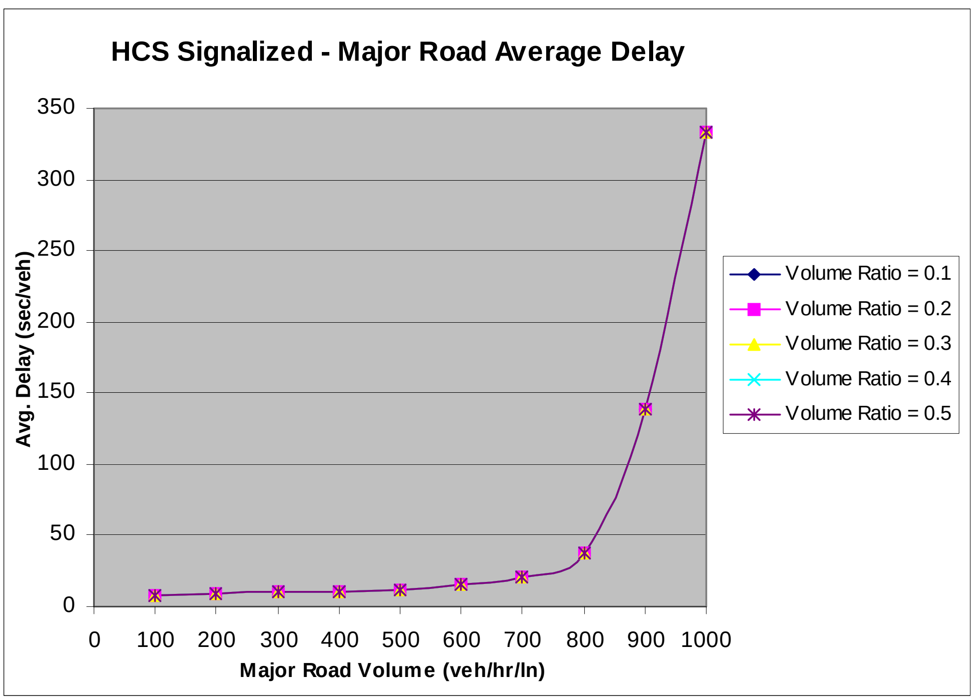


Figure D4. Major road average delay, volume comparison - HCS Signalized

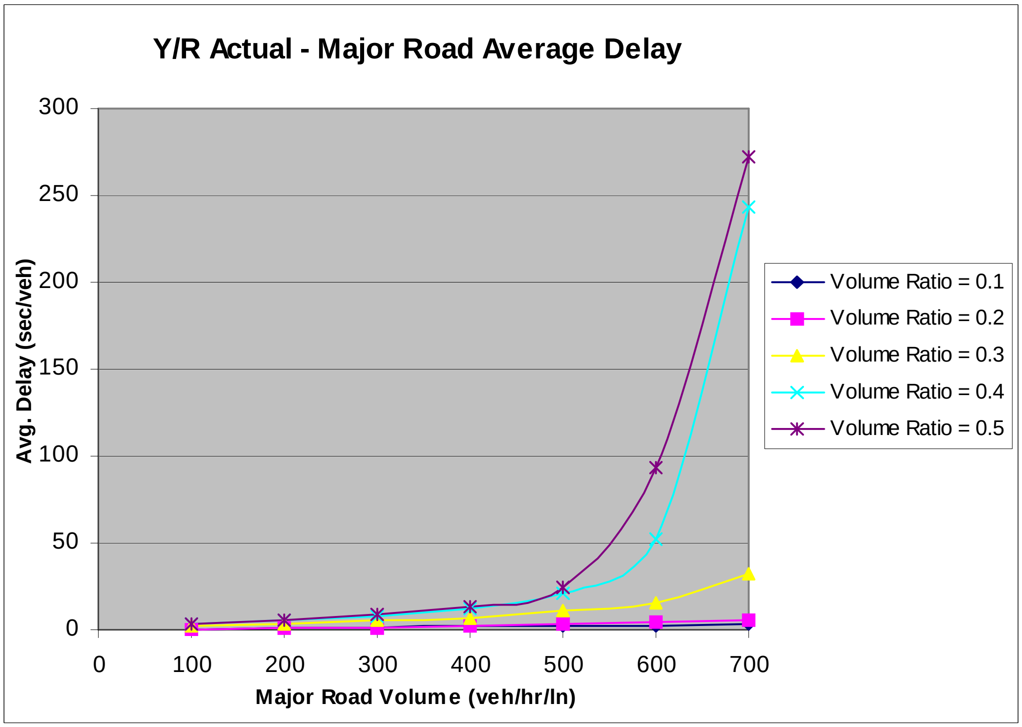


Figure D5. Major road average delay, volume comparison – VISSIM Actual Y/R

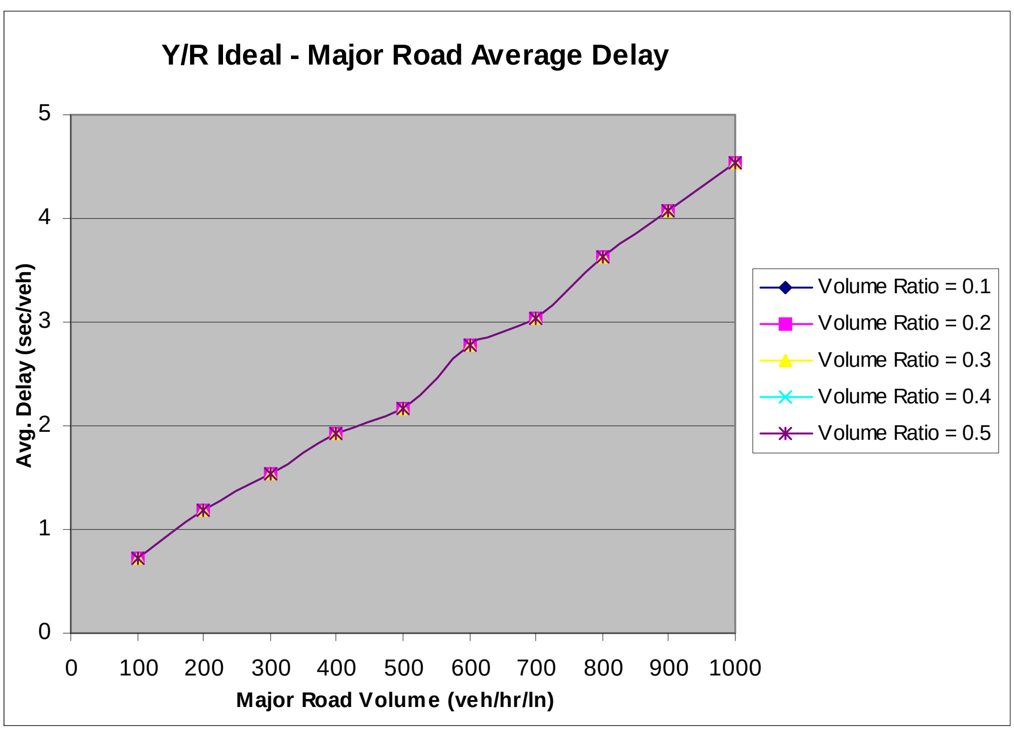


Figure D6. Major road average delay, volume comparison – VISSIM Y/R Ideal

APPENDIX E

MINOR ROAD AVERAGE DELAY

MINOR/MAJOR VOLUME RATIO ON X-AXIS

SCENARIO COMPARISON

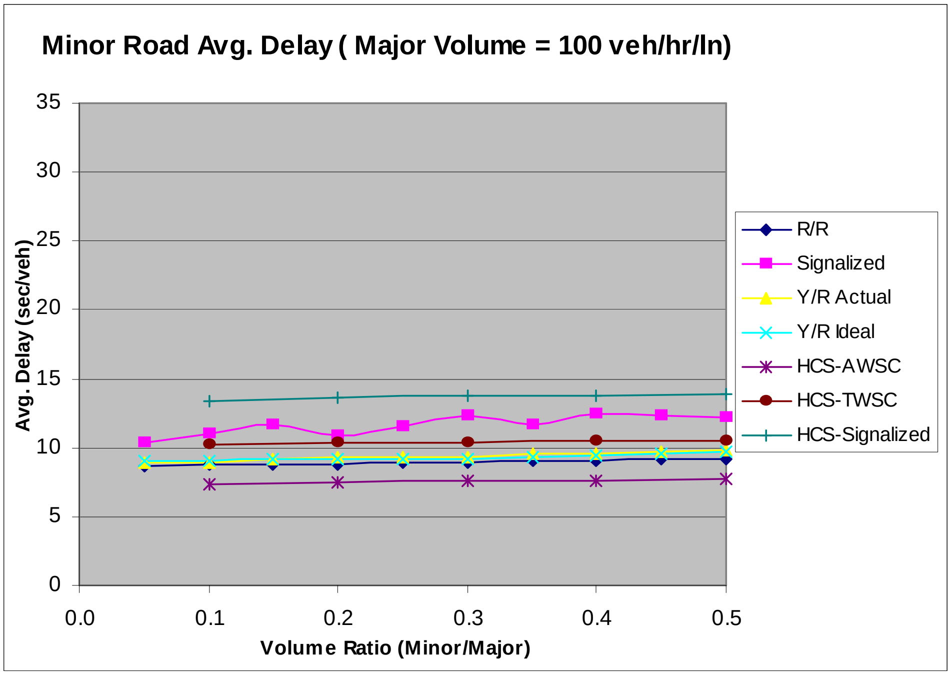


Figure E1. Minor road average delay, scenario comparison

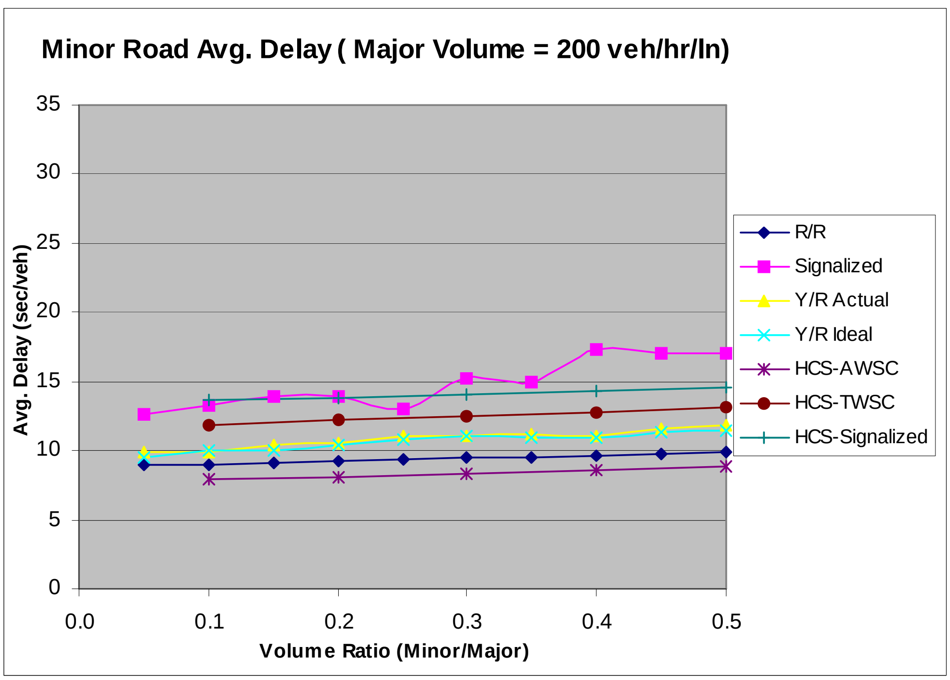


Figure E2. Minor road average delay, scenario comparison

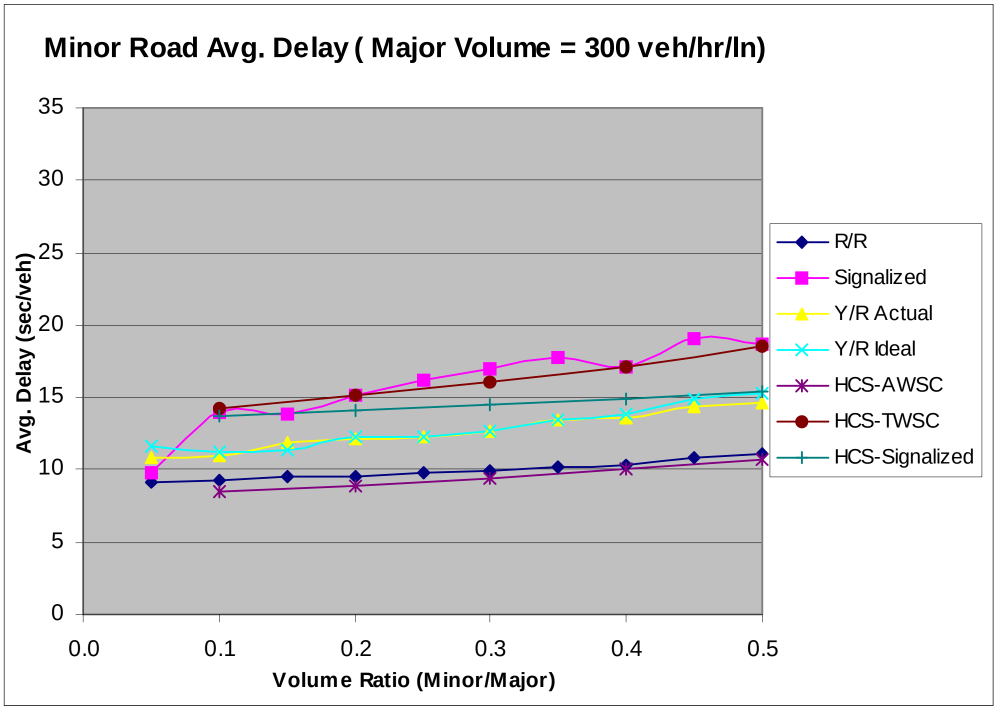


Figure E3. Minor road average delay, scenario comparison

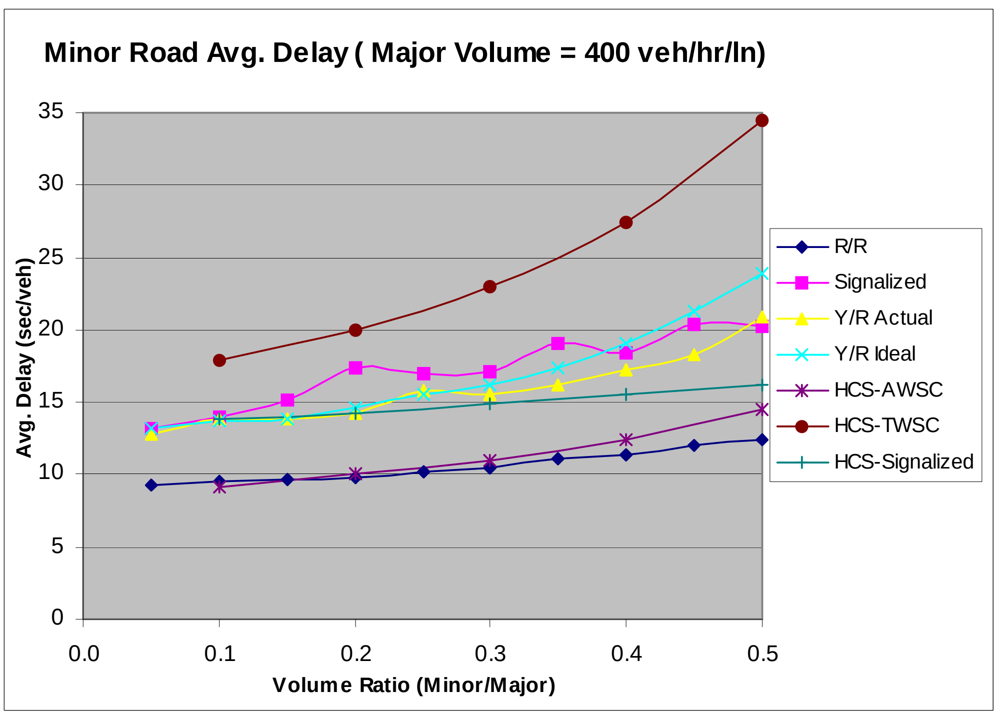


Figure E4. Minor road average delay, scenario comparison

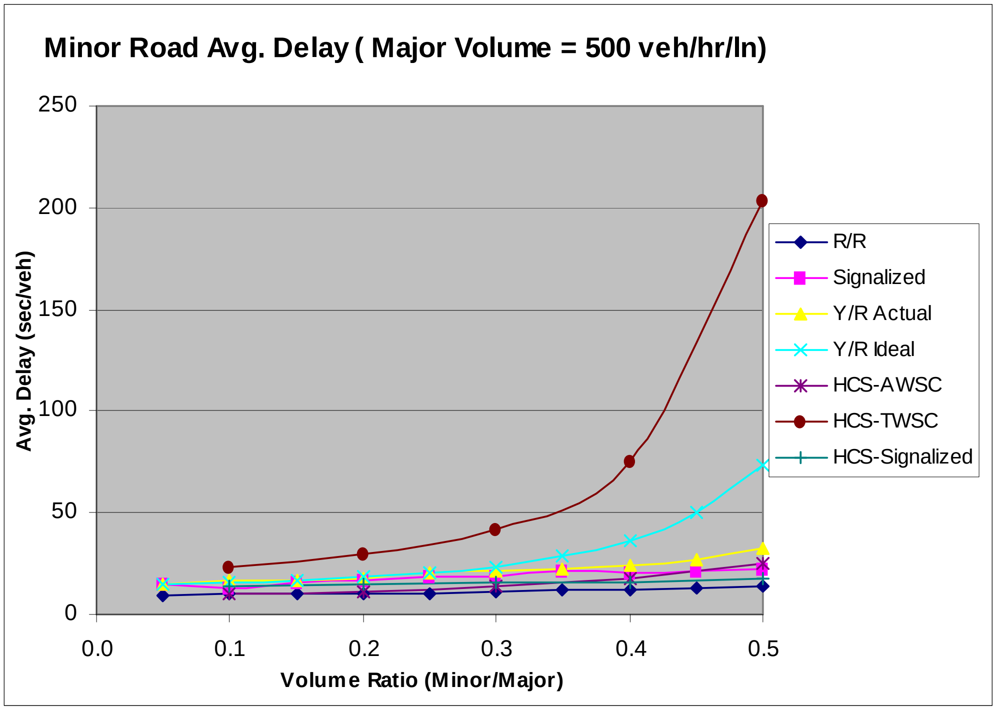


Figure E5. Minor road average delay, scenario comparison

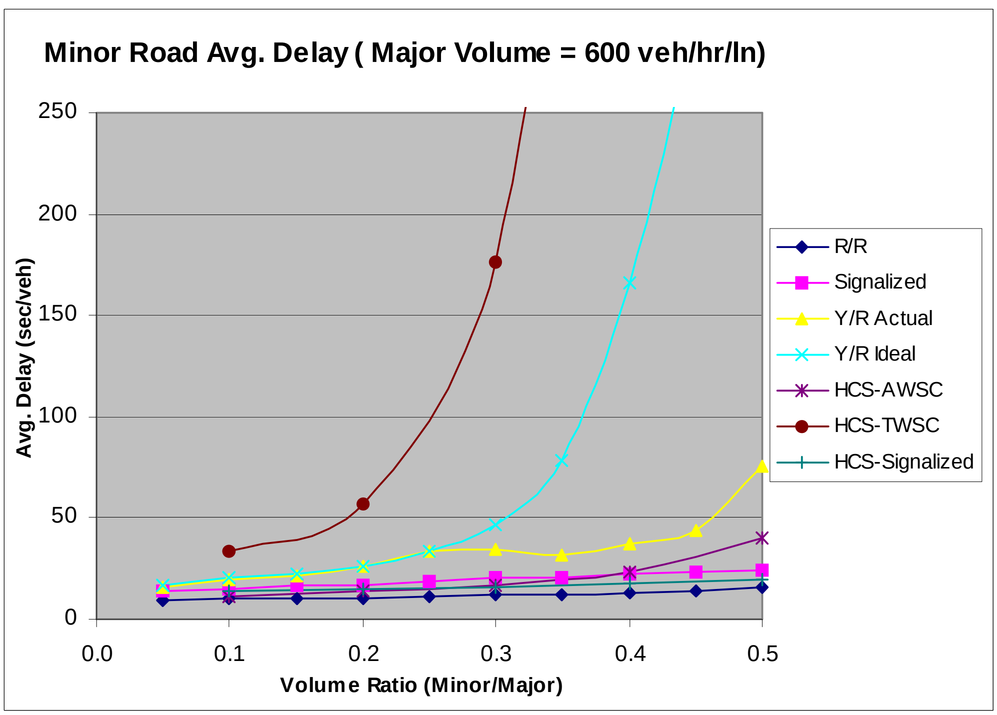


Figure E6. Minor road average delay, scenario comparison

APPENDIX F

MINOR ROAD AVERAGE DELAY

MAJOR VOLUME ON X-AXIS

SCENARIO COMPARISON

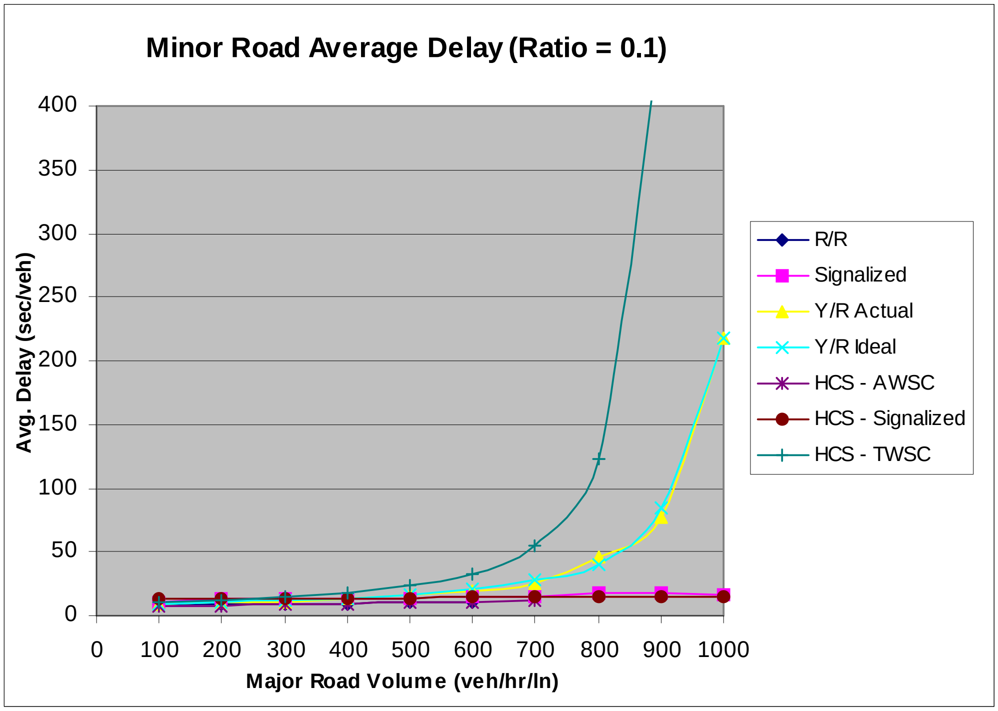


Figure F1. Minor road average delay, scenario comparison

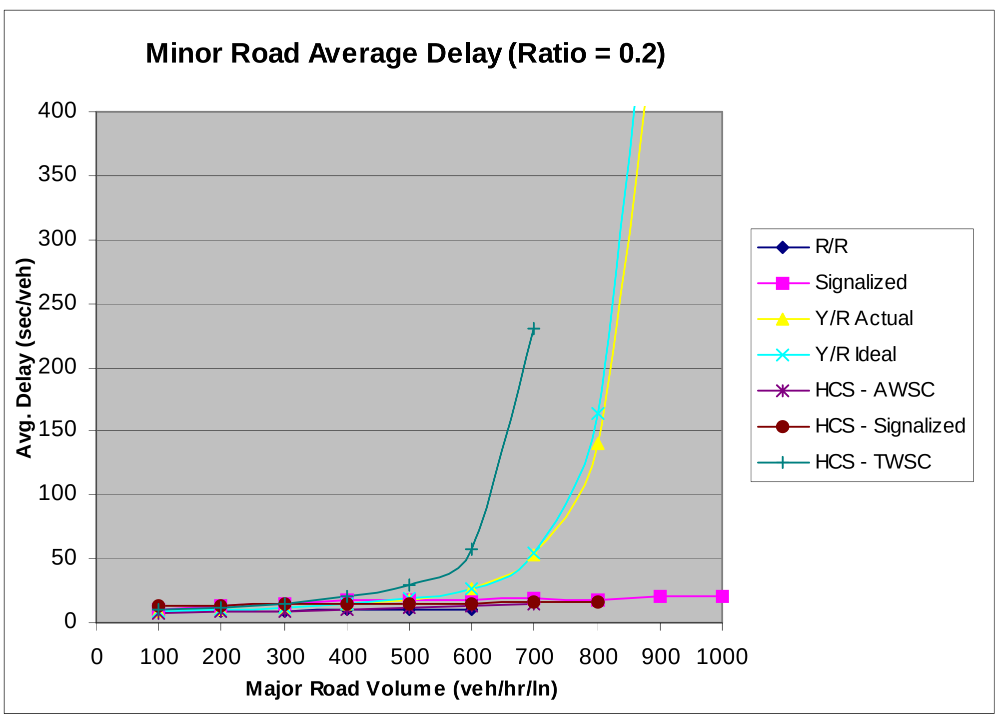


Figure F2. Minor road average delay, scenario comparison

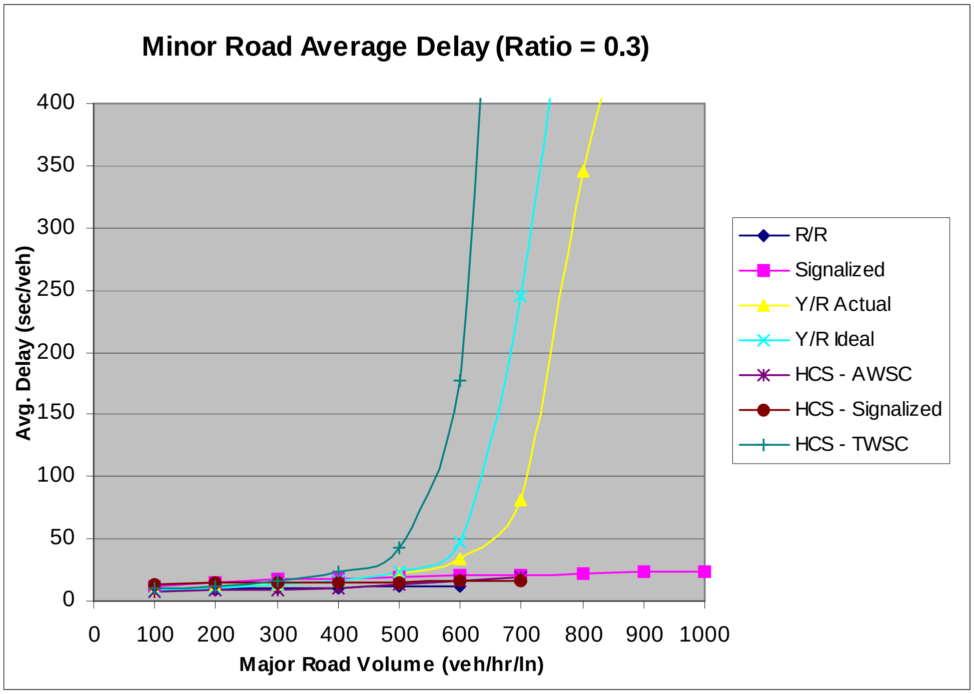


Figure F3. Minor road average delay, scenario comparison

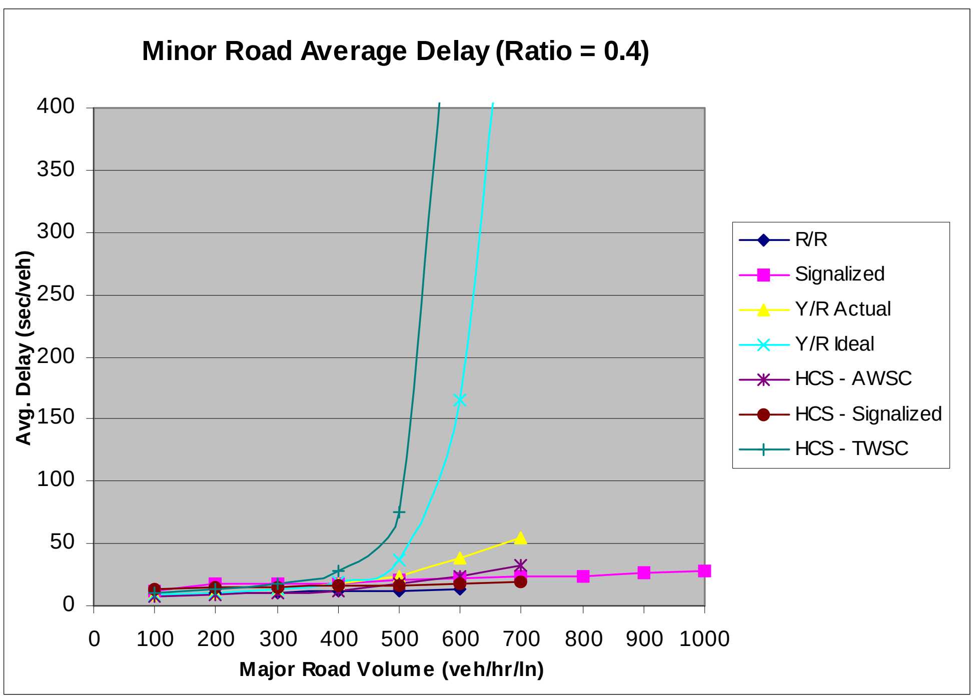


Figure F4. Minor road average delay, scenario comparison

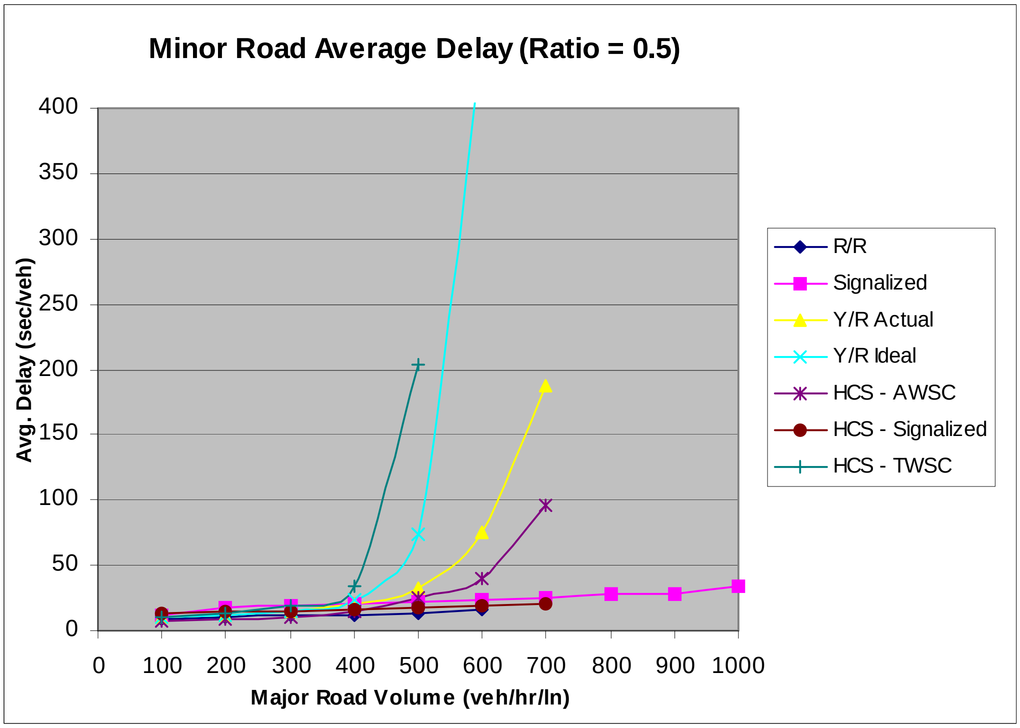


Figure F5. Minor road average delay, scenario comparison

APPENDIX G

VISUAL BASIC CODE

```
Attribute VB_Name = "Yellow_Red_Actual"

Public xxx As Integer 'variable that holds where to write data
Public yyy As Integer 'variable to hold beginning of new random seed
Public zzz As Integer 'variable for sub-sub run number
Public www As Integer 'variable for queue length analysis loop
Public RandomVal As Integer 'random seed variable
Public x1 As Integer 'multirun volume variable
Public x2 As Integer 'multirun random value variable
Public x3 As Integer 'multirun ratio variable
Public debugVAR As String
Public dumpVAR As String


'The following function is used to automate the multirun process
Sub vissim_multirun_volume1()
xxx = 1
www = 1
For x1 = 1 To 10 'volumes
    Worksheets("DELAY 1").Cells(x1 + 2, 18).Value = x1
    Worksheets("DELAY  1").Cells(x1  +  2,  19).Value  =  Time  'start  time
record
    Worksheets("Sheet1").Cells(3,               9).Value               =
Worksheets("Sheet1").Cells(3, 9).Value + 100 'Major street EB volume
    Worksheets("Sheet1").Cells(4,               9).Value               =
Worksheets("Sheet1").Cells(4, 9).Value + 100 'Major street WB volume

    For x2 = 1 To 5 'random number
    RandomVal = x2
    zzz = 1
        For x3 = 1 To 10 'ratio

            Worksheets("Sheet1").Cells(2,  5).Value  =  x1  &  "."  &  x2  &
      "." & zzz  'Simulation Run counter
            ratio_var = Worksheets("Sheet1").Cells(x3 + 2, 15).Value
            Worksheets("Sheet1").Cells(5,          9).Value            =
Worksheets("Sheet1").Cells(3, 9).Value * ratio_var 'Minor NB volume
            Worksheets("Sheet1").Cells(6,          9).Value            =
Worksheets("Sheet1").Cells(4, 9).Value * ratio_var 'Minor SB volume
            Worksheets("Sheet1").Cells(11,          2).Value           =
Worksheets("Sheet1").Cells(x3 + 2, 16).Value
            Worksheets("Sheet1").Cells(10,    2).Value    =    100    -
Worksheets("Sheet1").Cells(x3 + 2, 16).Value
            Worksheets("Sheet1").Cells(11,          3).Value           =
Worksheets("Sheet1").Cells(x3 + 2, 17).Value
            Worksheets("Sheet1").Cells(10,    3).Value    =    100    -
Worksheets("Sheet1").Cells(x3 + 2, 17).Value
            Call  vbcom_test1  'once  the  initial  variables  are  set  the
VISSIM recalling function is started
            xxx = xxx + 1
            zzz = zzz + 1
        Next x3
    Next x2
      Worksheets("DELAY 1").Cells(x1 + 2, 20).Value = Time
Next x1
      Worksheets("DELAY 1").Cells(2, 22).Value = xxx
End Sub
```

```
'This is the main function operating on the VISSIM simulation
Sub vbcom_test1()

Set vissim = CreateObject("VISSIM.vissim")
Set simulation = vissim.simulation
Set vehicles = vissim.net.vehicles
Set links = vissim.net.links
Set inputs = vissim.net.VehicleInputs
Set tcomps = vissim.net.TrafficCompositions
Set graphics = vissim.graphics

FolderID = Worksheets("Sheet1").Cells(15, 2).Value
FileID = Worksheets("Sheet1").Cells(16, 2).Value
UserID = Worksheets("Sheet1").Cells(17, 2).Value

'Load the network
Net2load  =  "C:\Documents  and  Settings\"  &  UserID  &  "\Desktop\"  &
FolderID & "\" & FileID & ".inp"

vissim.LoadNet Net2load
vissim.SetWindow 0, 0, 620, 600 'reset the windows size (y,x, height,
length)

'simulation parameters setting taken from Sheet1
simulation.Period = Worksheets("Sheet1").Cells(7, 2).Value
simulation.resolution = Worksheets("Sheet1").Cells(8, 2).Value
'simulation.speed = Worksheets("Sheet1").Cells(9, 2).Value
Type1_pre = Worksheets("Sheet1").Cells(10, 2).Value
Type2_pre = Worksheets("Sheet1").Cells(11, 2).Value
Type3_pre = Worksheets("Sheet1").Cells(12, 2).Value
Type1_abs = Worksheets("Sheet1").Cells(10, 3).Value
Type2_abs = Worksheets("Sheet1").Cells(11, 3).Value
Type3_abs = Worksheets("Sheet1").Cells(12, 3).Value

simulation.RandomSeed = RandomVal

Set controllers = vissim.net.SignalControllers
Set dets = vissim.net.SignalControllers(2).Detectors
Set eval = vissim.Evaluation

eval.AttValue("DELAY") = True
Set Delays = vissim.net.Delays
Set delay1 = Delays(1) 'Major EB delay
Set delay2 = Delays(2) 'Major WB delay
Set delay3 = Delays(3) 'Minor NB delay
Set delay4 = Delays(4) 'Minor SB delay


eval.AttValue("QUEUECOUNTER") = True
Set QueueCounters = vissim.net.QueueCounters
Set queue1 = QueueCounters(1) 'Minor NB queue counter
Set queue2 = QueueCounters(2) 'Major EB queue counter

Set TravelTime = vissim.net.TravelTimes
Set TT1 = TravelTime(1) 'Major EB travel time
Set TT2 = TravelTime(2) 'Major WB travel time
```

```
Set TT3 = TravelTime(3) 'Minor NB travel time
Set TT4 = TravelTime(4) 'Minor SB travel time

    For Each inp In inputs
        inpID = inp.ID

        Select Case inpID
                Case 1
                    inp.AttValue("VOLUME")                              =
Worksheets("Sheet1").Cells(3, 9).Value 'Major EB volume
                Case 2
                    inp.AttValue("VOLUME")                              =
Worksheets("Sheet1").Cells(4, 9).Value 'Major WB volume
                Case 3
                    inp.AttValue("VOLUME")                              =
Worksheets("Sheet1").Cells(5, 9).Value 'Minor NB volume
                Case 4
                    inp.AttValue("VOLUME")                              =
Worksheets("Sheet1").Cells(6, 9).Value 'Minor SB volume
                Case Else
                    MsgBox   "Something   went   wrong   during   volume
assignment!"
            End Select
    Next inp

    For i = 0 To simulation.Period 'this code will make the simulation
run on single step
        simulation.RunSingleStep

        'vehicle access method
        For j = 1 To vehicles.Count
            Set Vehicle = vehicles(j)
            distance1 = Vehicle.AttValue("LINKCOORD")
            vehLane = Vehicle.AttValue("LANE")
            If Vehicle.AttValue("TYPE") = 4 Then
                    If (Vehicle.AttValue("LINK") = 1) Then
                        If  (distance1  >  785  And  distance1  <  825)  Then
GoTo TypeChanger
                    End If
                    If (Vehicle.AttValue("LINK") = 2) Then
                        If  (distance1  >  778  And  distance1  <  818)  Then
GoTo TypeChanger
                    End If
            End If

cycleSIM:
        Next j
    Next i 'end of: For i = 0 To simulation.Period
GoTo DelayCalc

'The  following  function  wil  change  car  type  according  to  presence  on
the minor and percentage assigned on the spreadsheet

TypeChanger:
    'If vehicle.AttValue("TYPE") = 4 Then
    randCheck1 = Rand(1, 100)
```

```
            If      (dets(1).AttValue("DETECTION")      =      1      Or
dets(2).AttValue("DETECTION") = 1) Then
      'CASE 1: minor present
            Select Case randCheck1
                Case 0 To Type1_pre
                    Vehicle.AttValue("Type") = 1 'Type 1 drivers
                    Vehicle.AttValue("color") = vbGreen
                Case Type1_pre To (Type1_pre + Type2_pre)
                    Vehicle.AttValue("Type") = 2 'Type 2 drivers
                    Vehicle.AttValue("color") = vbRed
                Case Else
                    Vehicle.AttValue("Type") = 3 'Type 3 drivers
                    Vehicle.AttValue("color") = vbYellow
            End Select
        Else
      'CASE 2: minor absent
            Select Case randCheck1
                Case 0 To Type1_abs
                    Vehicle.AttValue("Type") = 1 'Type 1 drivers
                    Vehicle.AttValue("color") = vbGreen
                Case Type1_abs To (Type1_abs + Type2_abs)
                    Vehicle.AttValue("Type") = 2 'Type 2 drivers
                    Vehicle.AttValue("color") = vbRed
                Case Else
                    Vehicle.AttValue("Type") = 3 'Type 3 drivers
                    Vehicle.AttValue("color") = vbYellow
            End Select
        End If
    'End If

If i <> simulation.Period Then GoTo cycleSIM  'end of typechanger:

DelayCalc:

    study_interval = Worksheets("Sheet1").Cells(6, 2).Value

    Delay01  =  (delay1.GetResult(study_interval,  "DELAY",  "",  0)  +
delay2.GetResult(study_interval,  "DELAY",  "",  0))  /  2  'Major  street
cumulative delay
    Delay02  =  (delay3.GetResult(study_interval,  "DELAY",  "",  0)  +
delay4.GetResult(study_interval,  "DELAY",  "",  0))  /  2  'Minor  street
cumulative delay

    Worksheets("DELAY 1").Cells(xxx + 2, 1).Value = "Run " & x1 & "." &
x2 & "." & zzz 'simulation runs counter

    Worksheets("DELAY  1").Cells(xxx  +  2,  4).Value  =  Delay01  'Major
street average delay per vehicle
    Worksheets("DELAY  1").Cells(xxx  +  2,  7).Value  =  Delay02  'Minor
street average delay per vehicle

    Worksheets("DELAY     1").Cells(xxx     +     2,     2).Value     =
queue2.GetResult(study_interval, "MEAN") 'Major EB average queue
    Worksheets("DELAY     1").Cells(xxx     +     2,     5).Value     =
queue1.GetResult(study_interval, "MEAN") 'Minor NB average queue
    Worksheets("DELAY     1").Cells(xxx     +     2,     3).Value     =
queue2.GetResult(study_interval, "MAX") 'Major EB max queue
```

```
    Worksheets("DELAY 1").Cells(xxx + 2, 6).Value = queue1.GetResult(study_interval, "MAX") 'Minor NB max queue
    Worksheets("DELAY 1").Cells(xxx + 2, 8).Value = inputs(1).AttValue("VOLUME") 'Major EB THEORETICAL volume
    Worksheets("DELAY 1").Cells(xxx + 2, 10).Value = inputs(2).AttValue("VOLUME") 'Major WB THEORETICAL volume
    Worksheets("DELAY 1").Cells(xxx + 2, 12).Value = inputs(3).AttValue("VOLUME") 'Minor NB THEORETICAL volume
    Worksheets("DELAY 1").Cells(xxx + 2, 14).Value = inputs(4).AttValue("VOLUME") 'Minor SB THEORETICAL volume
    Worksheets("DELAY 1").Cells(xxx + 2, 16).Value = inputs(3).AttValue("VOLUME") / inputs(1).AttValue("VOLUME") 'Theoretical ratio of minor to major volumes
    Worksheets("DELAY 1").Cells(xxx + 2, 9).Value = TT1.GetResult(study_interval, "NVEHICLES", "", 0) 'Major EB ACTUAL volume
    Worksheets("DELAY 1").Cells(xxx + 2, 11).Value = TT2.GetResult(study_interval, "NVEHICLES", "", 0) 'Major WB ACTUAL volume
    Worksheets("DELAY 1").Cells(xxx + 2, 13).Value = TT3.GetResult(study_interval, "NVEHICLES", "", 0) 'Minor NB ACTUAL volume
    Worksheets("DELAY 1").Cells(xxx + 2, 15).Value = TT4.GetResult(study_interval, "NVEHICLES", "", 0) 'Minor SB ACTUAL volume
    Worksheets("DELAY 1").Cells(xxx + 2, 17).Value = ((TT3.GetResult(study_interval, "NVEHICLES", "", 0) + TT4.GetResult(study_interval, "NVEHICLES", "", 0)) / 2) / ((TT1.GetResult(study_interval, "NVEHICLES", "", 0) + TT2.GetResult(study_interval, "NVEHICLES", "", 0)) / 2) 'Actual ratio of minor to major volumes

The_end:
    simulation.Stop
    vissim.Exit


End Sub

'random number generator function

Public Function Rand(ByVal Low As Long, ByVal High As Long) As Long
  Rand = Int((High - Low + 1) * Rnd) + Low
End Function
```

REFERENCES

[1] Bansen, Justin. *Evaluation of Traffic Operations at Intersections in Malfunction Flash Mode*. Masters Thesis, Georgia Institute of Technology, May 2006.

[2] Jenior, Pete. *Observation and Modeling of Traffic Operations at Intersections in Malfunction Flash Mode*. Masters Thesis, Georgia Institute of Technology, May 2007.

[3] *State of Georgia Code*. Source: www.legis.state.ga.us. (Accessed June 2007).

[4] Benioff, B., C. Carson, and F. C. Dock. *A Study of Clearance Intervals, Flashing Operation, and Left-turn Phasing at Traffic Signals: Volume 3 Flashing Operation*. Final Report. FHWA-RD-78-48. Federal Highway Administration, Washington, D.C. May 1980.

[5] Moreno, L. and M. Demetsky. *Simulation of Flashing Signal Operations*. Final Report. FHWA/VA-83/11. Virginia Highway and Transportation Research Council, Charlottesville, VA. 1982.

[6] Salter, R.J. and E. A. Ismail. *Simulation of Two- and Four-Way Stop Control*. In Transportation Research Record 1320, TRB, National Research Council , Washington, D.C., 1991, pp. 227-233.

[7] Kacir, K.C., G. Hawkins, Jr., R.J. Benz, M.E. Obermeyer, and R.E. Bartoskewitz. *Evaluation of Flashing Traffic Signal Operation*. Research Report 1297-2F. Project No. 1297. Texas Transportation Institute, College Station, TX. November 1993.

[8] Kyte, M., Tian, Z., Mir, Z., Hammeedmansoor, Z., Kittelson, W., Vandehey, M., Robinson, B., Brilon, W., Bondzio, L., Wu, N., Troutbeck, R. *Capacity and Level of Service at Unsignalized Intersections; Final Report*, National Cooperative Highway Research Program Project 3-46, April 1996.

[9] Tian, Z., T. Urbanik, R. Engelbrecht, and K. Balke. *Variations in Capacity and Delay Estimates From Microscopic Traffic Simulation Models*. Transportation Research Record 1802, pp. 23-31, 2002.

[10] *VISSIM 4.10-12 User Manual*. PTV Planung Transport Verkehr AG. Karlsruhe, Germany, March 2005.

[11] *VISSIM COM User Manual*. PTV Planung Transport Verkehr AG. Karlsruhe, Germany, January 2006.

[12] *Highway Capacity Manual*. National Research Council, Washington, D.C. 2000.