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RIGHT TURN SPLIT: A NEW DESIGN TO ALLEVIATE WEAVING ON
ARTERIAL STREETS

by

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A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
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ABSTRACT

While weaving maneuvers occur on every type of roadway, most studies have focused on freeway maneuvers. Weaving occurring on non-freeway facilities, such as arterial streets, can cause significant operational problems. Arterial streets weaving typically occur when vehicles coming from a side street at an upstream intersection attempt to enter the main street from one side to reach access points on the opposite side at a downstream intersection by crossing one or more lanes. The freeway methodology to deal with weaving may not be applicable to arterial streets since arterial streets, unlike the freeways, tend to have shorter weaving lengths and lower speeds. This dissertation investigates the types of weaving movements occurring between two close-spaced intersections on an arterial street, presents the type of problems occurring due to the weaving movements, and recommends a new design to alleviate weaving on arterial streets.

Firstly, the dissertation examined the different weaving movements occurring between two close-spaced intersections at two sites in Florida. The two sites had a heavy right turn volume entering from the side street and two close-spaced intersections. The dissertation also explained the breakdown conditions caused by the weaving movements at the two sites. Secondly, the dissertation proposed a new design, Right Turn Split (RTS), to alleviate the operational problems caused by the weaving movements on arterial streets. The new design proposed separating the worst weaving movement entering the arterial from the other movements and providing a separate path for this movement to alleviate the delay on the arterial street. The new method is easy to implement and does not require much right of way.

Thirdly, the dissertation compared two microscopic models, SimTraffic and VISSIM, to choose the most suitable model to be used to study the operational benefits of the RTS design on the delay of the arterial street. Based on the results of the comparison, it was decided to use SimTraffic for the analysis due to the many features in intersection's coding and data entry. Fourthly, the dissertation proposed a new calibration and validation procedure for microscopic simulation models that focused on arterial streets. The procedure was applied on SimTraffic using the traffic data from the two studied sites in Florida. The proposed procedure appeared to be properly calibrating and validating the SimTraffic simulation model.

Finally, the calibrated and validated model was used to study the operational benefits of the proposed design. Using a wide range of geometric and volume conditions, 1,458 SimTraffic models, 729 before and after pairs, were created to compare the delay of similar scenarios before and after applying the RTS design. The results were analyzed graphically and statistically. The findings of the analysis showed that, for the geometric and volume conditions tested, the proposed design provided lower delay on the arterial street than the original conditions, which concludes that the RTS design provided a delay reduction.

This dissertation is dedicated to my parents, Amal and Salah El-din. They both instilled my desire for achievement and they always going to be my heroes.

I also dedicate this work to my caring wife, Dina, who has accepted the many hours of disruption to our life, to enable me to pursue this goal, and my sons Karim and Ali who also sacrificed in their loss of my time with them.

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CHAPTER 1. INTRODUCTION

Background

Most studies are only focused on freeway weaving and stops short in addressing weaving on nonfreeway facilities such as arterial streets. Freeway weaving occurs when two traffic streams traveling in the same direction must cross without the aid of a traffic control device. Similar movements occur on arterial streets typically when vehicles coming from a side street at an upstream intersection attempt to enter the main street from one side to reach access points on the opposite side at a downstream intersection by crossing one or more lanes. This type of weaving can cause significant operational and safety problems on the arterial streets. Arterials, unlike freeways, tend to have shorter weaving lengths and lower speeds.

Problem Description

Based on the literature review introduced in this dissertation, it was concluded that research directed at investigating weaving movements on arterial streets is not sufficiently understood and is still in its infancy. The literature is in need for a study that analyses the weaving movements on arterial streets, explains the effect of these movements on the traffic conditions, and recommends new solutions to alleviate the delay caused by these movements.

Objectives

The objectives of this dissertation are:

1. Studying the different types of weaving movements occurring between two intersections on an arterial street in two sites in Florida and explaining the breakdown conditions caused by the weaving movements (Chapter 2).
2. Introducing the Right Turn Split (RTS) design to alleviate the weaving problem on arterial streets when the system is failing due to the weaving movements (Chapter 3).
3. Comparing two microscopic models, SimTraffic and VISSIM, to choose the most suitable model to be used to study the operational effect of the proposed design on the arterial performance using simulation (Chapter 4).
4. Introducing a new procedure to calibrate and validate simulation models and using the new procedure to calibrate and validate a simulation model that replicates the existing conditions to make sure it provides meaningful results when used to study the operational benefits of the RTS design on the arterial performance (Chapter 5).
5. Conducting simulation runs using the calibrated simulation model to compare the delay of similar arterial segments before and after applying the RTS design for a wide range of geometric and volume conditions (Chapter 6).
6. Presenting the results and recommending future work (Chapter 7).

CHAPTER 2. GUIDELINES FOR WEAVING ON URBAN STREETS

Introduction

Traffic weaving, as included in the 2000 Highway Capacity Manual (HCM) is only focused on freeway weaving and the manual stops short in documenting weaving on arterial streets. Arterial streets weaving typically occur when vehicles coming from a side street at an upstream intersection attempt to enter the main street from one side to reach access points on the opposite side at a downstream intersection by crossing one or more lanes. The goal of this paper is to study the weaving operation between two intersections and to explain the breakdown conditions caused by weaving movements on an arterial street in two sites in Florida.

Literature Review

The purpose of the literature review is to achieve the following goals:

1. Understating the existing analysis tool for analyzing freeway weaving and its historical development.
2. Obtaining information on historical work done on arterial weaving.
3. Obtaining information on new solutions and designs to improve operations and delay at intersections that are most relevant to arterial weaving.

Weaving as Traditionally Understood for Freeways

Freeway weaving occurs when two traffic streams traveling in the same direction must cross without the aid of a traffic control device (HCM, 2000). Several models to analyze freeway weaving have been developed. The 1965 HCM included a procedure that used a monograph and predictive equation. The measures of effectiveness were capacity and speed of the weaving vehicles. The inputs to the model included the weaving section length, number of lanes, and the weaving and non-weaving volumes.

In the 1985 HCM, the document had a new method, which relied on two equations; one that predicted the average speed of weaving vehicles and the second that predicted the average speed of nonweaving vehicles in the section. The two equations have the same variables with different constants. The inputs to the equations included the weaving section length, number of lanes, volume ratio which is the weaving volume divided by total volume. In addition, a level-of-service (LOS) criteria was developed based on the average speed of weaving and nonweaving vehicles. Separate LOS designations were given for weaving and nonweaving traffic in recognition of the fact that constraints often force weaving vehicles to travel considerably slower than nonweaving vehicles. Three types of geometric configurations were defined in the 1985 edition. These types are as follows:

- Type A: Each weaving vehicle must complete one lane change in order to complete the desired weaving maneuver.

- Type B: One weaving movement can be completed without a lane change and the other movement requires only one lane change.
- Type C: One weaving maneuver can be completed without a lane change and the other movement requires at least two lane changes.

As a result of continuing research, the HCM was updated in 1994 and in 1997. The weaving analysis methodology was not updated in the 1994 update. In the 1997 update ([HCM, 1997](#)), a new methodology was adopted. The methodology was based on predicting the speed of weaving and nonweaving vehicles separately then an average speed and density for all vehicles is estimated and a LOS criteria was developed based on the estimated average density of all vehicles in the section. This methodology was adopted to be consistent with basic freeway sections. These criteria allowed for slightly higher densities at any given LOS threshold than on a comparable basic freeway segment or multilane highway segment. This follows the philosophy that drivers expect and will accept higher densities on weaving segments than on basic freeway or multilane highway segments. In the 2000 HCM, the weaving analysis methodology was not updated.

The HCM methodology is bounded by speeds from 15 to 65 at the limits of its predictive equations, was not developed in interrupted flow conditions and therefore is not likely to be applicable to conditions where traffic control influences arrival rates.

Historical Work on Arterial Weaving

Available sources on arterial weaving design were limited. [Iqbal \(1995\)](#) studied non-freeway weaving movements. Based on a search throughout the state of New Jersey and the metropolitan area of New York City, he classified the vast majority of nonfreeway weaving cases into two broad categories: 1) basic weave and 2) ramp weave. In the basic weave case, weaving starts where a ramp is merged into the arterial and stops at the diverge point of another ramp from the arterial. In ramp weaving, weaving takes place on a segment of highway between an on-ramp followed by an off-ramp connecting an arterial with a highway. The basic weaving maneuver takes place as a result of the on-ramp vehicles crossing the path of the off-ramp vehicles. This type is similar to the weaving on freeways but in the freeway case acceleration and deceleration lanes exist, as well as a long stretch of an auxiliary lane. One of the main criteria established for site selection was to have signal locations as far away as possible. Analytical models were developed to predict the speed for weaving and nonweaving vehicles along the weaving section. The freeway models, used to determine weaving and nonweaving speed in the HCM, were calibrated using the nonfreeway weaving data points. The original models used upper and lower speed limits of 65 mph and 15 mph, the study used upper limit of 45 mph for basic weave and in case of ramp weave, 40 mph for weaving speed and 55 mph for nonweaving speed. After developing the models, average running speed were used to establish a level of service criteria for the two types of weaving. The study excluded the case of weaving movements occurring between close-spaced intersections.

Jacobson et al. (1997) studied the weaving movement on frontage roads. The weaving movements were defined as the movement that occurs as vehicles exiting the freeway attempt to reach a driveway on the right side of the roadway and other frontage road vehicles attempt to enter the freeway on ramp. An analytical model was developed to predict the density of the weaving section on the frontage road as a function of frontage road volume, exit ramp volume, total driveway volume, frontage road configuration, and exit ramp to access spacing. The model was developed from the results of a computer simulation that was calibrated using field data from several frontage road sites in Texas. In addition, the research identified possible level of service boundaries that could be used to identify the quality of service provided on a particular section of frontage road. This study focused only on the weaving movement between a freeway off ramp and a driveway.

New Designs to Alleviate Delay on Arterial Streets

This section presents some of the new designs and solutions to alleviate delay on arterial streets. These studies do not specifically address weaving on arterial streets but they are the most relevant studies to the subject. Eyster (2005) developed new designs for use on arterial roadways that suffer from heavy congestion. These designs are called “Arterial Interchanges”. The key feature of this interchange design family is the use of one bridge to separate through flows and to redirect left turns to simple at-grade intersection of a left turn and one through movement on each roadway. The centerpiece bridge eliminates the major conflicts. Those conflicts are the crossing through movements and the left turns. This is a family of interchanges because there are

many possible variations in the basic components of the interchange. The proposed arterial interchange designs can be used at junctions that would range from urban arterial/urban collector all the way to freeway/suburban at-grade expressway. The author describes a systematic applications of this proposed family of interchange designs along an entire corridor could result a new form of super arterial roadway. The arterial interchanges were analyzed using traffic simulation (VISSIM). The capacity of the arterial interchange has proven to well exceed that of an at-grade intersection with six through lanes and double left turn lanes and has more capacity than a single point urban interchange or conventional diamond, but it has less capacity on the major route, because the total capacity of the interchange is more evenly distributed.

[Chu and Chaudhary \(2004\)](#) proposed three approaches for coordinating diamond interchanges with adjacent traffic signals on arterial streets to provide maximum progression for the through traffic. The authors explain that the operation of a diamond interchange can affect or be affected by the location, design, and operation of adjacent traffic signals and ramps. In many cases, the already complex nature of traffic through a diamond-interchange and adjacent traffic-signal system is further complicated by weaving and queuing caused by various traffic movements. The first two approaches proposed apply to undersaturated systems only and are simple to use. The third approach use iterative procedures to coordinate the system and applies to both undersaturated and saturated systems. To compare the performance of the approaches, traffic simulations, using PASSER IV and CORSIM, were conducted using existing data at two sites located in Texas and satisfactory results were observed from the simulations.

[Reid et al. \(2002\)](#) compared intersection capacity and traffic operations for different design alternatives for grade-separated intersections to provide some guidance to engineers on which grade separated intersection alternatives to consider under various traffic conditions. Seven grade-separated intersection designs were analyzed, including the compressed diamond, partial cloverleaf, single-point urban, median urban diamond, echelon, center-turn overpass, and single-loop. An eighth design, median u-turn intersection, was also analyzed to provide a comparison to a very efficient at-grade intersection. The analysis included four and six-lane roadways and considered average and high turning movement percentages. Travel time analysis results showed that the parclo and single point interchanges were consistently the most efficient, the median u-turn intersection was consistently the least efficient, and the other five design were in the middle. The authors recommend that designers of grade-separated intersections consider a parclo if right of way is available, a single point design if money is available for an expensive structure, and a median urban diamond where higher capacities are desired. However, as other designs have their unique niches, the authors suggest that engineers do not drop any of them from their menus of design possibilities.

[Bared and Kaisar \(2000\)](#) used traffic simulation (CORSIM) to study the operational benefits of the split intersection design. The split intersection design is a new design for urban and suburban intersections to relieve congestion and improve delay where the major highway is separated into two directional one-way roads comparable to an at-grade diamond junction. The split intersection facilitates smoother flows with less drive delay by reducing the number of required signal phases from four to three. Comparisons of vehicular delay between the single and the split

intersection revealed substantial savings in travel delay, particularly for higher entering volumes and higher left-turning movements.

Based on the literature review, it was concluded that research directed at investigating weaving movements on arterial streets is not sufficiently understood and is still in its infancy. The literature is in need for a study that analyses the weaving movements on arterial streets and explains the effect of these movements on the traffic conditions.

Arterial Weaving Geometry and Site Selection

The goal of this paper is to study the characteristics of the weaving movements occurring on arterial streets. Arterial streets weaving typically occur when vehicles coming from a side street at an upstream intersection attempt to enter the main street from one side to reach access points on the opposite side at a downstream intersection by crossing one or more lanes. Due to the different types of weaving movements, the many variables involved, and the limited data resources, this paper focuses only on the weaving movements occurring between two intersections on an arterial segment where no other access points, such as driveways or median openings, exist. In this case, the weaving movements will only result from the through vehicles attempting to turn right at the downstream intersection and from the side street vehicles attempting to turn left or go through at the downstream intersection. [Figure 2.1](#) shows the weaving movements occurring on the arterial segment.

Two sites were selected for the analysis. These two sites suffer from a delay problem due to the weaving movements (Shaaban, 2004a and Shaaban, 2004b). The first site was on State Road 421 between the I-95 Off-Ramp and Airport Road in Port Orange, Florida and the second site was on State Road 50 between State Road 408 Off-Ramp and Bonneville Drive in Orlando, Florida. The two sites exist at the exit ramp of a diamond interchanges where the side street vehicles enter the arterial street through a free right turn lane. These two sites have the following criteria: relatively short spacing between two signalized intersections that are running in coordination; moderate to heavy road volumes; and no driveways or median openings between the two signalized intersections. The arterial segment had two through lanes. The downstream intersection had a left turn lane and a right turn lane. The two sites are shown in [Figure 2.2](#).

Data Collection Methods and Reduction

Video cameras were used to collect the data. The cameras were used for two purposes. First, the cameras were used to record the operation of weaving movement. Second, the cameras were used to obtain volume counts and turning percentages along the arterials. To be able to achieve these two goals, the cameras were positioned on a high position (the I-95 bridge and the SR 408 bridge) to cover the weaving area. The weaving area was defined as the area between the end of the gore area at the first intersection to the stop bar at the second intersection. The cameras were zoomed in to capture the movement of each vehicle within the weaving section. In order to determine the location where the vehicle performed the weaving movement, road tubes were placed at a 100 feet spacing starting at the gore area. The tubes acted as distance meters. In

addition to the video, aerial photographs and detailed sketches of the two sites were obtained. These sketches included the geometry of each site including the number of lanes, channelization, auxiliary lanes, and the distance between the two signalized intersections. At each site, eight hours of data were collected on a normal weekday using the video recording equipment. The time periods were selected so that two hours in the morning period (7:00 a.m. to 9:00 p.m.), two hours in the midday period (11:00 a.m. to 1:00 p.m.), and four hours in the evening period (2:00 p.m. to 6:00 p.m.) were observed.

The reduction of the field data involved observing the videotapes of each site. The videotapes were used to observe the weaving movement and also to obtain accurate counts and turning percentages along the arterial. This method was used since it was hard to observe the weaving movements and to count the vehicles in real time at high volumes. Accuracy in video data is due mainly to the fact that the viewer is able to view the videotape more than one time. Therefore, the viewer can concentrate on a single movement and then when finished rewind the tape and observe a different movement. Data reduction sheets were created for each site so that the weaving distance and the origin-destination patterns of individual vehicles could be recorded. A sample of the data reduction sheets is shown in [Table 2.1](#). The weaving distance is defined as the distance from the gore area to the location where the vehicle crossed to the desired lane. Videos were then watched in slow motion to verify the weaving distance, the origin-destination information, and the number of lane changes required to complete the movement. The origin-destination volumes, the weaving distances, number of lane changes were recorded in one-minute increments.

Characteristics of Different Movements

Breakdown Conditions

By observing the videotapes of each site, the movement of 4,443 vehicles was tracked. The distance and type of weaving performed by each vehicle was recorded. Watching the videos from the two sites lead to several conclusions. First, breakdown condition, caused by the weaving movement, occurred in two cases. The first case occurred when the main street through volume was extremely heavy with moving queues observed extending onto the first intersection. In this case, vehicles entering from the side street could not find adequate gaps on the main street and had to reach a complete stop waiting for a gap on the main street. An example of this case is shown in [Figure 2.3](#). In the second case, the left turning volume at the second intersection was extremely heavy. Although the main street volumes were moderate and adequate gaps were available, vehicles entering from the side street and willing to perform a left turn at the second intersection had to stop blocking the free right turn lane and waiting for the left turn lane to clear. An example of this case is shown in [Figure 2.4](#).

Movement Types

It was also found that there is five types of weaving movements occurred. These types of movements are illustrated in [Figure 2.5](#). Type 1 and Type 2 originated from the mainline and attempted to reach the right turn lane at the second signalized intersection. Type 1 vehicles had

to perform one lane change in order to complete the desired weaving maneuver. Type 2 vehicles had to perform two lane changes in order to complete the desired weaving maneuver (change one lane to the second through lane then a second lane change to the right turn lane). Types 3, 4, and 5 are weaving movements originated from the side street free right turn lane to go through or turn left at the second signalized intersection. Type 3 vehicles had to perform one lane change in order to complete the desired weaving maneuver (move to the through lane). Type 4 vehicles had to perform two lane changes in order to complete the desired weaving maneuver (change one lane to the first through lane then a second lane change to move to the second through lane). Type 5 vehicles had to perform three lane changes in order to complete the desired weaving maneuver (the first lane change to move to the first through lane, the second lane change to move to the second through lane then the third lane change to the left turn lane).

As shown in [Figure 2.6](#), 64% of the weaving volume was originated from the side street free right turn lane and 34% was originated from the main street. The majority of weaving volume occurred between Type 1 (35%) and Type 3 (40%), which accounted for 75 % of the total weaving volume. Type 2 was the lowest weaving volume (1%), which indicated that most vehicles that wanted to perform the weaving movement from the main street preferred to change lanes to be in the outside through lane before entering the weaving area to minimize the number of lane changes to only one lane change. The percentage of Type 4 was 13%, which indicated that some of the vehicles preferred to change two lanes to be in the inside through lane on the main street. This is probably due to the impression that the inside through lane will be faster than the outside through lane due to less distraction after the intersection. Type 5 (11%) is mainly based on the number of vehicles that had to perform a left turn at the second intersection.

The average weaving distances for the 4,443 vehicles tracked for each type of weaving were calculated. The average weaving distance (D1) is the average of the weaving distances required to perform the first lane change measured from the end of the gore area (applicable to all types). The average weaving distance (D2) is the average of the weaving distances required to perform the second lane change measured from the end of D1 (applicable only to types 2, 4 and 5). The average weaving distance (D3) is the average weaving distances required to perform the third lane change measured from the end of D2 (applicable only to type 5).

As shown to [Figure 2.7](#), it was found that Type 5 has the minimum value of D1. These vehicles had to perform three lane changes and they had to start the weaving movement as soon as they enter from the side street to the main street. D1 for Type 1 was also low because some of the vehicles in this type started the weaving movement before the end of the gore area (driving on the gore area striping). The maximum value of D1 was for Type 3 where vehicles had to perform only one lane change. D1 for Type 2 and Type 4 were very close (157 feet and 143 feet respectively). These two types had to perform the same number of lane changes (two) in order to complete the desired weaving maneuver.

A comparison of D1, D2, and D3 was done for the two studied sites. The main difference between the two sites is the distance between the end of the gore area to the stop line at the second intersection (LG). LG for the first site was 532 feet and for the second site was 730 feet. It was found that D1, D2, and D3 decreased dramatically when LG decreased which indicates the

great effect of the distance between the two intersections on the average weaving distance for the different weaving types.

Conclusions and Recommendations

This paper has examined the different weaving movements occurring between two close-spaced intersections for two sites in Florida. The two sites have a heavy right turn volume entering from the side street and close-spaced intersections. The paper has also studied the breakdown conditions occurring on the two arterial segments and caused by the weaving movements. It was found that the breakdown conditions occur in two cases. The first case occurred when the main street through volume was heavy with moving queues observed extending onto the first intersection. In this case, vehicles entering from the side street could not find adequate gaps on the main street and had to reach a complete stop waiting for a gap on the main street. In the second case, the left turning volume at the second intersection was heavy and blocking the whole left turn lane. Although the main street volumes were moderate and adequate gaps were available, vehicles entering from the side street and willing to perform a left turn at the second intersection had to stop blocking the free right turn lane and waiting for the left turning vehicles to clear.

The analysis also revealed that the weaving distances were also affected by the distance between the two intersections. As the spacing between the two intersections increased, the weaving distances for all movements increased. By increasing the distance between the two intersections,

drivers will have more space and time to adjust and to perform the weaving movement. In addition, the weaving distances within the same site were affected by the number of lanes changed. If a vehicle wants to change three lanes, it will perform the first lane change at a much shorter distance than a vehicle that wants to change only one lane. Based on the literature review and the analysis introduced in this paper, it was concluded that weaving movements on arterial streets can cause major delay problems streets and it is recommended to find new solutions to solve this problem.

Table 2.1: An Example of Data Collection and Reduction for a Fifteen Minutes Period

TYPE 1		TYPE 2			TYPE 3		TYPE 4			TYPE 5			
TIME	D1	TIME	D1	D2	TIME	D1	TIME	D1	D2	TIME	D1	D2	D3
7:30	500				7:30	150							
	300					450							
						400							
						300							
					7:31	200	7:31	250	400				
						200							
						250							
						200							
						375							
						400							
						450							
7:32	600				7:32	400							
7:33	300				7:33	250	7:33	200	400	7:33	200	500	600
	250										50	200	350
	250												
7:35	250				7:35	350							
						600							
						400							
						375							
7:36	300				7:36	300	7:36	250	400				
7:37	300				7:37	100	7:37	100	300				
	250					300		150	300				
						275							
7:38	75				7:38	300	7:38	75	150				
						250		250	600				
						250							
						300							
						250							
						275							
					7:39	300	7:39	200	300				
						375							
						25							
						450							
						200							
						300							
					7:40	325	7:40	400	600				
						250		250	700				
						250							
7:41	200				7:41	275							
	275					750							
						200							
					7:42	200	7:42	300	700				
						275							
						200							
						75							
					7:43	550							
						350							
						700							
						275							
						325							
					7:44	400	7:44	250	375				

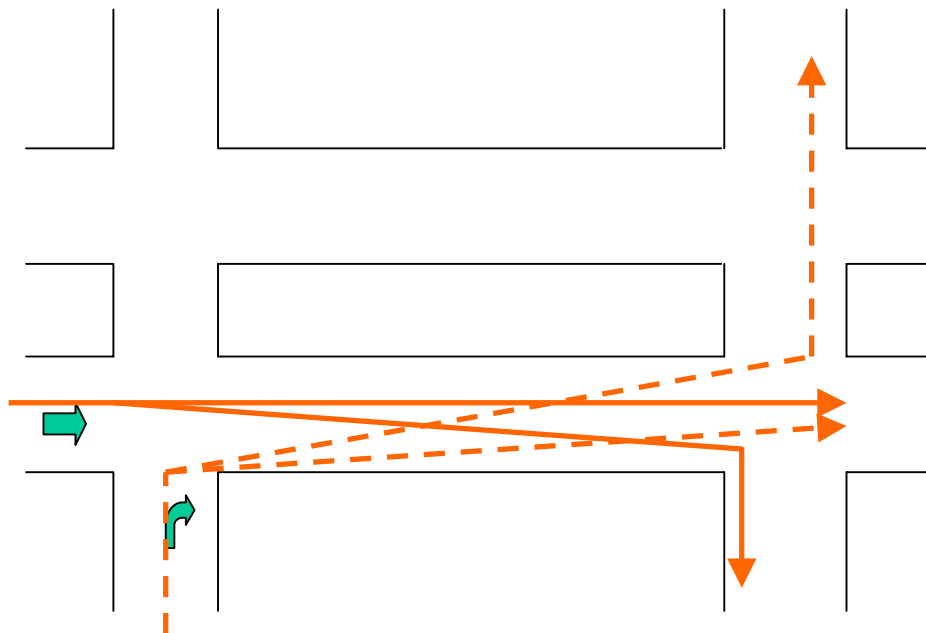


Figure 2.1: Weaving Movements Occurring Between Two Intersections

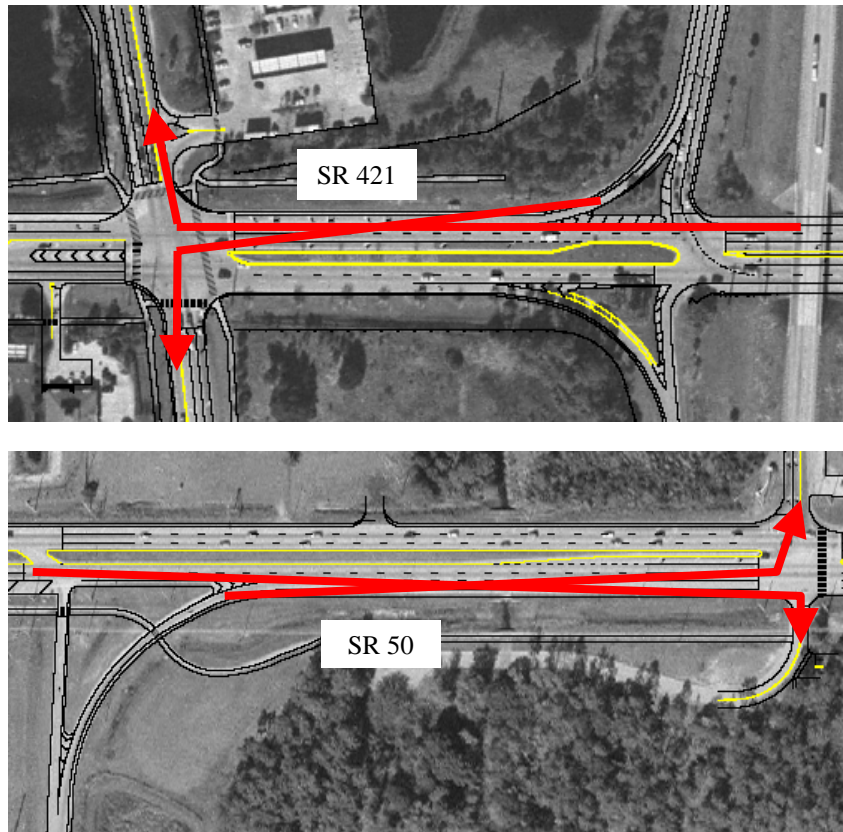


Figure 2.2: Aerials Maps Showing the Two Studied Sites



Figure 2.3: Breakdown Conditions Due to Heavy Mainline Through Volume



Figure 2.4: Breakdown Conditions Due to Heavy Mainline Left Turn Volume

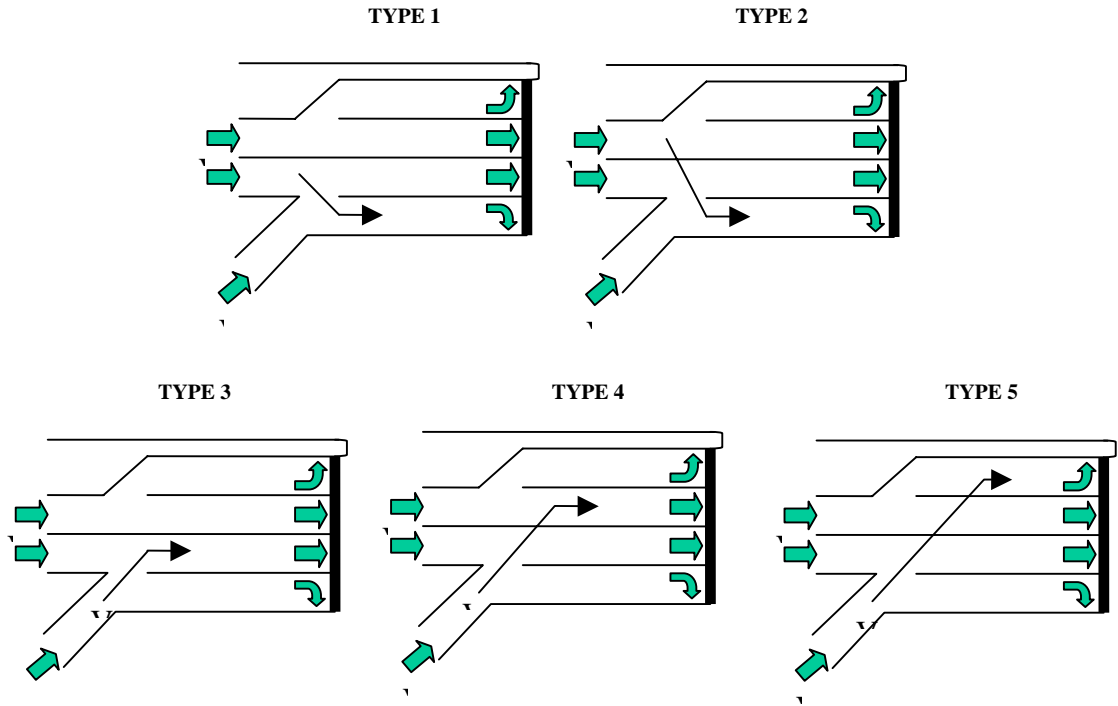


Figure 2.5: Different Types of Weaving Movements

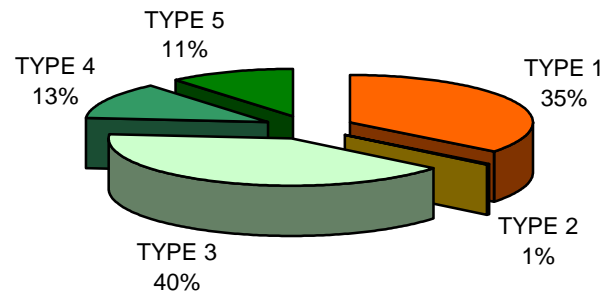


Figure 2.6: Volume Distribution

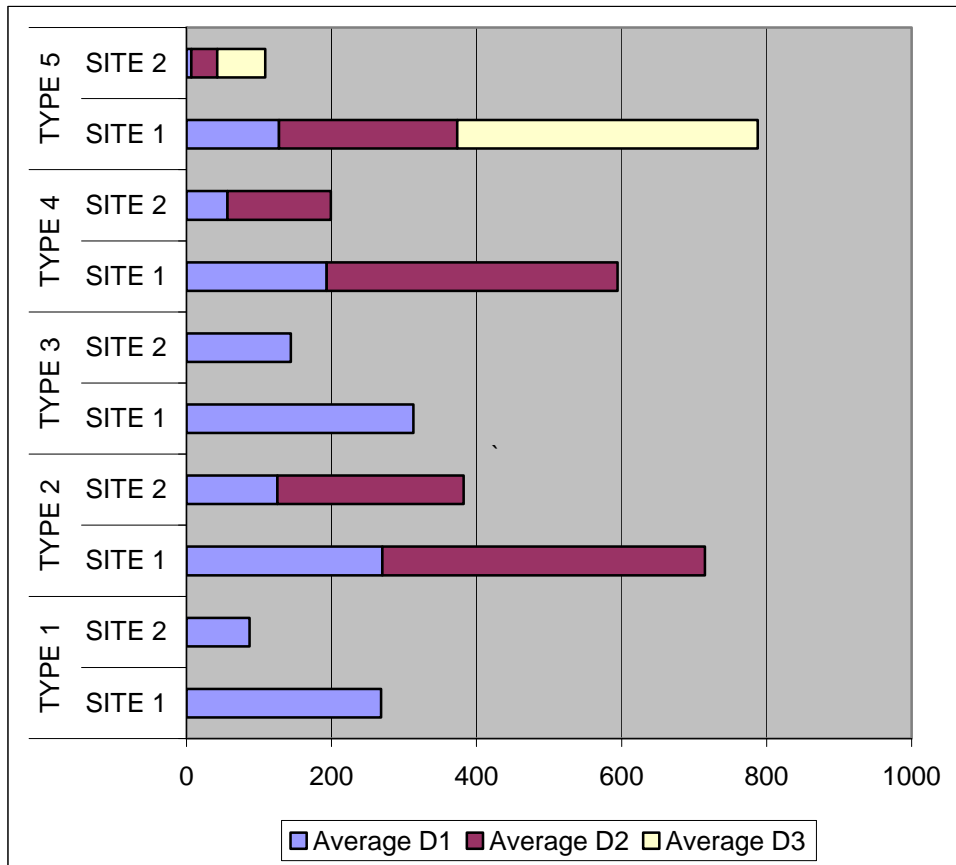


Figure 2.7: Average Weaving Distance for Different Types of Weaving

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CHAPTER 3. RIGHT TURN SPLIT, A NEW DESIGN TO ALLEVIATE WEAVING ON ARTERIAL STREETS

Introduction

Traffic weaving, as included in the 2000 Highway Capacity Manual ([HCM, 2000](#)), is only focused on freeway weaving and the manual stops short in documenting weaving on arterial streets. As show in [Figure 3.1](#), weaving on arterial streets typically occur when vehicles coming from a side street at an upstream intersection attempt to enter the main street from one side to reach access points on the opposite site at a downstream intersection by crossing one or more lanes. This paper is based on a real life problem at two sites in Florida ([Shaaban, 2004a](#) and [Shaaban, 2004b](#)). The two sites suffer from intrusive delay and unsafe conditions caused by the weaving movements generated from vehicles entering the arterial street from a side street. Since there are no guidelines on how to deal with this type of weaving movements, the goal of this paper is to study the characteristics of this type of weaving and to determine a methodology to alleviate the delay and the unsafe conditions caused by it.

Two sites were studied for the analysis. The first site was on State Road 421 between the I-95 Off-Ramp and Airport Road in Port Orange, Florida and the second site was on State Road 50 between State Road 408 Off-Ramp and Bonneville Drive in Orlando, Florida. The two sites are show in [Figure 3.2](#). The two sites exist at the exist-ramps of two diamond interchanges where the side street vehicles enter the arterial street through a free right turn lane. These two sites have the

following criteria: relatively short spacing between two signalized intersections that are running in coordination; moderate to heavy traffic volumes; and no driveways or median openings exist between the two signalized intersections. Both arterial segments had two through lanes. The downstream intersection for both sites had two auxiliary lanes, a left turn lane and a right turn lane.

Data Collection Methods and Reduction

Video cameras were used to collect the data. The cameras were used for two purposes: to record the operation of weaving movement and to obtain volume counts and turning percentages along the arterials. To be able to achieve these two goals, the cameras were positioned on a high location (the I-95 bridge and the SR 408 bridge) to cover the weaving area. The weaving area was defined as the area between the gore area at the first intersection to the stop bar at the second intersection. The cameras were zoomed in to capture the movement of each vehicle within the weaving section. In order to determine the location where the vehicle performed the weaving movement, road tubes were placed at a 100 feet spacing starting at the gore area. The tubes acted as distance meters. In addition to the video recording, aerial photographs and detailed sketches of the two sites were obtained. The sketches included the geometry of each site including the number of lanes, channelization, auxiliary lanes, and the distance between the two intersections. At each site, eight hours of data were collected on a normal weekday using the video recording equipment. The time periods were selected so that two hours in the morning period (7:00 a.m. to

9:00 p.m.), two hours in the midday period (11:00 a.m. to 1:00 p.m.), and four hours in the evening period (2:00 p.m. to 6:00 p.m.) were recorded.

The reduction of the field data involved observing the videotapes of each site. The videotapes were used to observe the weaving distance for each vehicle and also to obtain accurate counts and turning percentages along the arterial. The weaving distance is defined as the distance from the gore area to the location where the vehicle crossed to the desired lane. This method was used since it was difficult to observe the weaving movements and to count the vehicles in real time at high volumes. Acceptable accuracy of the video data is due mainly to the fact that the viewer is able to view the videotape more than one time. Therefore, the viewer can concentrate on one single movement and then when finished rewind the tape and observe a different movement. Data reduction sheets were created for each site so that the weaving distance and the origin-destination patterns of individual vehicles could be recorded. Videos were then watched in slow motion to verify the weaving distance, the origin-destination information, and the number of lane changes required to complete the movement. The origin-destination volumes, the weaving distances, number of lane changes were recorded in one-minute increments.

Data Analysis

By observing the videotapes of each site, the movements of 4,443 vehicles were tracked. It was found that there were five types of weaving movements occurred along the arterial segment. These types of movements are illustrated in [Figure 3.3](#). Type 1 and type 2 originated from the

mainline and attempted to reach the right turn lane at the second signalized intersection. Type 1 vehicles had to perform one lane change in order to complete the desired weaving maneuver. Type 2 vehicles had to perform two lane changes in order to complete the desired weaving maneuver (change one lane to the second through lane then a second lane change to the right turn lane). Types 3, 4, and 5 were the weaving movements originated from the side street free right turn lane to go through or turn left at the second signalized intersection. Type 3 vehicles had to perform one lane change in order to complete the desired weaving maneuver (move to the through lane). Type 4 vehicles had to perform two lane changes in order to complete the desired weaving maneuver (change one lane to the first through lane then a second lane change to move to the second through lane). Type 5 vehicles had to perform three lane changes in order to complete the desired weaving maneuver (the first lane change to move to the first through lane, the second lane change to move to the second through lane then the third lane change to the left turn lane).

As shown in [Figure 3.4](#), 64% of the weaving volume was originated from the side street free right turn lane (type 3, 4, and 5) and 34% was originated from the main street (types 1 and 2). The majority of weaving volume occurred between type 1 (35%) and type 3 (40%), which accounted for 75 % of the total weaving volume. Type 2 was the lowest weaving volume (1%), which indicated that most vehicles that wanted to perform the weaving movement from the main street preferred to change lanes to be in the outside through lane before entering the weaving area to minimize the number of lane changes to only one lane change. The percentage of type 4 was 13%, which indicated that some of the vehicles preferred to change two lanes to be in the inside through lane on the main street. This is probably due to the impression that the inside through

lane will be faster than the outside through lane due to less distraction after the intersection. Type 5 vehicles (11%) were the vehicles that entered from the side street and had to perform a left turn at the downstream intersection.

Breakdown Conditions

Watching the videos from the two sites lead to several conclusions regarding the breakdown conditions occurring at the two sites. It was found that the breakdown condition, caused by the weaving movements, occurred in three cases. The first case occurred when the main street through volume was extremely heavy with moving queues observed extending onto the first intersection. In this case, vehicles entering from the side street could not find adequate gaps on the main street and had to reach a complete stop waiting for a gap on the main street causing an excessive delay on the side street and increasing the potential of rear end and sideswipe collisions. An example of this case is shown in [Figure 3.5](#).

In the second case, the left turning volume at the second intersection was extremely heavy and extended beyond the left turn lane. Although the main street volumes were moderate and adequate gaps were available, vehicles entering from the side street and willing to perform a left turn at the second intersection had to completely stop blocking the free right turn lane, waiting for the left turn lane to clear, and causing excessive delay for the side street, and increasing the potential for rear end collisions. An example of this case is shown in [Figure 3.6](#).

In the third case, after waiting for the left turn lane to clear, some vehicles performed the weaving movement although no gaps were available, stopping in the middle of through lanes. This situation caused excessive delay for the main street and increased the potential of right angle collisions. An example of this case is shown in [Figure 3.7](#).

Based on the previous observations, it was found that the type 5 weaving movement was causing most of the excessive delay and the potential for rear end, angle, and sideswipe collisions. The type 5 vehicles had to perform three lane changes from the side street free right turn lane to move to the left turn lane at the downstream intersection during the different demand levels during the day. The main goal of this study was to provide a safe path for this type of weaving movement that will reduce the delay and will provide a safer environment along the arterial segment.

Proposed Design - Right Turn Split

The proposed design, Right Turn Split (RTS), is based on separating the type 5 weaving movement from the other movements before reaching the arterial street by directing the right turning vehicles from the side street to two separate right turn lanes. The additional right turn lane should be added to the side street at the stop bar. In this case, the type 5 vehicles are directed into the additional lane then to the left turn lane at the downstream intersection through the traffic signal at the upstream signalized intersection. Type 3 and 4 vehicles are directed into the free right turn lane.

In order to enforce the type 5 vehicles to use the new right turn lane at the stop bar instead of the free right turn lane, two barriers should be provided at two locations along the arterial segment. The first barrier should be placed at the gore area and between the free right turn lane and the outside through lane. The second barrier should begin at the same location where the first barrier ends but between the inside through lane and the left turn lane. The second barrier should end at the stop bar at the downstream intersection. The two traffic barriers will prevent drivers from attempting to access the left turn lane from the free right turn lane. [Figure 3.8](#) shows the existing conditions before applying the proposed design. [Figure 3.9](#) shows the proposed design, which will reduce the number of conflict points along this section by eliminating the worst weaving movement (type 5).

The proposed barrier can take different forms: delineators, painted striping, or raised concrete traffic separators. Delineators are retroreflective devices that can be mounted on grass, pavement, or raised concrete traffic separator to indicate a certain alignment, especially at night or in adverse weather. A raised concrete traffic separator is typically a six inches height of concrete barrier. The concrete barrier is commonly used between left turn and through lanes to offset opposing left turn lanes on four-lane divided roadways to improve sight distance ([4](#), [5](#)).

The three proposed barrier forms can be selected based on the right of way availability: (1) delineators only on the lane striping can be used when it is difficult to obtain any additional right of way, (2) two feet of painted striping supplemented with delineators can be used in case of limited right of way availability, and (3) four feet of raised concrete traffic separator can be used

in case of right way availability. In the last two forms, delineators should be used as an additional indication of the barrier because they will improve the visibility and reduce the potential of vehicles crossing the barrier.

A special signing arrangement is required to provide adequate signage for the side street approach in order to explain the new arrangement to the drivers. The three recommended signs shown in [Figure 3.9](#) describe the directions to the drivers. The first sign to the left will direct the vehicles to turn left at the upstream-signalized intersection. The second sign will direct the vehicles to turn right at the upstream signalized intersection then to the left turn lane at the downstream signalized intersection. The third sign will direct the drivers to the right turn lane at the upstream intersection. The signs should be placed overhead on a truss.

The Design of the Barriers

To place the two barriers, the distance from the end of the gore area to the end of the first barrier needs to be determined. This distance was called the *Split Distance*. As mentioned earlier, the second barrier starts where the first barrier ends and ends at the stop bar at the downstream intersection. The split distance should allow enough distance for the vehicles to perform all types of weaving movements except type 5. Three methods were considered to calculate the split distance.

The first method was to determine the lowest average-weaving-distance for all types of weaving except type 5. Out of the 4,443 vehicles tracked, 489 vehicles performed the type 5 weaving and were excluded from the analysis. Total of 3,954 vehicles were used in the analysis, 2,065 from Site 1 (SR 50) and 1,889 from Site 2 (SR 421). As shown in [Figure 3.10](#), it was found that type 4 had the lowest average-weaving-distance in both sites which was **193** feet for Site 1 and was **58** feet for Site 2. In addition, the weaving distances for all types of weaving for Site 1 were higher than Site 2. The main difference between the two sites was the spacing between the two intersections, which indicates that the weaving distances decreased dramatically when the spacing decreased.

The second method was to determine the most used weaving distance for all types except type 5 using the frequency distribution tables and charts. The frequency distribution table is a summary table in which the data are arranged into conveniently established, numerically ordered class groupings. The numbers of vehicles observed for each weaving distance group except type 5 were tabulated. The frequency for each weaving distance was then calculated in percentages as the number of vehicles for this weaving distance group divided by the total number of vehicles. [Figure 3.11](#) shows the frequency distribution table for the data collected for the two studied sites.

The frequency distribution curves were also created using the frequency distribution tables as shown in [Table 3.1](#). The frequency distribution curves plotted points, which represented the weaving distance for each group of vehicles versus the percentage frequency for the same weaving distance. Once the points were plotted, they were connected by a smooth curve. Then

the weaving distance for the highest point on each curve was determined. It was found that the weaving distances that occurred the most for the two studied sites were **295** feet for Site 1 and **98** feet for Site 2.

In the third method, the cumulative frequency distribution curves were prepared by plotting the weaving distance against the cumulative percentage frequency for the weaving distances for each site. The cumulative percentage frequency is defined as the percentage of vehicles that performed the weaving at or more than a given weaving distance and is shown in [Table 3.1](#). [Figure 3.12](#) shows the two charts prepared from the percentage frequency data. Once the points are plotted, they were connected by a smooth curve. The 85th percentile weaving distance was determined by entering the cumulative frequency distribution curve at 85% on the vertical axis, drawing a horizontal line to the curve, and dropping a vertical line from the intersection of the first line with the curve. The 85th percentile weaving distance is defined as the distance at or over which 85% of vehicles performed the weaving movement. It was found that the 85th percentile weaving distance was **168.7** feet for Site 1 and **39.4** feet for Site 2.

To determine the split distance, a comparison was done between the different values obtained from the three different methods to choose the lowest value. The results of the comparison are shown in [Table 3.2](#). It was found that the 85th percentile results were the lowest values, 168.7 feet for Site 1 and 39.4 feet for Site 2. Therefore, these values should define the split distance.

Conclusion and Further Study

The paper proposes the concept of RTS to alleviate the delay and unsafe conditions caused by the weaving movement on arterial streets. The design was based on a real traffic problem. Pilot studies were conducted at two arterial weaving sections in Florida to demonstrate the feasibility of the approach. The following conclusions became apparent through the course of this work:

The weaving movement performed by the vehicles entering an arterial and need to change lanes to turn at the next signalized intersection was the movement that caused the most delay and unsafe conditions for the arterial streets.

The paper proposes a new method to reduce the effect of this movement, RTS. The method is based on separating the worst weaving movement from the other weaving movements before reaching the arterial street. This was done by directing the side street vehicles to two separate right turn lanes. The vehicles are then directed to a special path on the arterial street leading to the left turn lane at the downstream intersection.

In order to enforce the vehicles to follow the proposed path, two barriers were provided along the arterial. The barriers can be in the form of delineators in case of no right of way, two feet of painted gore area supplemented with delineators for each barrier in case of limited right of way, and four feet of raised concrete traffic separator supplemented with delineators for each barrier in

case of right of way availability. Delineators were used in all cases to improve safety and to give additional guidance for the vehicles to avoid impacting the traffic separator.

To define the location of the two barriers (the split distance), three different methods were studied. The 85th percentile weaving distance was selected since it provided the lowest split distance. This 85th percentile weaving distance is defined as the distance at or over which 85% of all drivers, except type 5 drivers, performed their weaving movement. This proposed design did not require much right of way but required a special signing arrangement to explain the new path to the drivers.

The findings of this study will be used to implement the new design on the two pilot locations. It is recommended to study the effects of this design on the delay and the safety of the arterial segment after implementation.

Table 3.1: Frequency Distribution Table for Weaving Distance Data

Site 1 - SR 50				Site 2 - SR 421			
Weaving Distance (feet)	No. of Vehicles (n)	Vehicles (%)	Cum. Veh (%)	Weaving Distance (feet)	No. of Vehicles (n)	Vehicles (%)	Cum. Veh (%)
0	20	0.97%	100.00%	0	360	19.06%	100.00%
50	77	3.73%	99.03%	50	363	19.22%	80.94%
100	142	6.88%	95.30%	100	619	32.77%	61.73%
150	189	9.15%	88.43%	150	199	10.53%	28.96%
200	334	16.17%	79.27%	200	220	11.65%	18.42%
250	307	14.87%	63.10%	250	38	2.01%	6.78%
300	410	19.85%	48.23%	300	48	2.54%	4.76%
350	120	5.81%	28.38%	350	12	0.64%	2.22%
400	147	7.12%	22.57%	400	14	0.74%	1.59%
450	60	2.91%	15.45%	450	16	0.85%	0.85%
500	120	5.81%	12.54%		1889	100.00%	
550	32	1.55%	6.73%				
600	69	3.34%	5.18%				
650	8	0.39%	1.84%				
700	30	1.45%	1.45%				
	2065	100.00%					

Table 3.2: Different Split Distance Values

	Site 1 (feet)	Site 2 (feet)
Lowest Average Weaving Distance	193	58
Most Occuring Weaving Distance	295	98
85th Percentile Weaving Distance	168.7	39.4

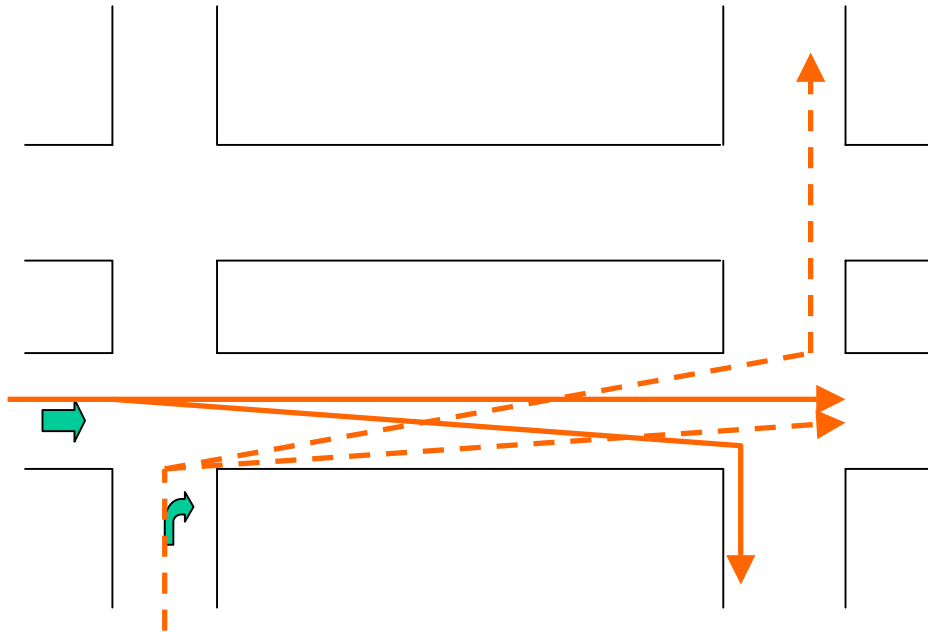


Figure 3.1: Weaving Movements Occurring Between Two Intersections

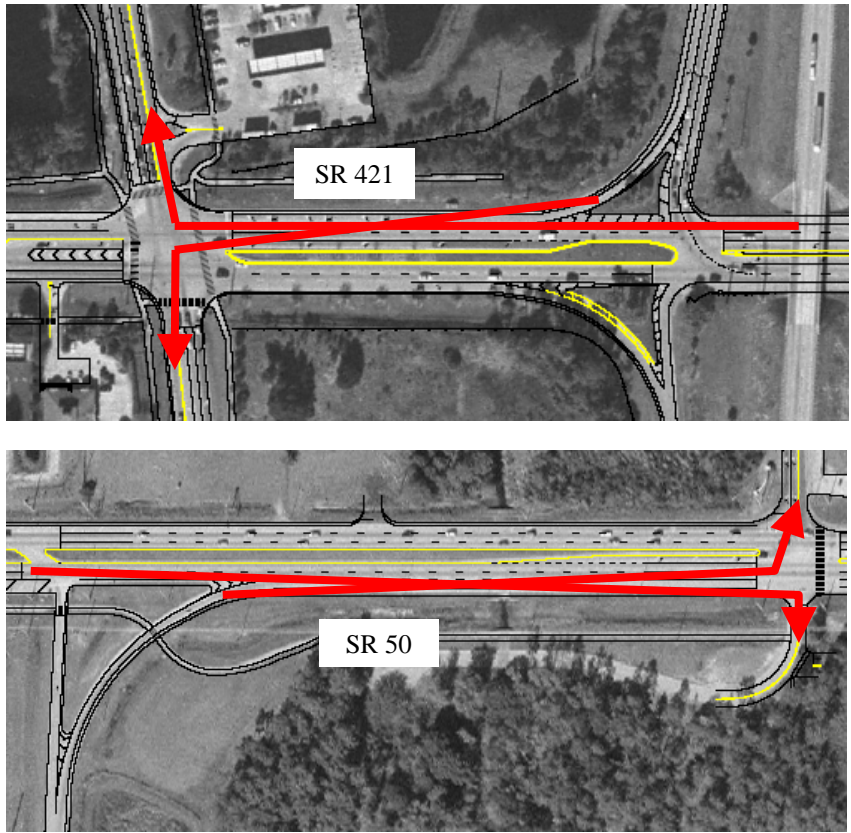


Figure 3.2: Aerial Photos for the Two Selected Sites

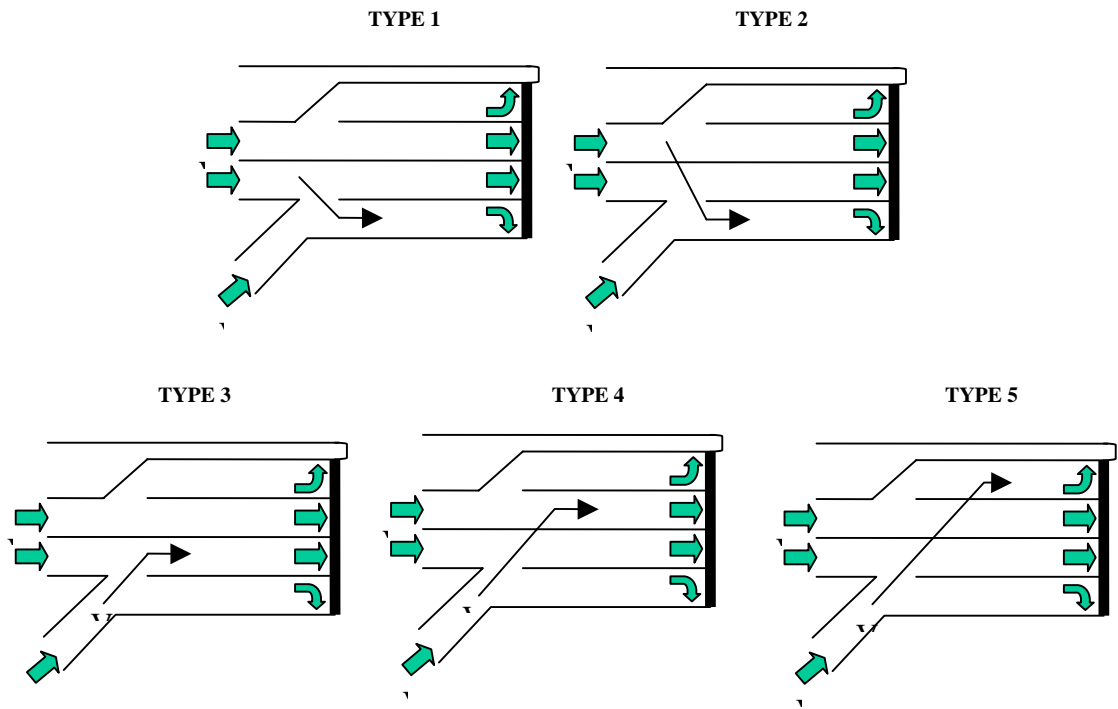


Figure 3.3: Different Types of Weaving Movements

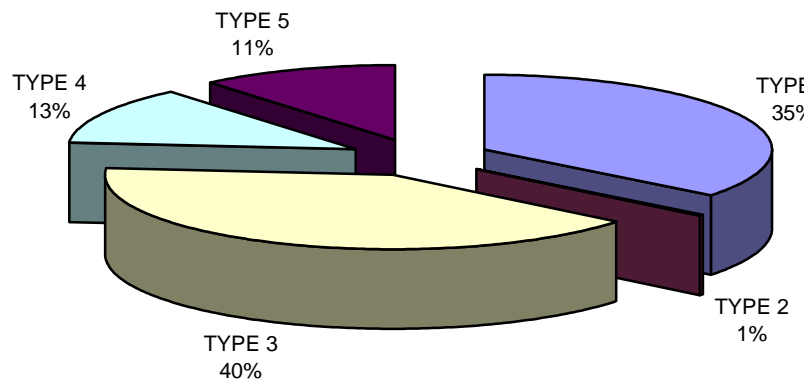


Figure 3.4: Volume Distribution



Figure 3.5: Breakdown Conditions Due To Heavy Mainline Through Volume



Figure 3.6: Breakdown Conditions Due To Heavy Mainline Left Turn Volume



Figure 3.7: Breakdown Conditions Due To Heavy Mainline Left Turn Volume And Aggressive Side Street Vehicles

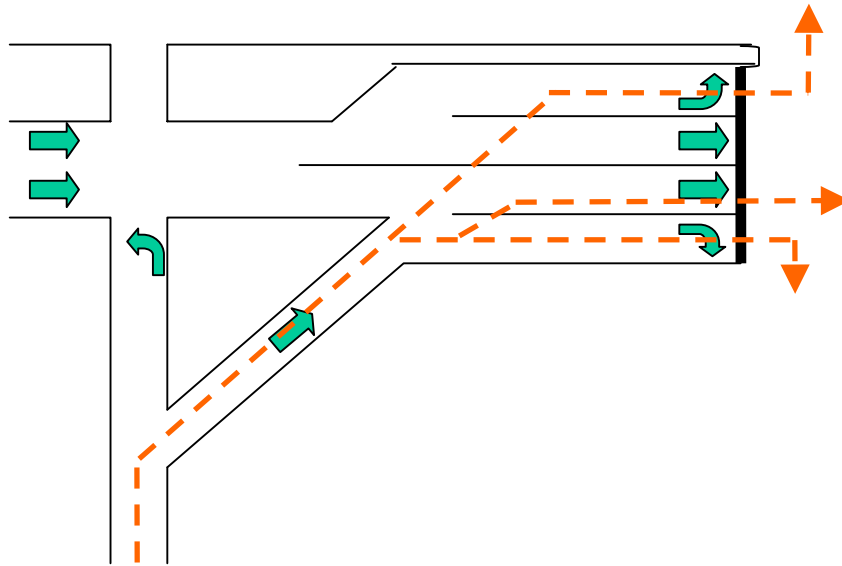


Figure 3.8: Movements Before Applying the RTS Concept

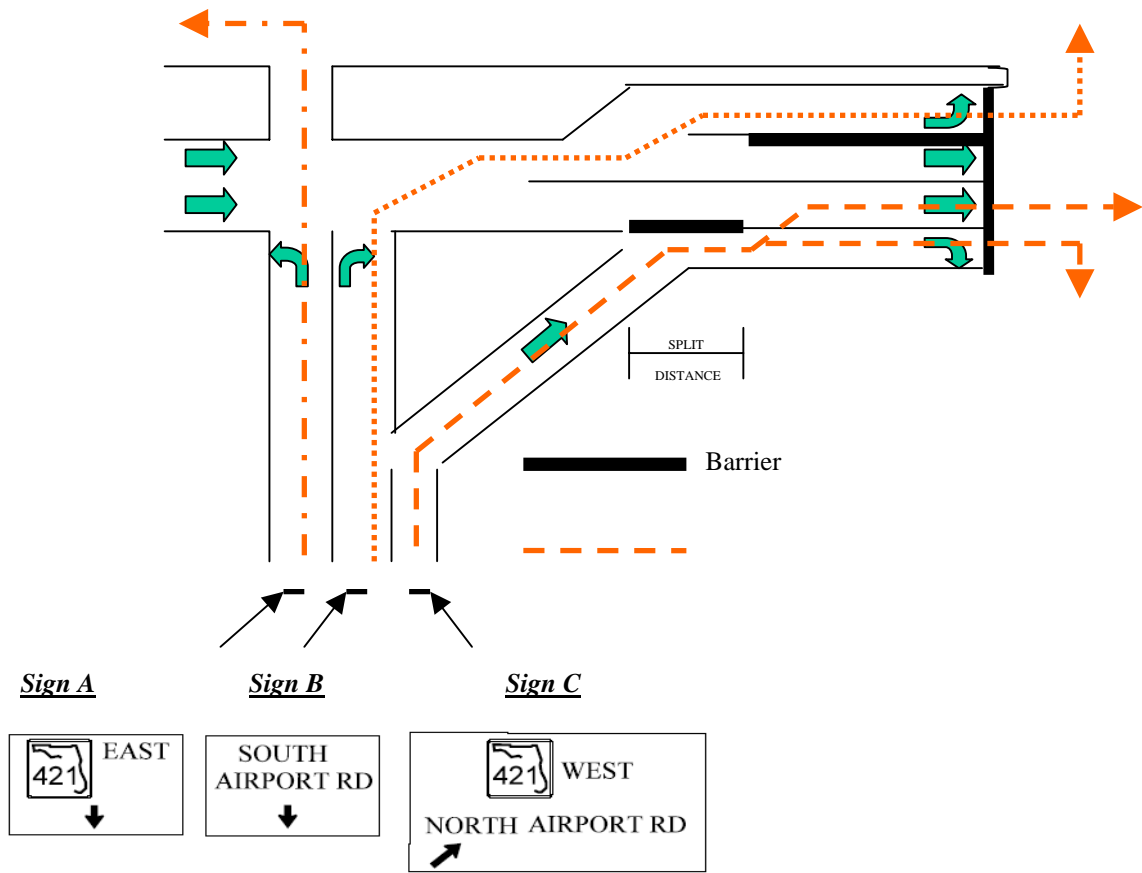


Figure 3.9. Movements After Applying the RTS Concept

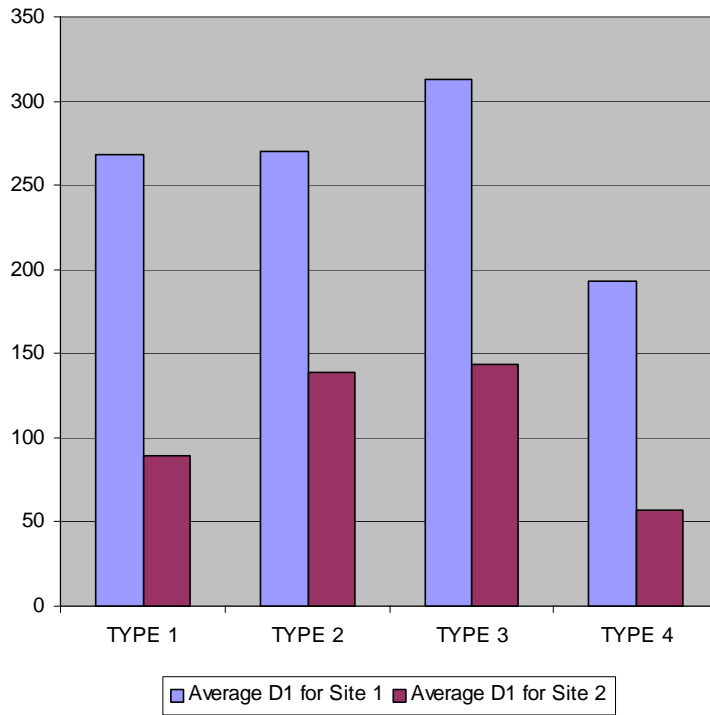


Figure 3.10: Average Weaving Distance for Different Types of Weaving

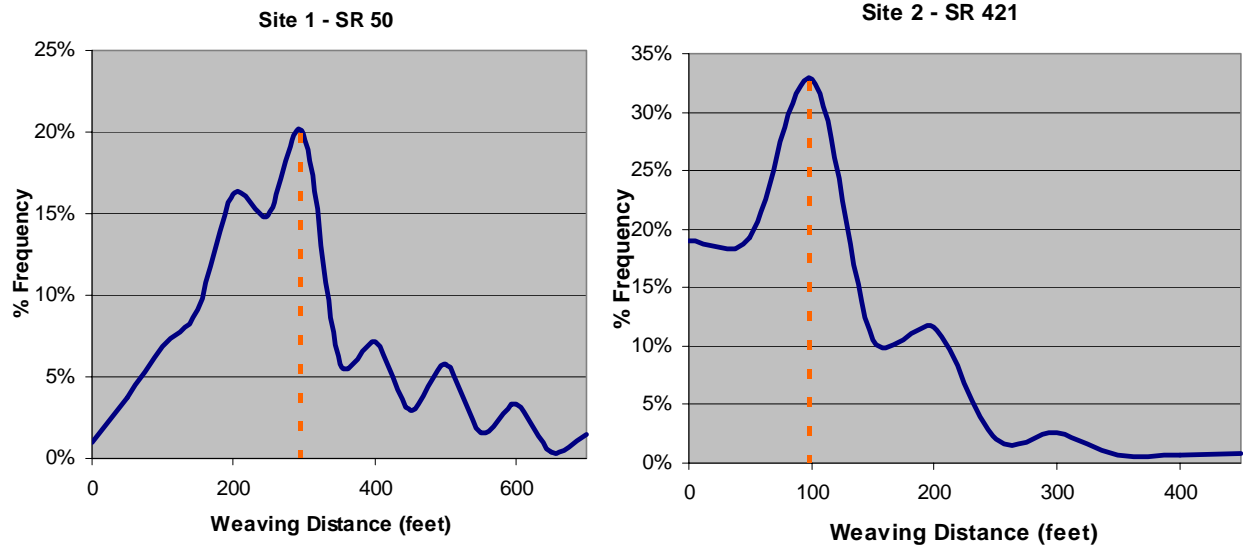


Figure 3.11: Frequency Distribution Curves for the Weaving Distance Data

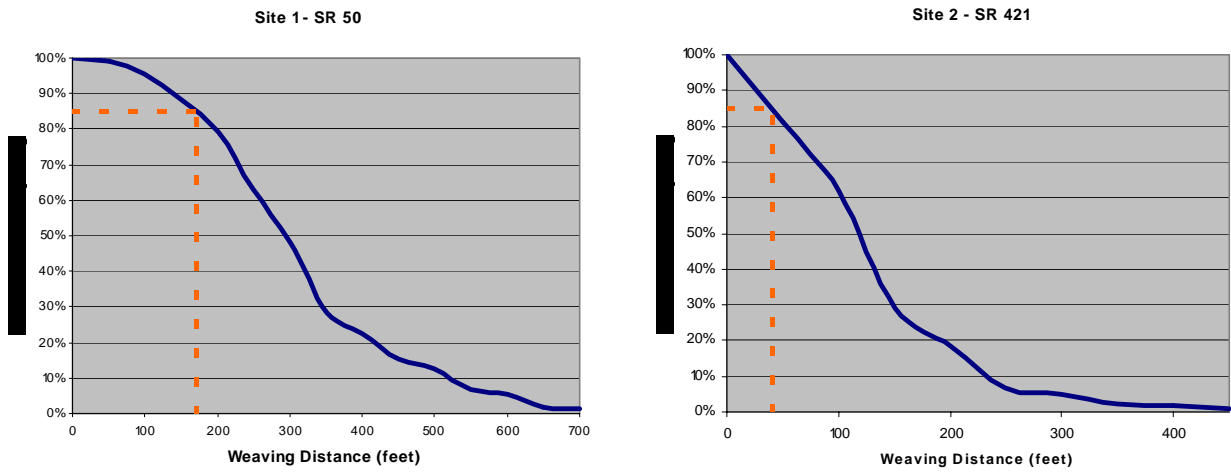


Figure 3.12: Cumulative Frequency Distribution Curves for the Weaving Distance Data

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CHAPTER 4. COMPARISON OF SIMTRAFFIC AND VISSIM MICROSCOPIC - TRAFFIC SIMULATION TOOLS IN SIGNALIZED INTERSECTIONS MODELING

Introduction

Microscopic simulation models are becoming increasingly important tools in the transportation engineering profession. These models became very popular in helping to assess the performance of a traffic network with complex components, which are difficult sometimes to model analytically. If used correctly, simulation tools allows users to conduct experiments to evaluate the traffic performance of a network under different scenarios in a fast and cost-effective way, without having to disrupt traffic operations in a real network and potentially compromise public safety. In recent years, several microscopic simulation models have been developed to analyze and evaluate arterials and signalized intersections. Two of them are SimTraffic and VISSIM, which are the subject of comparison in this paper.

SimTraffic is the simulation tool in a software couple consisting of the coordinated models, SYNCHRO and SimTraffic. SimTraffic model was developed in 1999 by Trafficware Corporation (founded in 1994) which is a privately held California Software Company headquartered in Albany, California, United States ([Trafficware, 2004](#)).

Synchro is a macroscopic traffic software program that replicates the signalized intersection capacity analysis as specified in the 2000 edition of the Highway Capacity Manual ([HCM 2000](#)). Macroscopic level models represent traffic in terms of aggregate measures for each movement at the intersections. Equations are used to determine measures of effectiveness such as delay and queue length. The analysis can then be simulated with SimTraffic simulation model. In addition to calculating capacity, Synchro can also optimize cycle lengths and splits, eliminating the need to try multiple timing plans in search of the optimum. All values are entered in easy-to-use forms. Calculations and intermediate results are shown on the same forms. If the intersection is coordinated, Synchro calculates the progression factor. Synchro is fully interactive, when a value is changed, the results are updated automatically. Synchro can also build input files for CORSIM and the HCS. The timing plans can then be simulated using SimTraffic or CORSIM for more detailed analysis. SimTraffic can be started automatically from Synchro ([Synchro User Guide, 2003](#)).

SimTraffic is a microscopic simulation model. SimTraffic has the capability to simulate a wide variety of traffic controls, including a network with traffic signals operating on different cycle lengths or operating under fully-actuated conditions. Most other traffic analysis software packages do not allow for a direct evaluation of traffic conditions operating under varying cycle lengths and traffic control ([SimTraffic User Guide, 2003](#)).

VISSIM is a microscopic, time step and behavior based simulation model developed to analyze the full range of functionally classified roadways and public transportation operations. VISSIM

model was developed at the University of Karlsruhe, Germany during the early 1970's and the commercial distribution of VISSIM launched in 1993 by PTV Transworld AG. In the U.S., ITC Incorporated distributes and supports the program ([VISSIM 3.6 User Manual, 2000](#)).

The model consists of two primary components: (1) simulator and (2) signal state generator (SSG). The simulator generates traffic where the user graphically builds the network. The SSG is separate from the simulator. It is where the signal control logic resides. Here, the user has the ability to define the signal control logic and thus emulate any type of control logic found in a signal controller manufacturer's firmware. The SSG permits the user to analyze the impacts of signal operations including, but not limited to: fixed time, actuated, adaptive, transit signal priority, and ramp metering. It is important to note that fixed time control can be implemented in the simulator. The SSG reads detector information from the simulator every time step. Based on the detector information, the SSG decides the status of the signal display during the subsequent time step ([VISSIM 3.6 User Manual, 2000](#)).

The objective of this paper is to perform a comparative evaluation of Version 6.0 of SimTraffic and Version 3.6 of VISSIM. The evaluation is based on the author's experience in coding and modeling a signalized intersection. Both simulation tools were compared in terms of graphical user interface, modeling capabilities, traffic behavior, and simulation output.

Methodology

In this evaluation, the signalized intersection of SR 421 and Airport Road in Port Orange City, Florida was used as the primary test intersection. Turning volumes counts were obtained for the intersection during the peak morning period (7:00 AM to 8:00 AM) on a typical weekday. The traffic signal timings were also obtained from the maintaining agency during the same period. A field inventory was conducted at the intersection to obtain intersection geometry and dimensions, including auxiliary turn lane lengths, lane widths, taper lengths, and turning and curb radii. In addition, an aerial map for the intersection was obtained to investigate the possibility of importing a background aerial as an aid for coding and for presentation purposes (Shaaban, 2004).

This signalized intersection, which was coded in both SimTraffic and VISSIM, was used to accomplish the evaluation tasks. Screenshots of the coded intersection in SimTraffic and VISSIM are shown in [Figure 4.1](#) and [Figure 4.2](#) respectively.

User Interface

The user interface evaluation was based on investigating the coding method and the preparation of the intersection for simulation.

Components

While VISSIM Modeler offers coding, simulation control and visualization, SimTraffic users need to first use Synchro for coding, save the file in Synchro and then load it into SimTraffic using a command in Synchro. Any changes needed have to be done in Synchro first then load it into SimTraffic.

Navigation

SimTraffic and VISSIM have similar navigation style as Microsoft Windows. For instance, scroll bars are used for navigation with similar functions of the scroll bars in Windows.

Background Graphics

Both software packages allow of a set of imported background images as an aid for coding. In SimTraffic the background has to be imported in Synchro. Synchro gives greater flexibility by accepting formats in AutoCad dxf, bitmap bmp, and jpg while VISSIM supports background in only bmp format. The background can be scaled in both software packages.

3D Objects, Animation and Video

In SimTraffic, simulations can only be viewed in 2D. In VISSIM, view can be toggled between 2D and 3D simply by clicking an icon. In addition, only VISSIM can record a video of a 3D simulation run in the AVI format that can be viewed on any computer using any video player software.

Units Setup

Both software packages allow the user to change the units from English units (feet) to Metric units (m) and vice versa.

Modelling Capabilities

In this category, the modeling capabilities of SimTraffic and VISSIM are compared.

Intersection Coding

VISSIM models streets and intersections as links and connectors. Links are defined for each approach. Each approach is represented by one link. Connectors are then used to simulate turning areas and lane expansions and compressions at the intersections. This method requires an

additional effort in coding intersections since the user has to draw the information into the model (length of left and right turn lanes, taper, path of the turning vehicles to the receiving lanes, path of a u-turn, etc.).

Synchrho models streets and intersection as links and nodes. Links are defined for each approach and nodes are defined for each intersection. Storage lengths are entered as a value and the path of the turning lanes is created automatically which reduces time and effort in entering data.

Links

In VISSIM, the link characteristics that can be entered are number of lanes (maximum 20 lanes), lane width, grade (positive values define an incline), and type of vehicles that are not allowed to use this link (useful in case of bus lane, HOV lane, etc.).

In Synchro, the link characteristics that can be entered are lane type (left, left and u-turn, through, shared through and left, shared through and right, and right), number of lanes (maximum 8 lanes), area type (CBD and other), lane width, and grade.

Curved Links

In VISSIM, curved links are formed by a group of linear section pieces. In Synchro, two curve control points set the curvature on the link. These two control points determine the start and ending tangent angles and also influence the shape of the curve. The curves in Synchro are Bezier curves and are based on cubic equations. It should be possible to approximate most curves using one or two segments. It is also possible to create a 270 degree loop ramp using 2 segments. Most other alignments should be possible with a single segment.

Special Lanes

VISSIM allows particular lanes of a link to be closed to certain vehicle types. This option can be very useful for special lanes such as HOV-only lane. Restrictions can be enforced by creating a separate vehicle type for the HOV vehicles, and by closing the HOV-only lanes to all non-HOV types. This option is not available in the SimTraffic.

Right Turn Channelization

In VISSIM, right turn channelization can be created using connectors. Connectors are used to connect links. The shape of the connectors can take the form of a curve by increasing the number

of intermediate points on the connector. This option can be done repeatedly in order to obtain the exact curve needed.

In SimTraffic, Synchro can create a right turn channelization by inputting the curve radius. This option can be done repeatedly in order to obtain the exact curve needed. The aerial map in the background can be helpful in both cases to follow the existing curve at the intersection.

Volume Entry

In VISSIM, in case of small networks or single signalized intersection, the routing decisions concept is used. This end of the link is defined as a routing decision point. Each routing decision point can have multiple destinations resembling a tree with multiple branches. These branches will represent the turning movements (left, u-turn, through, and right). Volumes are then entered to each destination as a percentage of the main volume. The disadvantage of this method is that the user has to calculate the percentage for each movement. The advantage of this method is that if for any reason the link volume changed, the percentages do not have to be changed.

In SimTraffic, volumes are entered at each intersection using Synchro. At each intersection, volumes for each movement (left, u-turn, through, and right) for each approach are entered in the appropriate cell. Volumes are entered in the form of vehicles per hour. If traffic between

intersections is not balanced, SimTraffic will assume a traffic source or sink (driveway or side street). This method is much easier for the user.

Traffic Generation and Signal Operation

Trip Generation

In VISSIM, trips are added to the entry points of each link based on the traffic volumes for this link. Vehicles enter the link based on a Poisson distribution. If the defined traffic volume exceeds the link capacity, the vehicles are stacked outside the network until space is available again. If any stacked vehicles cannot enter the network within the defined time interval, a message is written to a log file and the user is notified at the end of the simulation.

In SimTraffic, trips are added to the entry points of each link based on the volume counts at the downstream intersection. The trip generator in SimTraffic will attempt to place the vehicle in any allowed lane at either full speed, half speed or stopped. If the defined traffic volume exceeds the link capacity, the vehicles will be placed in denied entry status. Vehicles in denied entry status will be attempted to be placed in later time slices.

Car Following

In VISSIM, the model contains a psychophysical car following model for longitudinal vehicle movement. The model is based on the continuous work of Wiedmann (1974, 1991). Vehicles follow each other in an oscillating process. As a faster vehicle approaches a slower vehicle on a single lane it has to decelerate. The action point of conscious reaction depends on the speed difference, distance and driver behavior. [Figure 4.3](#) indicates the oscillating process of this approach. The thresholds of [Figure 4.3](#) are explained in an abbreviated form. Driver specific perception abilities and individual risk behavior is modeled by adding random values to each of the parameters as shown for AX ([VISSIM 3.6 User Manual, 2000](#)).

Where:

AX = Desired distance between the fronts of two successive vehicles in a standing queue.

AX = VehL + MinGap + RND1 · AXMult with RND1 normally distributed N(0.5, 0.15)

ABX = Desired minimum following distance which is a function of AX, a safety delta distance BX and the speed

ABX = AX + BX · \sqrt{v}

SDV = Action point where a driver consciously observes that he approaches a slower car in front. SDV increases with increasing speed differences ($\sqrt{\Delta v}$). In the original work of Wiedemann an additional threshold cldv (closing delta velocity)

is applied to model additional deceleration by usage of the brakes with a larger variation than SDV.

OPDV = Action point where the following driver notices that he is slower than the leading vehicle and starts to accelerate again. The variation of OPDV is large (Todsiev, 1963).

SDX: = Perception threshold to model the maximum following distance which is about 1.5 - 2.5 times ABX.

A following driver reacts to a leading vehicle on up to a certain distance, which is about 150 m. The minimum acceleration and deceleration rate is set to be 0.2 m/s². Maximum rates of acceleration depend on technical features of vehicles, which are usually lower for trucks than the personal desire of its driver. The model includes a rule for exceeding the maximum deceleration rate in case of emergency. This happens if ABX is exceeded. The values of the thresholds depend on the present speed of the vehicle. [Figure 4](#) denotes the values for two different speeds to display a current set of values.

In SimTraffic, the model contains two car-following models; fast following model and slow following mode. SimTraffic's car following model will attempt to have the trailing car following the leading car with 1 second of headway between vehicles. Fast following is used when the leading vehicles is above 2 ft/sec. The following formulas are used for fast following:

$$D_{safe} = DBv + \min (spdU^2 - spdV^2, 0) / 2 * decelNormal - spdV * HW$$

Where:

Dsafe = distance between vehicles

SpdU = speed of leading vehicle

SpdV = speed of trailing vehicle

DBv = distance between vehicles

HW = desired headway

Slow following is used to track a slow or stopped vehicle or to stop at a fixed point such as the stop bar. SimTraffic defines a number of acceleration rate used depending on the situation involved. The maximum possible deceleration rate (decelMax) is 12 ft/s², this is normally reserved for crisis situations such as a driver decelerate suddenly on a yellow light. To slow for an upcoming turn, vehicles will decelerate at 4 ft/s², this is decelNormal. The minimum possible acceleration (accelMin) is 2 ft/sec². For slow following, the following methods are used:

$$DB2 = DBv - 2 * spdU / 10$$

$$dv2 = (spdV + 2 * accelMin / 10)^2 / (2 * DB2)$$

$$dv4 = (spdV + 4 * accelMin / 10)^2 / (2 * DB2)$$

$$dv6 = (spdV + 6 * accelMin / 10)^2 / (2 * DB2)$$

Where:

DB2 = new distance between vehicles after 0.1 second

dv2 = deceleration required after acceleratinh at 2 * accelMin

dv4 = deceleration required after acceleratinh at 4 * accelMin

dv6 = deceleration required after acceleratinh at 6 * accelMin

- If dv_2 , dv_4 , or $dv_6 > -decelNormal$ then the vehicle will accelerate by $2*accelMin$, $4*accelMin$, or $6*accelMin$ respectively subject to the vehicle's maximum acceleration capabilities.
- If $dv_2 < -decelNormal$ then $dV = -spdV_2 / (2*DB_2)$
- If $DB_2 < 0$ then $dV = -decelMax$

Where:

DV = recommended acceleration (deceleration)

The acceleration must be greater or equal to $-decelMax$ and less than or equal to the vehicle's maximum acceleration capabilities.

Lane Changing

In VISSIM, a hierarchical set of rules is used to model lane changes. A driver has a desire to change lane if he has to drive slower than his desired speed due to a slow leading vehicle or in case of an upcoming junction with a special turning lane. Then the driver checks whether he improves his present situation by changing lanes. Last he checks whether he can change without generating a dangerous situation. In case of multi-lane approaches towards intersections this method will lead to evenly used lanes unless routing information forces vehicles to keep lanes.

Lane changing in SimTraffic is described in [Figure 4.5](#) where:

- The Mandatory Distance is the distance back from the stop bar where a lane change must commence. If a vehicle is not able to commence its lane change before this point, it will stop and wait for an opening. Vehicles in the next lane will cooperate to allow this vehicle to merge in.
- The Positioning Distance is the distance back from the Mandatory point where a vehicle first attempts to change lanes. The positioning distance is added to the Mandatory distance. Beyond the positioning distance, vehicles are unaware about upcoming lane change requirements.

For the first 2/3 of the distance between the positioning point and the mandatory point vehicles will attempt a positioning lane change. Aggressive drivers will ignore positioning lane changes and even move the other way to avoid a queue. Some driver types will not cooperate with positioning lane changers. After the 2/3 point, vehicles will attempt a mandatory lane change. All vehicles are forced to cooperate with mandatory lane changers. In the mandatory zone, vehicles will match the speed of the target lane and merge as soon as conditions are available.

Actuated Signal Operation

Since the studied intersection was operating under an actuated signal, only this option was compared in the two packages. In VISSIM, in order to model an actuated signal, an external signal state generator should be used. This signal state generator allows users to define their own signal control logic including any type of special features (e.g. transit priority, railroad

preemption, emergency vehicle preemption, etc.). VISSIM models detectors as a network element of user-definable length. A message impulse is transmitted to the signal controller as soon as a vehicle reaches this element with its front and another one when it leaves it with its tail. This information is then interpreted by the signal control logic.

In a SimTraffic actuated-coordinated signal, each phase has a start time and an end time. The end time is the force-off point for actuated phases and the yield point for coordinated phases. When the coordinated phases reach their first yield point, the phases enter Ready to Yield state. While in Ready to Yield state, the signal can yield to any actuated phase when its start time appears. Once all the coordinated phases yield, the signal enters Yielded State. In Yielded State all actuated phases are serviced in turn until the actuated phases reappear. Any unused time from actuated phases can be used later by other actuated phases. Each actuated phase is terminated when it gaps out or at its yield point, whichever comes first. When both coordinated phases come back, the signal enters Display Main State. The signal remains in Display Main State until the first yield point. No actuated phases can be displayed during this state.

In SimTraffic, extension detectors are placed according to the detector settings. If the detection zone is greater than 100 ft (30 m), two detectors are placed. If the detection zone is greater than 200 ft (60 m) long, three detectors are used. The size of the detectors when two or more are used is 6 ft (1.8 m). If there is no extension detector within 20 ft (6 m) of the stop bar, a calling only detector is assumed at the stop bar. This calling detector will only place calls when the phase is not green.

Simulation Output

VISSIM creates different types of output files (text files) that contain information about the Measures of Effectiveness such as travel times, delay times, and queues. Some evaluations may result in an online window representation such as signal times table. The text files use semicolons as delimiters and they can easily be imported in spreadsheet applications in order to use them for further calculations or graphical representation.

SimTraffic contains a number of reports to report on the Measures of Effectiveness such as speed, delay, stops, queuing, fuel consumption, and emissions. SimTraffic reports are organized by intersection and are labeled with street names and lane groups. The reports in SimTraffic are configurable allowing the level of detail, the measures of effectiveness included, and arterials summaries to be listed.

Other Considerations

Technical Support

Both VISSIM and SimTraffic have websites. The website for VISSIM is <http://www.english.ptv.de/> and the website for SimTraffic is <http://www.trafficware.com>. On the websites, information on their software and downloads can be obtained. Both VISSIM and

SimTraffic offer a great service to their customers. The user can attach the simulation file to an Email along with a brief statement of the problem. The technical support will run the simulation and reply with a response. SimTraffic can be downloaded from the website as a demo. The demo version allows for example files to be viewed and simulated. However, files cannot be edited. In addition, a demo version for VISSIM can be ordered through the website. It can be ordered by filling an Order Demo Form from the VISSIM website. Discussion groups are also available for users of VISSIM and SimTraffic to share ideas and post messages and questions.

Documentation

To majority of the users, program documentation is the most important source of reference. VISSIM and SimTraffic provide comprehensive information on the functions and traffic models in their manuals. Both manuals are straightforward in organization and explain the functionality of each of the menus, buttons, and other controls available for the user.

Price

According to the SimTraffic website, a single user license for Synchro 6 plus SimTraffic 6 costs \$3,099. This price includes license, software, manuals, and 2 years free technical support. Each product can be bought separately. The price of the Synchro 6 package is \$2,299 and the price of the SimTraffic package is \$999 ([Trafficware website, March 2004](#)).

There was no information available on the VSSIM website about the price ([ITC-World website, March 2004](#)). By calling the customer service, a list for prices was obtained for the latest version of VISSIM (version 3.7). The evaluation in this research work was conducted using VISSIM version 3.6. The price list contains three levels of prices (I, II, and III). The main difference between level I and II is the 3D animation/AVI creation tool in Level II. Level III has additional capabilities of modeling transit and advanced signal features such as railroad preemption and basic bus and light rail priority. Level I price is \$2,000, Level II price is \$4,000, and Level III price is \$15,000. For the purpose of this research, Level II price was used in the comparison with SimTraffic. According to the VISSIM website, a VISSIM license comes with the software, a hardware lock, users manuals, and free software update for one year from date of purchase. Level II price was used for the purpose of this study comparison.

Summary

The comparisons of the different aspects of VISSIM and SimTraffic have been summarized in Table 1. Each component is given a rating in the scale of 1 to 3 where 3 indicates a “Very Good” level, 2 indicates an “Acceptable” level, and 1 indicates a “Need Improvements” level. Depending on the different requirements, users can choose the model that suits their needs. This comparison was based on the authors’ experience in using VISSIM and SimTraffic in modeling one signalized intersection. Both VISSIM and SimTraffic were run with the default parameter values. Updated versions are constantly being released by developers. The results of this

evaluation may be different for a different type of analysis or for different versions of SimTraffic and VISSIM.

It should be noted that a new version of VISSIM (version 3.7) became available in the market by the time this paper was written. The evaluation conducted in this paper did not take into consideration any new additions or features in the new version of VISSIM. According to the VISSIM website, one of the main changes in the latest version of VISSIM is the capability of importing the data from a Synchro file into VISSIM.

Table 4.1: Summary of Evaluation Results

Criteria	VISSIM	SimTraffic
Components	3	2
Navigation	3	3
Background Graphics	2	3
3D Objects, Animation and Video	3	1
Intersection Coding	1	3
Links	3	3
Curved Links	2	3
Special Lanes	3	1
Right Turn Channelization	2	3
Volume Entry	2	3
Signal Timing	2	3
Actuated Phasing	2	3
Simulation Output	2	3
Technical Support	3	3
Documentation	3	3
Price	3	3

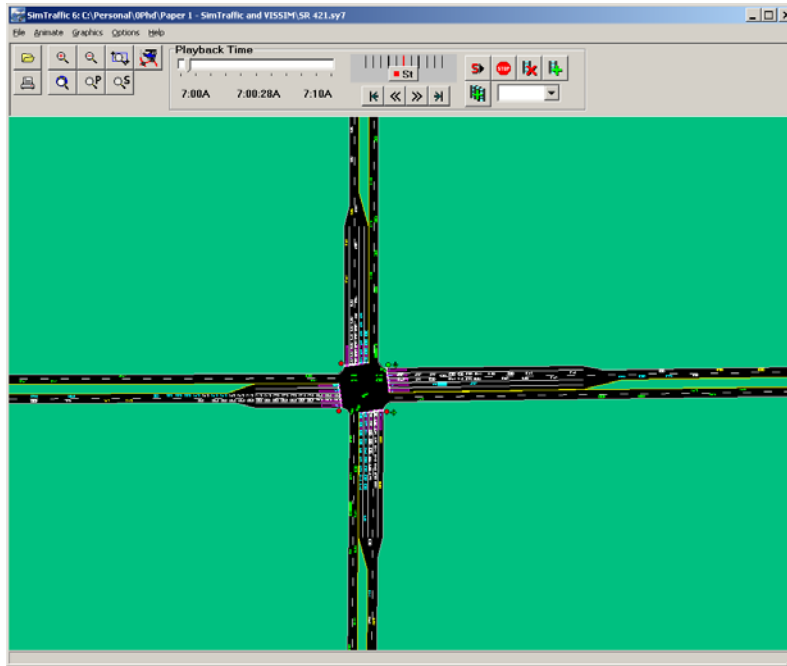


Figure 4.1: Studied Intersection Loaded in Version 6.0 of SimTraffic Modeler.

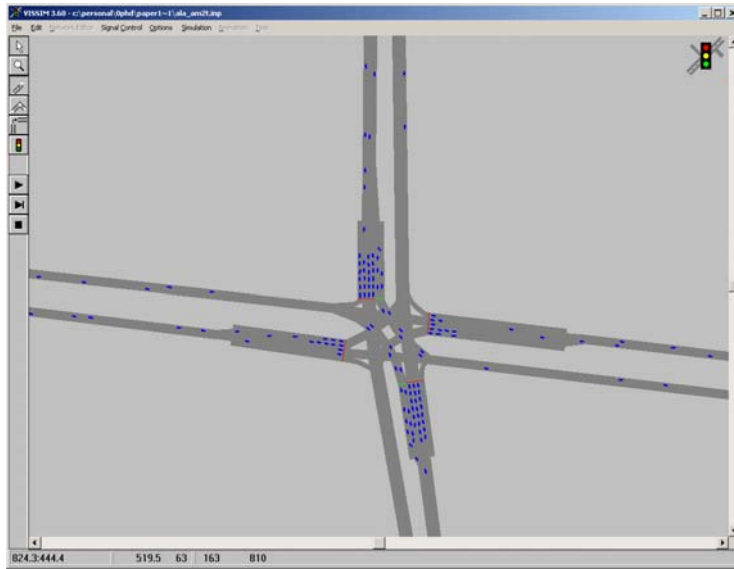


Figure 4.2: Studied Intersection Loaded in Version 3.6 of VISSIM Modeler.

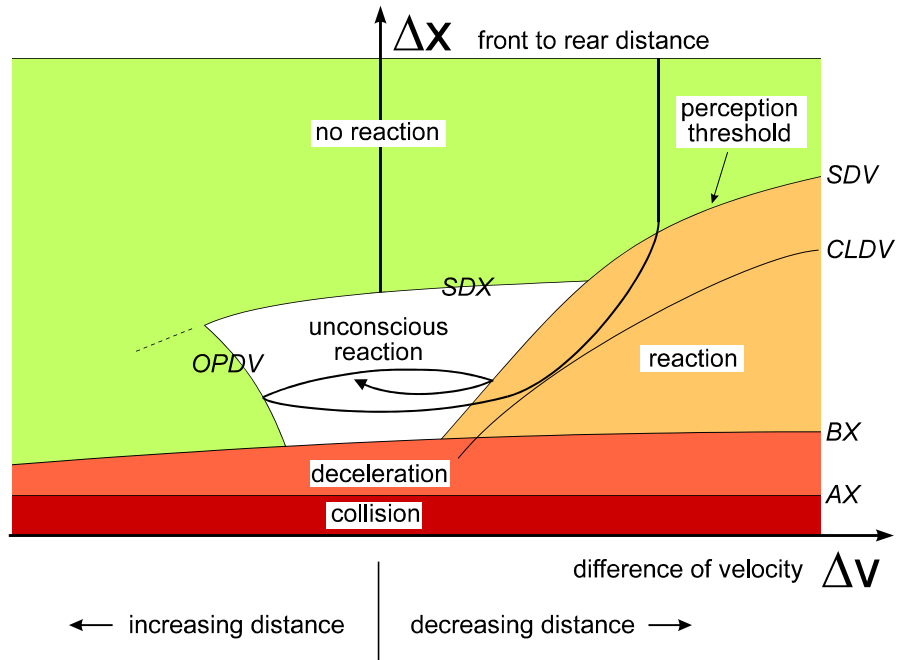


Figure 4.3: Car-following Model of Wiedemann.

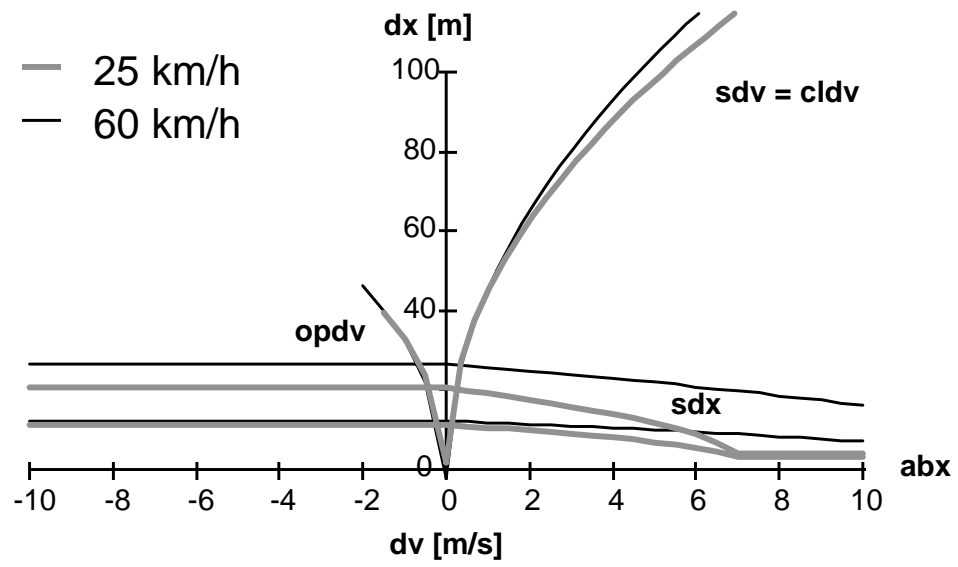


Figure 4.4: Car-following Thresholds Used in Urban Situations as a Function of the Speed

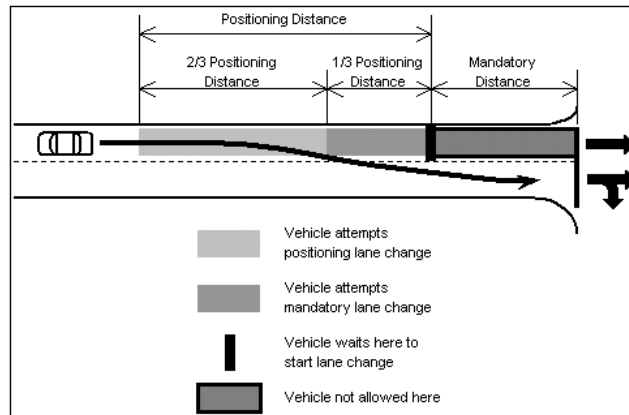


Figure 4.5: Lane Changing in SimTraffic

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CHAPTER 5. A CALIBRATION AND VALIDATION PROCEDURE FOR MICROSCOPIC SIMULATION MODEL - A CASE STUDY OF SIMTRAFFIC FOR ARTERIAL STREETS

Introduction

Microscopic simulation models are becoming increasingly important tools in modeling transport systems because simulation is faster, safer, and less expensive than field implementation and testing. While these simulation models can be beneficial, the models must be calibrated and validated before they can be used to provide meaningful results.

Microscopic simulation models contain several independent parameters to describe traffic control operation, traffic flow characteristics, and the driver behavior. These models contain default values for each parameter, but the user also is allowed to input a range of values for each parameter. Changing the values of these parameters during calibration should be based on field measurements or conditions.

Several methods have been established to provide a calibration process for different microscopic simulation models for arterial streets. Hellinga (1998) proposed a calibration process consisting of seven steps: i) defining study goals and objectives, ii) determining required field data, iii) choosing measures of performance, iv) establishing evaluation criteria, v) network representation, vi) driver routing behavior, and vii) evaluation of model outputs. This process

provides basic guidelines, but does not give a direct procedure for conducting calibration and validation.

Park and al. (2003) described a calibration process consisting of nine component steps: i) determination of measures of effectiveness, ii) data collection, iii) identification of calibration parameters, iv) experimental design, v) run the simulation “N” times, vi) development of a surface function, vii) determination of parameter sets based on surface function, viii) evaluation of parameter sets, ix) collection of new data set for validation. This process was demonstrated through a case study. The procedure focused on the calibration and validation for the microscopic simulation model VISSIM for signalized intersections. The study utilized a single day of data collection and two measures of performance. The proposed procedure appeared to be effective in the calibration and validation for the model.

Merritt (2004) proposed a methodology for calibration and validation of the stochastic microscopic traffic simulation model CORSIM, focusing on Swedish road traffic conditions. The test site consists of a five-kilometer section of an arterial road in Sweden. The procedure proposed consisted of seven steps: i) case study design, ii) identification of calibration parameters, iii) data collection, iv) measures of effectiveness and goodness-of-fit, v) confidence interval, vi) validation with independent data set, and vii) criteria for model evaluation. The study utilized two time periods, characterizing midday and a morning traffic scenario and four measures of performance. Field data from the midday traffic scenario were used to calibrate CORSIM, while the morning traffic scenario was used for the validation process. The proposed

procedure showed that the quality of the model is improving and applicable to Swedish road traffic conditions.

The objective of this paper is to propose a calibration and validation procedure and to apply it to the microscopic simulation model SimTraffic. The calibration and validation process was developed using real data collected from two test sites in Florida.

Test Site and Simulation Model

Test Sites

The criteria used to select the arterial segment included:

- segment that is located between two signalized intersections that are running in coordination;
- segment that experienced moderate to heavy road volumes; and
- segment with relatively short spacing between the two signalized intersections.

These criteria were selected to calibrate a model that can be used to study the weaving movements between two signalized intersections. Two sites were selected for the analysis. One site was used for the calibration process and the other was used in the validation process. The first site was on State Road 421 between the I-95 Off-Ramp and Airport Road in Port Orange,

Florida and the second site was on State Road 50 between State Road 408 Off-Ramp and Bonneville Drive in Orlando, Florida. Aerial photos for both sites are shown in **Error!**
Reference source not found..

Simulation Model - SimTraffic

SimTraffic (2003), developed in 1999 by Trafficware Corporation, is the simulation tool used in this paper. SimTraffic is one part of a software couple consisting of the coordinated models, Synchro and SimTraffic. SimTraffic is a microscopic simulation model that has the capability to simulate a wide variety of traffic controls, including a network with traffic signals operating on different cycle lengths or operating under fully-actuated conditions. SimTraffic Version 6.0 was the version used in this research.

Synchro (2003) is a macroscopic traffic software program that implements the Intersection Capacity Utilization method for determining intersection capacity. This method compares the current volume to the intersection ultimate capacity. Synchro also implements the methods of the 2000 edition of the Highway Capacity Manual for signalized intersections. Macroscopic level models represent traffic in terms of aggregate measures for each movement at the intersections. Equations are used to determine measures of effectiveness such as delay and queue length. The analysis can then be simulated with SimTraffic simulation model. In addition to calculating capacity, Synchro can also optimize cycle lengths and splits, eliminating the need to try multiple timing plans in search of the optimum. All values are entered in easy-to-use forms. Calculations

and intermediate results are shown on the same forms. If the intersection is coordinated, Synchro calculates the progression factor. Synchro is fully interactive, when a value is changed, the results are updated automatically. Synchro can also build input files for CORSIM and the HCS. The timing plans can then be simulated using SimTraffic or CORSIM for more detailed analysis. SimTraffic can be started automatically from Synchro. Synchro Version 6.0 was the version used in this research.

Traffic Characteristics

SimTraffic employs a formula that makes vehicles track the leading vehicle at a fixed headway. The headway depends on driving speed, driver type, and link type. This control over the headway allows SimTraffic to be adjusted to capture local speed, headway and saturated flow rate conditions.

In SimTraffic, the maximum possible vehicle deceleration rate is 12 ft/s^2 , vehicle decelerates at 4 ft/s^2 when turning, and between 4 ft/s^2 and 8 ft/s^2 when changing lanes. For acceleration rate in SimTraffic, each vehicle type has a maximum acceleration rate. Ten types of vehicles are available in SimTraffic. Vehicle can accelerate at the maximum acceleration at speed 0, and have zero acceleration at the vehicle's maximum speed. The maximum acceleration rate declines linearly as speed increases. The maximum acceleration varies in SimTraffic by vehicle type between 2 and 10 ft/s^2 at 0 mph. In SimTraffic the reaction time to a green light varies by driver type between 0.5 and 0.2 seconds. The reaction time to yellow lights ranges by driver type

between 0.7 to 1.7 seconds. In SimTraffic all turns have the same speed but the turning speed of each link can be changed independently. The turning speeds defaults to 13 ft/s for right turns and 22 ft/s for left turns. As mentioned before, turning vehicles decelerates at 4 ft/s^2 .

Signal Characteristics

SimTraffic is capable to stimulate pre-timed, semi-actuated, and actuated signal operations as well as coordinated control strategies. Synchro, the macroscopic analytical software associated with SimTraffic, is capable of calculating signal optimization and delay estimation using its deterministic model analogous to HCS and TRANSYT-7F. These capabilities reduce the work during the design of signal phasing and timing for an intersection.

Geometry Characteristics

An intersection is represented in SimTraffic as a node and the streets as links. The link length is defined in SimTraffic as the distance between the upstream and the downstream intersections. Thus, the link length does not need to be specified because the length is calculated automatically by the system using the coordinates of the central points of intersections. In SimTraffic, exclusive left turn lanes are assumed in the median if the specified length of the left turn is shorter than the link length. The median width is equal to the maximum width of the left turn lanes at the immediate intersection. The median for each end of a link is calculated

independently so it is possible to have medians expanding for both left turn lanes. If there are left turn lanes at both ends of a link, the left turn lanes share the same median width. In order to have through lanes in a link aligning between intersections, in both models, the median for the approach with the thinner median will have its median widened, but only at the end of the link at the intersections.

Proposed Procedure

The proposed procedure developed for the calibration and the validation process consists of the following eight steps: i) identification of measures of effectiveness; ii) data collection; iii) identification of calibration parameters; iv) determination of number of simulation runs per scenario; v) determination of total number of simulation runs; vi) visualization of the animation; vii) relative error; and viii) validation with a new data.

1- Identification of Measures of Effectiveness

In this step, appropriate measures of effectiveness should be determined. Measures of effectiveness could be average travel time between two data collection points in a network, travel time for a specific lane, queue length, speed, delay, etc. Some measures of effectiveness are easy to collect in the field such as the queue length. Other measures of effectiveness such as speeds or delays are not easy to obtain in the field.

In the case study, two measures of effectiveness were selected for the calibration and validation process. These two measures of effectiveness are the maximum queue length between the two signalized intersections in feet and the travel distance on the right-most lane in miles. The maximum queue is obtained from the field by multiplying the number of vehicles that completely stop in the queue by 20 feet (15 feet length of the car plus 5 feet distance between the stopped cars). The travel distance is simply a summation of the vehicle distance traveled on the right-most lane in miles. The right-most lane was selected because it had the lowest volume, which will make it easier to monitor. These performance measures were used because of their ease to obtain from the field and from the SimTraffic outputs. Other measures of effectiveness such as delays are hard to obtain in the field but could be obtained from the SimTraffic outputs.

2- Data Collection

Data collection for the two studied sites took place over one day at each site in February 2004. At each site, eight hours of data were collected on a normal weekday using video recording equipment. The time periods were selected so that two hours in the morning period (7:00 a.m. to 9:00 p.m.), two hours in the midday period (11:00 a.m. to 1:00 p.m.), and four hours in the afternoon period (2:00 p.m. to 6:00 p.m.) were observed. The reason for collecting data for different time periods during the day is to make sure that the model is calibrated and validated for different demand levels during the day including different timing plans during the day.

Video cameras were used to collect the data. The cameras were used for three purposes: i). to obtain accurate counts and turning percentages along the arterials, ii) to determine the maximum queue length between the two intersections, and iii) to determine the travel distance for the right-most lane.

To be able to achieve these three goals, the cameras were positioned on a high position (on the I-95 bridge at the first site and on the SR 408 bridge at the second site) to cover the arterial street between the two signalized intersections. [Figure 5.2](#) shows pictures taken from the video cameras positions. The cameras were zoomed in to capture the movement between the two signalized intersections. In order to determine the travel distance on the right-most lane, road tubes were placed at a 100 feet spacing starting at the gore area. The road tubes acted as distance meters. The cameras recorded the location where every vehicle entered the right-most lane and the road tubes determined the distance from this location to the stop bar at the downstream intersection. [Figure 5.3](#) shows the road tubes placement on one of the sites. In addition to the video, aerial photographs of the two sites were obtained and detailed sketches of each site were also constructed. These sketches included the geometry of each site including the number of lanes, channelization, auxiliary lanes, and the distance between the two signalized intersections. Finally, phases, splits, minimum green times, offsets, gap out times were obtained from the maintaining agency. This information was necessary for the data entry in the simulation model.

3- Identification of Calibration Parameters

The following section describes the SimTraffic parameters used in the calibration process and their acceptable ranges. These parameters include the travel speed, the turning speed, the headway factor, and the lane change distance. These parameters were selected since they have the greatest effect on arterial streets, which are the study focus.

Travel Speed

The travel speed is defined in SimTraffic as the normal safe speed which cars travel along the link, usually the speed limit. This speed should be the free flow speed and not field observed speed reduced for traffic congestion and signal delay. The existing speed limit on the studied site was 45 miles per hour. Acceptable ranges for the travel speed were determined to be 35 miles per hour and 55 miles per hour. The lower value was selected because it did not seem reasonable for a vehicle to have a desired speed of 30 miles per hour and the higher value was selected because 60 miles per hour seemed too high for this urban road.

Turning Speed

The turning speed is the speed for vehicles while inside the intersection. This information is entered in Synchro but only used when modeling in SimTraffic. The turning speed defaults to 9

miles per hour for right turns and 15 miles per hour for left turns. In SimTraffic, the turning speeds of each link can be changed independently. SimTraffic assumes a deceleration rate of 4 ft/s^2 when approaching a turn. Acceptable ranges for the turning speed were determined to be 7 to 11 miles per hour and 12 to 18 miles per hour. They values were selected based on approximately plus and minus twenty percent of the default speed.

Headway Factor

SimTraffic uses the link's headway factor to adjust headways and thus saturated flow rates for individual lane groups. The headway factor is a factor based on the lane width, the grade, the parking, the bus stops, and the area type. By default, the headway factor in SimTraffic is 1.0. This value is calibrated to give flow rates of about 1850 vehicles per hour per lane (vphpl) for speeds above 30 mph. This flow rate is typically experienced by urban traffic conditions. The SimTraffic manual recommends a headway factor of 0.9 for saturation flow rate of 2050 vphpl, and 0.8 for saturation flow rate of 2250 vphpl. For the case study, arterial streets, the acceptable range used for this parameter was 0.9 to 1.1. Larger or smaller values seemed unreasonable.

Lane Change Distance

The lane change distance in SimTraffic is the sum of two distances: i) the mandatory distance and ii) the positioning distance. The mandatory distance is the distance back of the stop bar

where a lane change must commence. If a vehicle is not able to commence its lane change before this point, it will stop and wait for an opening. Vehicles in the next lane will cooperate to allow this vehicle to merge in. The default value of the mandatory distance is 200 feet. The positioning distance is the distance back from the mandatory point where a vehicle first attempts to change lanes. The default value for the positioning distance is 300 feet. The positioning distance is added to the mandatory distance as shown in [Figure 5.4](#) to form the lane change distance. Beyond the positioning distance, vehicles are unaware about upcoming lane change requirements. The SimTraffic manual recommends an adjustment in the range of 50% to 200% to both distances. Acceptable values for the mandatory distance were 100 and 400 feet and for the positioning distance were 150 to 600 feet.

Three values per parameter were used in the calibration process. All possible combination scenarios of these variables and levels were performed for each hour of the eight hour counted at the first site. The process is $3 \times 3 \times 3 \times 3 \times (8 \text{ hr})$ factorial designs resulting 648 cases.

4- Determination of Number of Simulation Runs Per Scenario

SimTraffic is a stochastic simulation model, which reply upon random numbers to release vehicles, assign vehicle type, select their destination and their route, and to determine their behaviors as the vehicles move through the network. Therefore, multiple simulation runs using different seed numbers are required and the average results of several simulation runs can reflect the average traffic condition of a specific scenario.

In order to determine the number of simulation runs, we need to know the variance of a number of performance measures from simulation results, which was unknown before simulation. A number of simulation runs need to be executed first and then the required number of runs can be calculated according to the mean and standard deviation of a performance measure of these runs:

$$N = \left(t_{\alpha/2} \cdot \frac{S}{\mu \cdot \varepsilon} \right)^2$$

where μ and S are the mean and standard deviation of the performance measure based on the already conducted simulation runs; ε is the allowable error specified as a fraction of the mean μ ; $t_{\alpha/2}$ is the critical value of t-distribution at significance level α .

Twenty simulations were performed to obtain initial estimates of the means and standard deviations over the measure of effectiveness (maximum queue and travel distance for the right-most lane). A 90% confidence interval and a 5% allowable error were used in the calculation. The minimum number of replications N needed was lower than twenty; therefore, no additional simulation runs were needed.

5- Determination of Total Number of Simulation Runs

648 scenarios were needed based on three parameters per variable and eight different hours of data during the day. Twenty simulation runs needed to be performed for each scenario (twenty random seed number). Therefore, the total number of runs needed was 12,960 runs.

It should be noted that SimTraffic has a useful feature called “Record-Multiple Runs”. This feature can perform and record a simulation on multiple runs. A dialog will appear allowing the user to select the number of runs to simulate. The random seed number will change for every simulation run. SimTraffic will provide a statistical average for the multiple simulation runs. This feature was used in this analysis to run the twenty runs with different seed numbers for each scenario in one step.

Another useful feature in SimTraffic called “Database access” was used to reduce the data entry effort. In this feature, the user creates two files. One file for the volume data and one file the timing data. The volume file stores turning movement counts for different hours during the day in addition to the intersection number and time of the volume data. Volume counts could be entered into the volume file via automatic counters or data entry personnel. With automatic data collection, it is possible to get thousands of volume counts into the volume file. The timing file stores information about the timing plans including splits, cycle lengths, and offsets during the day. This data can vary by time of day and thus multiple timing records for each intersection are allowed.

The first site, SR 421 between the I-95 southbound off-ramp and Airport Road, was used for the calibration process. The turning movements volumes for each hour for the first site were entered in the volume file. Timing including timing plans, splits, cycle lengths, and offsets along the day were entered in the timing file. SimTraffic was set to run the simulation 8 times for 8 intervals representing the eight hours with twenty runs for each interval after a warming-up period of 15

minutes. Due to these two useful options in SimTraffic, 160 runs for each scenario (twenty random seeded runs for eight different hours) were performed in one step. The total number of runs performed was 12,960 runs. At the end, SimTraffic provided reports showing the outputs as the average values for the twenty runs for each interval.

6- Visualization of the Animation

Visualization is important when a microscopic simulation model is used for the analysis. While obtaining measures of performance from the simulation close to the observed in the field is important, if the animations are not realistic the model cannot be claimed calibrated. The following step in the calibration process was to make sure that the animations of the simulation model look realistic to the real life. The first twenty simulation runs performed were used to verify if there are any runs with unacceptable animations. An example of the SimTraffic animation is showed in [Figure 5.5](#). Animations were viewed at different simulation times in order to verify if the animations were realistic in all conditions (peak hours and non-peak hours). It was found that the simulation animation including the lane changing and signal operation looked realistic and no vehicles were observed blocking any lanes or failed to perform a lane changing operation.

7- Relative Error

As mentioned earlier, the variables selected for the calibration and validation study were the maximum queue length on the arterial street between the two signalized intersections and the travel distance on the right-most lane. The next step in the calibration procedure was to calculate the relative error. The relative error calculates the difference between the observed and the simulated values as a percentage. This calculation was performed for each measure of effectiveness for each hour for each scenario. The relative error is found using the formula:

$$RE = \frac{OBS - SIM}{OBS} \times 100\%$$

where OBS and SIM are the observed and simulated values respectively. The observed and simulated values for each hour were tabulated for each scenario for the two variables. The results of the simulation runs for one of the scenarios are shown in [Table 5.1](#). The relative error was calculated for each hour for each variable. The average relative error was then calculated for the total eight hours for each variable disregarding the sign (negative or positive). Finally, the total average relative error was determined as the average of the average relative error for the two variables disregarding the sign. The simulation run containing the set of values that returns lowest total average relative error defines the optimal calibration parameters and simulation values.

8- Validation with a New Data

The second site, SR 50 between SR 408 eastbound off-ramp and Bonneville Drive, was used in the validation process. The optimal set of parameters values obtained from the calibration step was entered in SimTraffic. The turning movements volumes for the second site were entered in the volume file. Due to the limited data resources and in order to obtain more data intervals, 15-min intervals were used in this step resulting 32 intervals. Timing including timing plans, splits, cycle lengths, and offsets along the day were entered in the timing file.

SimTraffic was set to run the simulation for 32 intervals representing the eight hours with twenty runs for each interval for a total 640 runs using the optimal calibration parameters. The 640 runs resulted 32 values of the maximum queue and for the travel distance for the right-most lane. The maximum queue and the travel distance for the right-most lane were obtained from videotapes for every 15-min interval.

According to Kelton and Law (7), there are two approaches to statistically compare the outputs from the simulation and the field. There two approaches are the visual inspection and the confidence-interval method (t-test). Visual inspection method is mainly comparing the output in a graphical way. If X_i is the maximum queue obtained from the field and Y_i is the corresponding maximum queue obtained from the simulation model, a graph is created such that the horizontal axis denotes each interval (32 intervals) and the vertical axis denotes X_i and Y_i for each interval. The user can then eyeball the difference to see if there is any interval with a high difference

between the two values. [Figure 5.6](#) shows the two charts created for the validation process. One chart to compare the maximum queue and the other is to compare the travel distance. The visual inspection showed that there are no major differences between the simulated data and the field data.

The second approach is the confidence interval, which is a reliable approach for comparing the simulated and the field data. For the purpose of this step, the 32 values of the maximum queue and the travel distance the 32 field observations for the same variables were used. The t-distribution helps in testing whether or not the two sample means come from equal or non-equal populations. The null hypothesis H_0 that is tested is:

$$H_0 : \mu_1 = \mu_2$$

$$H_1 : \mu_1 \neq \mu_2$$

where μ_1 is the population mean for the field data and μ_2 is the population for the simulated data. If the null hypothesis is rejected, this infers that the two sample means come from different populations and are different. To compute the two-sample t-test, the mean and the standard deviation were calculated. Using a confidence interval of 95%, the confidence interval method suggested that there was no significant difference between the field and simulated values for the two measure of effectiveness.

Conclusions and Recommendations

This paper proposed a calibration and validation procedure for microscopic simulation models. The procedure focused on the model calibration of an arterial segment that includes signalized intersections. The procedure was demonstrated using an example case study. The calibrated and validated procedure appeared to be properly effective in the calibration and validation of the microscopic simulation model SimTraffic for arterial streets. Although this procedure was applied only on SimTraffic, the proposed procedure can be potentially applied to other simulation packages as well.

The procedure focuses on the importance of type of data and how it is useful to use different sites and different time periods (morning, midday, and evening) in the process to test the model during different conditions and different types of demand (peak hours and non-peak hours). The paper also discussed the importance of understanding all the useful features in each microscopic simulation package because some features can save a lot of effort and time during the calibration and validation process.

This study only used a single day of data collection at each site and two measures of effectiveness. It is recommended to confirm the results of the procedure by testing the model using multiple days of field data, if possible. It is also recommended to use other measure of effectiveness such as travel time, delays, average speed, fuel consumption, or fuel emissions to see if they produce different results.

Table 5.1: Comparison of Observed and Simulated Values

Hour	Calibration data - Site 1 - Scenario 17					
	Measure of Effectiveness					
	Maximum queue			Travel distance		
	(feet)			(miles)		
	Observed Value	Simulated Value	Relative Error	Observed Value	Simulated Value	Relative Error
7:00 AM to 8:00 AM	320	280	12.50%	4.0	4.8	-20.00%
8:00 AM to 9:00 AM	540	495	8.33%	5.5	6.8	-23.64%
11:00 AM to 12:00 PM	250	276	-10.40%	4.5	5.0	-11.11%
12:00 PM to 1:00 PM	250	218	12.80%	9.4	8.9	5.32%
2:00 PM to 3:00 PM	740	671	9.32%	6.1	5.6	8.20%
3:00 PM to 4:00 PM	740	688	7.03%	5.1	5.5	-7.84%
4:00 PM to 5:00 PM	720	687	4.58%	5.8	5.3	8.62%
5:00 PM to 6:00 PM	620	673	-8.55%	8.0	7.3	8.75%
Average Relative Error			9.19%			11.68%
Total Average RE	10.44%					

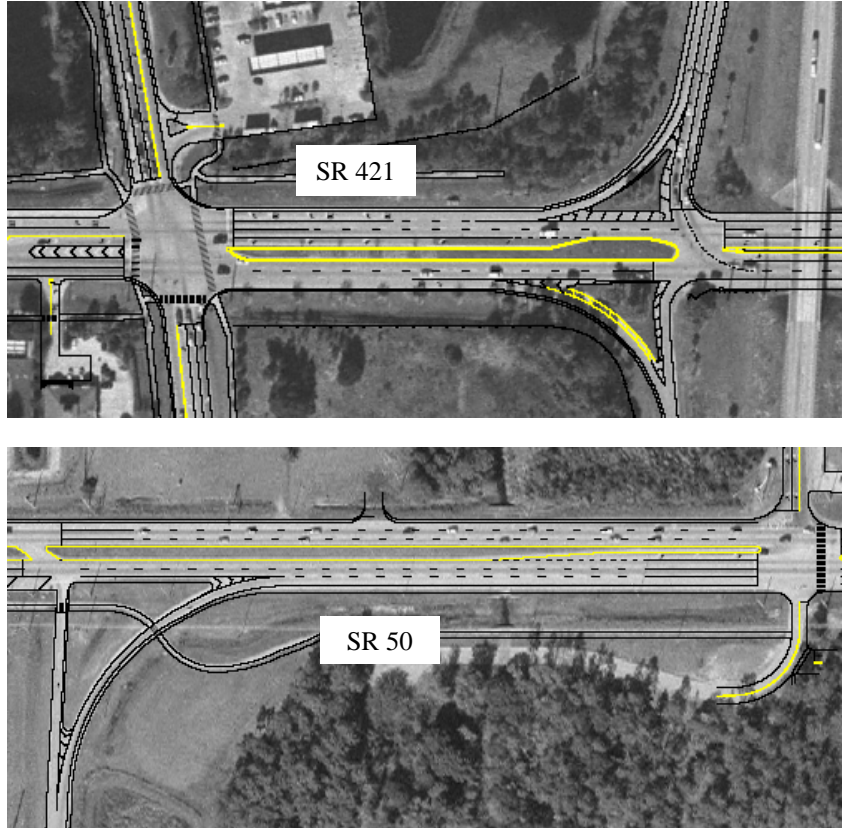


Figure 5.1: Aerial Photos for the Two Selected Sites



Figure 5.2: Pictures Taken From the Video Cameras Positions for the Two Studied Sites



Figure 5.3: Road Tubes Placed Every 100 Feet Along The Studied Segment

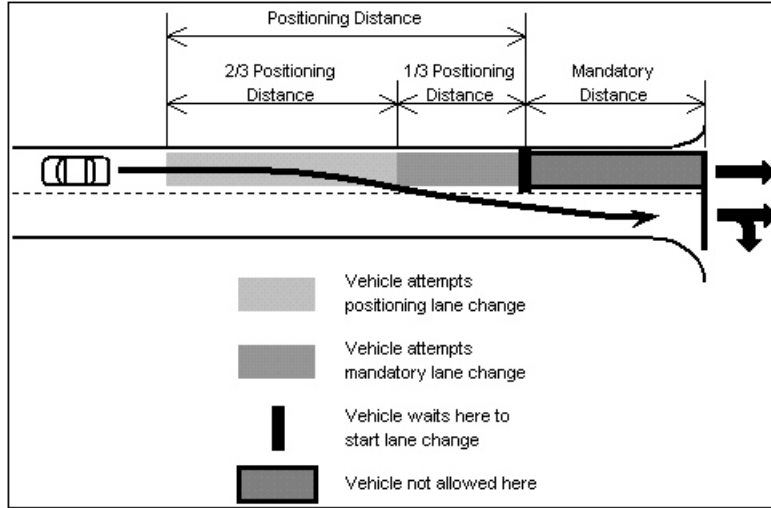


Figure 5.4: Lane Change in SimTraffic

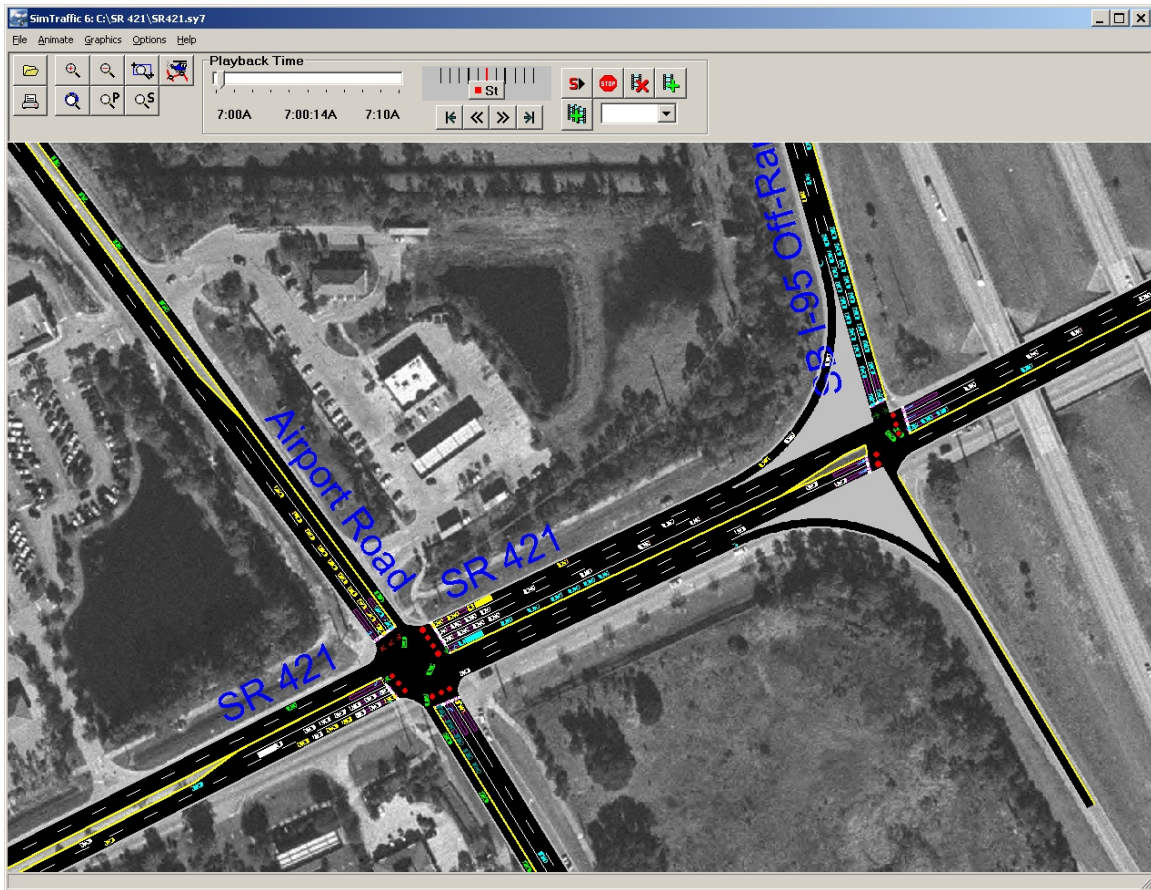


Figure 5.5: Example of an Animation of SimTraffic on SR 421

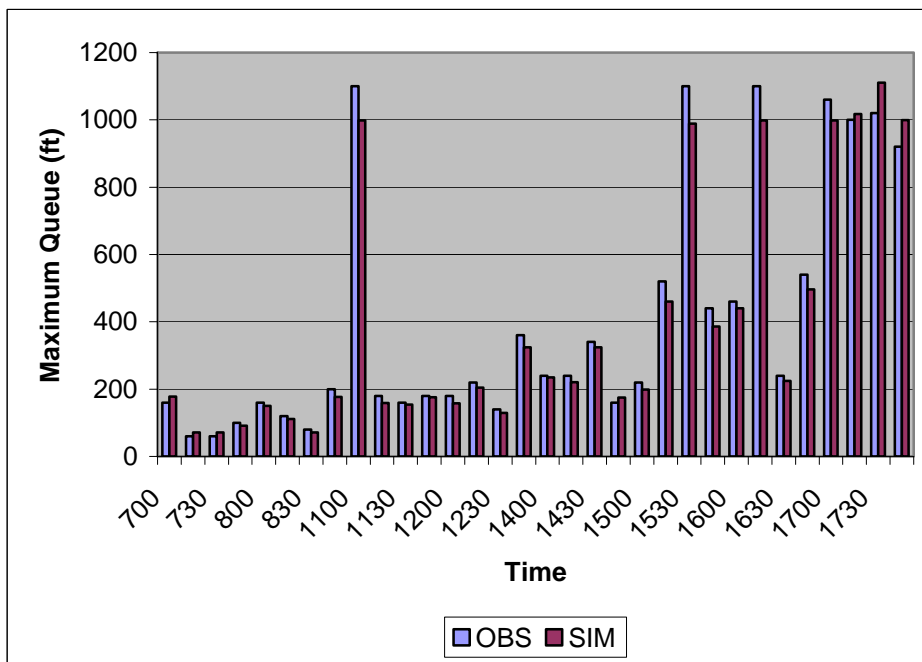
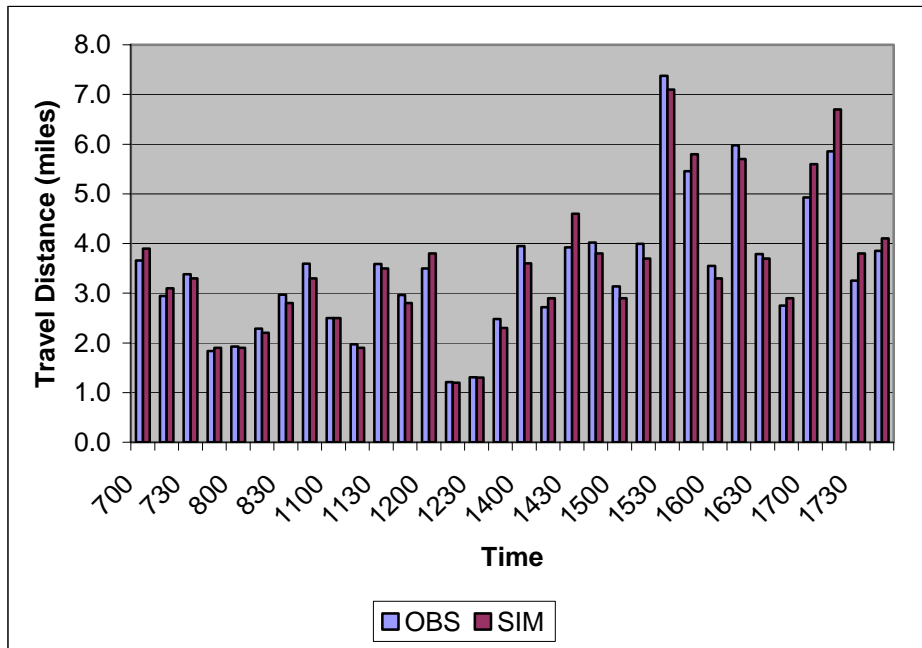


Figure 5.6: Field Vs. Simulated Data for the Second Site

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CHAPTER 6. OPERATIONAL BENEFITS OF THE RIGHT TURN SPLIT CONCEPT

Introduction

The concept of Right Turn Split (RTS) is a new design to alleviate the delay and reduce the potential of collision caused by weaving movements on arterial streets. Arterial streets weaving typically occur when vehicles coming from a side street at an upstream intersection attempt to enter the main street from one side to reach access points on the opposite side at a downstream intersection by crossing one or more lanes. The design was developed based on a real traffic problem. Pilot studies were conducted at two arterial weaving sections in Florida to demonstrate the feasibility of the approach. The pilot studies revealed that the worst weaving movement was the movement performed by the vehicles entering an arterial and crossing three lanes to access an auxiliary lane at the downstream intersection. This movement caused severe delay and high potential for collisions on the arterial streets. The new design proposes separating the vehicles causing the worst weaving movement from the other weaving movements before reaching the arterial street. The RTS design recommends directing the side street vehicles to two separate right turn lanes instead of one right turn lane. The additional right turn lane should be added to the side street at the stop bar. In this case, the vehicles, desiring to turn left at the downstream intersection, are directed into the additional lane then to the left turn lane at the downstream intersection.

In order to enforce these vehicles to use the new right turn lane at the stop bar instead of the free right turn lane, two barriers should be provided at two locations along the arterial segment. The first barrier should be placed at the gore area and between the free right turn lane and the outside through lane. The second barrier should begin at the same location where the first barrier ends but between the inside through lane and the left turn lane. The second barrier should end at the stop bar at the downstream intersection. The two traffic barriers will prevent drivers from attempting to access the left turn lane from the free right turn lane. The proposed design, illustrated in [Figure 6.1](#), will reduce the number of conflict points along this section.

The proposed barrier can take different forms: delineators, painted striping, or raised concrete traffic separators. Delineators are retroreflective devices that can be mounted on grass, pavement, or raised concrete traffic separator to indicate a certain alignment, especially at night or in adverse weather. Raised concrete traffic separators are usually six inches height. The three types of proposed barrier offer different alternative based on the right of way availability: (1) delineators only on the lane striping could be used when it is difficult to obtain any additional right of way, (2) two feet of painted striping supplemented with delineators could be used in case of limited right of way availability, and (3) four feet of raised concrete traffic separator could be used in case of right way availability. In the last two forms, delineators should also be used as an additional indication of the barrier because they will improve the visibility and reduce the potential of vehicles crossing the barrier. A special signing arrangement should be installed to provide adequate signage for the side street approach in order to explain the new arrangement to the drivers. The special signage is illustrated in [Figure 6.1](#).

To define the location where the first barrier should end which is the same location where the second barrier should start (the split distance), three different methods were studied and the 85th percentile weaving distance was selected since it provided the lowest split distance for the two sites studied during the pilot studies. The 85th percentile weaving distance is defined as the distance at or over which 85% of all drivers, except the vehicles that will be separated, performed their weaving movement. For detailed design and description of the analysis, the reader is referred to [Shaaban and Radwan \(2005a\)](#).

By directing vehicles performing the worst weaving movement through a safer path, the RTS design is expected to decrease the delay on the arterial street, reduce the conflict points, and improve safety. However, there remains a challenge to demonstrate that RTS design is actually effective and provides delay reduction. It is, therefore, the intent of this paper to study the impacts of the RTS installation based on a before-and-after study of the delay on an arterial street. To conduct the before-and-after study, the delay before and after will be compared for multiple volume conditions with microscopic simulation analysis to determine how the delay of the arterial segment differ over a wide range of volume levels. This paper present the analysis methodology used for this research, the research results, and finally, the conclusions.

Analysis Methodology

Method of Analysis

To provide a more comprehensive comparison of the arterial street operations, multiple volume conditions were developed for evaluation. The arterial segment had one geometric condition for this study. The only geometric variable selected for this analysis was the spacing between the two intersections along the arterial segment.

Microscopic simulation was selected as the method for evaluating and comparing the delay on the arterial segment before and after applying the RTS design. Micro-simulation provides better estimation for the operational conditions for closely spaced or interacting intersections as compared to macroscopic analysis techniques. A wide range of volume levels was evaluated, including near capacity and overcapacity conditions. Microscopic simulation is better suited to providing reliable measure of effectiveness (MOE) under congested conditions where macroscopic analysis techniques typically breakdown and provide enormous results. *Total Delay* was selected for performing the operational comparison. Total delay, in hours, is equal to the travel time for all vehicles on all lanes minus the travel time it would take the vehicles with no other vehicles or traffic control devices during one hour. This MOE was selected because it focuses on the operation of the arterial.

Analysis Tools

The analysis was conducted with SimTraffic version 6.0. SimTraffic ([SimTraffic User Guide, 2003](#)), developed in 1999 by Trafficware Corporation, is one part of a software couple consisting of the coordinated models, Synchro and SimTraffic. SimTraffic is a microscopic simulation model that has the capability to simulate a wide variety of traffic controls, including a network with traffic signals operating on different cycle lengths or operating under fully-actuated conditions. Synchro ([Synchro User Gide, 2003](#)) is a macroscopic traffic software program that implements the Intersection Capacity Utilization method for determining intersection capacity. SimTraffic 6.0 was selected as the simulation program for this study in lieu of other simulation programs because of its capability of compiling and computing vehicle movement, as well as the many features in intersection's coding and data entry ([Shaaban and Radwan, 2004](#)).

Calibration

To ensure meaningful and appropriate results for the study, the SimTraffic model was calibrated and validated using real traffic data for two sites in Florida that has the same exact geometrics used in this research. The calibration and validation procedure used the data from one site for the calibration procedure and the data from the other site for the validation procedure. The data used in the process was collected during different time periods (morning, midday, and evening) and different demand levels (peak hours and non-peak hours) during a normal weekday. The

calibrated and validated model appeared to be properly effective and to replicate the existing conditions (Shaaban and Radwan, 2005b).

The calibrate model was used to replicate the before case. To replicate the after case, a copy of the calibrated model was modified to include the proposed RTS design. To split the right turning vehicles to two different destinations, an additional node was added at the downstream intersection. This way it was possible to create two right turn lanes at the downstream intersection, one right turn lane exist at the stop bar and is stop controlled and the other is separated from the other lanes by an island and has a free operation. Using the origin-destination feature in SimTraffic, the vehicles at the first right turn lane were directed to the left turn lane at the downstream intersection and the vehicles at the second right turn lane were directed to the through and right turn lanes at the downstream intersection. The animation was then viewed in SimTraffic and the new model showed that the vehicles behavior replicated the proposed RTS design. A SimTraffic snapshot for the model before and after applying the RTS design are shown in [Figure 6.2](#) and [Figure 6.3](#).

Base Geometric Conditions

The goal of this research was to compare the operations of an arterial segment before and after applying the RTS design using comparable geometrics. Only one geometric data set was selected to be evaluated which is the spacing between the upstream and the downstream intersection. Otherwise, it was important to select geometrics that were general and applicable to real world

conditions. The geometrics used in this research were selected based on real world conditions in two sites in Florida where the RTS design will be implemented (Shaaban and Radwan 2005a).

The key geometric assumptions for the arterial street are:

- Relatively short spacing between two signalized intersections that are running in coordination;
- No driveways or median openings between the two signalized intersections;
- Two through lanes in each direction for the main street;
- A left turn lane at the downstream intersection;
- A continuous right turn lane at the downstream intersection;
- A free right turn lane for the cross street at the upstream intersection.

The *Spacing* between the two intersections on the arterial street was the only geometric variable changed in this research due its importance. Spacing had a high effect on the weaving distance of the pilot studies conducted at two arterial weaving sections in Florida two using real life data (Shaaban and Radwan 2005a). Three spacing levels were selected to range from considerably very close-spaced intersections to considerably average spacing. Average spacing was selected based on half the maximum weaving segment length recommended by the 2000 HCM. The 2000 HCM recommends applying its weaving analysis procedure only to segments up to 2500 ft long, suggesting that segments longer than that are considered basic freeway segments, except for the ramp influence areas near the entry and exit gore areas. The different values used for the spacing variable are shown in Figure 6.4.

Volume Scenarios

A range of volume conditions was developed to test the operations on the arterial street. Three separate volume distributions were developed on the main street for the through vehicles that will perform left, through, and right movements at the downstream intersection and for each of these distributions, three volume levels were defined that ranged from light volume levels to over capacity conditions. In addition, two separate volume distributions were developed on the side street from the right turning vehicles that will perform left and through movements at the downstream intersection and for each of these distributions, three volume levels were defined that ranged from light volume levels to over capacity conditions. The development of the higher volume conditions was an iterative process in which the volumes were increased by a factor and then evaluated in SimTraffic to determine that the arterial street is operating under breakdown conditions. It is important to note that during the volume development process, the signal timings was less involved since signal cycle lengths, timings, and offsets were developed using the optimization option in Synchro.

Finally, having six variables, five volumes related and one for the spacing, and having three levels for each variable resulted 729 scenarios for the before case and 729 scenarios for the after case, totaling 1458 scenarios. All volume distributions and volume levels can be seen in [Figure 6.4](#).

Operational Assumptions

Several operational assumptions were made when setting up the test cases. The goal was to provide a direct comparison between the two cases, before and after applying the RTS design, by minimizing the number of variables to contend with at the conclusion of the analysis. For instance, the arterial segments were analyzed under isolated conditions so the delay would not be affected by adjacent intersections other than the two intersections at the upstream and the downstream of the arterial segment.

Traffic signals were coded as fully-actuated signal control and as coordinated in SimTraffic for the analysis which was similar to the existing conditions for the two studied sites during the pilots study. Signal phases were obtained from the existing arterial segments studied in the pilot study. Signal splits and offsets and cycle lengths were optimized in Synchro after we reached capacity condition during the volume iteration process. The numbers obtained from the optimization step were used for all the scenarios for the existing and the proposed conditions.

A geometric assumption was made regarding the configuration of the right turn lane on the upstream site street in all cases. Right turns can be separated or not separated from the through and left movements by an island. It was assumed that an island separates the right turn lane at the upstream intersection. In addition, the right turn lane operation at downstream intersection can be stop controlled, yield controlled, or free. It was assumed that the operation of the right turn lane is free as they enter the main street. These conditions were selected since they provide the worst

conditions as far as vehicles entering the main street with minimal constraints and they also replicate the two studied sites in the pilot study.

Analysis

Six selected variables with three levels each resulted 1,458 scenarios, 729 scenarios for the before case and 729 scenarios for the after case. Because of SimTraffic's stochastic nature, twenty SimTraffic simulation runs were conducted for each scenario and the results were averaged. Each of the twenty SimTraffic runs used a different random number seed. The same random number seeds were used in each scenario (Shaaban et Radwan, 2005a). Delay was obtained for each scenario for the before and after cases and the difference in delay for each two similar scenarios was calculated.

Results

Out of the 729 pairs, 560 pairs (76.82%) showed improvements in total delay after applying the RTS design. Table 6.1 summaries the results for all the before and after test cases. The results were further investigated graphically and statistically.

Graphical Evaluation

Main Effects

The main effects studied in this research were the effects of the main factors: Spacing (SP), Main Street Going Left volume (ML), Main Street Going Through volume (MT), Main Street Going Right Volume (MR), Side Street Going Left volume (SL), and Side Street Going Through volume (ST) on the delay-before and the delay-after applying the RTS design. The effects of these factors on the delay before and the delay after were studied graphically. The results are summarized graphically in [Figure 6.5](#) through [Figure 6.10](#). In all figures, the y-axis represents the average delay for all the runs for a specific level for a specific factor for a specific condition (before or after) and the x-axis represents the three levels for the same specific factor. Several observations can be made from the results. Firstly, the two microscopic models provided similar delay trends over different spacings ([Figure 6.5](#)). It is definitely apparent that the delays were always reduced as spacing increased for the range of spacings tested. This is probably because vehicles had a longer distance to perform the weaving movements. More importantly, it was found that the delay trends were always lower in case of the delay after for the range of spacings tested, which indicates an improvement in delay after applying the RTS design.

Secondly, the two microscopic models also provided similar delay trends over different volume levels for all five volume related factors studied. The trend of ML, MT, MR, SL, and ST appeared to decrease with the increase of traffic volumes for the five studied factors. The results

are summarized graphically in [Figure 6.6](#) through [Figure 6.10](#). These results were expected based on the basic relation between delay and volume, when volume increases. Finally, it was found that the delay trends were always lower in case of the delay after for the range of volumes tested, which indicates an improvement in delay after applying the RTS design

Interactions

In addition to graphically studying the main effects of all factors, the interactions between the main factors were also studied graphically. The only problem with graphically studying interactions is that interaction plots give no indication of the size of the experimental error and must be interpreted with a little caution. The interactions between pairs of factors in an experiment involving three or more factors can be done by comparing separate interactions plots at the different levels of a third factor. For example, an interaction between the three factors, Delay, SP, and ML, is considered a 2 x 3 x 3 experiment, where Delay has two levels (before and after), SP has three levels (750, 1000, and 1250), and ML has three levels (200, 300, and 400). To study the interaction of the three factors, a separate SP x ML interaction plot should be plotted for each delay level, which means two plots, one for the delay-before and one for the delay-after. If the lines within each plot are not parallel, it indicates that the factors, SP and ML, possibly interact (*two-factor interactions*). If the pattern in the two plots is different, it means that the factors SP and ML apparently interact in a different way at each level of factor Delay. This indicates a probable Delay x SP x ML interaction effect (*three-factor interactions*).

All possible interaction combination plots between the six studied factors and the delay were created, which resulted 30 plots (15 combinations and two plots for each combination). The results are summarized graphically in [Figure 6.11](#) through [Figure 6.25](#). Each figure shows two graphs, one for the delay-before case and one for the delay-after case. In all figures, the y-axis represents the average delay for all the runs corresponding to a specific level for two different factors.

Some factors showed no interactions in both cases, the before and after, such as SP x ML, ML x MR, and ML x ST, which indicated a negligible two-factor interaction and three-factor interaction. Other factors showed interactions in both cases with the same pattern between the two plots for before and after such as SP x MT, SP x MR, SP x ST, ML x MT, MT x MR, MT x ST, and MR x ST, which indicated a two-factor interaction and a negligible three-factor interaction. The rest of combinations, SP x SL, ML x SL, MT x SL, MR x SL, and SL x ST, showed interaction in the delay-before case and no interaction in the delay-after case, which indicated a three-factor interaction. This means that the interaction effect between the two factors apparently changed with changing the level of delay. It should be noted that most of these three-factor interaction involved SL. These results apparently shows the interaction of SL with the other factors changed after applying the new concept of RTS and that SL did not have the a significant effect on the volumes and spacing factors after applying the RTS design. As mentioned earlier, interaction plots give no indication of the size of the experimental error and must be interpreted with caution, that's why it necessary to verify these results statistically.

Paired t Test

In addition to the graphical evaluation and in order to statistically determine whether any improvement or no improvement exist between the before and after conditions for the 729 pairs, a statistical test, Paired t Test, was performed to test if improvement occurred after applying the new design. The Paired t Test was used because the 729 scenarios can be considered matching or pairing cases. The null and alternative hypotheses are stated as follows:

$$H_o : \mu \leq 0$$

$$H_1 : \mu > 0$$

Where μ is the difference in delay between the before and after condition for each scenario. This is a one-tailed test since the rejection region is entirely contained in the upper tail of the sampling distribution of the mean. The decision rule is

$$\text{Reject } H_o \text{ If } t > 1.645$$

Since $t = 3.5$ which is more than 1.645, our decision is to reject H_o , and we conclude that, for the geometric and volume conditions tested, the proposed design provided lower delay on the arterial street than the original conditions. The analysis results are shown in [Table 6.2](#).

Multivariate Analysis of Variance

The Paired t-test gives a main conclusion if the variation between the two groups, before and after, is significant or not. In order to analyze the main and interaction effects of the independent variables on multiple dependent variables, the before and the after cases, a statistical analysis tool known as Multivariate Analysis of Variance (MANOVA) was selected to perform the analysis. Univariate One-Way Analysis of Variance (ANOVA) could not be used since we were dealing with two dependent variables, the delay before applying the RTS design (delay-before) and the delay after applying the RTS design (delay-after) in addition to the six independent variables. The MANOVA analysis was conducted using the SAS statistical analysis package at a level of significance of 5 percent.

The first step in the MANOVA analysis is test the *Main Effect* for all independent variables and interactions using the Wilks' Lambda test. If there is no significant main effect, the analysis for this specific independent variable or interaction is ended. If there is a significant main effect, the second step is to determine the significance of all independent variables and interactions on each dependent variable using the F Value and the P Value. If there is significance for one dependent variable and not for the other, the analysis is ended. If there is significance on both dependent variables for the same independent variable or interaction, the *Discriminant Function* is then calculated to determine the contribution or the effect of each independent variable or interaction on each dependent variable.

Main Effects

The MANOVA results showed that all six independent variables, SP, ML, MT, MR, SL, and ST, have significant influence on the two dependent variables, the delay-before and the delay-after. In addition, the influence of all six independent variables on the delay-after was higher on the delay-after than on the delay-before based on the Discriminant Function calculations obtained from the SAS output, which explains the reduction in delay for the delay-after case. The results for the MANOVA analysis for the main factors are shown in [Table 6.3](#).

Interactions

Several observations can be made from the MANOVA results regarding interactions between independent variables:

1. The results revealed a significant interaction between SP and the three volume related independent variables, MR, MT, and ST, in the before and after cases, which is to say that the spacing has as significant affect on most of the weaving movements. This is maybe because is when spacing increases, weaving vehicles will have a longer distance to accelerate and to find gaps to perform the weaving movements. When spacing decreases, weaving vehicles have a short distance to perform the weaving movements, which in most cases will require the vehicles to

slow down to find a gap, which will increase the delay. These results agree with the graphical evaluation results.

2. The results revealed a significant interaction between SP and SL only in the before case. This is maybe because in the after case the SL vehicles do not weave any more and perform their weaving movement through a separate path with no conflicts with other movements. Therefore, increasing or decreasing the spacing will not affect it. These results agree with the graphical evaluation results.
3. The results showed that there is no significant interaction between SP with ML. This is maybe because left turning vehicles coming from the main street only have to change one lane to move to the left turn lane without weaving with any movements. In addition, it is believed that the length of the left turn lane can be the factor that affects ML and not the spacing between the two intersections. These results agree with the graphical evaluation results.
4. The results showed a significant interaction between ML and MT. This is maybe because a heavy through volume on the main street can block the left turn lane at the downstream intersection causing starvation for the left turning vehicles, which will increase the delay for the left turn lane at the downstream intersection. These results agree with the graphical evaluation results.

5. The results also revealed a significant interaction between ML and SL only in the before case. This is may be because a heavy main street going left volume can block the left turn lane leaving no gaps for the side street going left at the downstream intersection vehicles and increasing the delay on the segment in the before case. However, in the after case, the SL vehicles move mostly during the side street phase and the ML vehicles move during a different phase which explains the no significance in the after case. These results agree with the graphical evaluation results.

6. The results revealed no significant interaction between ML and MR. This is maybe because these two movements come from the same approach, the main street at the upstream intersection, and change lanes in the two different directions. ML vehicles change lanes to move to the left turn lane at the downstream intersection and MR vehicles change lanes to move to the right turn lane at the downstream intersection, which results minimum conflict between the two movements. In addition, based on the field observations, most of the vehicles for these two movements change lanes before even reaching the upstream intersection, where ML vehicles move to the inside through lane to be ready to turn left at the downstream intersection and MR vehicles move to the outside through lane to turn right at the upstream intersection. These results agree with the graphical evaluation results.

7. The results revealed no significant interaction between ML and ST. This is maybe because these two movements come from two different approaches at the upstream intersection to go to two non-conflicting movements at the downstream intersection, which cause minimal influence between the two movements. These results agree with the graphical evaluation results.

8. The results showed a significant interaction between MT and MR. This is maybe because a heavy through volume on the main street can block the path for right turning vehicles at the downstream intersection and increasing the delay for the right turn lane at the downstream intersection. On the other hand, a heavy MR volume will slow down to weave to the right turn lane at the downstream intersection causing an increase in the delay on the through lane at the downstream intersection. These results agree with the graphical evaluation results.

9. The results revealed a significant interaction between MT and SL only in the before case. In the before case, this is maybe because a heavy through volume on the main street reduces the number of gaps for SL vehicles. However, in the after case, SL vehicles move mostly during the side street phase when MT vehicles are stopped which explains the no significance in the after case. These results agree with the graphical evaluation results.

10. The results revealed a significant interaction between MT and ST in the before and the after cases. This is maybe because a heavy through volume on the main street can reduce the number of gaps for ST vehicles. ST vehicles have the same path in the before and after cases and they will always conflict with the main line going through vehicles which explains the non significance in both cases. These results agree with the graphical evaluation results.
11. The results also revealed a significant interaction between MR and SL only in the before case. The explanation for that is that MR vehicles weave with SL vehicles in the before case. However in the after case, SL vehicles move mostly during the side street phase when MR vehicles are stopped at the upstream intersection, which explain the non significance in the after case. These results agree with the graphical evaluation results.
12. The results showed a significant interaction between SL and ST only in the before case. The explanation for that is, in the before case, those two movements are originated from the same approach and from the same lane, the right turn lane at the downstream intersection. A volume increase in one of the two movements may block the other and increase the delay on the right turn lane at the downstream intersection. In the after case, the two movements are originated from the same approach but in two different lanes. The ST vehicles have free operation

and the SL vehicles have to stop at the traffic signal at the downstream intersection. These results agree with the graphical evaluation results.

The results for the MANOVA analysis for the interaction factors are shown in [Table 6.4](#).

Conclusions

The goal of the research presented was to determine if the operations of the arterial street would improve after applying the RTS design. To test the operations of the arterial street, a single geometric test case was developed for the before and after cases with geometric that have equivalent characteristics. Six variables, the spacing and five volume variables, were developed with three levels each. This resulted in the development of 1,458 SimTraffic models, 729 scenarios for the before condition and 729 scenarios for the after condition.

The graphical and statistical analysis conducted showed that for the geometric, volume, and the traffic control conditions tested, the RTS design provided better system operational performance than the original conditions. The arterial street had lower total delay after applying the RTS design in most cases. A more detailed analysis using the statistical analysis tool MANOVA showed that all six independent variables studied have significant influence on the delay-before and the delay-after. Another important finding after studying the interactions between the independent variables is that the side street vehicles going left at the downstream intersection did

not have a significant interaction with all other volumes related variables and spacing after applying the RTS design.

It is important to summarize the study methods and assumptions to help the reader determine how this study can be of use to the transportation industry. The study was based on one geometric data set in which comparable geometries were defined and assumed to be equal. The SimTraffic calibration and validation was conducted with field data and field calibration from two sites in Florida. Only signal phasing was utilized from the field data. Splits, offsets, and cycle lengths were optimized using Synchro. The arterial segment was also assumed to isolated for the analysis, meaning no median openings or driveways affected the traffic patterns along the arterial segment.

In summary, the RTS design reduced the delay on the arterial street for the cases studied. Further study could include additional geometric data sets to determine how geometric variations affect the operational benefits along the arterial street after applying the RTS design.

Table 6.1: Percentage of Improvements for Each Variable

Variable		Total Runs	Percentage of Runs Improved after Applying the RTS Concept
Spacing	750	243	77.78%
	1000	243	76.13%
	1250	243	76.54%
Main Line Going Left	200	243	85.60%
	300	243	84.77%
	400	243	60.08%
Main Line Going Through	900	243	87.24%
	1000	243	76.95%
	1100	243	66.26%
Main Line Going Right	50	243	87.24%
	75	243	76.95%
	100	243	66.26%
Side Street Going Left	50	243	82.72%
	100	243	72.84%
	150	243	74.90%
Side Street Going Through	200	243	85.60%
	400	243	85.19%
	600	243	59.67%
Total no. of runs improved		560 out of 729	76.82%

Table 6.2: Paired -Test Output

	Delay	Delay Proposed
Mean	22.68902606	21.92962963
Variance	64.50221457	69.44708791
Observations	729	729
Pearson Correlation	0.744243189	
Hypothesized Mean Difference	0	
df	728	
t Stat	3.499598302	
P(T<=t) one-tail	0.000247158	
t Critical one-tail	1.646949386	
P(T<=t) two-tail	0.000494316	
t Critical two-tail	1.963226168	

Table 6.3: Statistical Results for the Main Factors Influencing delay

	Main Effect Wilk's Lambda Significance*	Effect on Delay-	Effect on Delay-	Discriminant Function	
		Before F Value P Value Significance*	After F Value P Value Significance*	Delay-Before	Delay-After
Spacing (SP)	0.786 Yes	31.13 <.0001 Yes	53.92 <.0001 Yes	0.00575332	0.00951591
Main Line Going Left (ML)	0.578 Yes	44.34 <.0001 Yes	185.71 <.0001 Yes	0.00433522	0.01064127
Main Line Going Through (MT)	0.501 Yes	74.74 <.0001 Yes	237.80 <.0001 Yes	0.0047601	0.01035444
Main Line Going Right (MR)	0.774 Yes	30.75 0.0047 Yes	51.17 0.0031 Yes	0.00501965	0.00952309
Side Street Going Left (SL)	0.779 Yes	19.01 <.0001 Yes	70.34 <.0001 Yes	0.00452358	0.1051891
Side Street Going Through (ST)	0.138 Yes	687.66 <.0001 Yes	1259.06 <.0001 Yes	0.00566257	0.00960353

*Significant at the 5 percent significance level

Table 6.4: Statistical Results for the Interaction Factors Influencing delay

	Main Effect Wilk's Lambda Significance*	Effect on Delay-Before F Value P Value Significance*	Effect on Delay-After F Value P Value Significance*	Discriminant Function	
				Delay-Before	Delay-After
SP*ML	0.992 No				
SP*MT	0.926 Yes	7.50 <.0001 Yes	10.13 <.0001 Yes	0.00493621	0.00818456
SP*MR	0.941 Yes	6.91 <.0001 Yes	3.11 0.0149 Yes	0.00883968	0.00357289
SP*SL	0.893 Yes	5.64 0.0002 Yes	1.97 0.0967 No		
SP*ST	0.898 Yes	9.19 <.0001 Yes	8.6 <.0001 Yes	0.00681219	0.00951026
ML*MT	0.955 Yes	7.20 <.0001 Yes	5.44 <.0001 Yes	0.00690361	0.00815818
ML*MR	0.991 No				
ML*SL	0.873 Yes	6.05 <.0001 Yes	1.54 0.07 No		
ML*ST	0.997 No				
MT*MR	0.932 Yes	6.10 <.0001 Yes	5.44 0.0003 Yes	0.00690361	0.00815818
MT*SL	0.972 Yes	3.05 0.0166 Yes	1.84 0.12 No		
MT*ST	0.854 Yes	4.74 0.0009 Yes	22.3 <.0001 Yes	0.00389459	0.01089937
MR*SL	0.929 Yes	6.05 <.0001 Yes	1.32 0.09 No		
MR*ST	0.971 Yes	4.4 0.0016 Yes	16.66 <.0001 Yes	0.00496917	0.01019853
SL*ST	0.864 Yes	8.6 <.0001 Yes	1.67 0.0756 No		

*Significant at the 5 percent significance level

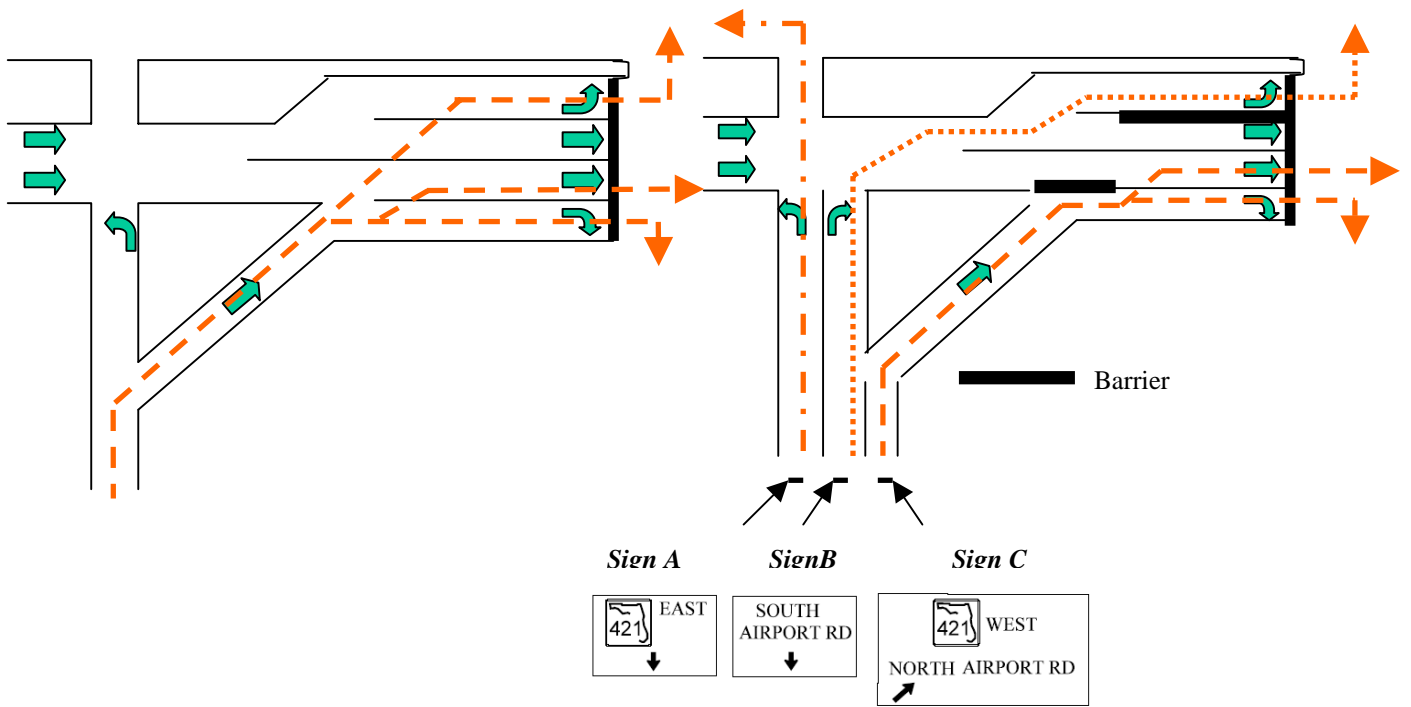


Figure 6.1: Before and After Applying the RTS Concept

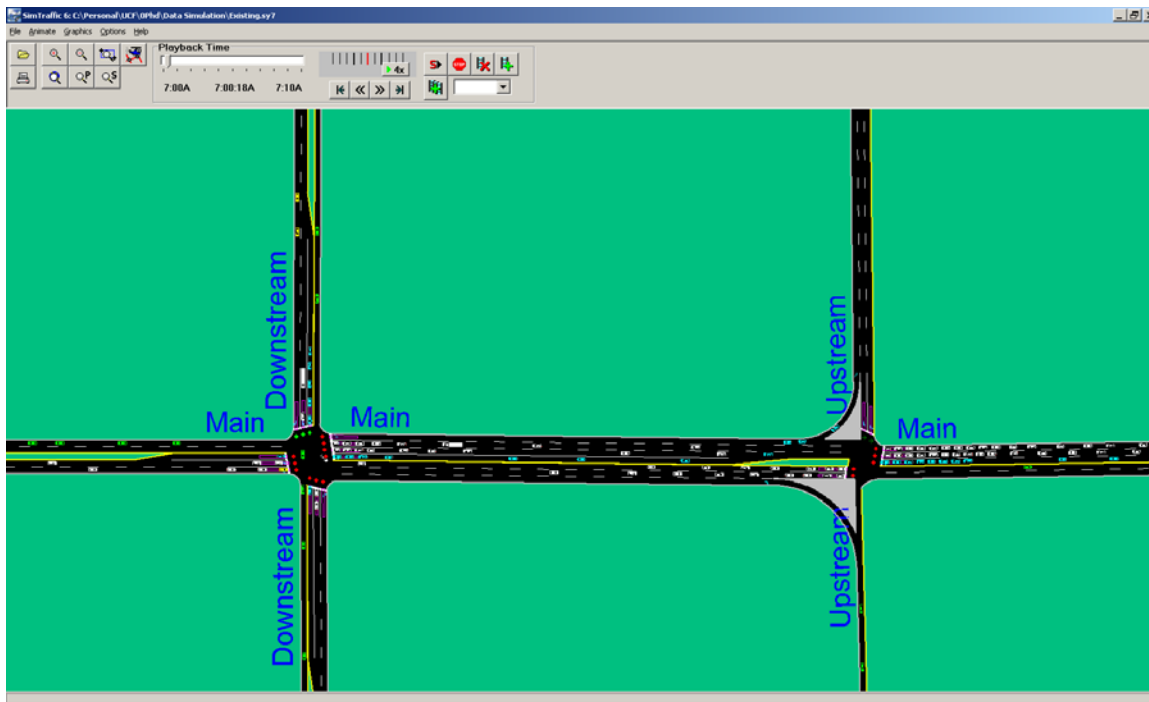


Figure 6.2: SimTraffic Snapshot Before Applying the RTS Concept

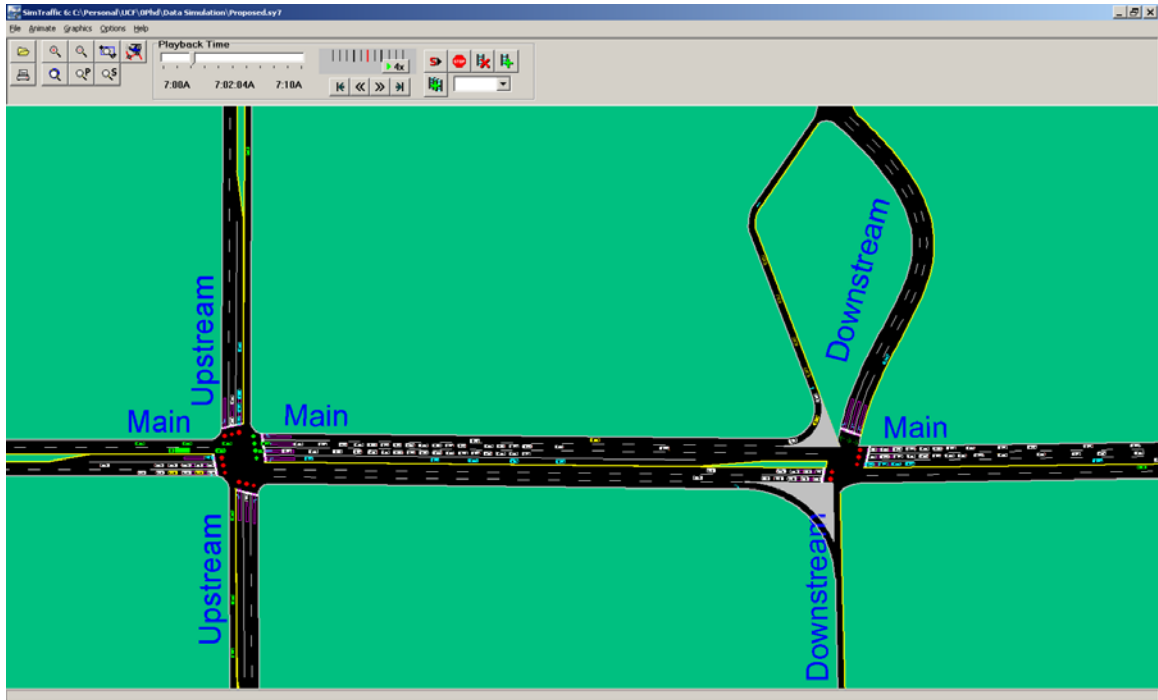


Figure 6.3: SimTraffic Snapshot After Applying the RTS Concept

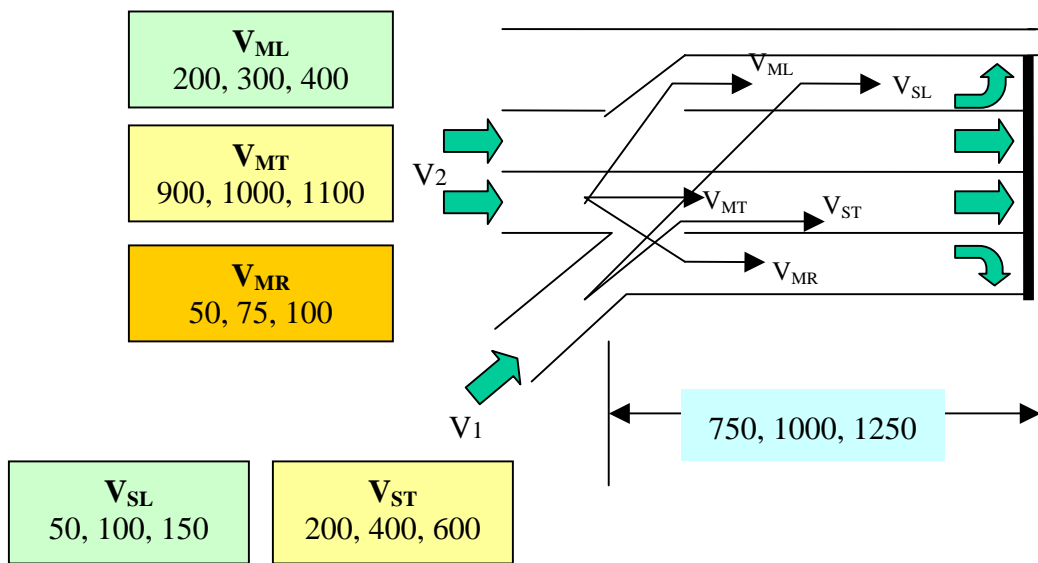


Figure 6.4: The Variables that were Simulated in SimTraffic

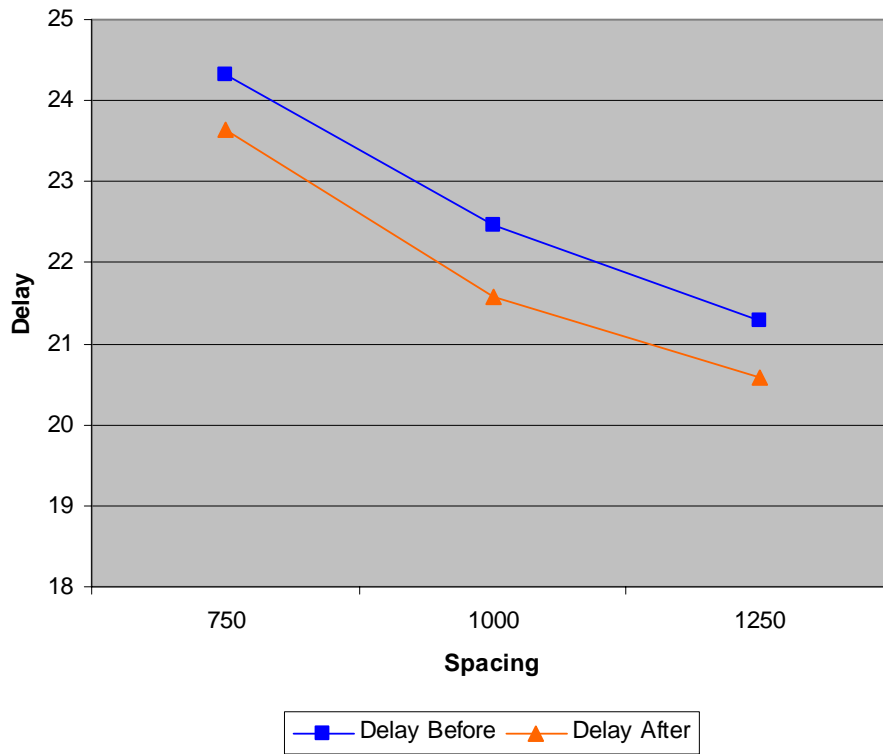


Figure 6.5: Delay Before and After - Spacing

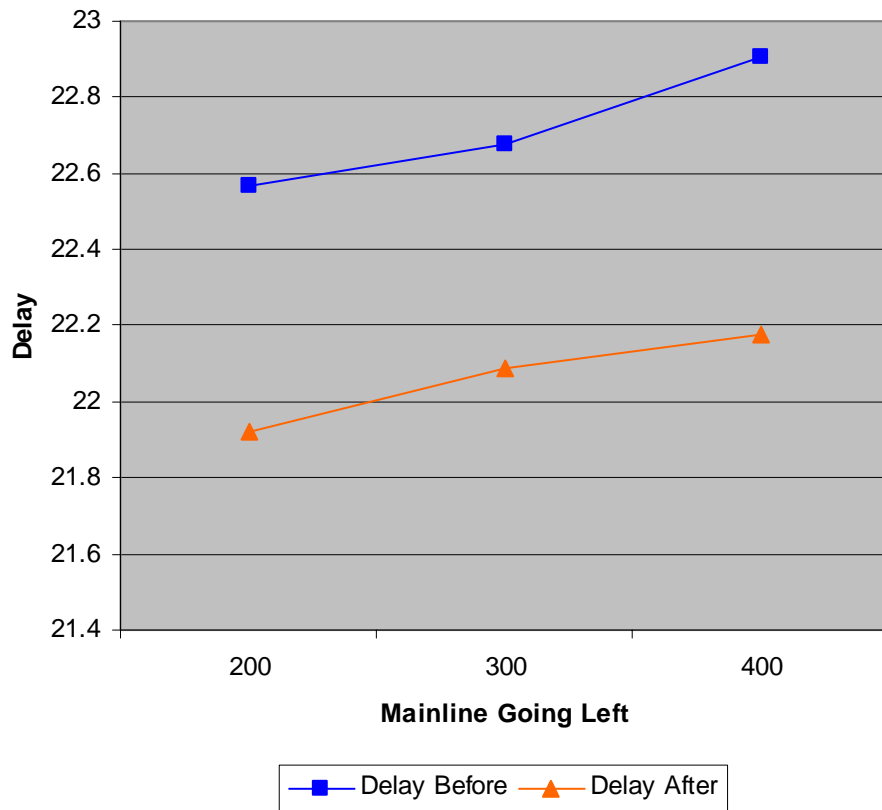


Figure 6.6: Delay Before and After – Mainline Going Left

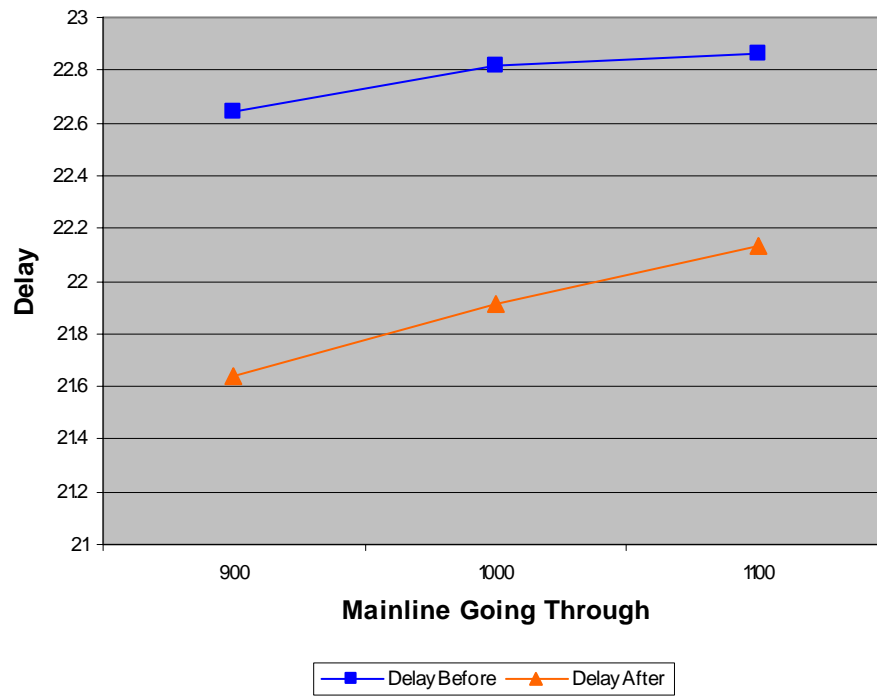


Figure 6.7: Delay Before and After – Mainline Going Through

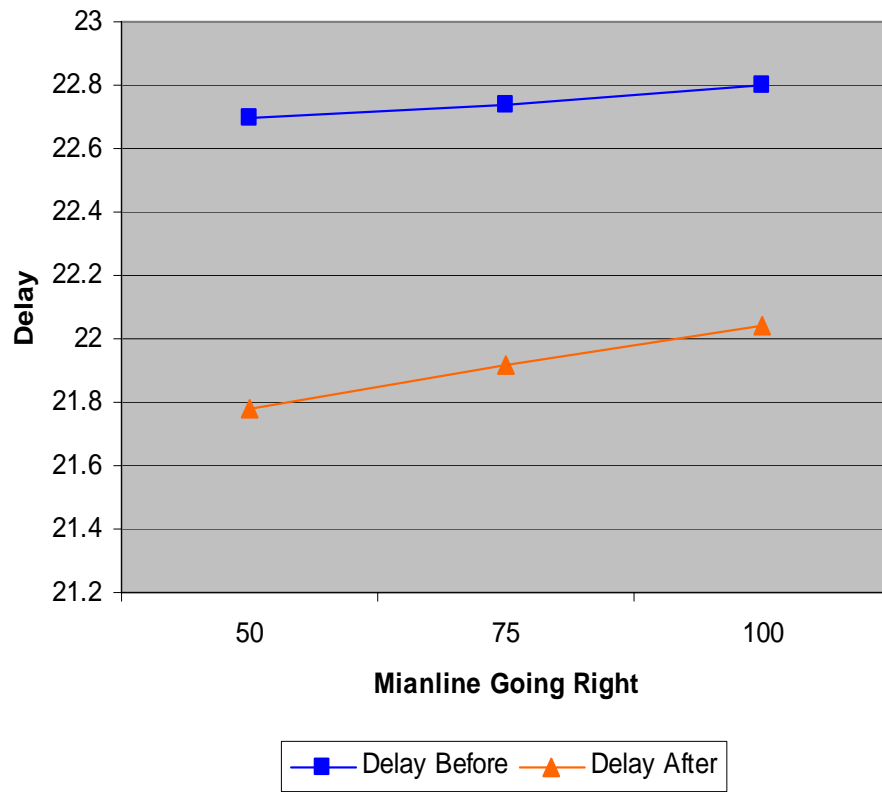


Figure 6.8: Delay Before and After – Mainline Going Right

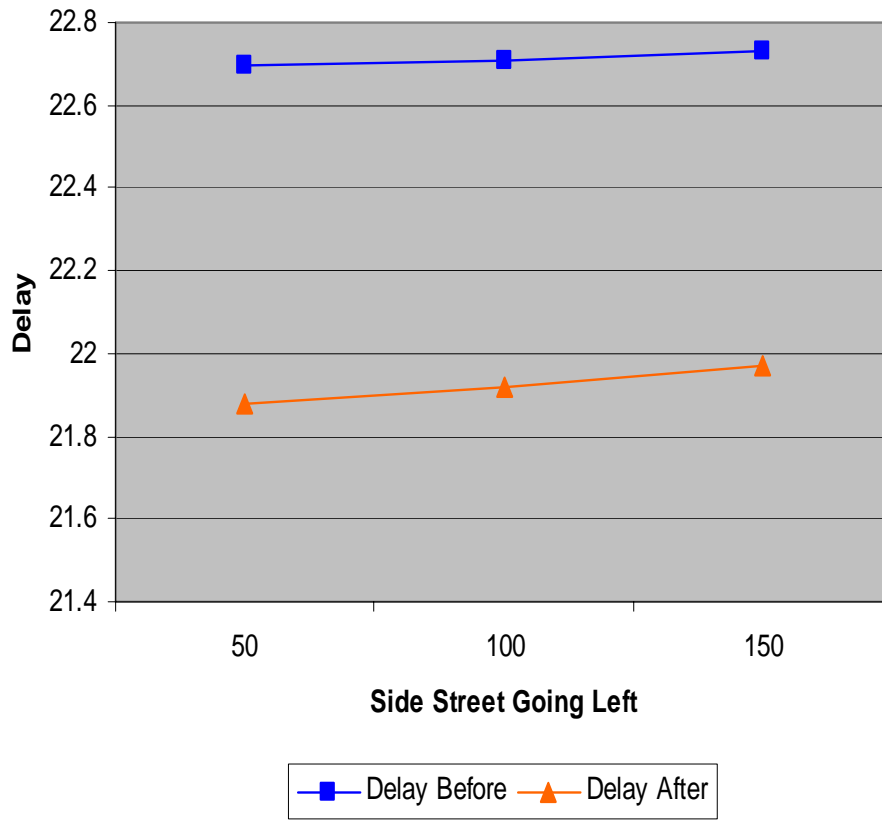


Figure 6.9: Delay Before and After – Side Street Going Left

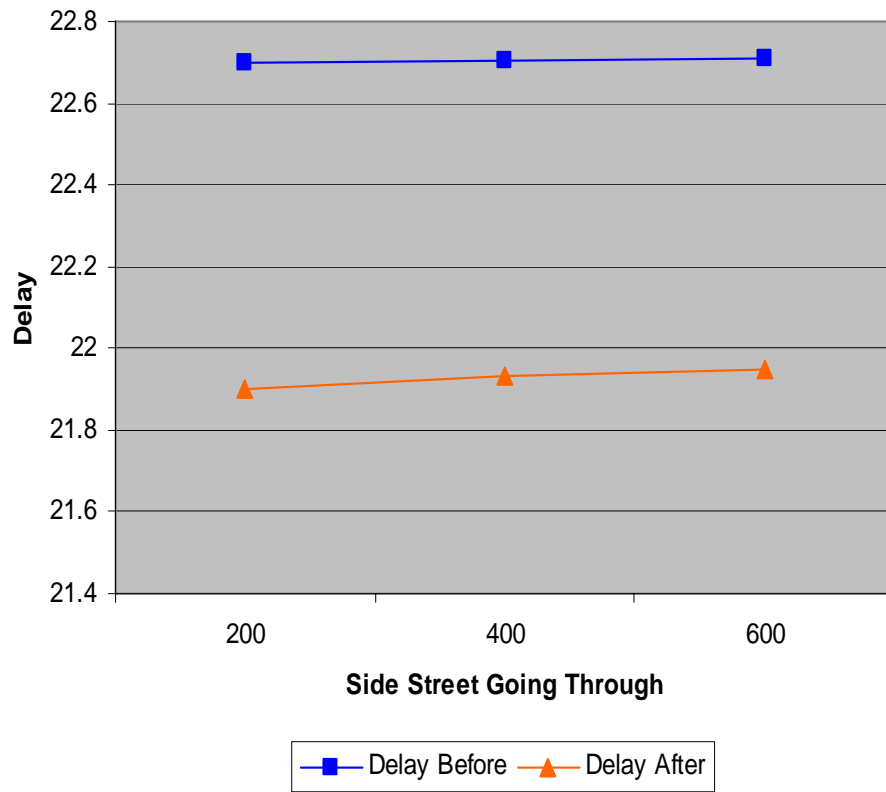


Figure 6.10: Delay Before and After – Side Street Going Through

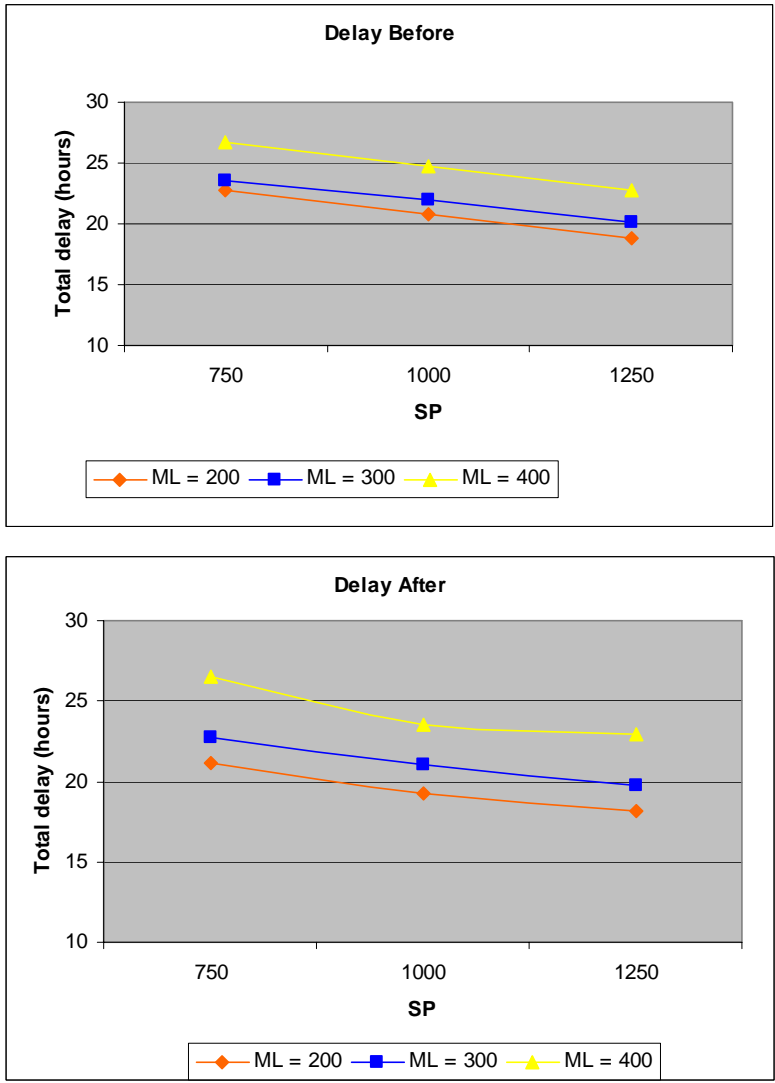


Figure 6.11: Delay Before and After – Interaction Between Spacing and Main Line Going Left

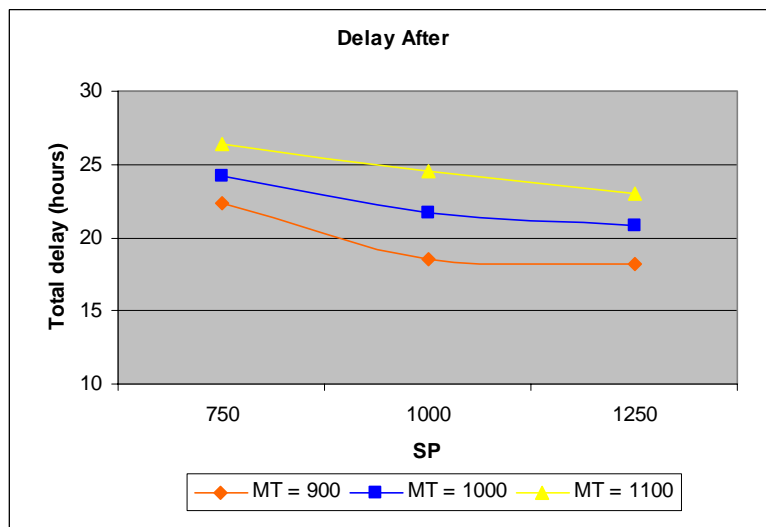
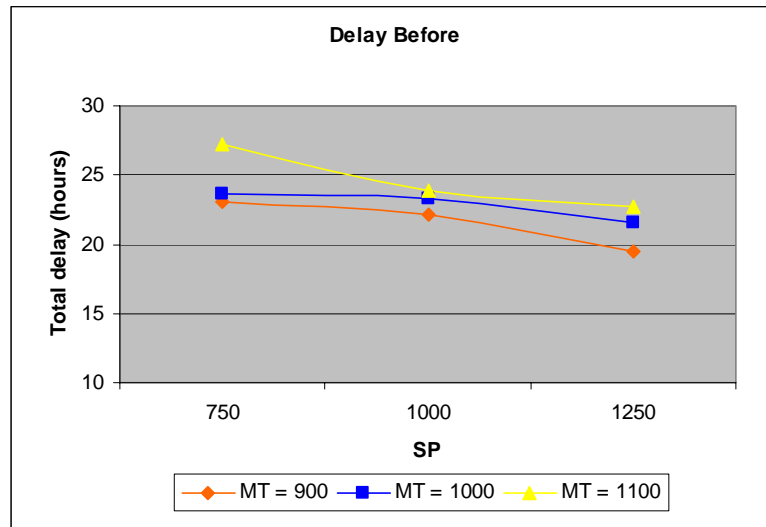


Figure 6.12: Delay Before and After – Interaction Between Spacing and Main Line Going Through

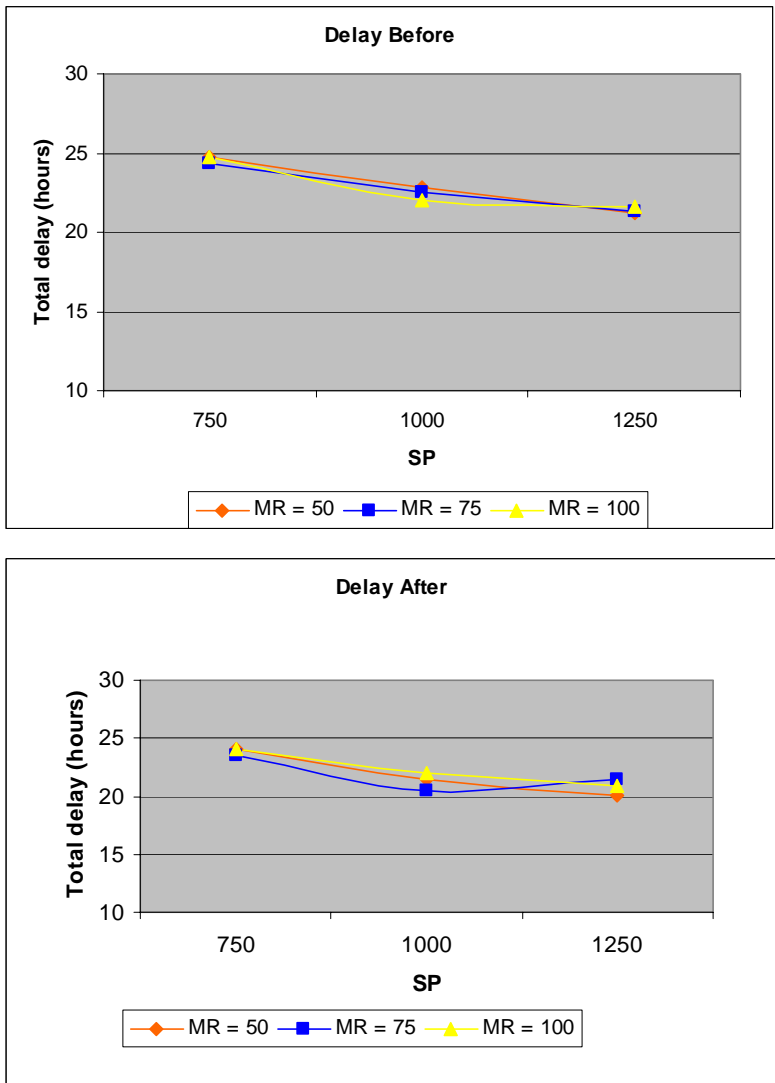


Figure 6.13: Delay Before and After – Interaction Between Spacing and Main Line Going Right

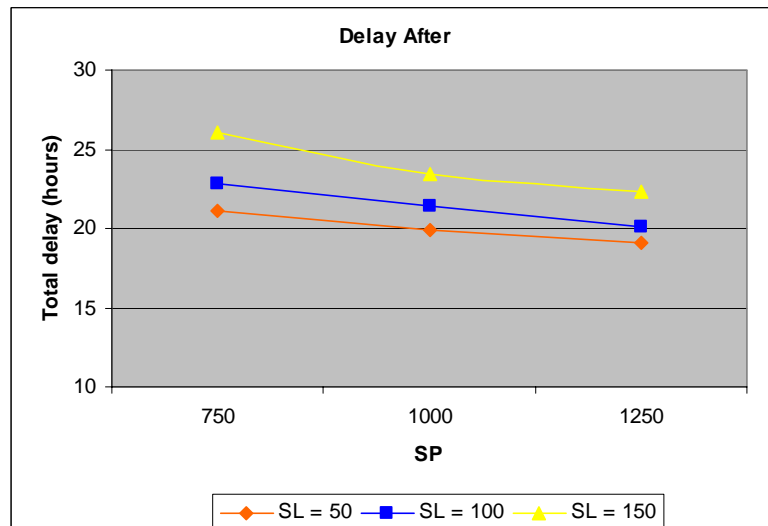
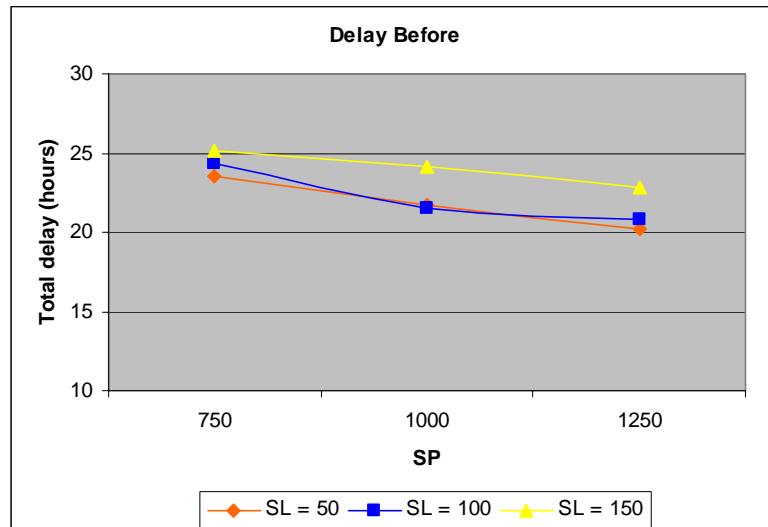


Figure 6.14: Delay Before and After – Interaction Between Spacing and Side Street Going Left

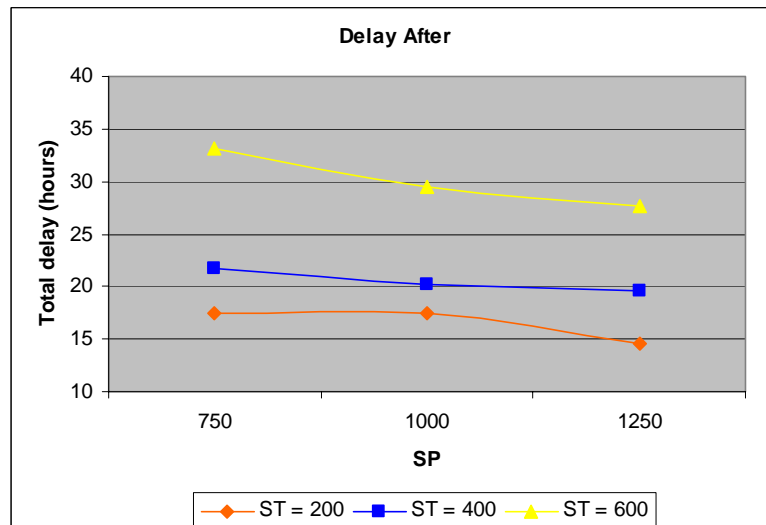
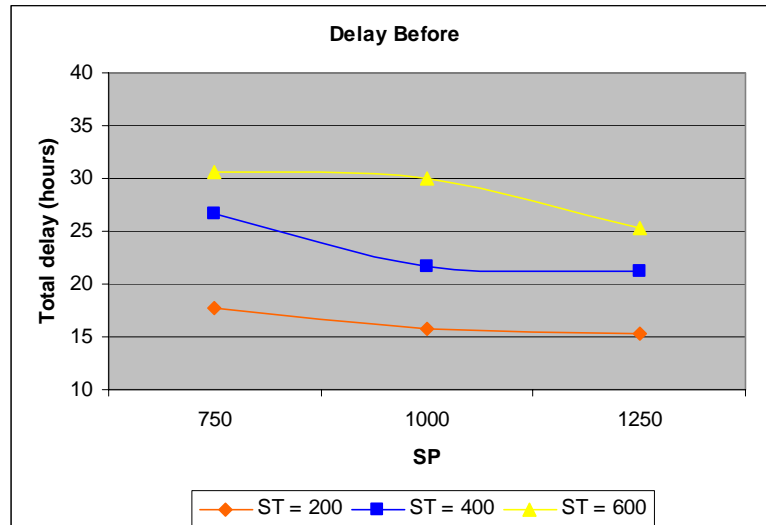


Figure 6.15: Delay Before and After – Interaction Between Spacing and Side Street Going Through

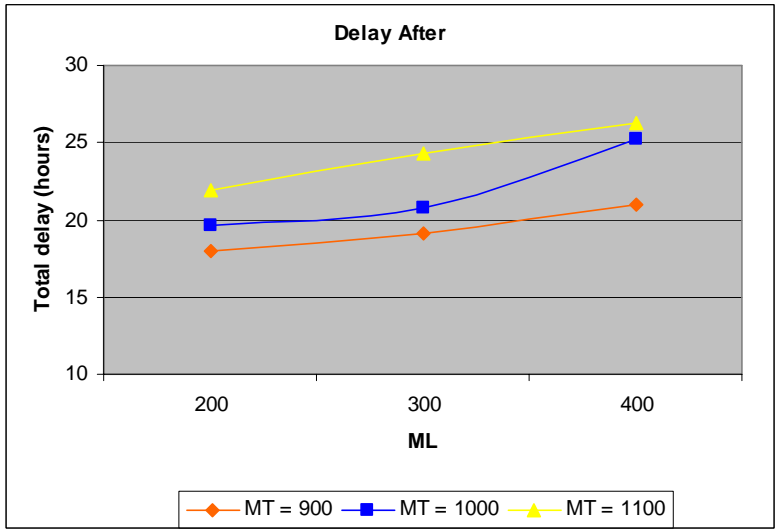
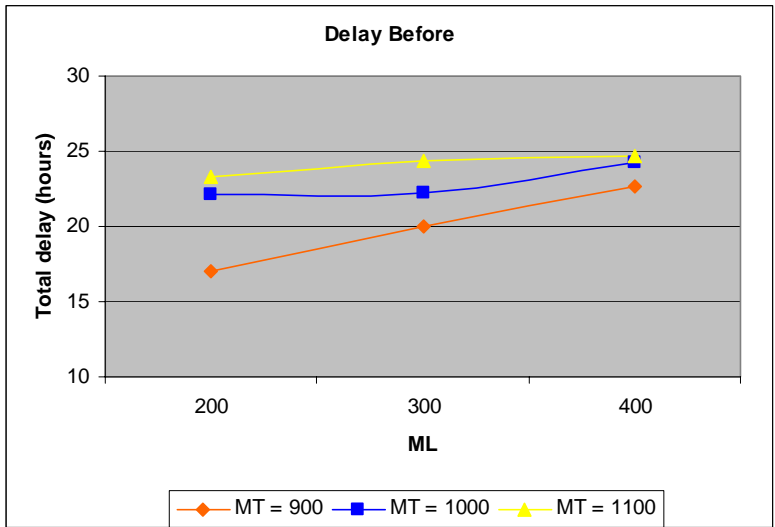


Figure 6.16: Delay Before and After – Interaction Between Main Line Going Left and Main Line Going Through

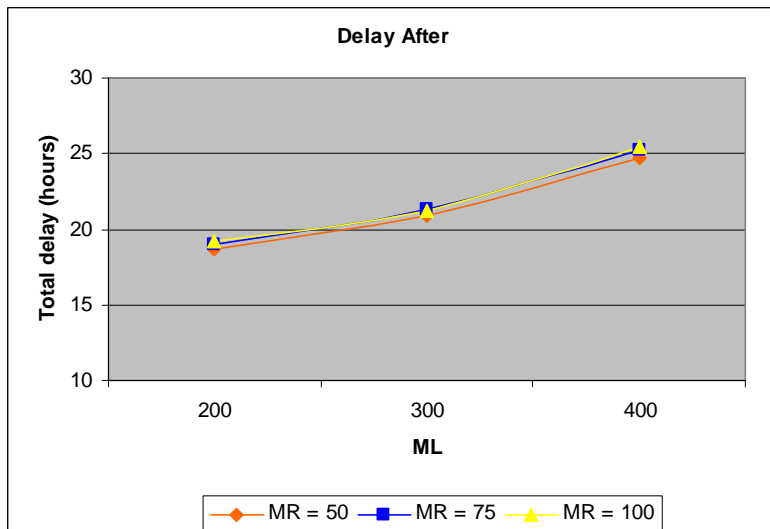
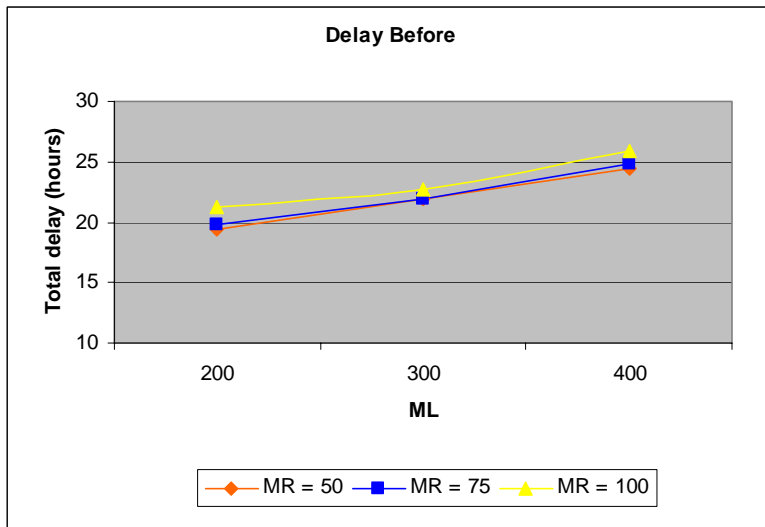


Figure 6.17: Delay Before and After – Interaction Between Main Line Going Left and Main Line Going Right

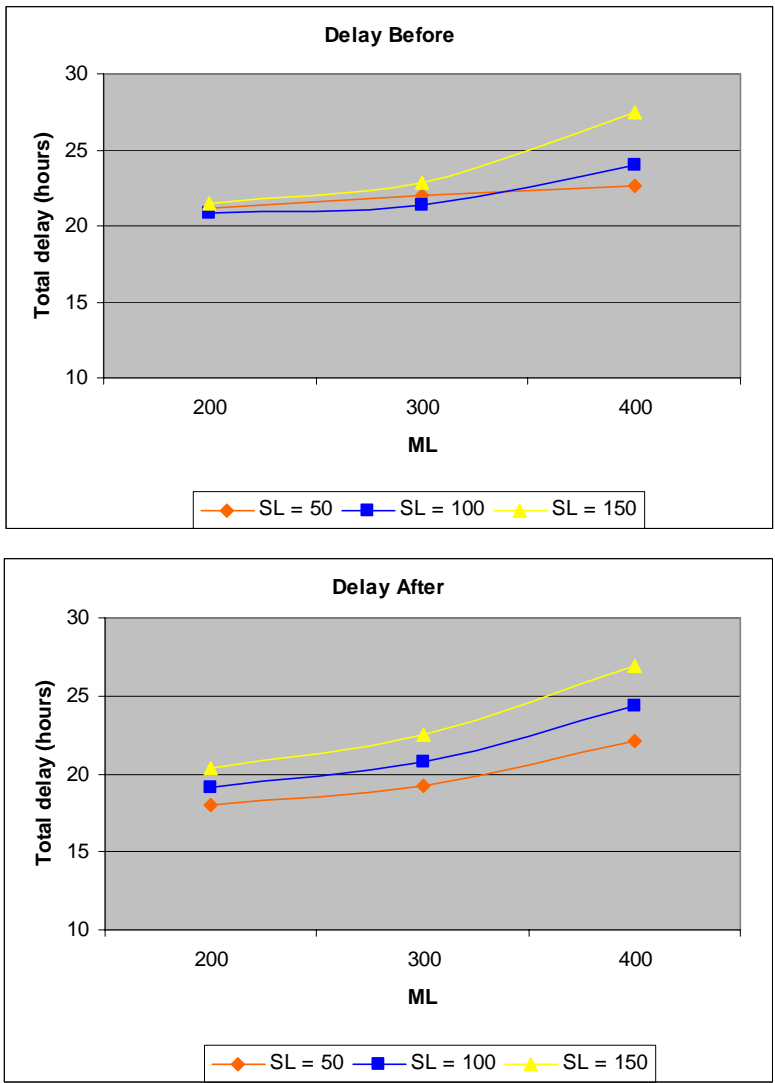


Figure 6.18: Delay Before and After – Interaction Between Main Line Going Left and Side Street Going Left

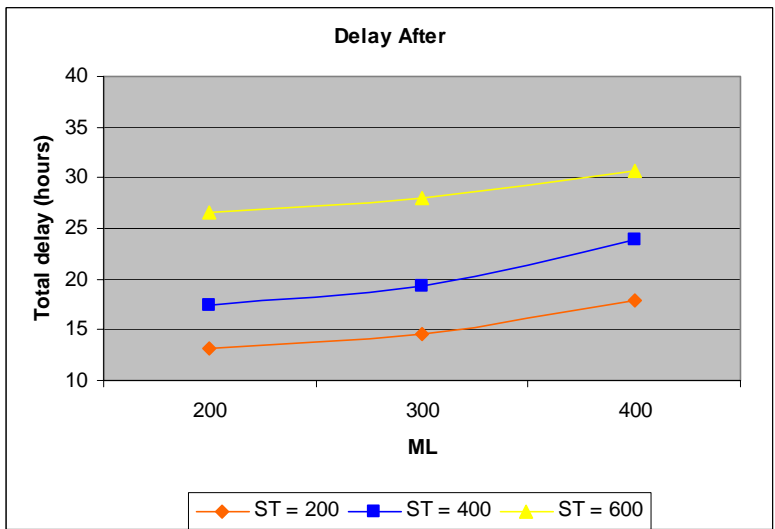
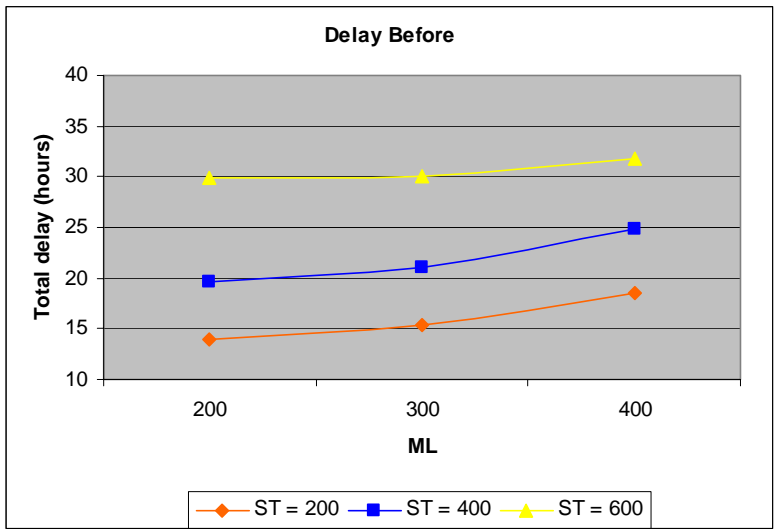


Figure 6.19: Delay Before and After – Interaction Between Main Line Going Left and Side Street Going Through

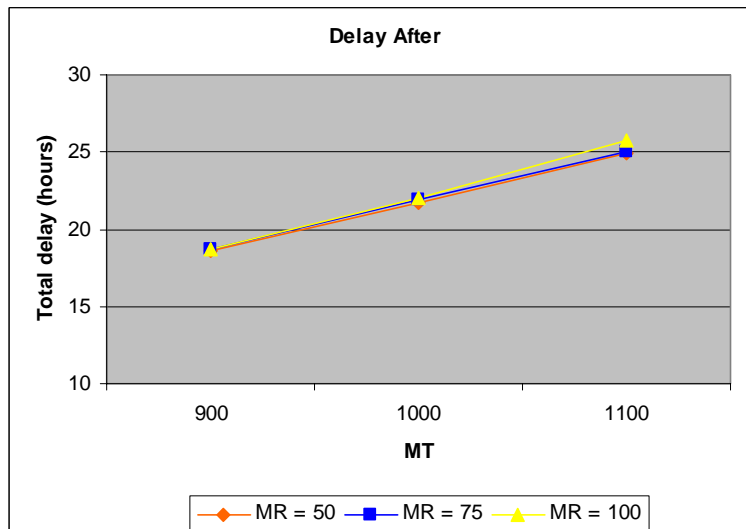
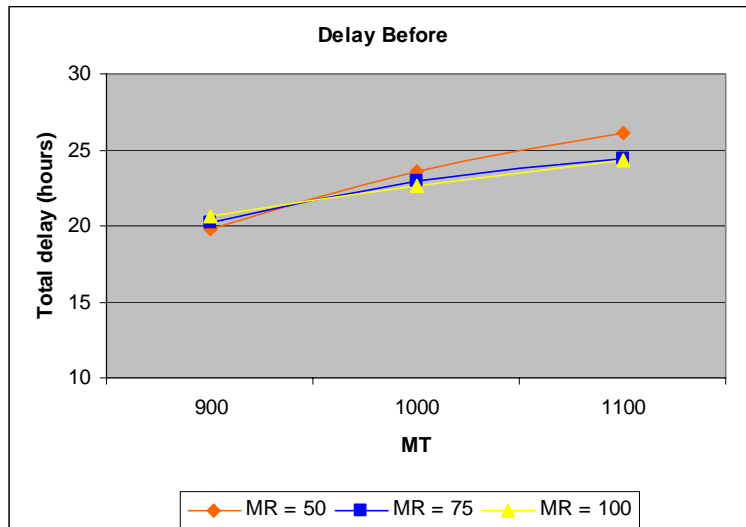


Figure 6.20: Delay Before and After – Interaction Between Main Line Going Through and Main Line Going Right

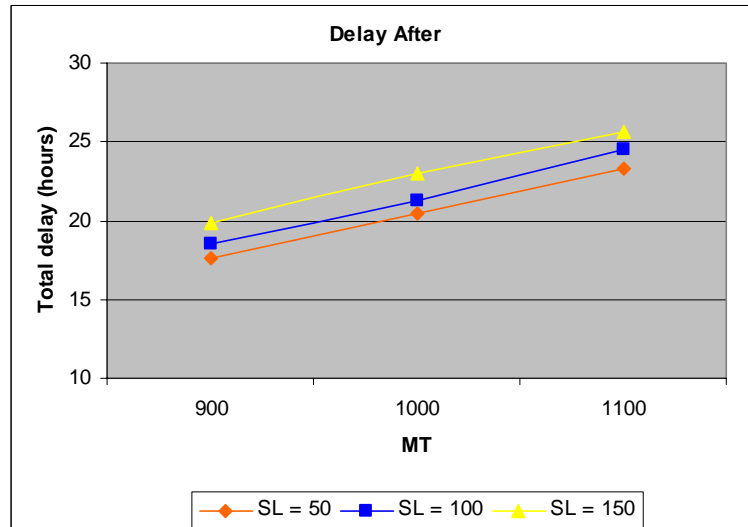
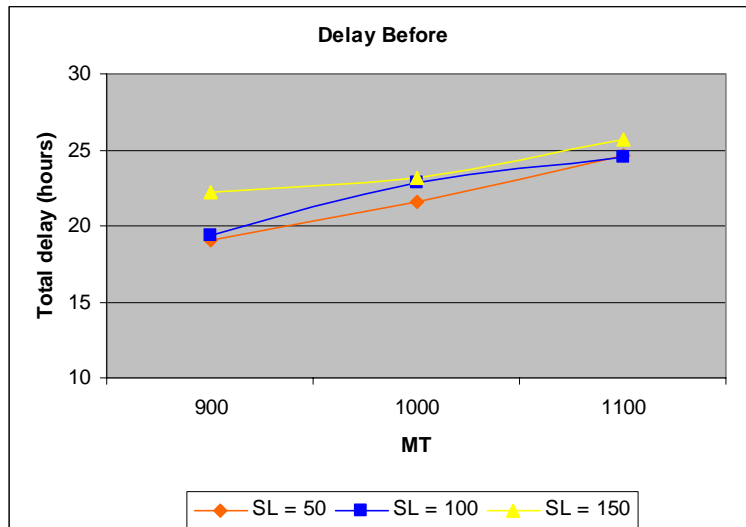


Figure 6.21: Delay Before and After – Interaction Between Main Line Going Through and Side Street Going Left

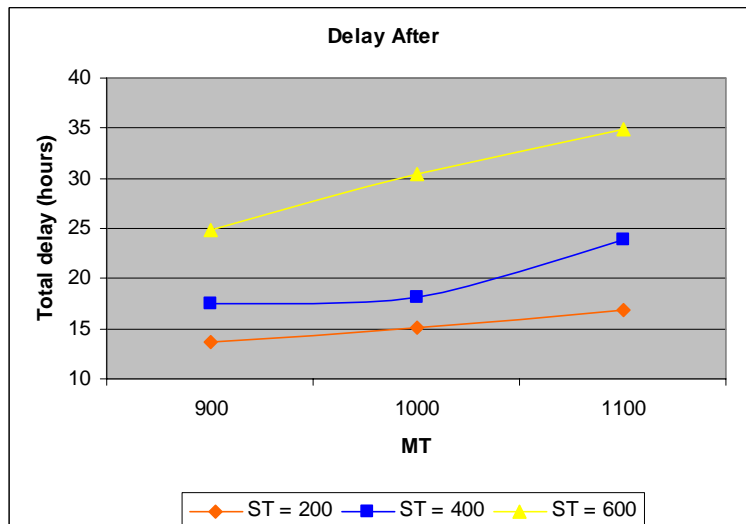
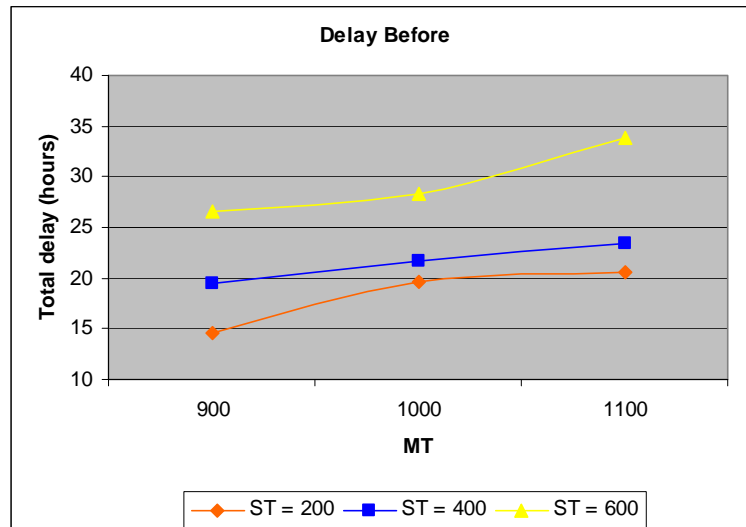


Figure 6.22: Delay Before and After – Interaction Between Main Line Going Through and Side Street Going Through

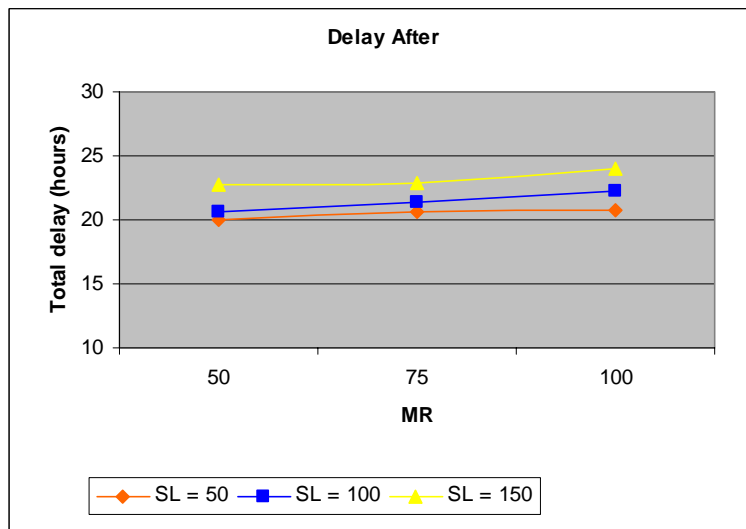
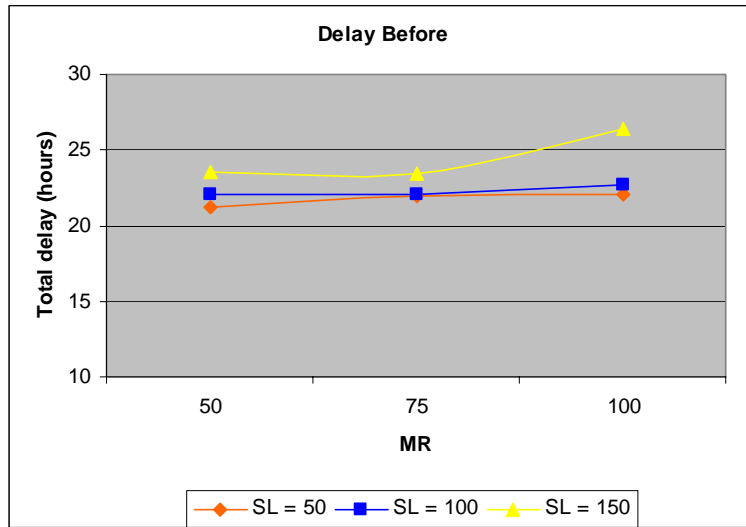


Figure 6.23: Delay Before and After – Interaction Between Main Line Going Right and Side Street Going Left

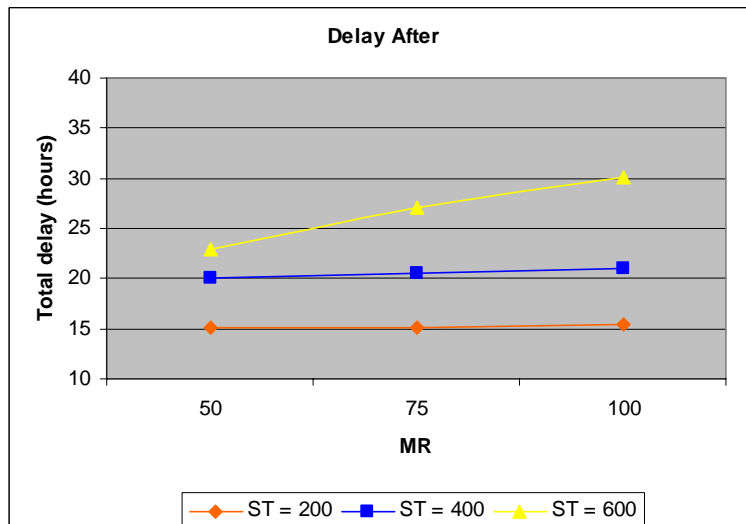
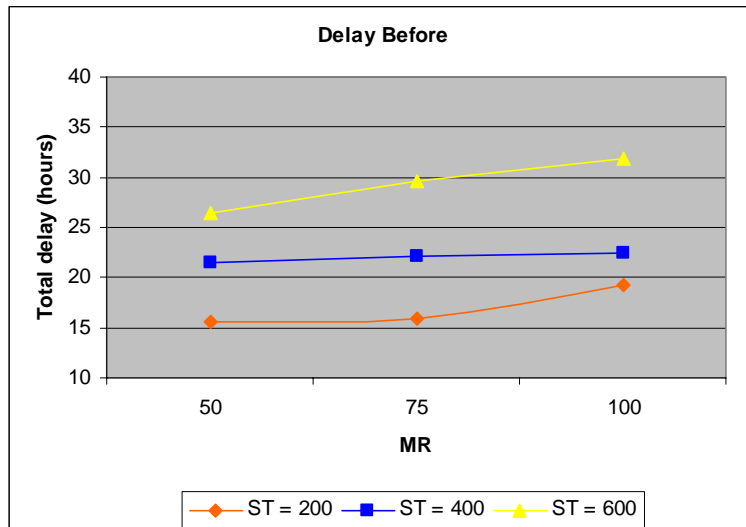


Figure 6.24: Delay Before and After – Interaction Between Main Line Going Right and Side Street Going Through

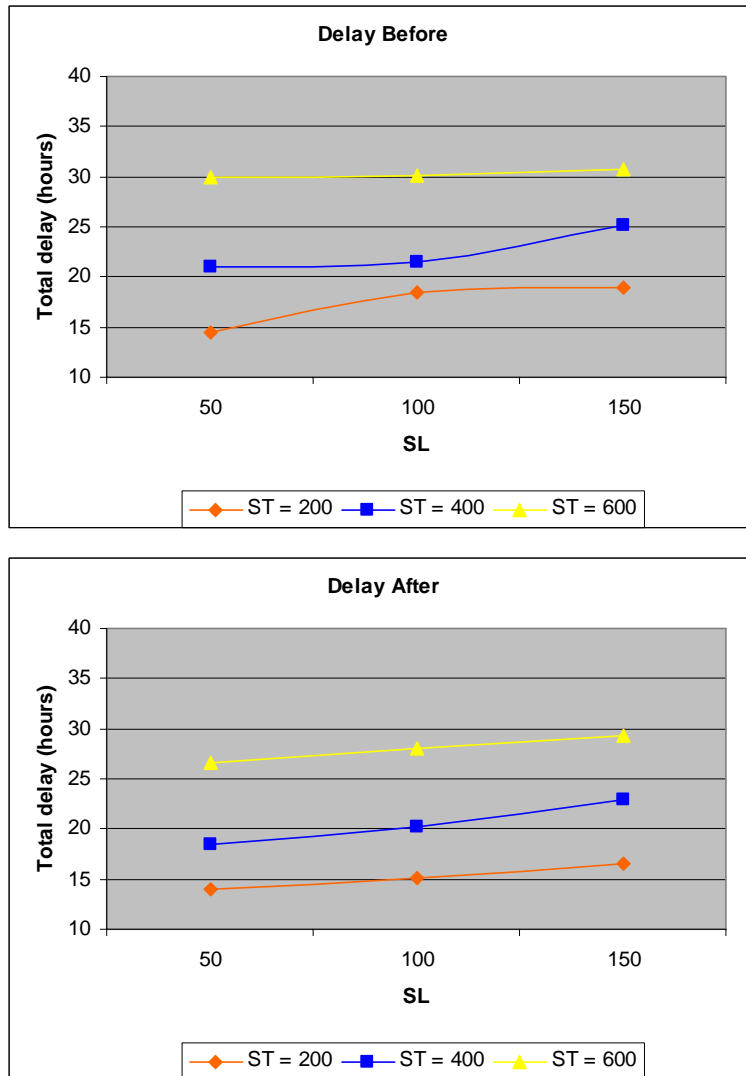


Figure 6.25: Delay Before and After – Interaction Between Side Street Going Left and Side Street Going Through

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CHAPTER 7. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This dissertation has examined the different weaving movements occurring between two close-spaced intersections for two sites in Florida. The two sites have a heavy right turn volume entering from the side street and close-spaced intersections. The dissertation has also studied the breakdown conditions occurring on the two arterial segments caused by the weaving movements. It was found that the breakdown conditions occur in two cases. The first case occurred when the main street through volume was heavy with moving queues observed extending onto the first intersection. In this case, vehicles entering from the side street could not find adequate gaps on the main street and had to reach a complete stop waiting for a gap on the main street. In the second case, the left turning volume at the second intersection was heavy blocking the left turn lane. Although the main street volumes were moderate and adequate gaps were available, vehicles entering from the side street and willing to perform a left turn at the second intersection had to stop blocking the free right turn lane and waiting for the left turn lane to clear.

The analysis also revealed that the weaving distances were affected by the distance between the two intersections. As the spacing between the intersections increases, the weaving distances increase. By increasing the distance between the two intersections, drivers will have more space and time to adjust and to perform the weaving movement. In addition, the weaving distances within the same site were affected by the number of lanes changed. If a vehicle wants to change three lanes, it will perform the first lane change at a much shorter distance than a vehicle that wants to change only one lane.

The dissertation proposed the Right Turn Split (RTS) design to alleviate the delay caused by the weaving movements on arterial streets. Pilot studies were conducted at two arterial weaving sections in Florida to demonstrate the feasibility of the approach. The method is based on separating the worst weaving movement from the other weaving movements before reaching the arterial street. This was done by directing the side street vehicles to two separate right turn lanes. The vehicles are then directed to a special path on the arterial street leading to the left turn lane at the downstream intersection.

In order to enforce the vehicles to follow the proposed path, two barriers should be provided along the arterial. The barriers can be in the form of delineators in case of no right of way, two feet of painted gore area supplemented with delineators for each barrier in case of limited right of way, and four feet of raised concrete traffic separator supplemented with delineators for each barrier in case of right of way availability. Delineators should be used in all cases to improve safety and to give additional guidance for the vehicles to avoid impacting the traffic separator. To define the location of the two barriers (the split distance), three different methods were studied. The 85th percentile weaving distance was selected since it provided the lowest split distance. The 85th percentile weaving distance is defined as the distance at or over which 85% of all drivers, except type 5 drivers, performed their weaving movement. The proposed design did not require much right of way but required a special signing arrangement to explain the new path to the drivers.

The dissertation compared two microscopic simulation models, SimTraffic and VISSIM, to figure out the most suitable package for this research. Each component was given a rating in the scale of 1 to 3 where 3 indicates a “Very Good” level, 2 indicates an “Acceptable” level, and 1 indicates a “Need Improvements” level. Depending on the different requirements, users can choose the model that suits their needs. This comparison was based on the authors’ experience in using VISSIM and SimTraffic in modeling signalized intersections. Both VISSIM and SimTraffic were run with the default parameter values. SimTraffic proved to be more suitable for this research. SimTraffic was easy to use, and had many useful features that can save time and effort especially when dealing with intersections.

The dissertation also presented a new calibration and validation procedure for microscopic simulation models. The procedure focused on the model calibration of arterial segments that include signalized intersections. The procedure was demonstrated using an example case study. The calibrated and validated procedure appeared to be properly effective in the calibration and validation of the microscopic simulation model SimTraffic for arterial streets. Although this procedure was applied only on SimTraffic, the proposed procedure can be potentially applied to other simulation packages as well.

The procedure focused on the importance of type of data and how it is useful to use different sites and different time periods (morning, midday, and evening) in the process to test the model during different conditions and different types of demand (peak hours and non-peak hours). The procedure also discussed the importance of understanding all the useful features in each

microscopic simulation package because some features can save a lot of effort and time during the calibration and validation process.

In order to determine the operational benefits of the RTS design, the calibrated model was used to do a before and after study for different scenarios. Six variables, the spacing and five volume variables, were developed with three levels each. This resulted in the development of 1,458 SimTraffic models (729 pairs). The graphical and statistical analysis conducted showed that for the geometric, volume, and traffic control conditions tested, the RTS design provided better system operational performance than the original conditions. The arterial street had lower total delay after applying the RTS design. The study was based on one geometric data set in which comparable geometries were defined and assumed to be equal. The SimTraffic calibration and validation was conducted with field data and field calibration from two sites in Florida. Only signal phasing was utilized from the field data. Splits, offsets, and cycle lengths were optimized using Synchro. The arterial segment was assumed to be isolated for the analysis, meaning no median openings, or driveways affected the traffic patterns along the arterial segment.

Further study could include additional geometric data sets to determine how geometric variations affect the operational benefits along the arterial street. Finally, the findings of this research will be used to implement the new design on the two pilot locations. It is also recommended to study the effects of the new design on the delay and the safety of the arterial segment after implementation.