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Effects of Light Rail Transit on Traffic Congestion

by

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16. Abstract

Many regions around the United States are considering developing light rail transit (LRT) systems as an alternative transportation mode. LRT has been cited by the Portland Tri-Met transit agency as a way to help influence development by promoting more desirable and sustainable land uses near the LRT lines. Light rail is also generally less expensive to construct and operate than other kinds of rail transit systems. LRT is an attractive option because of its ability to be located in a variety of settings, from tracks on an exclusive right-of-way to shared lanes with cars and trucks in an urban street. There is a great possibility for vehicles to experience additional delays when there is interference by LRT operations, such as in the case of at-grade crossings or due to priority being given to LRT vehicles at signalized intersections at the expense of conflicting turning movements.

This study examines the effects of light rail crossings on average delays experienced by vehicles. Using the VISSIM 3.70 computer simulation model, four scenarios were examined: isolated crossings of two-lane and four-lane roads, a case in which light rail transit is located in the median of a street, and a larger network that includes four crossings. The effects of variable traffic volumes and light rail crossing frequencies were studied in the isolated intersection scenarios. The scenario with LRT in the median and the larger network examined the effects of different crossing frequencies as well as full traffic signal preemption.

The results of the simulated test scenarios indicate that the average additional delays from light rail transit crossings increase with increasing light rail crossing frequencies and increasing traffic volumes up to the roadway's capacity. As the road enters an over saturated condition, the average total delays continue to increase, but the difference in total delays with and without light rail decreases from the unsaturated condition. Preemption of traffic signals near light rail crossings increases the total delay experienced by vehicles that are in conflict with the light rail crossing, but it tends to improve travel times for the no conflicting movements due to the increased green time. Based on these results, it is determined that traffic volumes at crossings and the frequency of light rail crossings are important variables that affect the average additional delays experienced by vehicles.

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Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

1.1. Characteristics of Light Rail Transit

Light rail transit (LRT), according to the Transportation Research Board's Committee on Light Rail Transit, is defined as "a metropolitan electric railway system characterized by its ability to operate single cars or short trains along exclusive rights of way at ground level, on aerial structures, in subways or, occasionally, in streets, and to board and discharge passengers at track or car-floor level" [1]. This definition allows for the inclusion of older streetcar-style systems as well as new LRT lines that have begun service in the past thirty years. It also separates LRT from systems that do not use electricity to power their vehicles and those that require full grade separation because a third rail is used.

1.2. Classification of Light Rail Transit Systems

Some light rail transit systems currently in operation date back to the streetcar era of the early 20th century, while others have only begun operation within the last five years [2]. Light rail systems can be found in a variety of land use contexts, from suburbs to high-density central business district areas, and they can operate in a range of right-of-way types. Because of the wide variations in operating characteristics among LRT systems, researchers have attempted to create classification schemes for comparison purposes. Operating speeds and alignment types are two characteristics of LRT systems that can be used for classification [3].

1.2.1. Speed-based classification

Many early classifications of light rail transit systems used the average operating speed as the basis for grouping [3]. According to Transit Cooperative Research Program

(TCRP) Report 17, the use of average speed is acceptable in that it can reflect the diversity of LRT systems [3]. On systems that use primarily one type of right-of-way, the use of average speed could be a good way to differentiate among systems that use different types, since higher speeds can be obtained with a greater degree of exclusivity [3]. However, this classification scheme does not fully account for the use of multiple alignment types and speed changes from block to block that can be found in some of the more recently constructed LRT systems [3].

1.2.2. Alignment-based classification

TCRP Report 17 suggests that the use of alignment types as the basis for classification would be the most appropriate method to categorize systems for planning and operations purposes [3]. When designing a new LRT system, the type of alignment that is eventually selected often is a result of the design goals of the system and the area surrounding the LRT tracks, including costs, service considerations, and operational features [3]. From a planning and operations point of view, similar alignment classes have similar features and concerns with respect to safety and effects on traffic [3].

The alignment classification system recommended by TCRP 17 includes three basic alignment classes: *exclusive* (type a), using full grade separation; *semi-exclusive* (type b), with grade crossings as well as segments of separate right-of-way; and *non-exclusive* (type c), which includes the light rail operating in a shared right-of-way with motor vehicles, other transit vehicles, or pedestrians [3]. From these three classes, TCRP 17 further defines nine types of alignments, which are listed in Table 1.

Table 1. Classification of Alignments [Source: TCRP Report 17]

Class	Category	Description of Access Control
Exclusive:	Type a	Fully grade-separated
Semi-Exclusive:	Type b.1	Separate right-of-way
	Type b.2	Shared right-of-way protected by 6-inch high curbs and fences
	Type b.3	Shared right-of-way protected by 6-inch high curbs
	Type b.4	Shared right-of-way protected by mountable curbs, striping, and/or lane designation
	Type b.5	LRT/Pedestrian mall adjacent to a parallel roadway
Non-Exclusive:	Type c.1	Mixed traffic operation
	Type c.2	Transit mall
	Type c.3	LRT/Pedestrian mall

1.3. Preemption of Street Traffic

A concern that sometimes arises among citizens and public officials during the planning for a new LRT system is that frequent light rail crossings will create unacceptable delays for regular street traffic. Traffic signals are often used with LRT systems in order to allow light rail vehicles to cross an intersection safely. In order to accommodate scheduling and as an incentive for people to use transit, light rail vehicles might be given a priority when they arrive at a signalized intersection. As Hood, Hicks, and Singer pointed out in “Light Rail Preemption of Traffic Signals: A Question of Balance,” giving light rail vehicles priority at signals presents a challenge to engineers of balancing the needs of transit with those of the street traffic [4]. The problem is especially significant when the LRT operates along a corridor with coordinated signals as well as when there are frequent preemption calls [4]. In Baltimore, engineers found that preemption calls were causing excessive traffic delays resulting from the LRT vehicle crossing as well as the time required for the signals to become synchronized once again [4].

1.4. Where Are LRT Systems Located?

Light rail transit facilities in North America are typically located in major cities, sometimes extending into their suburbs. Some of the oldest LRT systems still in operation, such as those in Boston and Philadelphia, were developed from the early streetcars that operated in those areas [5]. In 1975, there were light rail or streetcar facilities in only ten North American cities [1]. After the late 1970s, many cities decided to pursue light rail as a way to create a higher capacity transit system that is cheaper and potentially less disruptive to the surrounding environment than heavy rail systems, while providing an alternative to new road construction. Proponents of LRT also claim that it can positively affect changes in land use patterns towards more sustainable and desirable uses.

According to the National Transit Database, there were 23 LRT systems in the United States in 2002, many of which are concentrated in the Northeast and in the western part of the country [6]. Light rail is also found in several cities in Canada, Mexico, and throughout Europe [7]. One notable system is in Portland, Oregon, where according to its operator, the MAX light rail system serves as the backbone for transit in addition to being a catalyst for developing preferred land use patterns in that region [8].

Many cities around the country have recently considered LRT as a way to improve their transit service. In the past year, new LRT systems have opened in Houston and between Trenton and Camden in southern New Jersey [9, 10]. Charlotte, Minneapolis, Seattle, and Norfolk are cities where LRT systems are in various stages of planning or construction [11, 12, 13, 14].

1.5. Project Objectives

The objectives of this project are:

- To identify factors of light rail transit crossings that affect street traffic
- To investigate additional delays experienced by vehicles due to frequent LRT crossings
- To demonstrate a methodology for estimating the traffic impacts caused by at-grade light rail crossings that can be used by planners and traffic engineers who are designing LRT systems.

1.6. Project Purpose and Scope

With a number of light rail transit facilities in the planning stages of development, it would be advantageous to know how those facilities might have an effect on regular street traffic. If delays are unacceptable, grade separation or other mitigation measures may be required, potentially increasing time and money costs. It may be advantageous for transit agencies and planners to have an idea of the necessary measures that may be needed early in the process. However, at present, there has been little research that has attempted to quantify the effects of the interactions between light rail vehicles and street traffic for general cases. This study attempted to quantify the effects of LRT crossings on street traffic as well as to develop a methodology that will allow planners of light rail transit facilities to evaluate directly the delay impacts of LRT crossings.

This project examined the changes in average total vehicular delays associated with at-grade crossings of light rail transit lines with streets. A methodology that allows for direct evaluation of the delay impacts using VISSIM 3.70, an advanced traffic simulation modeling program, will be presented. Four example scenarios were considered: an isolated crossing of a two-lane road, an isolated crossing of a four-lane road, an intersection in which the LRT is located in the median of a street, and a larger network that includes multiple crossings. The frequency of light rail crossings and traffic volumes on the roads in conflict with these crossings were considered as the primary variables affecting the change in delay.

1.7. Thesis Overview

A review of relevant literature is presented in Chapter 2. Chapter 3 describes a methodology for determining additional delays caused by light rail transit crossings, including descriptions of the scenarios that were considered for this project. Results from applications of the methodology are discussed in Chapter 4, with conclusions and recommendations detailed in Chapter 5.

Chapter 2: Review of Relevant Literature

2.1. Previous Studies

2.1.1. Delay Impacts of Light Rail Transit Grade Crossings

A Master of Science thesis by James Curtiss Cline, Jr., of Texas A&M University examined the delays that could be attributed to LRT at-grade crossings in 1986 [15]. Cline used the NETSIM computer simulation model to test four scenarios with light rail crossings: an isolated crossing, an adjacent intersection crossing, a series of coordinated intersections with preemption, and a case study based on a corridor in Houston [15]. The study found that the volume to capacity (v/c) ratio was the major factor in the delay experienced per vehicle at an isolated crossing. For a crossing near an adjacent intersection, the distance between the intersection and the crossing as well as the v/c ratio were major components of the delay, but traffic traveling parallel to the LRT line did not appear to be affected greatly. Locations of LRT crossings within a coordinated signal network did not appear to affect the traffic significantly. The results from the Houston case study showed that most of the effects were shown to be localized near crossings; there did not appear to be a network wide effect on delays.

2.1.2. San Diego Trolley "Traffic Impacts of Light Rail Transit"

Shortly after LRT service began in San Diego in 1981, planning began for a northeast extension of the system toward the cities of Lemon Grove and La Mesa (now in operation, known as the Orange Line) [16, 17]. Because of concerns raised by citizens and government officials in those cities, a study was commissioned to analyze how the presence of LRT would affect traffic operations. The researchers for this study expressed their results in terms of level of service at key intersections that would likely be affected by the presence of LRT under a “worst case” condition of afternoon peak period volumes and 7.5-minute headways [16]. From their estimates using a Greenshield’s model as well as from a demonstration project, they found that queues generated from LRT crossings could be dissipated after one traffic signal cycle, with dissipation times ranging from 6 to 33 seconds [16]. A demonstration project involving gate crossings along the proposed LRT right-of-way appeared to show that the estimates were correct in predicting that queues would not last longer than one signal cycle, and that regular crossings would not negatively impact traffic in Lemon Grove or La Mesa.

2.2. Environmental Impact Statements

As part of the environmental review process required under the National Environmental Policy Act of 1969 (NEPA), a study of the impacts that would result from new light rail transit projects must be taken into consideration and included in the Environmental Impact Statement (EIS) that is submitted [18]. In the EIS, the major traffic impacts that would likely result from the project are noted and compared to other project alternatives and the “no-build” option. These impacts are typically included in the section describing the “affected environment” [18]. They often include results of forecasting models and incorporate elements of approved long-range transportation plans that are expected to be in place by the time of the LRT system opening, with traffic simulation models used to estimate the impacts of the light rail system that may be created from changes in modal splits or from at-grade crossings of light rail vehicles. Mitigation strategies are recommended in the report to address the areas where the preferred LRT alternative would create significant negatively effects to crossing traffic.

2.2.1. Norfolk/Virginia Beach Light Rail EIS

The Final Environmental Impact Statement for the Norfolk/Virginia Beach east-west light rail project, prepared for Tidewater Regional Transit (now Hampton Roads Transit), included a review of the transportation impacts that would likely occur as a result of construction of an LRT system between downtown Norfolk and the Virginia Beach Oceanfront [19]. The traffic volumes used in the study were forecasted for the year 2018 using the region's existing long-range transportation plan and data obtained from the regional planning organization. Alternatives that were considered in the EIS included the no-build alternative, a no-build plus transportation systems management (TSM) alternative, and the "preferred alternative" that included TSM strategies and the light rail system. Construction of alternative roadways in this area was not considered. The transportation impacts of the proposed LRT system were characterized using average total vehicular delay and level of service ratings at signalized intersections and for segments of major roadways along the corridor, using the CORSIM model, and assuming year 2018 conditions and that TSM strategies were already in place by then. The study found that the level of service at the major intersections along the corridor in 2018 would not have changed with or without LRT; many of them would already be operating at a level of service F, the worst of the six categories. The intersections appeared to be evenly split between those that would have an overall delay increase with LRT and those that would have an overall decrease, but the changes were small as a percentage of total delay. According to the EIS, the rail would help to reduce traffic volumes on some segments; however, as with the intersections, the analysis showed that there would be no change in the level of service along any of those segments. The EIS also proposes strategies for traffic control at each of the at-grade crossings along the corridor, ranging from closing streets, to adding signals and warning devices, to full grade separation.

2.2.2. Dallas Southeast Corridor Light Rail Transit EIS

A proposed extension of the Dallas DART light rail system includes a number of at-grade crossings [20]. In addition to the EIS requirements, a previously existing agreement between DART and the City of Dallas required all of the potential at-grade crossings to be analyzed to determine the impacts that would be created as a result of light rail operations. If the level of service or queue lengths along a road adjacent to the LRT would be unacceptable (defined as a drop in two or more levels of service or if the LRT caused the road to drop to LOS F) as a result of LRT operations, then DART would be required to provide mitigation measures in the form of lane additions or grade separations. The EIS provided a summary of all of the crossings and their geometric characteristics, but there was no quantitative information regarding the queue lengths or delays experienced by vehicles (or expected to be experienced), with or without light rail.

The study also performed a queue analysis to see which crossings and signalized intersections near the proposed LRT line might experience problems. That analysis showed that most of the impacts on signalized intersections near LRT at-grade crossings occurred when the intersection was within 500 ft of a crossing [20]. Those intersections were analyzed further, considering light rail vehicle arrivals during different portions of an assumed signal cycle. Based on that analysis, recommendations were made for improvements to some of those intersections. Most of the suggested improvements involved providing exclusive right turn lanes to store vehicles that would be stopped by the light rail crossings. Other potential crossings in neighborhoods and those with light traffic volumes were recommended for closure.

2.3. Guidelines for Design of Light Rail Grade Crossings

A report commissioned by the Institute of Transportation Engineers (ITE) examined the design and operations of LRT at-grade crossings. It includes a summary of all of the LRT at-grade operations in North America at the time and recommendations to deal with some of the main problems found at crossings, most of which were concerned with safety and consistency of traffic control devices. This report did not look specifically at delays experienced by traffic at those crossings, however. The subject of delays experienced by traffic at those crossings was not specifically addressed by the report, however. The researchers found that accurate crossing volume data was difficult to obtain, but the information that they did collect indicated that most of the light rail crossings had an ADT of less than 10,000 vehicles per day [21]. Crossing volumes of over 20,000 vehicles per day were observed for 8% of the intersections, and 1.5% had ADT volumes of greater than 40,000 vehicles per day [21]. This report stated that those volumes corresponded to guidelines for LRT grade separation that were proposed by another ITE committee which stated that grade crossings were acceptable for volumes of 15-20,000 vehicles per day and that crossings in the 20-40,000 range may be acceptable with further study [21].

This report also compares the designs of older LRT systems with those that have been constructed more recently. Many of the older systems that were descended from streetcars such as those in San Francisco, Philadelphia, Boston, and New Orleans, have more frequent stops and less separation from motor vehicles, including operations in the street right-of-way. More modern systems like the ones located in Edmonton, Portland, and San Diego tend to have faster operating speeds due to their increased level of separation and being given priority at traffic signals along their routes. A large number of the newer systems operate either in an exclusive right-of-way or in a street median.

2.4. Reducing the Effects of Traffic Signal Preemption

Engineers for the Maryland State Highway Administration looked at ways to reduce the delays of street traffic at the coordinated intersections while not reducing the level of service of the light rail [4]. Some of the ideas that they considered were

- Allowing turning movements that were not in conflict with the LRT to proceed through the intersection while the LRT is crossing
- Allowing the signal controller to select the phase that operates first after the LRT vehicle clears the intersection based on traffic demand
- Experimenting with different signal sequences used to clear vehicles from the LRT tracks.
- Looking for ways to reduce the disruption to the coordinated signals that results from frequent LRT preemption calls
- Holding the transit vehicle at the intersection until there is a convenient moment in the cycle for it to clear the intersection and still allow for efficient traffic movement [4].

These ideas were tested using advanced signal controller technology on an express bus route along a highway between Baltimore and Annapolis, Maryland. With the express buses, the engineers found that bus travel times decreased by 14-18%, and automobiles sometimes also experienced a decrease in travel time because of the additional green time given for the buses [4]. Similar concepts were being tested (as of the writing of the paper) with light rail at two groups of intersections in the Baltimore area, and they show much promise in helping to balance transit preemption with the needs of automobile traffic [4].

Koch, Chin, and Smith studied how to optimize signal timings for the benefit of both LRT and street traffic along a transit mall with cross streets [22]. Their approach considers the total traffic delay and the total passenger delay together using real-time sensor data. The data is used to calculate a measure of effectiveness that determines how well the system is optimized; the results then affect how the signals operate [22]. This concept has been tested using computer simulations of the Baltimore Central Business District area during the afternoon peak period. The researchers found that this method was effective in reducing the total delay for both modes; however, it resulted in greater delays for the LRT than there would have been if there was just preemption [22].

Skabardonis discusses more possible methods of signal control for transit priority that could be applicable to light rail as well as buses [23]. He considers both "passive priority strategies" (those involving setting timing plans to favor transit vehicles given a preset schedule) as well as "active priority strategies" (preemption at individual signals or making adjustments to the entire system based on data collected in real time) [23].

2.5. Overview of the Literature

There have been few studies that have attempted to quantify the delays resulting from LRT at-grade crossings. Those that have done so appear to be based on older computer models that have since been improved with technology that is more powerful and with a better understanding of how transportation systems behave. The more recent works that involve this topic primarily consist of Environmental Impact Statements. While modern simulation tools might be used during the environmental review process to consider impacts of a proposed LRT line on traffic, Environmental Impact Statements are by their nature not intended to look at general situations outside of their specific projects. Once an LRT system has been constructed, signal timing strategies are very important for successfully balancing the sometimes conflicting needs of efficient transit operations and reduction of street traffic delays.

Chapter 3: Methodology

3.1. Use of Computer Simulation Models

One of the goals of this project is to demonstrate a methodology for identifying effects of light rail transit grade crossings that can be used during the planning process. It would be quite difficult to collect sufficient field data from currently operating LRT systems that could be considered applicable for scenarios outside of those particular systems. Light rail systems can contain a variety of geometric and traffic conditions that are unique to the cities where they are located. To verify field data would require traveling with several people between several cities that have light rail systems, which was seen as time-and cost-prohibitive. In addition, there is no guarantee that the data used to calibrate a model could be accurately reflect the local conditions in a place where an LRT system currently does not exist. Therefore, the use of a computer simulation model to represent situations where there could be light rail transit systems is an appropriate option. Simulation models have been used to represent hypothetical and real-life situations with great success, and the quality of modeling software has improved with greater computing capability and increased knowledge concerning the behavior of systems that are being modeled.

VISSIM 3.70 was selected to be the software package used to model various situations involving the interaction between LRT vehicles and regular street traffic for this project. VISSIM is a microscopic, time-step simulation model developed by a German company. It is particularly well suited for this project because of its ability to represent explicitly a variety of transportation modes, including light rail and other forms of public transportation, as well as different geometric and traffic control configurations [24].

3.2. Measure of Effectiveness

The primary measure of effectiveness used in this project is the average total vehicular delay, which is also used by the Highway Capacity Manual to evaluate the level of service at intersections [25]. According to the VISSIM 3.70 User Manual, the total delay of a vehicle is determined by subtracting the “theoretical travel time” from the “actual travel time” that it takes for the vehicle to go between two points in the simulation [24]. The “theoretical travel time,” as defined by VISSIM, is the amount of time that it would take for a vehicle to move between two points at its desired free flow speed, in the absence of other vehicles or traffic control devices such as signals or stop signs [24]. The average total delay is given as an output by VISSIM for user-specified segments in each network.

Each of the scenarios in this project was tested without LRT crossings to obtain a baseline average total delay. Average total delays were then obtained for each scenario including a range of LRT crossing frequencies. The difference between the average total delay with LRT crossings and the baseline average total delay without LRT crossings is the *average additional delay*:

average additional delay = average total delay with LRT crossings – average total delay without LRT.

3.3. Description of Test Scenarios

In order to determine the effects of light rail transit crossings on traffic delays, four scenarios were developed that included at-grade crossings of light rail transit vehicles: isolated perpendicular crossings of two- and four-lane roads, an intersection with the light rail line in the median of the main street, and a larger network that includes four at-grade crossings.

3.3.1. Two-lane Isolated Intersection

The two-lane isolated intersection scenario allows for the effects of LRT without effects of nearby intersections to be studied. In this case, traffic is traveling in the northbound and southbound directions, with the LRT crossing east and westbound, as shown in figure 1. The southbound approach begins approximately 2300 ft north of the crossing, and the northbound approach begins approximately 2600 ft south of the crossing; these distances were thought to be long enough to be able to capture the delays of vehicles that would be affected by the LRT crossing. Detectors placed on the LRT tracks approximately 1000 ft before the crossing in each direction activate the traffic signals located on the street approaches of the crossing, which is the VISSIM model's representation of all warning devices at the crossing. The signal is programmed so that the signal controlling the street traffic is red for a minimum of twenty seconds before the light rail vehicle is permitted to cross; this amount of time is the MUTCD minimum for "heavy" railroad crossings, but it is also acceptable for LRT uses [27]. Within the model, this has the potential effect of light rail vehicles being stopped for several seconds at the intersection before crossing. The additional crossing time resulting from the acceleration of the light rail vehicles over the relatively short street width should not significantly add to the overall crossing time, however.

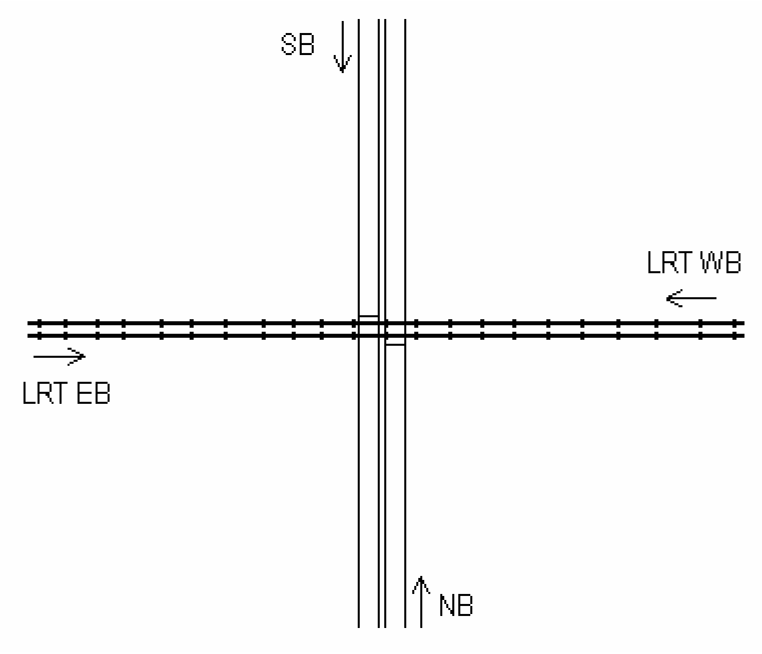

Figure 1. Two-lane isolated intersection

The light rail vehicles used in this simulation are composed of two 92 ft long cars, for a total of 184 ft in length. Their speeds were set to range between 36 and 42 mph, one of the available speed ranges that is provided by default in VISSIM. This speed range would be appropriate for the crossing types that are being studied in this project [25]. The arrival frequencies of light rail vehicles were specified in VISSIM by defining a deterministic “service rate” for the transit lines in each direction. Randomness in actual arrival times was modeled using a “dummy stop” shortly after the light rail vehicles enter the network. The dwell times for light rail vehicles at the dummy stop were modeled using a normal distribution with mean of 60 seconds and standard deviation of 20 seconds, which is the default setting in VISSIM. All other parameters in VISSIM remained at the default settings.

This scenario was tested using one-directional traffic volumes of 250, 500, 700, 1000, 1250, 1500, 1750, and 2000 vehicles per hour and light rail frequencies of 5, 10, 15, and 20 minutes in each direction, potential ranges that one might encounter during a peak hour situation representing light traffic to over saturated conditions. One-directional traffic volumes were used because the delays experienced by vehicles on one approach of an LRT crossing are independent of those on the other. Separating the crossing volumes by direction allows for better results when testing their effects on average additional delay experienced by vehicles.

3.3.2. Four-lane Isolated Intersection

This scenario is similar to the two-lane isolated intersection described in the previous section but with a street cross section of four lanes instead of two, as shown in figure 2. The southbound approach is approximately 1110 ft long, and the northbound approach is approximately 1330 ft long. The detectors and warning devices for the light rail crossing have the same settings as the two-lane scenario, with the same twenty second minimum time before the light rail vehicle is permitted to cross.

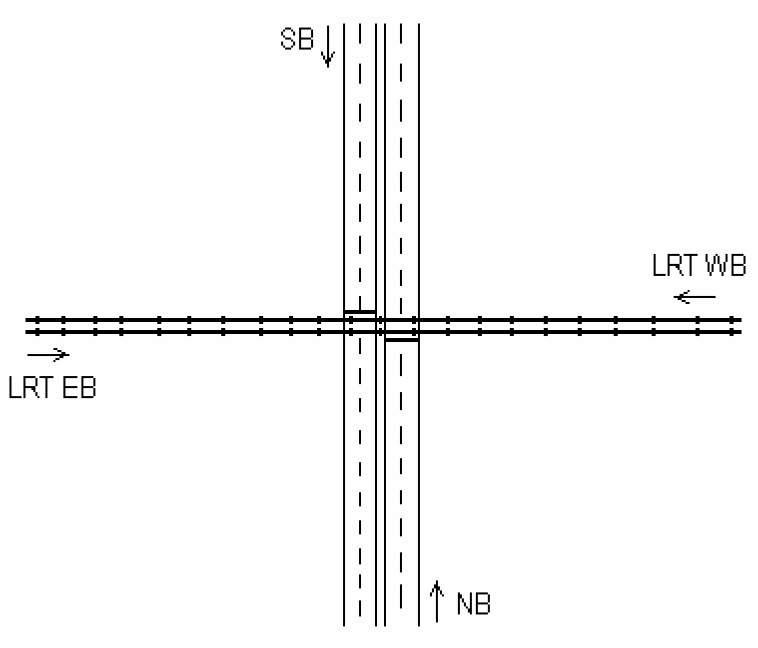

Figure 2. Four-lane isolated intersection

The same light rail vehicle characteristics (of length, speed, and acceleration) that applied to the two-lane crossing apply to this scenario as well, as do the dummy stops near the light rail entry into the simulation. For this scenario, one directional traffic volumes of 500, 1000, 1750, 2500, 3000, 3600, 4000, and 6000 vehicles per hour were tested with light rail frequencies of 5, 10, 15, and 20 minutes.

3.3.3. Light Rail in Median

The third scenario involves the case of light rail located in the median of a four-lane highway, as shown in figure 3. This case includes an at-grade intersection with another street carrying a smaller vehicle volume, allowing for an analysis of how the presence of the light rail affects intersection operations through traffic signal preemption.

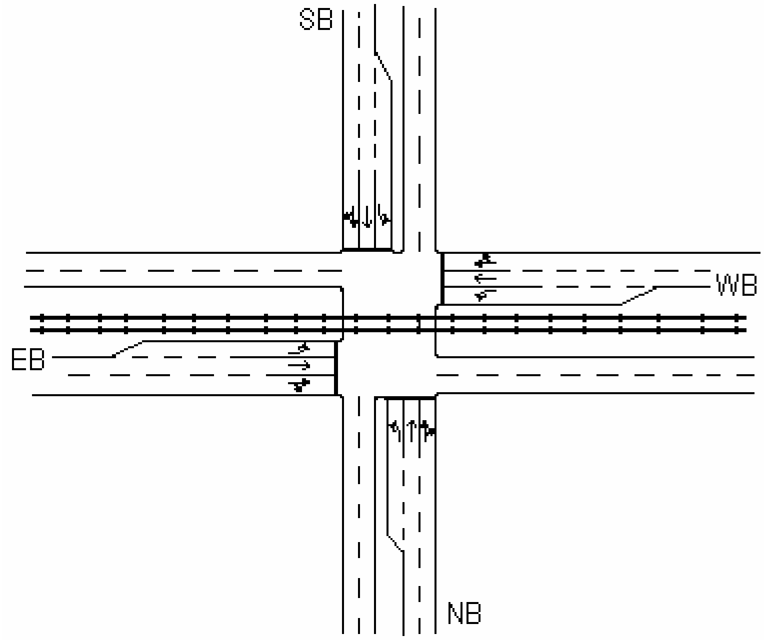

Figure 3. Intersection with LRT in median

An optimized signal timing plan was generated using the Synchro 6 traffic signal software package based on the same traffic volumes and geometry information that were put into the VISSIM model. Relevant signal timing information was taken from the

Synchro output and included in a NEMA signal controller within the VISSIM model, assuming that the signal is actuated and uncoordinated (since there is only one intersection in the network). The input volumes and NEMA controller settings used for this intersection can be found in Appendix A.

Signal preemption for the light rail is tested in this scenario. In the first case, light rail vehicles share the same green phases as the through movements parallel to the tracks; there is no signal preemption at all. To model this, a traffic signal head set for the same phase as the main street through movement was placed on the light rail lines. For this absence of preemption, there is no additional delay to the street traffic, so only average total delay to the light rail vehicles was measured.

In the second case, light rail vehicles are allowed to preempt the traffic signal. When a light rail vehicle arrives at a detector located approximately 700 ft from the intersection, the preemption sequence begins. If there is an active green phase for conflicting movements, they are automatically set to red, and the through movements parallel to the LRT tracks (including the LRT itself) are given a green light. This level of preemption is based on the railroad signal preemption that is provided with the NEMA signal controller interface.

The same light rail vehicles as those used in the previously described scenarios are found in this one as well. Light rail arrival frequencies of 5, 10, 15, and 20 minutes were tested. As LRT vehicles entered the network, they were required to stop at a “dummy stop” to account for variations in actual arrival times, just like the light rail vehicles in the two- and four-lane isolated intersection scenarios did. The input traffic volumes remained the same for all of the arrival frequencies that were tested, and all other VISSIM model parameters remained at their default settings.

3.3.4. I-264/Virginia Beach Boulevard Corridor Network

This scenario, which allows for examination of spillover effects from frequent light rail crossings, is based on a portion of the Interstate 264/Virginia Beach Boulevard corridor between Lynnhaven Parkway and Rosemont Road in Virginia Beach, Virginia. Figure 4 shows a computer screen image of the VISSIM network used in this scenario. The LRT line in this network is located on railroad tracks that have been proposed to be abandoned by Norfolk Southern Railroad and used for a light rail line from downtown Norfolk to the Virginia Beach Oceanfront. There are four LRT at-grade crossings in this network: on Rosemont Rd. (figure 5), S. Plaza Trail (figure 6), N. Lynnhaven Rd. (figure 7), and Lynnhaven Parkway (figure 8).

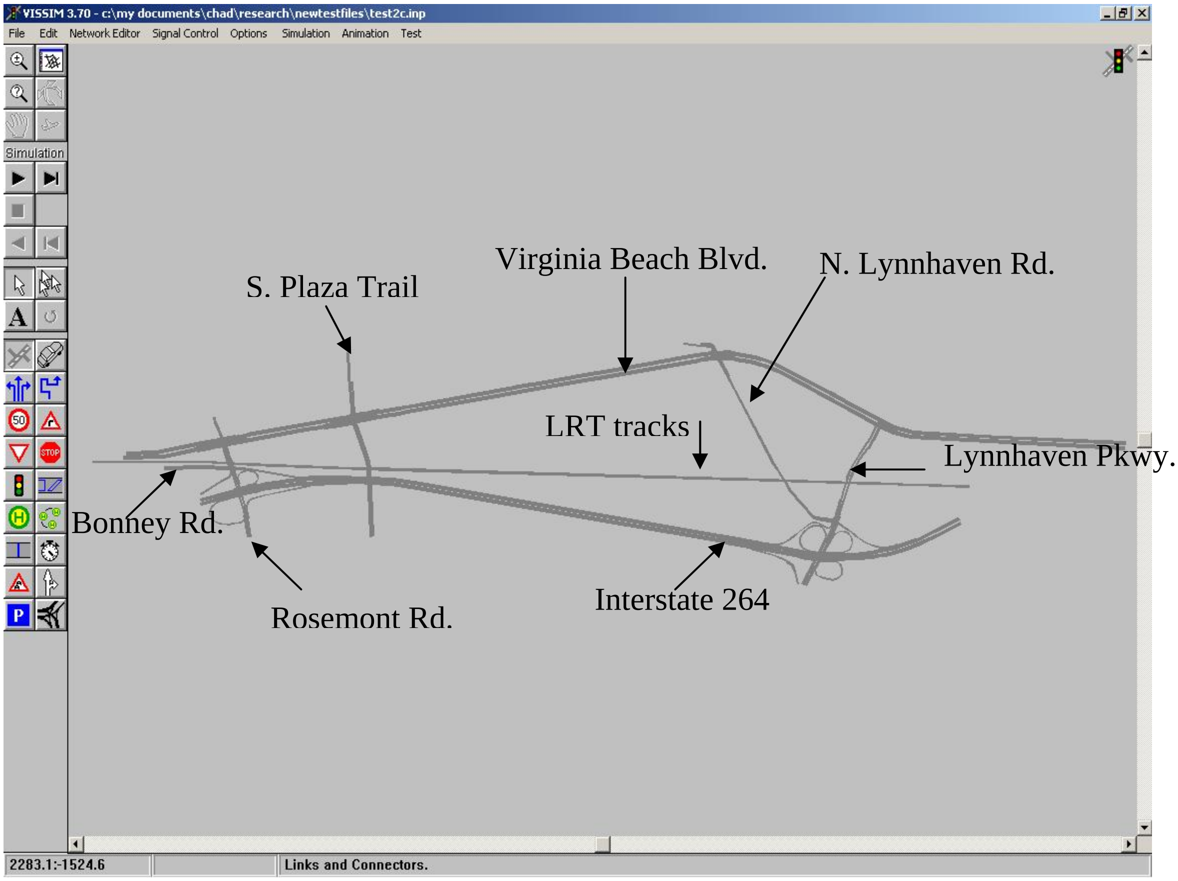

Figure 4. I-264/Virginia Beach Blvd. corridor network

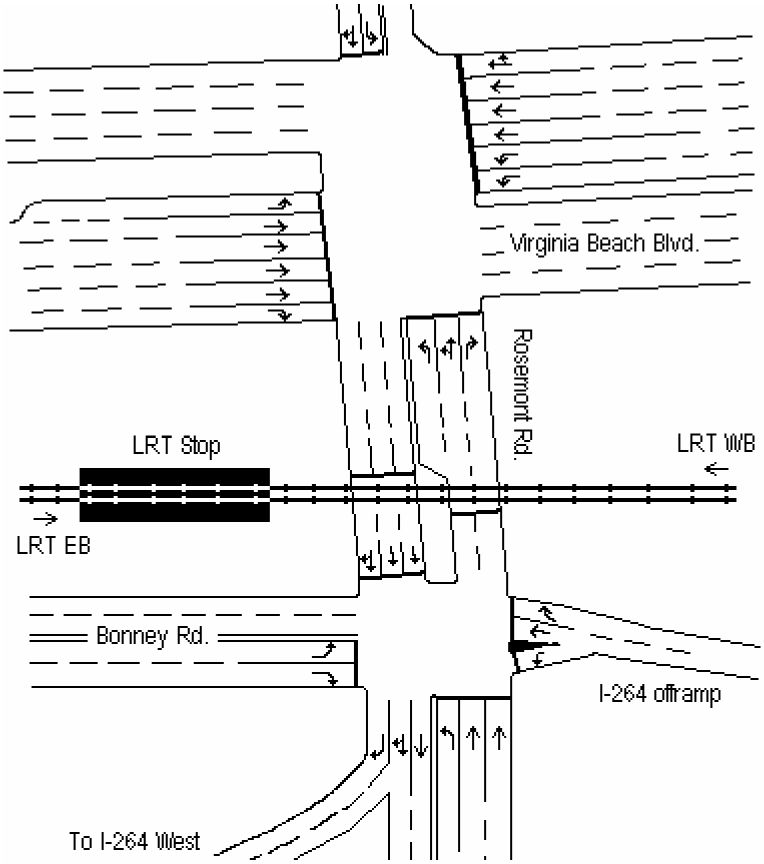

Figure 5. Sketch of Rosemont Rd. Crossing

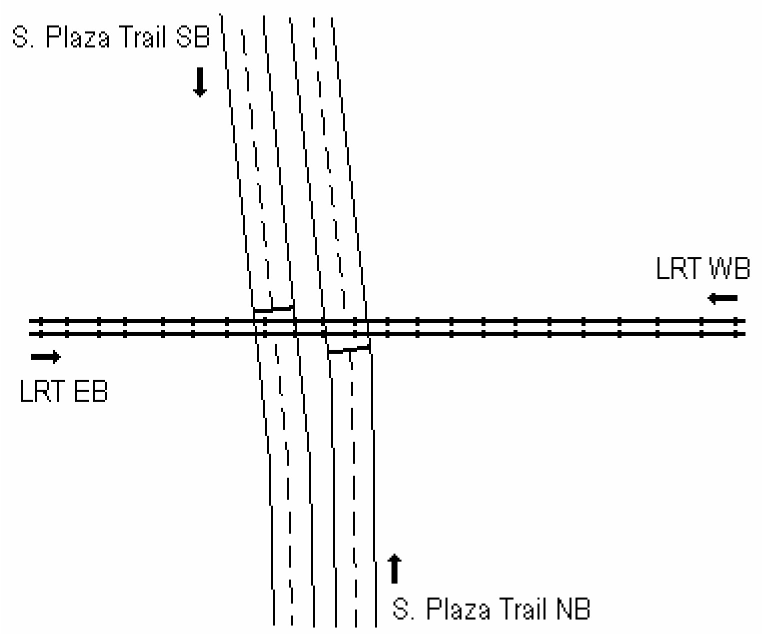

Figure 6. Sketch of S. Plaza Trail Crossing

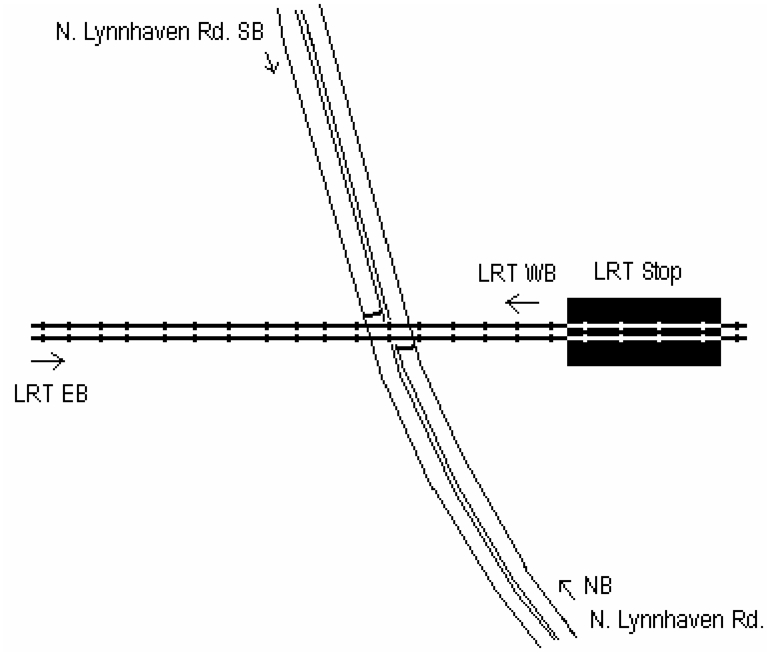

Figure 7. Sketch of N. Lynnhaven Road Crossing

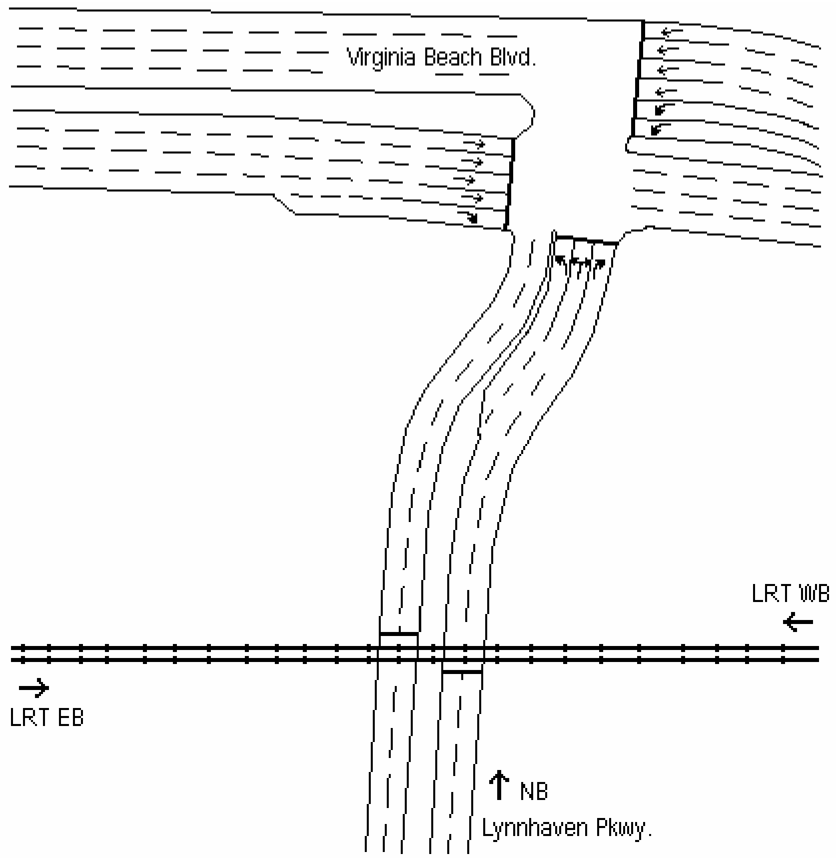

Figure 8. Sketch of Lynnhaven Pkwy. Crossing

The input traffic volumes used for this network were based on ADT volumes obtained from the City of Virginia Beach's Department of Public Works website [28]. Volumes for turning movements at intersections were estimates derived from the volumes on each approach. There are six traffic signals in this network:

- Lynnhaven Parkway and N. Lynnhaven Rd.
- Virginia Beach Blvd. and Lynnhaven Parkway
- Virginia Beach Blvd. and N. Lynnhaven Rd.
- Virginia Beach Blvd. and S. Plaza Trail
- Virginia Beach Blvd. and Rosemont Rd., and
- Rosemont Rd. and Bonney Rd.

The Synchro software package was used to get optimal signal timings at each of these intersections, treating them as actuated and uncoordinated with the rest of the network. All six signals use a NEMA controller that is included in the VISSIM software, like the one used in the LRT in median scenario. There is full preemption at all four of the LRT at-grade crossings in the network with the warning devices (represented by traffic signals) required to be activated for at least twenty seconds before the light rail vehicle is permitted to cross.

The light rail vehicles used in this scenario have the same physical characteristics as those used in the other three scenarios that have been tested. There are two light rail stops in each direction, one located just west of the Rosemont Rd. crossing and another between the Lynnhaven Pkwy. and N. Lynnhaven Rd. crossings. The rest of the network parameters remained at their default settings. With the traffic volumes remaining the same, this network was evaluated for light rail arrival frequencies of 5, 8, 10, 12, 15, 20, and 30 minutes.

3.4. Other Variables

In addition to the variables that were examined in the previous scenarios, preliminary evaluations were performed to determine whether other variables are important in influencing the additional delays experienced by vehicles at a light rail crossing. Two potential factors, percentage of heavy trucks and the presence of a driveway upstream of the light rail crossing, were studied as variations of the four-lane isolated intersection scenario that was described in section 3.3.2.

3.4.1. Percentage of Heavy Trucks

In the previously described scenarios, the default setting of 2% heavy trucks was maintained. To determine the effects of heavy trucks on the delays, the traffic composition was adjusted for cases that included no trucks, 5% trucks, and 10% trucks. The four-lane isolated intersection described in section 3.3.2 was used with an input traffic volume of 3000 vehicles/hour. The delays were evaluated using the VISSIM model for both approaches with LRT crossing frequencies of 0, 5, 10, 15, and 20 minutes.

3.4.2. Driveways

The influence of driveways on average additional vehicular delays was also examined. For this case, the four-lane isolated intersection described in section 3.3.2 was modified to include a driveway upstream of the LRT crossing. As shown in figure 9, each driveway was placed approximately 900 ft from the crossing. Only right turns were permitted into and out of each driveway.

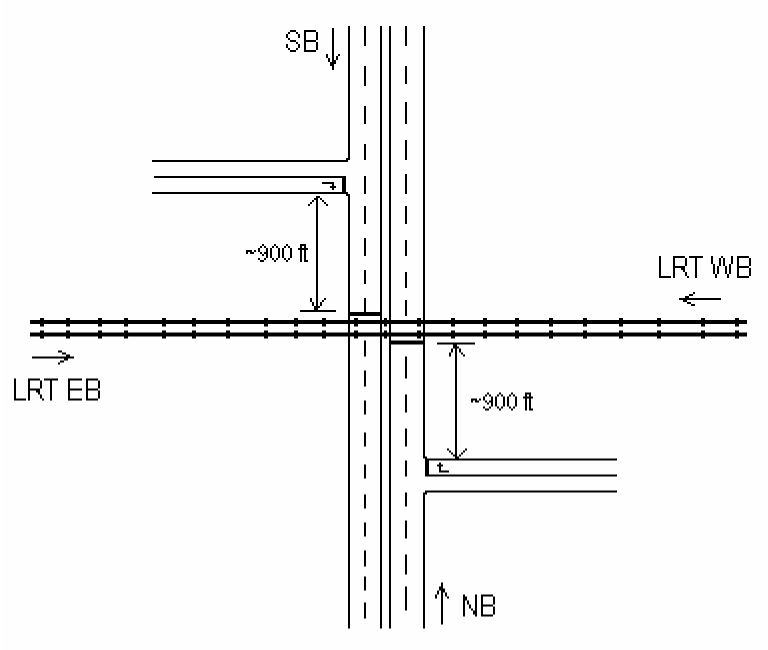

Figure 9. Sketch of Crossing with Driveways Scenario

Input traffic volumes of 3000 vehicles/hour were entered for the main roadways and 75 vehicles per hour for the driveways in each direction. LRT crossing frequencies of 0, 5, 10, 15, and 20 minutes were evaluated for this scenario.

Chapter 4: Results

4.1 Isolated Intersections

4.1.1. Two-lane Isolated Intersection

The two-lane isolated intersection scenario was evaluated using the VISSIM software for a base case that included no light rail crossings as well as for four different LRT crossing frequencies: 5, 10, 15, and 20 minutes. For each frequency, a range of input traffic volumes from 250 to 2000 vehicles per hour in each direction was considered, though the actual number of vehicles counted in the simulation varied due to randomness and the inability of the model to generate all of the vehicles during the simulation period when the input volume was greater than the roadway capacity. Forty simulation runs were performed for each combination of input volume and LRT crossing frequency, and data was collected in each direction (northbound and southbound segments).

Table 2 shows the average total delays experienced by vehicles without LRT crossings in the two-lane isolated intersection scenario. This table primarily represents operational delay, the result of other vehicles affecting the capacity of a roadway. Even at low volumes, operational delay can exist, such as when a vehicle traveling at a lower speed is preventing vehicles behind it from traveling at their higher desired speeds. The "input volume" represents the number of vehicles that the VISSIM model was told to generate for each direction. The columns showing the "average number of vehicles" indicate the average number of vehicles that were actually detected by the model over the forty simulation runs. The average total delay experienced by vehicles ranged from under one second for volumes around 250 vehicles/hour in each direction to more than 16 seconds as the volumes approach 2000 vehicles/hour, as shown in table 1.

Table 2. Average total delay without LRT crossings

Input Volume (veh/hr)	NB average number of vehicles	NB average total delay (sec/veh)	SB average number of vehicles	SB average total delay (sec/veh)
250	241	0.90	246	0.92
500	486	1.73	489	1.77
750	730	2.53	734	2.60
1000	974	3.37	975	3.43
1250	1216	4.36	1219	4.45
1500	1459	6.01	1463	6.03
1750	1699	10.00	1705	9.86
2000	1863	18.18	1868	16.87

4.1.1.1. 5 Minute Frequency

The average additional delays for the two-lane isolated intersection scenario and 5-minute LRT crossing frequency are shown in tables 3 and 4, and in figure 10. As the number of vehicles increases, the additional delays also increase from 3.6 seconds/vehicle to more than 31 seconds/vehicle for the northbound delay segment and more than 27 seconds/vehicle for the southbound segment. As volumes increased, the range of observed additional delays based on the simulation runs also became greater.

Table 3. Average additional delay for northbound 2-lane isolated intersection with 5-minute frequency

Input volume (veh/hr)	Average number of vehicles simulated	Average additional delay (sec/veh)	Maximum delay	Minimum delay
250	241	3.59	4.8	2.1
500	486	4.27	6.1	2.8
750	730	5.45	8.0	3.1
1000	974	7.12	10.8	4.7
1250	1216	10.28	15.7	5.9
1500	1459	17.70	26.9	11.3
1750	1699	31.87	40.3	20.3
2000	1863	25.54	32.6	18.1

Table 4. Average additional delay for southbound 2-lane isolated intersection with 5 minute frequency

Input volume (veh/hr)	Average number of vehicles simulated	Average additional delay (sec/veh)	Maximum delay	Minimum delay
250	246	3.58	5.6	1.9
500	489	4.20	6.3	2.7
750	734	5.63	9.2	3.5
1000	975	7.30	10.5	4.6
1250	1219	10.65	14.0	6.1
1500	1463	17.08	27.0	9.8
1750	1705	27.26	34.5	20.7
2000	1868	21.71	26.4	15.7

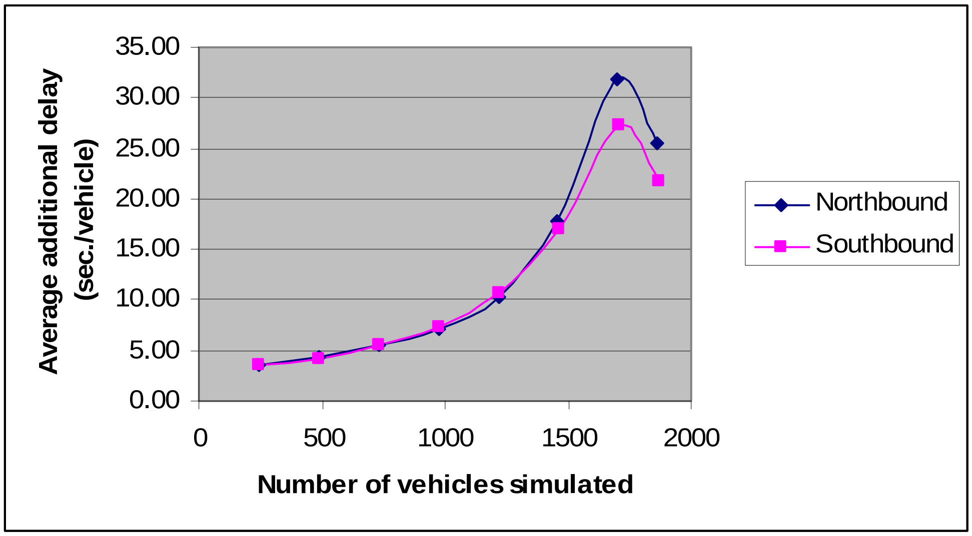

Figure 10. Average additional delays for 2-lane isolated intersection, 5-minute frequency

4.1.1.2. 10 Minute Frequency

At the 10-minute frequency, the average additional delays experienced by crossing vehicles decreased by more than half from the 5-minute frequency. Tables 5 and 6 and figure 11 show that the average additional delays ranged from approximately 1.75 seconds/vehicle to 14.9 seconds/vehicle in the northbound segment and from 1.78 to 13.1 seconds/vehicle in the southbound.

Table 5. Average additional delay for northbound 2-lane isolated intersection with 10-minute frequency

Input volume (veh/hr)	Average number of vehicles simulated	Average additional delay (sec/veh)	Maximum delay	Minimum delay
250	241	1.75	2.9	0.9
500	486	2.12	3.6	1.1
750	730	2.61	4.2	1.2
1000	974	3.57	5.8	2.0
1250	1216	4.79	7.8	2.3
1500	1459	7.77	11.6	3.8
1750	1699	14.89	20.5	9.1
2000	1863	11.87	18.1	6.7

Table 6. Average additional delays for southbound 2-lane isolated intersection with 10-minute frequency

Input volume (veh/hr)	Average number of vehicles simulated	Average additional delay (sec/veh)	Maximum delay	Minimum delay
250	246	1.78	3.2	0.9
500	489	2.04	3.1	1.1
750	734	2.69	4.0	1.5
1000	975	3.57	5.4	1.8
1250	1219	5.31	8.5	2.7
1500	1463	8.14	12.7	4.0
1750	1705	13.17	18.5	6.4
2000	1868	10.10	14.7	6.4

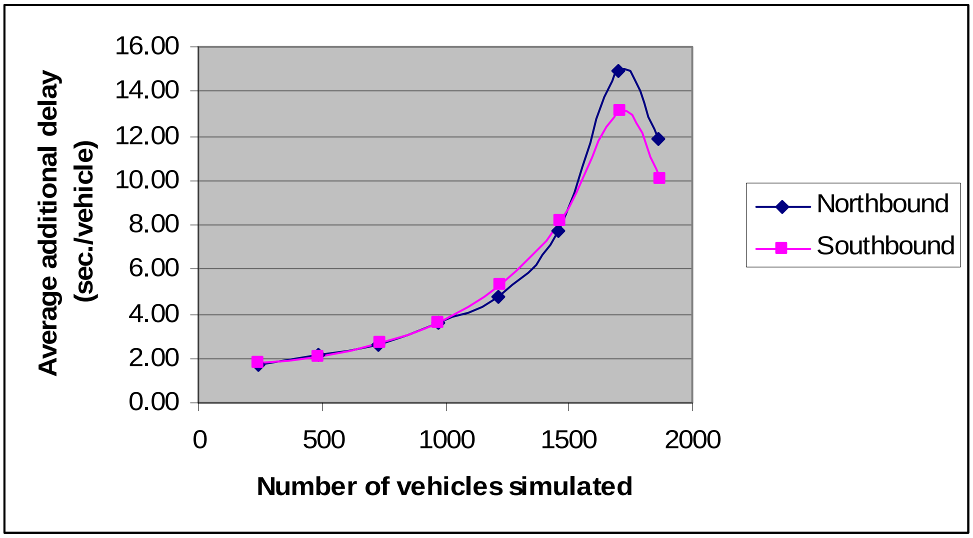

Figure 11. Average additional delays for 2-lane isolated intersection with 10-minute crossing frequency

4.1.1.3. 15 Minute Frequency

The following tables and figure show that the average additional delays with LRT crossings every 15 minutes ranged from 1.23 seconds/vehicle at the 250 vehicles/hour input volume to 9.43 seconds/vehicle at the 1750 vehicle/hour volume in the northbound segment, and from 1.10 seconds/vehicle to 8.71 seconds/vehicle in the southbound segment.

Table 7. Average additional delays for northbound 2-lane isolated intersection with 15-minute frequency

Input volume (veh/hr)	Average number of vehicles simulated	Average additional delay (sec/veh)	Maximum delay	Minimum delay
250	241	1.23	2.3	0.6
500	486	1.46	2.4	0.2
750	730	1.95	3.7	1.1
1000	974	2.25	4.6	0.9
1250	1216	3.11	5.1	1.3
1500	1459	5.19	9.4	1.9
1750	1699	9.43	15.4	4.6
2000	1863	7.64	12.5	3.2

Table 8. Average additional delays for southbound 2-lane isolated intersection with 15-minute frequency

Input volume (veh/hr)	Average number of vehicles simulated	Average additional delay (sec/veh)	Maximum delay	Minimum delay
250	246	1.10	2.7	0.3
500	489	1.41	2.5	0.0
750	734	1.76	3.3	0.6
1000	975	2.48	5.4	0.8
1250	1219	3.48	6.9	1.3
1500	1463	5.16	12.0	1.4
1750	1705	8.71	13.8	2.9
2000	1868	6.43	11.6	2.9

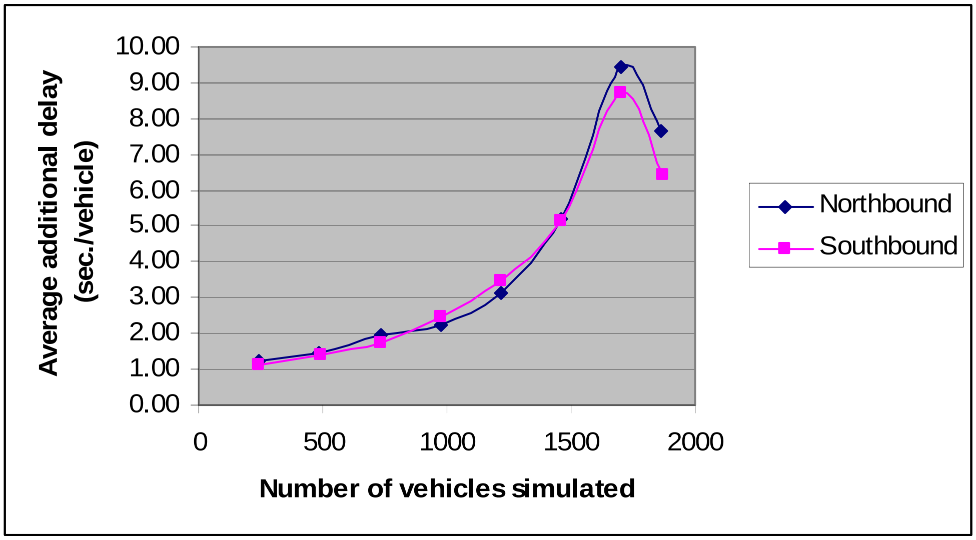

Figure 12. Average additional delays for 2-lane isolated intersection with 15-minute crossing frequency

4.1.1.4. 20 Minute Frequency

The average additional delays in tables 9 and 10 indicate a continuation of the decreasing delay with decreasing frequency trend that has been shown in the previous tables. At the 20-minute frequency, the average additional delays in the northbound segment ranged from 0.83 to 7.07 seconds/vehicle, and the southbound segment showed additional delays from 0.77 to 6.30 seconds/vehicle.

Table 9. Average additional delays for northbound 2-lane isolated intersection with 20-minute frequency

Input volume (veh/hr)	Average number of vehicles simulated	Average additional delay (sec/veh)	Maximum delay	Minimum delay
250	241	0.82	1.9	0.2
500	486	1.10	2.6	0.4
750	730	1.26	2.5	0.5
1000	974	1.65	3.3	0.7
1250	1216	2.22	4.6	1.1
1500	1459	3.55	5.9	1.1
1750	1699	7.07	17.8	2.4
2000	1863	5.61	9.5	2.0

Table 10. Average additional delays for southbound 2-lane isolated intersection with 20-minute frequency

Input volume (veh/hr)	Average number of vehicles simulated	Average additional delay (sec/veh)	Maximum delay	Minimum delay
250	246	0.77	1.7	0.1
500	489	0.98	2.0	0.4
750	734	1.35	2.8	0.5
1000	975	1.77	3.1	0.7
1250	1219	2.57	5.9	0.7
1500	1463	4.13	7.8	1.7
1750	1705	6.30	11.5	2.0
2000	1868	4.85	10.1	1.4

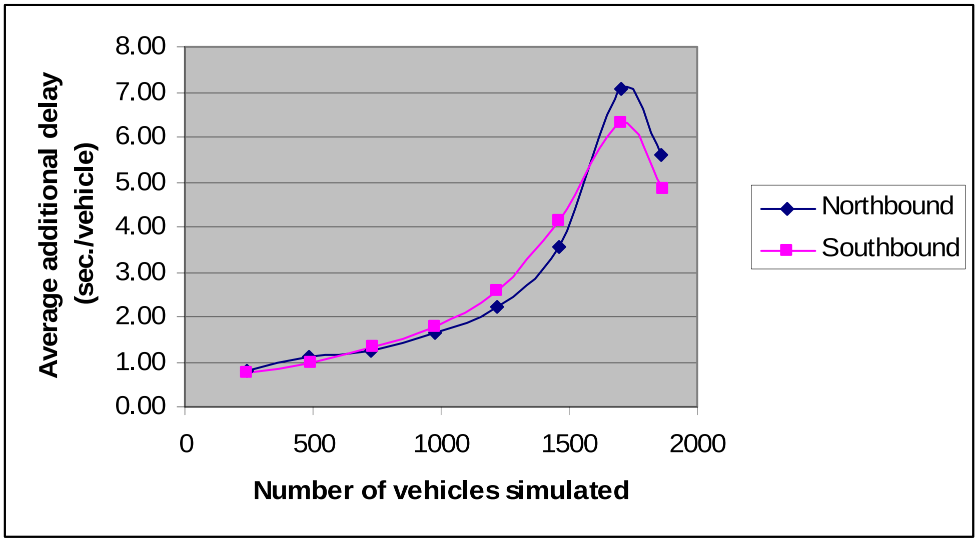

Figure 13. Average additional delays for 2-lane isolated intersection with 20-minute crossing frequency

4.1.1.5. Summary of Two-lane Isolated Intersection Results

The results from this two-lane isolated intersection scenario show that the average additional delays experienced with light rail crossings tended to increase with more frequent crossings as well as with higher volumes until the volume is greater than the saturation flow rate of 1800 vehicles/hour that is calculated in Appendix B. For the over saturated conditions, the average *total* delay continues to increase with higher volumes and crossing frequencies, but the average *additional* delay for over saturated conditions is lower than the additional delays for volumes just under capacity. This is because the addition of the light rail crossing changes the roadway from being an uninterrupted facility to one that is signalized. When the demand volume becomes greater than the capacity of a roadway that is controlled by signals, the volume of vehicles being served becomes equal to the saturation flow rate. Even as more vehicles enter a signalized network, the saturation flow rate does not decrease, so the total delay does not increase as quickly. In the case of an un-signalized facility, however, the flow rate continues to decrease as the volume increases beyond its capacity, and there is an increase in the total delay that is experienced by vehicles when compared to an uncongested condition. The average additional delay is defined as the difference between the total delays without light rail crossings and those with crossings, so when total delays without crossings increase at a greater rate than those with LRT crossings for identical traffic volumes, the average *additional* delay will decrease.

To verify that the delays with LRT crossings were significantly different from the delays without crossings, a paired *T*-test was performed comparing the average total delays for each scenario with the average total delays without LRT crossings. The tests indicated that the increase in delay was significantly different from that without LRT at 95% confidence level. Although the statistical tests show that there is a change in average total delay with the addition of LRT crossings, the actual delay experienced by an individual vehicle will vary depending on when the vehicle arrives at the crossing relative to the light rail. For example, the smallest delays would occur for vehicles arriving at the crossing between light rail arrivals, after queues that formed during the previous LRT arrival have dissipated.

4.1.2. Four-lane Isolated Intersection

The four lane isolated intersection was evaluated in VISSIM for a range of input traffic volumes from 500 to 6000 vehicles per hour in each direction, with the actual number of vehicles being varied due to random vehicle generation and the capacity of the network. Forty simulation runs were performed for each combination of traffic volume and arrival frequency, as well as a base scenario without any light rail crossings, similar to the setup of the two-lane isolated intersection. Table 10 shows the average delay for this intersection without any LRT crossings:

Table 11. Average total vehicular delays for 4-lane isolated intersection without LRT crossings

Volume (vph)	Delay NB (s)	Delay SB (s)	Average (s)
500	0.47	0.44	0.45
1000	1.82	1.83	1.83
1750	3.76	3.76	3.76
2500	5.81	5.83	5.82
3000	7.44	7.49	7.46
3600	7.72	7.59	7.66
4000	20.48	19.43	19.96
6000	20.71	20.02	20.37

4.1.2.1. 5 Minute Frequency

Tables 12, 13, and figure 14 show the average additional delays with the four-lane isolated intersection at the 5-minute crossing frequency. For input volumes from 500 to 3000 vehicles/hour, the delays gradually increase, and then a spike occurred at 3600 vehicles/hour (an actual volume of approximately 3250 vehicles/hour) as the volume of the roadway approaches its saturation flow rate of 3600 vehicles per hour. The maximum additional delay among the volumes that were tested was found at the 3600 vehicle/hour level, almost 31 seconds/vehicle in the northbound segment and approximately 28.3 seconds/vehicle in the southbound.

Table 12. Average additional delays for northbound 4-lane isolated intersection with 5-minute frequency

Input volume (veh/hr)	Average number of vehicles simulated	Average additional delay (sec/veh)	Maximum delay	Minimum delay
500	480	2.14	2.9	1.5
1000	956	2.39	3.2	1.6
1750	1672	3.01	3.6	2.2
2500	2383	4.29	5.4	3.1
3000	2858	6.60	8.4	5.2
3600	3251	30.99	36.3	19.2
4000	3651	20.70	23.0	18.0
6000	3670	20.73	23.3	17.5

Table 13. Average additional delays for southbound 4-lane isolated intersection with 5-minute frequency

Input volume (veh/hr)	Average number of vehicles simulated	Average additional delay (sec/veh)	Maximum delay	Minimum delay
500	486	2.18	2.9	1.4
1000	961	2.31	3.1	1.8
1750	1681	3.15	3.7	2.6
2500	2391	4.49	5.7	3.5
3000	2866	6.93	8.9	5.4
3600	3264	28.32	35.3	22.8
4000	3672	18.10	20.3	15.2
6000	3686	18.35	21.4	14.5

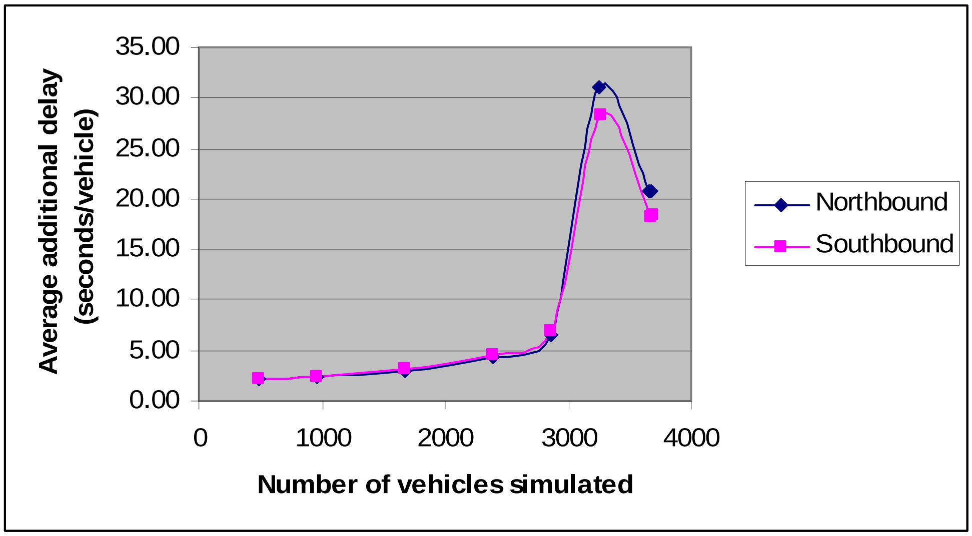

Figure 14. Average additional delays for 4-lane isolated intersection with 5-minute crossing frequency

4.1.2.2. 10 Minute Frequency

Like the two-lane intersection, the average additional delays experienced by vehicles on the four-lane isolated intersection with 10 minute frequencies are close to half as much as those seen with the 5-minute frequency. The smallest additional delays were again found at the lowest volumes, with an average of 1.12 seconds/vehicle in the northbound segment and 1.15 seconds/vehicle in the southbound. The highest average additional delays were 14.39 seconds/vehicle northbound and 13.3 seconds/vehicle southbound at the 3600 vehicle/hour input volume (which registered approximately 3250 vehicles during the actual simulation). As shown in figure 15, the shape of the curve depicting additional delays against the number of vehicles is similar to that of the curve for the 5-minute frequency.

Table 14. Average additional delays for northbound 4-lane isolated intersection with 10-minute frequency

Input volume (veh/hr)	Average number of vehicles simulated	Average additional delay (sec/veh)	Maximum delay	Minimum delay
500	480	1.12	1.7	0.7
1000	956	1.07	1.6	0.7
1750	1672	1.38	1.8	0.9
2500	2383	1.93	2.7	1.2
3000	2858	3.09	4.1	2.0
3600	3251	14.39	22.7	8.1
4000	3651	8.99	11.7	6.3
6000	3670	9.27	12.2	7.0

Table 15. Average additional delays for southbound 4-lane isolated intersection with 10-minute frequency

Input volume (veh/hr)	Average number of vehicles simulated	Average additional delay (sec/veh)	Maximum delay	Minimum delay
500	486	1.15	1.5	0.7
1000	961	1.07	1.5	0.5
1750	1681	1.46	2.0	1.0
2500	2391	1.98	2.6	1.4
3000	2866	3.21	4.6	1.8
3600	3264	13.30	19.6	9.3
4000	3672	7.96	9.3	5.7
6000	3686	8.10	10.7	5.5

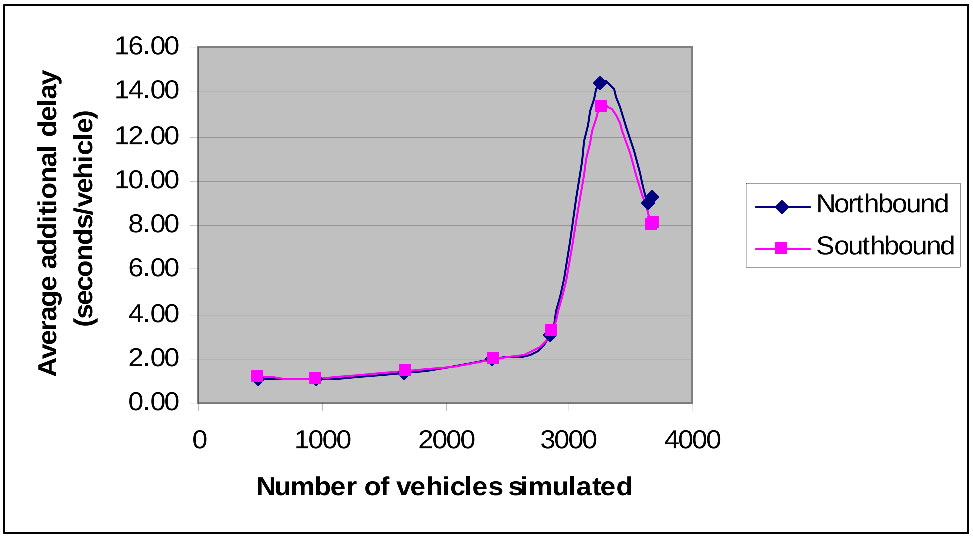

Figure 15. Average additional delays for 4-lane isolated intersection with 10-minute frequency

4.1.2.3. 15 Minute Frequency

At the 15-minute LRT crossing frequency, the average additional delays experienced by vehicles continued to decrease from those at the 5 and 10-minute frequencies. While paired *T*-tests indicate that the increase in average delays with light rail crossings is insignificant at the 95% confidence level, the average additional delays were less than one second/vehicle for input volumes from 500 to 1750 vehicles/hour and between one and two seconds/vehicle for the 2500 and 3000 vehicle/hour input volumes. At 3600 vehicles/hour, there was a sharp increase in the average additional delays, to 10.15 seconds/vehicle for the northbound segment and 9.65 seconds/vehicle for the southbound. As the volumes increased to create over saturated conditions, the average additional delays dropped to approximately 5 seconds/vehicle.

Table 16. Average additional delays for northbound 4-lane isolated intersection with 15-minute frequency

Input volume (veh/hr)	Average number of vehicles simulated	Average additional delay (sec/veh)	Maximum delay	Minimum delay
500	480	0.73	1.2	0.4
1000	956	0.64	1.1	0.3
1750	1672	0.78	1.3	0.5
2500	2383	1.14	1.8	0.6
3000	2858	1.68	2.6	0.9
3600	3251	10.15	18.2	6.6
4000	3651	5.05	7.3	2.9
6000	3670	5.50	7.7	3.6

Table 17. Average additional delays for southbound 4-lane isolated intersection with 15 minute frequency

Input volume (veh/hr)	Average number of vehicles simulated	Average additional delay (sec/veh)	Maximum delay	Minimum delay
500	486	0.80	1.2	0.5
1000	961	0.70	1.2	0.4
1750	1681	0.90	1.3	0.6
2500	2391	1.21	1.8	0.9
3000	2866	1.95	3.1	1.1
3600	3264	9.65	15.4	7.0
4000	3672	4.84	7.2	2.7
6000	3686	4.94	7.3	3.0

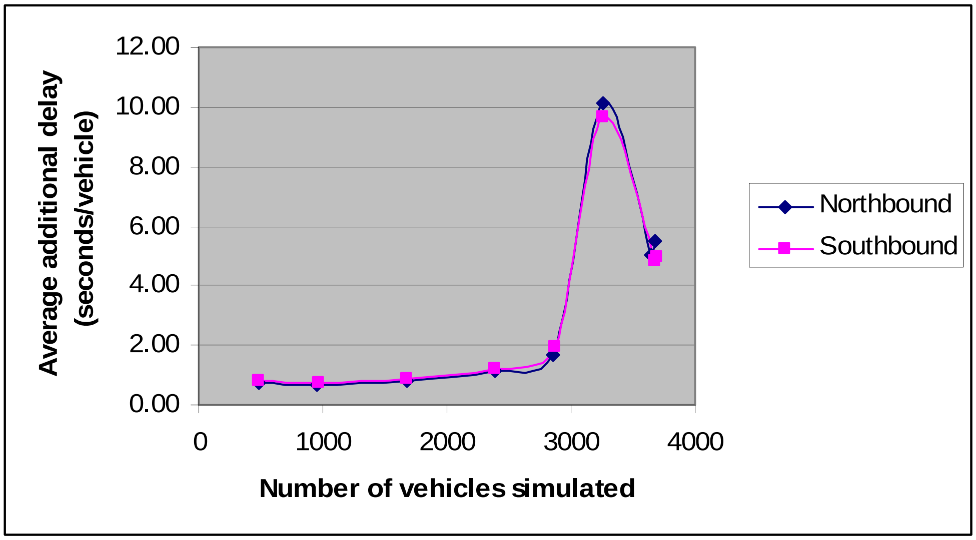

Figure 16. Average additional delays for 4-lane isolated intersection with 15-minute crossing frequency

4.1.2.4. 20 Minute Frequency

For the 20-minute crossing frequency, the average additional delays followed a similar trend as those for the 15 minute frequency. Additional delays were below 1.25 seconds/vehicle for all of the input volumes under 3000 vehicles/hour in each direction, and then there is an increase to 8.35 seconds/vehicle in the northbound segment and 7.80 seconds/vehicle in the southbound segment at 3600 vehicles/hour.

Table 18. Average additional delays for northbound 4-lane isolated intersection with 20-minute frequency

Input volume (veh/hr)	Average number of vehicles simulated	Average additional delay (sec/veh)	Maximum delay	Minimum delay
500	480	0.57	1.0	0.3
1000	956	0.42	0.7	0.2
1750	1672	0.54	0.9	0.2
2500	2383	0.75	1.3	0.3
3000	2858	1.19	2.2	0.5
3600	3251	8.35	17.5	4.6
4000	3651	3.23	4.9	1.5
6000	3670	3.60	5.8	1.7

Table 19. Average additional delays for southbound 4-lane isolated intersection with 20-minute frequency

Input volume (veh/hr)	Average number of vehicles simulated	Average additional delay (sec/veh)	Maximum delay	Minimum delay
500	486	0.66	1.0	0.4
1000	961	0.46	0.8	0.2
1750	1681	0.58	0.9	0.3
2500	2391	0.84	1.3	0.5
3000	2866	1.24	2.2	0.6
3600	3264	7.80	14.9	4.9
4000	3672	3.31	5.6	1.2
6000	3686	3.25	4.8	0.8

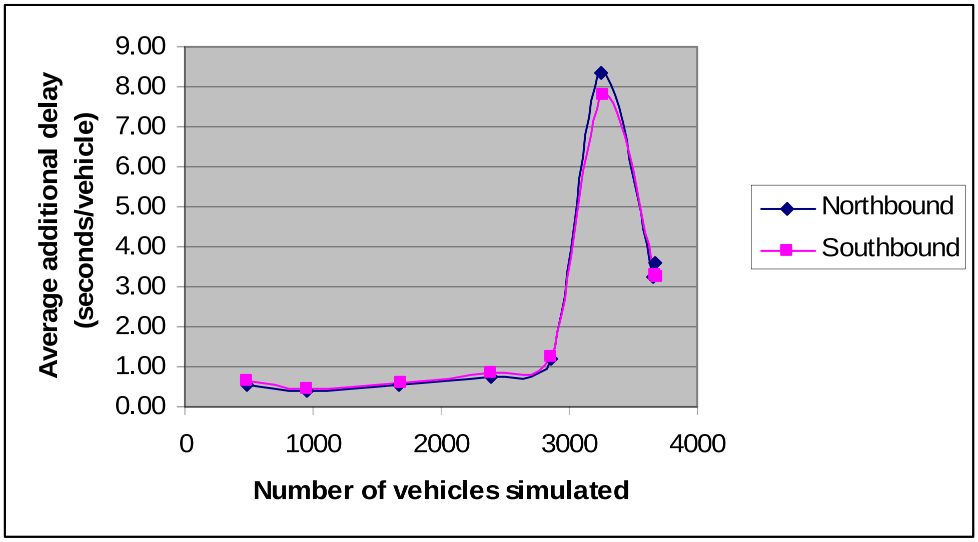

Figure 17. Average additional delays for 4-lane isolated intersection with 20-minute crossing frequency

4.1.2.5. Summary of Four-lane Isolated Intersection Results

As with the two-lane isolated intersection scenario, the average additional delay experienced by vehicles on the four-lane isolated intersection increased with greater crossing frequency and with greater volumes when the traffic volume was less than the saturation flow rate of 3600 vehicles/hour. For over saturated conditions, VISSIM was unable to allow the full number of the vehicles that were specified to enter the simulation, though the actual number of vehicles that passed through the delay segments continued to increase by small amounts. Because not all of the vehicles were able to enter the network, it is likely that the segments used to measure the total delays were unable to capture the full extent of queues generated during the LRT crossings. This would result in an underestimation of the total delay for vehicles in the over saturated roadway condition. In the over saturated conditions, there was a sharp drop in the average additional delay from the peak delays that occurred at the traffic volumes just under the saturation flow rate. The paired *T*-tests comparing the differences in total delay with and without LRT crossings that were performed for all frequencies and volumes in this scenario indicated that the average delay with LRT crossings were significantly different from the average delay without LRT at the 95% confidence level.

4.2. LRT in Median Scenario

This scenario, described in chapter 3, was simulated using the VISSIM software forty times for each LRT arrival frequency with and without traffic signal preemption. The mean delay was computed for each arrival frequency and compared to a base case that included the same traffic volumes and signal timings but without any light rail. The traffic signal had a cycle length of 130 seconds. Different random number seeds were used for each run, and the length of the simulation was one hour (3600 seconds).

4.2.1. With Signal Preemption

4.2.1.1. Approaches Parallel to the LRT Tracks

Tables 20 and 21 show the additional delays on the approaches parallel to the LRT tracks; left turning movements are in conflict with the crossing in this case. While the light rail vehicle is crossing, the signal allows movements that are not in conflict with the tracks (in this case, the through and right turn movements) to have a green light. This results in those movements receiving more green time than they would have had without preemption. For the eastbound approach, the right turns experienced an improvement in travel times, from an average of 32.8 seconds per vehicle for the 5 minute crossing frequency to 6.3 seconds for crossings every 20 minutes. Vehicles traveling straight through the intersection in the eastbound direction experienced an average travel time savings from 27.1 seconds per vehicle at the 5-minute frequency to 5.61 seconds at the 20-minute frequency.

Although the through and right turning movements on the westbound approach also received additional green time due to the light rail preemption, it was observed during the simulation that delays in this direction were affected by vehicles spilling back from the left turn lane onto the main roadway. Because of this, the results from the westbound approach could not be used to develop a pattern that would indicate an increase or a decrease in delay (or travel time savings) with LRT crossing frequency.

Table 20. Average additional delays for eastbound approach, LRT in median scenario

LRT crossing frequency (min.)	Right turns	Max.	Min.	Through	Max.	Min.	Left turns	Max.	Min.
0	116.98			111.54			185.16		
5	-32.78	-3.5	-57.0	-27.11	-10.0	-44.3	103.19	351.8	-98.1
10	-13.25	15.6	-37.5	-12.29	3.3	-30.5	15.10	205.8	-165.7
15	-9.41	7.6	-32.4	-8.11	1.5	-25.5	53.80	228.8	-96.9
20	-6.26	16.5	-27.3	-5.61	8.2	-23.0	38.94	272.1	-173.8

Table 21. Average additional delays for westbound approach, LRT in median scenario

LRT crossing frequency (min.)	Right turns	Max.	Min.	Through	Max.	Min.	Left turns	Max.	Min.
0	137.32			144.96			584.72		
5	2.99	46.2	-47.8	-0.37	34.7	-48.1	52.82	185.5	-153.9
10	10.63	56.3	-31.7	2.42	37.8	-31.0	12.38	110.9	-118.2
15	5.15	58.6	-29.2	-1.14	27.4	-24.7	3.92	139.1	-103.2
20	2.41	37.9	-27.3	-0.52	38.1	-26.9	-4.79	112.6	-122.0

Paired *T*-tests with a 95% confidence level were performed to determine if there is a statistically significant difference between the average total delays with and without LRT crossings. Based on these tests, it was found that there was no significant difference for all of the westbound turning movements except for left turns at the 5-minute crossing frequency and right turns at the 10-minute frequency, indicating that the LRT preemption did not result in a significant change in the average delays experienced by those vehicles.

For all of the eastbound turning movements and crossing frequencies, however, the *T*-tests did indicate statistically significant differences in the average total delay, with 95% confidence.

4.2.1.2. Approaches Perpendicular to the LRT Tracks

The following tables show the additional delays for streets perpendicular to the LRT line.

Table 22. Average additional delays for southbound approach, LRT in median scenario

LRT crossing frequency (min.)	Right turns	Max.	Min.	Through	Max.	Min.	Left turns	Max.	Min.
0	15.73			13.71			17.22		
5	4.76	9.7	1.3	4.03	6.8	-0.5	6.34	15.9	-0.1
10	2.47	7.8	-0.4	2.21	5.0	0.3	3.67	13.3	-4.0
15	1.53	4.4	-1.8	1.49	3.9	-0.6	2.02	7.9	-3.8
20	1.53	8.2	-1.4	0.88	3.7	-1.2	1.62	10.0	-4.5

Table 23. Average additional delays for northbound approach, LRT in median scenario

LRT crossing frequency (min.)	Right turns	Max.	Min.	Through	Max.	Min.	Left turns	Max.	Min.
0	15.45			14.01			14.57		
5	4.88	12.0	0.8	4.00	8.6	1.3	3.50	8.7	-1.7
10	2.41	7.8	-0.3	2.04	4.4	0.2	1.58	5.6	-3.0
15	1.28	4.6	-2.9	1.13	2.8	-1.1	1.04	5.1	-2.3
20	1.11	4.9	-1.6	0.83	2.7	-1.0	0.84	3.9	-2.6

The average additional delays for the approaches perpendicular to the LRT line appear to follow a similar pattern as the two- and four-lane isolated intersections that were discussed previously. The greatest average additional delays were found with the 5-minute crossing frequency, ranging from 3.5 seconds for northbound left turns to 6.34 seconds for southbound left turns. As LRT crossings became less frequent, the average additional delays decreased. There did not appear to be any spillback from the left turn lanes that would block the flow of through and right turning vehicles. Paired *T*-tests were performed to determine if there are statistically significant differences between the average total delays with and without LRT crossings. At the 95% confidence level, the tests indicated that additional delays do exist for all of the turning movements perpendicular to the LRT line.

4.2.2. Without Signal Preemption

Without signal preemption, light rail vehicles are subject to the same traffic signal cycles as the other vehicles in the network. As a result, the average delay experienced by light rail is dependent on the traffic signal cycle length as well as when the vehicles arrive at the intersection: if there is a green signal upon arrival, there would be no delay for that vehicle. If the light rail line is factored into a coordinated signal system, delays might also be reduced without having full interruption of signal cycles.

Table 24 shows the average delay experienced by the light rail vehicles in this scenario for both the eastbound and the westbound directions. There does not appear to be a distinct pattern that emerges from this particular case.

Table 24. Delays experienced by light rail vehicles without preemption

LRT frequency	EB	WB
5 min.	22.07	21.87
10 min.	20.73	20.78
15 min.	18.63	22.69
20 min.	18.16	22.98

4.3. Virginia Beach Corridor Network Scenario

This scenario was tested using the VISSIM model for a base case without light rail and for LRT arrival frequencies from 5 to 30 minutes; all other network settings remained the same. Forty simulation runs of one hour (3600 seconds) were performed for each arrival frequency. Average delays were computed for thirteen segments within the network, all of which included a crossing of the light rail line. The results in this section are grouped by individual crossings within the network.

4.3.1. Rosemont Road Crossings

The LRT crossing across Rosemont Road was evaluated in the VISSIM model with three delay segments: one in the southbound direction between Virginia Beach Blvd. and Bonney Rd., one in the northbound direction between Virginia Beach Blvd. and Bonney Rd., and another in the northbound direction from north of Interstate 264 to Virginia Beach Blvd.

The southbound segment (segment 1) had an average volume of 747 vehicles during the simulation period, with 1149 vehicles for the northbound Bonney-Virginia Beach Blvd. segment (segment 2) and 874 vehicles for the northbound I-264 to Virginia Beach Blvd. Segment (segment 3). Without light rail crossings, the average total delays were 10.85 seconds/vehicle on segment 1, 4.27 seconds/vehicle for segment 2, and 33.45 seconds/vehicle for segment 3, which includes a traffic signal at Bonney Road. Table 24 shows the average additional delays for these three segments. For segments 1 and 3, the average additional delays tend to increase as LRT crossing frequency increased. This pattern did not appear with segment 2; there was a small range of average additional delays, from 0.85 seconds/vehicle at the 30-minute frequency to 1.74 seconds/vehicle at the 10-minute frequency. More frequent crossings than 10 minutes appeared to result in a slightly smaller additional delay, on average. The location of segments 1 and 2 likely affected the results, since queues were shown to spill back from behind the point where the segments begin, indicating that the spillback queues would affect both of the nearby intersections that were not included in those segments. The placement of segment 2 also does not allow for preemption of the Rosemont/Bonney Rd. signal to be accounted for. The paired *T*-tests that were performed indicate that the average delays with LRT crossings are significantly different from those without crossings at the 95% confidence level.

Table 25. Average additional delays for Rosemont Rd. crossings

Crossing Frequency (min.)	SB Average additional delay (sec/veh)	Max	Min	NB Avg. additional delay (sec/veh)	Max	Min	NB Avg. additional delay (sec/veh)	Max	Min
5	8.55	10.9	6.1	1.36	2.8	-0.3	78.36	96.4	61.9
8	5.64	7.5	3.6	1.67	3.3	0.2	52.13	63.2	35.1
10	3.66	5.4	1.4	1.74	3.2	0.4	44.57	57.4	23.3
12	2.75	4.7	1.2	1.60	3.0	0.5	33.76	53.8	15.2
15	2.68	4.9	1.1	1.36	2.3	0.3	27.63	48.9	7.5
20	1.66	3.3	0.3	1.16	2.3	-0.2	21.22	44.1	4.1
30	0.95	2.3	-0.6	0.85	2.1	-0.4	13.09	31.8	1.0

4.3.2 South Plaza Trail Crossings

Delays were calculated for S. Plaza Trail in both the southbound and northbound directions. Over the forty simulation runs, there were an average of 473 vehicles counted in the southbound segment and 596 in the northbound during the one-hour long simulation period.

The following tables show the average total delay without light rail and the average additional delay with light rail as calculated by VISSIM for these two segments.

Table 26. Average additional delays for S. Plaza Trail crossings

Crossing Frequency (min.)	SB Average additional delay (sec/veh)	Max	Min	NB Average additional delay (sec/veh)	Max	Min
5	2.85	4.0	2.0	4.48	7.7	1.7
8	1.96	2.5	1.3	3.04	7.5	0.5
10	1.45	2.2	0.7	2.46	4.7	0.2
12	1.14	1.7	0.5	2.05	6.8	-0.3
15	0.89	1.5	0.3	1.83	5.4	-0.2
20	0.65	1.2	0.2	2.08	29.5	-0.4
30	0.30	0.7	0.0	1.00	4.3	-0.8

Without light rail, there was a base average delay of 0.19 seconds/vehicle in the southbound direction and 3.89 seconds/vehicle in the northbound. With LRT crossings, the average additional delays ranged from 2.85 seconds/vehicle to 0.30 seconds/vehicle, with a similar pattern of increasing delay with increasing frequency as found in many of the other scenarios that have been tested. For vehicles traveling northbound, the average additional delays were greater than those experienced by vehicles traveling south; this is consistent with results from other scenarios in that greater volumes experience increased additional delays with LRT crossings. The average additional delays in the northbound direction range from 4.48 seconds/vehicle at the highest crossing frequency tested to 1 second/vehicle at the 30-minute frequency. At 20 minutes, the northbound additional delay is greater than those of both the 12 and 15-minute frequencies but by no more than 0.2 seconds/vehicle.

The paired *T*-tests that were performed indicated with 95% confidence that additional delays were created as a result of the presence of LRT crossings at all of the frequencies that were tested.

4.3.3. N. Lynnhaven Road Crossings

For the light rail crossing at N. Lynnhaven Rd., delay was calculated by VISSIM in the southbound and the northbound directions. The southbound segment had an average of 803 vehicles and the northbound had 559 vehicles during the simulation period. The following tables show the average additional delays for the various LRT crossing frequencies that were tested:

Table 27. Average additional delay for N. Lynnhaven Rd. crossings

Crossing Frequency (min.)	SB Average additional delay (sec/veh)	Max	Min	NB Average additional delay (sec/veh)	Max	Min
5	34.26	75.7	14.5	5.77	7.4	4.1
8	9.58	27.7	4.0	3.04	3.8	2.1
10	6.43	9.0	3.5	2.33	3.1	1.2
12	5.16	7.9	1.7	1.97	2.8	0.9
15	3.85	6.7	2.0	1.70	2.7	0.9
20	2.69	6.0	0.5	1.17	1.9	0.4
30	1.49	3.2	-0.1	0.82	1.7	0.2

803 vehicles traveled on the southbound segment and had an average total delay without LRT of 2.78 seconds/vehicle. 559 vehicles were counted on the northbound segment; they had an average total delay of 0.68 seconds per vehicle without light rail crossings. At the highest LRT crossing frequency, the southbound average additional delay increased to more than 34 seconds per vehicle and was at 1.49 seconds/vehicle at the 30-minute frequency. The average additional delays for northbound vehicles ranged from 5.77 seconds/vehicle at 5 minutes to 0.82 seconds/vehicle at the 30-minute crossing frequency. Compared with the two-lane isolated intersection scenario, the southbound additional delays are much higher than those found closer to an input volume of 750 vehicles/hour: 34.26 vs. 5.63 seconds/vehicle with the isolated intersection at the 5-

minute crossing frequency. The additional delays in the northbound direction were more consistent with the values obtained in the two-lane isolated intersection scenario.

4.3.4. Lynnhaven Parkway Crossings

Delay on Lynnhaven Parkway was determined for segments in the northbound and southbound directions in the VISSIM model. The northbound segment had an average of 1264 vehicles during the simulated hour, while the southbound segment carried an average of 1067 vehicles. The following table shows the average additional delay for the LRT frequencies that were evaluated:

Table 28. Average additional delay for Lynnhaven Pkwy. crossings

Crossing Frequency (min.)	SB Average additional delay (sec/veh)	Max	Min	NB Average additional delay (sec/veh)	Max	Min
5	6.04	13.5	3.9	2.25	3.2	1.0
8	2.96	4.4	1.6	1.80	2.8	0.9
10	2.49	3.7	1.1	1.33	1.9	0.7
12	2.09	3.4	0.9	1.13	1.9	0.4
15	1.55	2.9	0.5	0.90	1.6	0.0
20	1.08	1.9	-0.3	0.73	1.8	-0.1
30	0.62	1.6	-0.1	0.40	1.1	-0.3

The average total delay without LRT crossings was 1.65 seconds per vehicle in the northbound direction and 1.83 seconds/vehicle in the southbound. As shown in table 27, the average additional delay in the northbound direction ranges from 2.25 seconds/vehicle to 0.40 seconds/vehicle. There appeared to be a steady decrease in the averages as LRT crossing frequencies decreased with the northbound vehicles. With the southbound vehicles, the greatest average delay was 6.04 seconds/vehicle at the 5-minute frequency, and then the average additional delay dropped more than 3 seconds at the 8-minute crossing frequency. From that point on, there was a more gradual decrease in the average additional delays, all the way to the lowest value of 0.62 seconds/vehicle that occurred with the least frequent crossing level that was tested. The paired *T*-tests that were performed indicate that the average delays with LRT crossings are significantly different from those without crossings at the 95% confidence level.

4.3.5. Virginia Beach Blvd. Turning Movements

4.3.5.1. Virginia Beach Blvd./Rosemont Rd.

Turning movements from Virginia Beach Blvd. onto southbound Rosemont Rd. were also examined during the simulation. There were an average of 272 left turns from westbound Virginia Beach Blvd. and 328 right turns from eastbound Virginia Beach Blvd. onto southbound Rosemont Rd. Table 29 shows the average additional total delay with light rail crossings:

Table 29. Average additional delays for turns from Virginia Beach Blvd. onto Rosemont Rd.

Crossing Frequency (min.)	WB (left turns) Average additional delay (sec/veh)	Max	Min	EB (right turns) Avg. additional delay (sec/veh)	Max	Min
5	61.12	97.5	34.7	-35.65	6.2	-87.8
8	24.32	32.2	15.0	-35.24	15.6	-78.8
10	22.99	33.2	11.0	-25.73	7.6	-68.7
12	17.65	30.4	9.5	-19.75	15.1	-64.5
15	13.03	46.9	4.1	-21.16	17.3	-55.5
20	8.16	67.6	0.8	-13.01	27.3	-42.0
30	4.60	42.5	-1.9	-8.31	43.8	-53.4

Without LRT crossings, the average total delay per vehicle was 50.8 seconds for left turns from westbound Virginia Beach Blvd. and 250.2 seconds for right turning vehicles from eastbound Virginia Beach Blvd. onto southbound Rosemont Rd. As shown in Table 29, the average additional delays for left turning vehicles ranged from 61.2 seconds/vehicle at the 5-minute LRT crossing frequency to 4.6 seconds with a 30-minute frequency. Between the 5 and 8-minute frequencies, there was a large drop in the average additional delay, from 61.1 to 24.32 seconds/vehicle. The right turning vehicles experienced a travel time savings from 35.65 seconds/vehicle with a 5 minute crossing frequency to 8.31 seconds/vehicle at 30 minutes. This travel time savings can be attributed to the preemption of the signal at Virginia Beach Blvd. and Rosemont Rd.; when a light rail vehicle is crossing, the signal is set to give a green light to the through and right turning movements in both directions of Virginia Beach Blvd. Allowing the signal to continue with its normal cycle during LRT crossings would have likely resulted in queues extending into the intersection and blocking traffic. The paired *T*-tests that were performed for these turning movements indicate that the average delays with LRT crossings are significantly different from those without crossings at the 95% confidence level.

4.3.5.2. Virginia Beach Blvd./Lynnhaven Pkwy.

Left and right turns from Virginia Beach Blvd. onto Lynnhaven Pkwy. were also considered in this scenario. During the simulation, there was an average of 816 vehicles turning left from westbound Virginia Beach Blvd. onto southbound Lynnhaven Pkwy. and 251 vehicles turning right from eastbound Virginia Beach Blvd. Without light rail crossings, the average total delay for left turning vehicles was 230.41 seconds/vehicle and 20.37 seconds/vehicle for right turning vehicles.

The average total delay without light rail crossings was 230.4 seconds/vehicle for left turns and 20.4 seconds/vehicle for the right turns. Table 30 shows the average delay for different LRT arrival frequencies:

Table 30. Average additional delays for turns from Virginia Beach Blvd. onto Lynnhaven Pkwy.

Crossing Frequency (min.)	WB (left turns) Average additional delay (sec/veh)	Max	Min	EB (right turns) Avg. additional delay (sec/veh)	Max	Min
5	0.53	33.6	-46.1	6.82	15.6	0.4
8	-0.70	45.7	-40.0	3.78	8.8	-1.9
10	-3.06	32.8	-35.3	3.28	7.0	0.3
12	-1.18	43.4	-36.0	2.09	6.6	-2.3
15	-0.71	56.4	-33.3	1.88	6.4	-3.3
20	-4.95	42.2	-53.1	1.25	6.7	-4.1
30	-2.97	48.8	-42.4	0.03	4.0	-3.8

The paired *T*-tests that were performed for these turning movements indicate that one cannot detect a significant difference between the delays with or without LRT for the left turning movement from westbound Virginia Beach Blvd. onto southbound Lynnhaven Pkwy. at any of the LRT crossing frequencies and for the right turning movement from eastbound Virginia Beach Blvd. onto southbound Lynnhaven Pkwy. at the 30 minute frequency. For the other frequencies that were simulated with the right turning movement, the *T*-tests indicated that there was a significant difference between the average delays with and without LRT for those turns at the 95% confidence level.

4.4. Other Variables

A preliminary analysis of the data obtained from the simulations examined the influence of truck volumes and driveways on the average additional delays with LRT crossings. Figure 18 shows the average additional delays for the various truck volumes based on five simulation runs. The greatest proportion of trucks and crossing frequencies tested increased the average additional delays by 2 to 3 seconds. As crossing frequencies and truck volumes decreased, the average additional delays begin to converge.

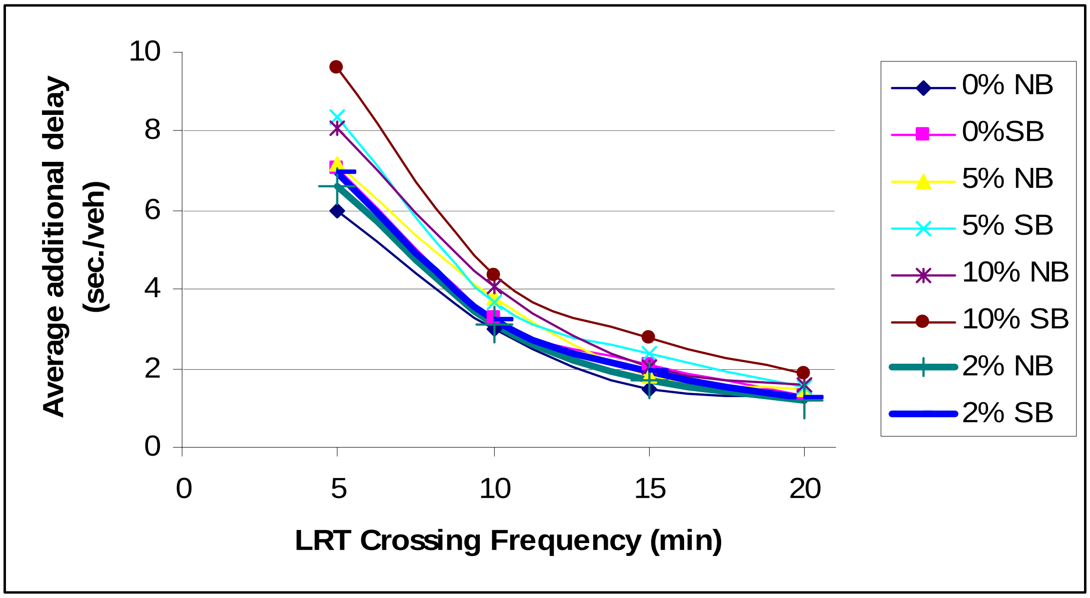

Figure 18. Average additional delays for variable percentages of trucks

Figure 19 shows the average additional delays experienced by vehicles with a driveway upstream of the LRT crossing in each direction. The preliminary results based on five simulation runs show that the additional delays for this scenario were within 0.5 seconds/vehicle of the corresponding additional delays *without* driveways. This indicates that the presence of driveways near LRT crossings does not create a condition that would substantially affect the additional delays experienced by vehicles.

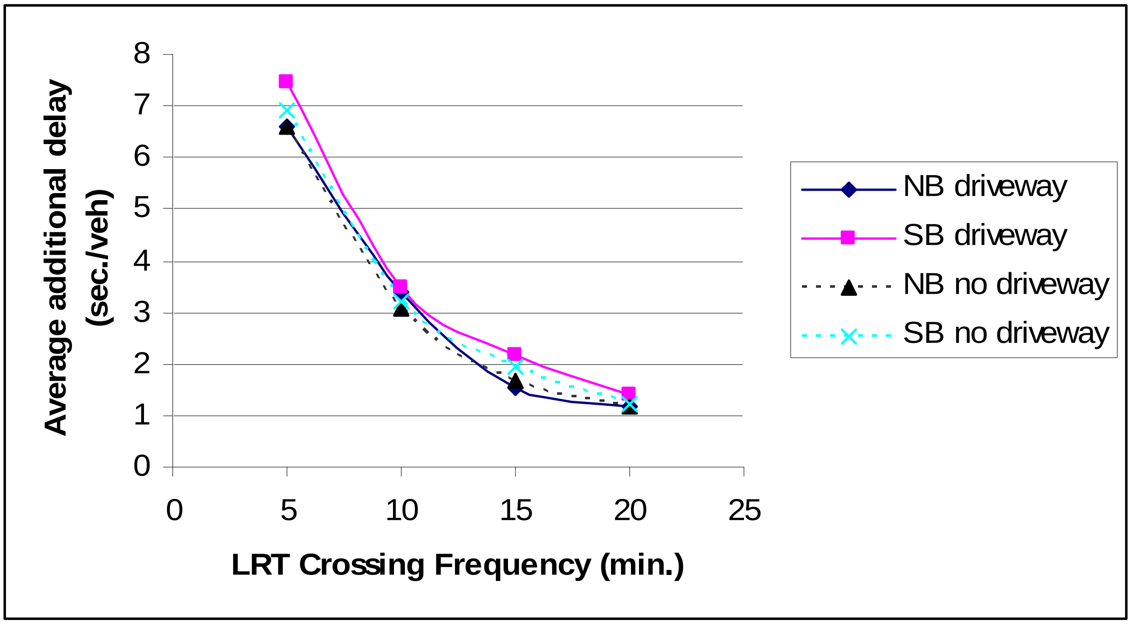

Figure 19. Average additional delays for driveway test scenario

4.5. Summary of Results

For the two-lane and four-lane isolated intersections, additional delays created by LRT crossings tend to increase with higher traffic volumes and more frequent crossings until the volume to capacity ratio becomes greater than 1, then the additional delays decreased. Figures 20 and 21 show how average additional delays varied with traffic volumes and crossing frequencies based on the two- and four-lane isolated intersection scenarios together.

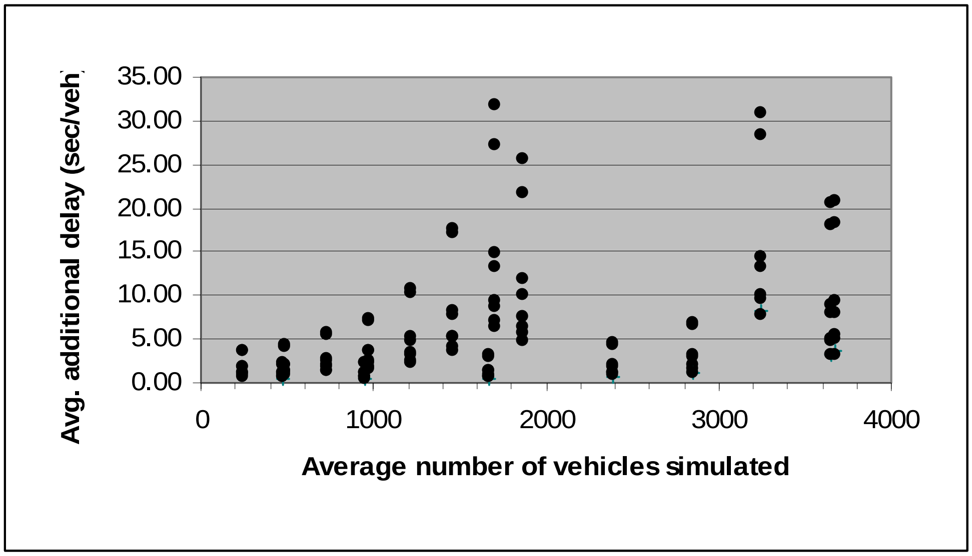

Figure 20. Average additional delays vs. number of vehicles

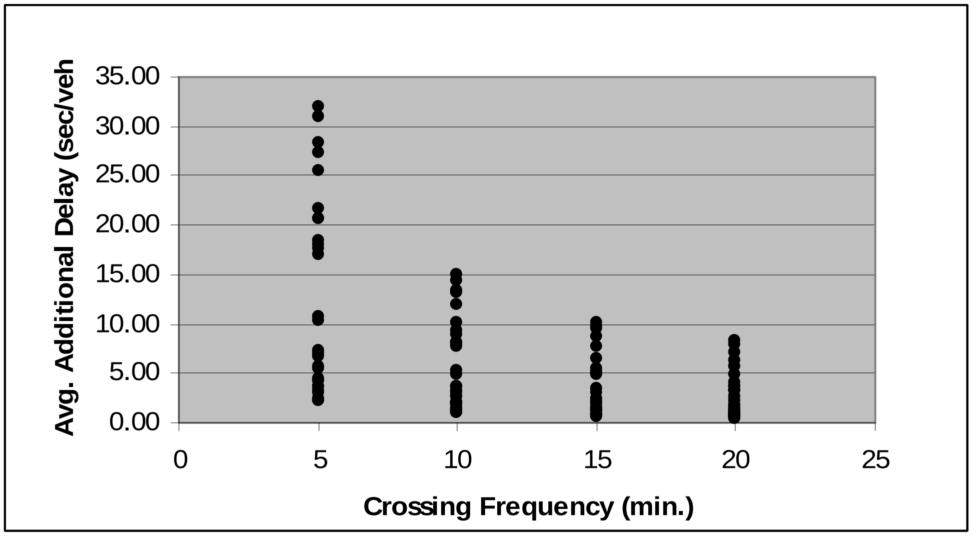

Figure 21. Average additional delays vs. LRT crossing frequency

When light rail operates within the median of a street, the delays experienced depend on the turning movement and its relationship to the crossing; those that are in conflict with the LRT tend to have higher delays. In the case of a larger network, the proximity of a LRT crossing to other intersections influences the delay as well.

The following table summarizes the maximum additional delays that were found for each of the variables that was examined in the scenarios:

Table 31. Summary of maximum average additional delays for each variable that was tested

Variable	Maximum average additional delay	Source
Vehicle crossing volume	31 seconds/vehicle	Table 3
LRT crossing frequency	31 seconds/vehicle	Table 12
Signal preemption	103 seconds/veh. (left turns parallel to LRT); 6.3 sec./veh. (perpendicular to LRT); 33 sec./veh. savings (through parallel to LRT)	Table 20, Table 22
Percentage of trucks	9.5 seconds/vehicle	Figure 18
Presence of driveways near crossing	7 seconds/vehicle	Figure 19

Chapter 5: Findings, Conclusions, and Recommendations

This report examined the impacts of at-grade light rail transit crossings on the change in average total delay experienced by vehicles. It presented a methodology to estimate the average additional delay created by frequent at-grade LRT crossings using VISSIM computer simulation software.

5.1. Findings

Many factors have the potential to affect the change in delays that occurs with at-grade LRT crossings. The number of vehicles crossing, the frequency of crossings, intersection geometry, and some signal preemption configurations have been addressed in this study. Other factors that have an impact include the presence of driveways or intersections near crossings, the composition of the traffic itself (for example, the number of heavy trucks or driver familiarity), and various degrees of priority given to light rail vehicles when they arrive at an intersection.

The VISSIM 3.70 computer simulation model is an acceptable tool to determine the impacts of LRT crossings on street traffic. The model allows for a wide range of conditions to be considered, which is useful because there is a great amount of design flexibility within light rail systems. VISSIM 3.70 has the capability to model transit operations explicitly, so it can be used to evaluate simple designs as well as more complex scenarios that might involve transit, street traffic, and pedestrians.

For a two-lane isolated intersection, there was an average of 3.6 seconds of additional delay per vehicle with approximately 250 vehicles crossing and almost 32 seconds/vehicle of additional delay with 1700 vehicles crossing the light rail tracks. As light rail crossing frequencies decreased from 5 to 10 minutes, the average additional delays decreased by close to half, to a maximum of 14.9 seconds/vehicle. At the 15 minute crossing frequency, there was a maximum of 9.4 seconds/vehicle of average additional delay, and it was at 7.1 seconds/vehicle with crossings every 20 minutes and a traffic volume of 1700 vehicles/hour.

It was shown that increasing crossing frequencies causes the additional average delay to increase up to the point when the volume reaches the saturation flow rate. At that point, average additional delay decreases and starts to show little change, although the average total delay continues to increase. This is because adding the LRT crossing changes the flow from uninterrupted to signalized. As traffic volumes increase, the capacity of the roadway decreases and total delays go up in an uninterrupted flow situation; however, in a signalized intersection, the total flow remains constant at the level of the saturation flow rate when demand exceeds capacity, so the increase in total delay is not as great. The increase in delay that happens when the roadway without LRT is over capacity makes the average total delay closer to that found with LRT crossings, therefore making the average additional delay smaller, since it is the difference between the two delay values.

The four-lane isolated intersection case showed that average additional delays are lower than those for the two-lane case. For lower traffic volumes, between 500 and 3000 vehicles/hour in each direction, the average additional delays range from 2.1 sec./vehicle to 6.9 sec./vehicle at the 5 minute crossing frequency. There is a sharp increase in the total delay to 31 seconds/vehicle at 3250 vehicles/hour, then a slight decrease to around 21 seconds per vehicle as the roadway becomes over saturated. When the light rail frequencies decrease, there is a corresponding decrease in additional delays. At the 20 minute frequency, for example, the maximum additional delay is 8.3 seconds/vehicle. The average additional delays for crossing traffic volumes below 3000 vehicles/hour in each direction were all under 2 seconds.

With more complex roadway and crossing geometry, such as the case when the LRT is located within a street median or as part of a larger network, the change in delay is also dependent on the degree of coordination and preemption of traffic signals within the network. If traffic signals are set to allow no conflicting phases to proceed during LRT crossings, an average travel time savings could result. For the LRT in median scenario, there was an average travel time savings of approximately 30 seconds per vehicle for the movements parallel to the light rail tracks. Left turns on the main approaches that were in conflict with the light rail experienced significant delays ranging from more than 100 seconds/vehicle to approximately 15 seconds/vehicle. The approaches that were perpendicular to the tracks experienced average additional delays from a maximum of 6.3 seconds/vehicle with a crossing frequency of 5 minutes to under 1 second for the 20 minute crossing frequency.

The crossings in the Virginia Beach network showed results that were consistent with the additional delay values found in the two- and four-lane isolated crossings when there were unsaturated conditions and crossings that were far enough from other traffic signals that the queues did not spill back into those intersections.

5.2. Conclusions

Based on the results from the four scenarios that were tested, it appears that light rail crossing frequency and the number of vehicles at the crossing have a great effect on the average increase in delays experienced by those vehicles. When the roadway is in an over saturated condition, the total delay continues to increase with increasing volumes and crossing frequencies, but additional delay attributed to light rail crossings is not as great as it would be if it were under capacity.

Preemption of traffic signals to allow light rail vehicles to cross has an effect on the vehicles on all approaches. For approaches that conflict with the light rail crossing, there is an increase in delay. Travel time savings may result on some approaches if additional green time is given to no conflicting phases during a light rail crossing. Individual results are likely more dependent on the traffic volume and capacity of a given location, however.

5.3. Recommendations

During the initial planning for a light rail line, special consideration should be given to the traffic volumes at the proposed at-grade crossings as well as the proposed service frequency during the peak periods. If the level of service is expected to include five-minute crossing frequencies or if at-grade crossings are proposed for streets that are near capacity, measures such as widening roads at crossings, providing extra space for turning vehicles, or constructing a grade-separated crossing should be considered. The VISSIM model can be used to evaluate the effects of a proposed LRT system.

Planners and engineers can use the following table as a guide to determine whether light rail crossings would create an average of more than ten seconds of additional delay per vehicle, the amount of the average total delay that separates level of service B from level of service C at a signalized intersection [25]. .

Table 32. Reference table for identifying whether LRT crossings would increase average delay by more than 10 seconds

Number of Lanes (one direction)	One-directional Traffic Volume (veh./hr)	LRT Crossing Frequency	Average additional delay under 10 seconds?
1	< 1250	> 10 minutes	yes
1	> 1250	> 10 minutes	no
1	1250 < vol < 2000	< 10 minutes	yes
1	1251 < vol < 2000	> 10 minutes	no
2	< 3000	any	yes
2	> 3000	> 10 minutes	no
2	> 3000	< 10 minutes	yes

5.3.1. Suggestions for Future Research

Further investigation of light rail crossings near signalized intersections is important for determining their effects. The effects of other variables on average total delay with the presence of light rail should also be studied. Various degrees of preemption and signal recovery algorithms should be examined for coordinated signal systems as well as for isolated intersections. If light rail is expected to reduce traffic volumes along a particular roadway segment, expansion of this methodology to quantify those effects might be useful.

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Appendix A. Intersection volumes for LRT in median scenario

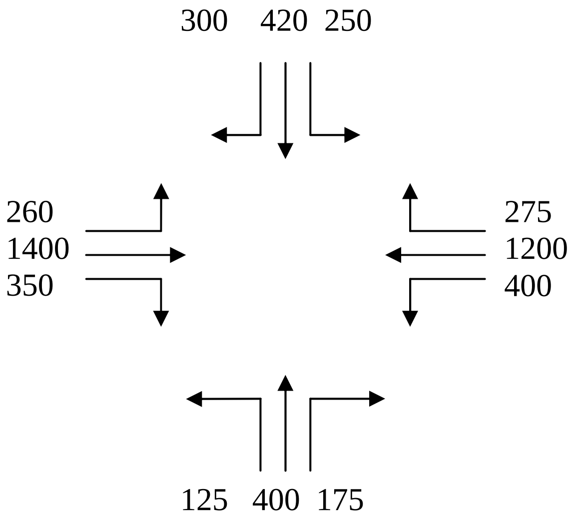
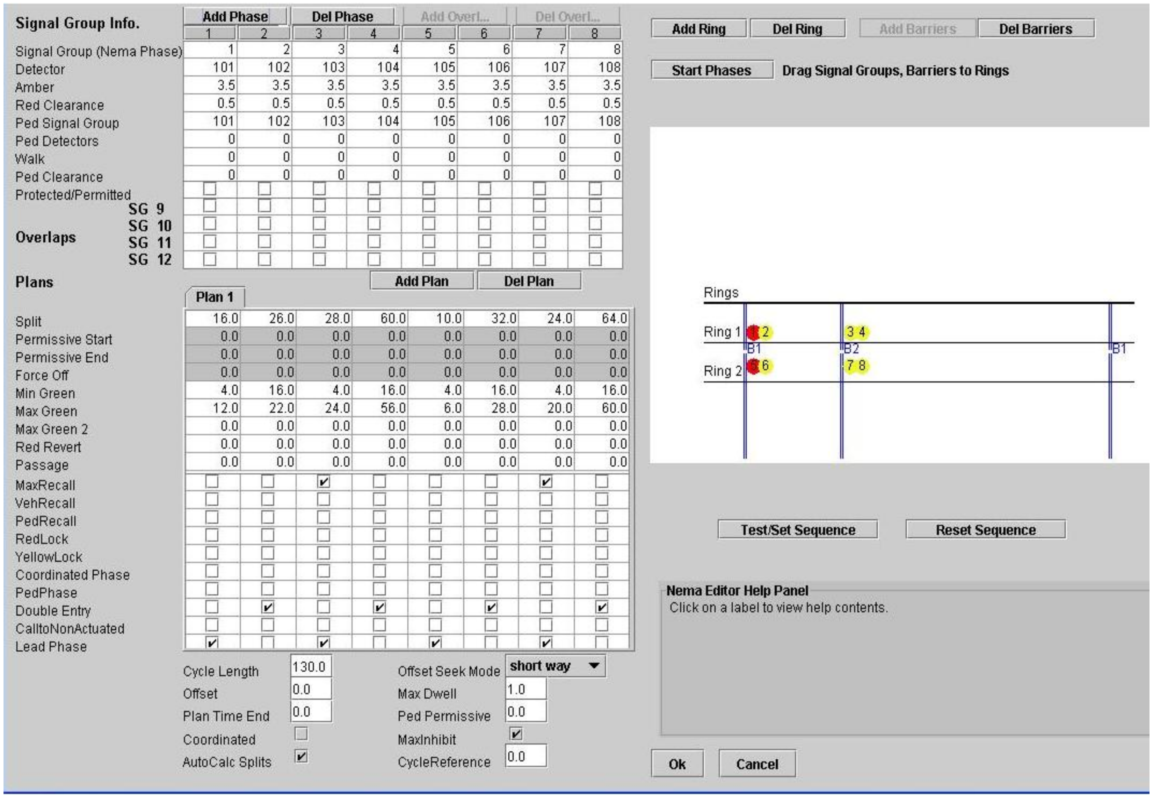


Figure 22. Turning Volumes for LRT in Median Scenario



Signal Group Info.

	1	2	3	4	5	6	7	8
Signal Group (Nema Phase)	1	2	3	4	5	6	7	8
Detector	101	102	103	104	105	106	107	108
Amber	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Red Clearance	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Ped Signal Group	101	102	103	104	105	106	107	108
Ped Detectors	0	0	0	0	0	0	0	0
Walk	0	0	0	0	0	0	0	0
Ped Clearance	0	0	0	0	0	0	0	0
Protected/Permitted	☐	☐	☐	☐	☐	☐	☐	☐
Overlaps **SG 9**	☐	☐	☐	☐	☐	☐	☐	☐
SG 10	☐	☐	☐	☐	☐	☐	☐	☐
SG 11	☐	☐	☐	☐	☐	☐	☐	☐
SG 12	☐	☐	☐	☐	☐	☐	☐	☐

Plans

Plan 1

Split	16.0	26.0	28.0	60.0	10.0	32.0	24.0	64.0
Permissive Start	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Permissive End	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Force Off	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Min Green	4.0	16.0	4.0	16.0	4.0	16.0	4.0	16.0
Max Green	12.0	22.0	24.0	56.0	6.0	28.0	20.0	60.0
Max Green 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Red Revert	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Passage	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MaxRecall	☐	☐	☑	☐	☐	☐	☑	☐
VehRecall	☐	☐	☐	☐	☐	☐	☐	☐
PedRecall	☐	☐	☐	☐	☐	☐	☐	☐
RedLock	☐	☐	☐	☐	☐	☐	☐	☐
YellowLock	☐	☐	☐	☐	☐	☐	☐	☐
Coordinated Phase	☐	☐	☐	☐	☐	☐	☐	☐
PedPhase	☐	☐	☐	☐	☐	☐	☐	☐
Double Entry	☐	☑	☐	☑	☐	☑	☐	☑
CalltoNonActuated	☐	☐	☐	☐	☐	☐	☐	☐
Lead Phase	☑	☐	☑	☐	☑	☐	☑	☐

Cycle Length	130.0	Offset Seek Mode	short way
Offset	0.0	Max Dwell	1.0
Plan Time End	0.0	Ped Permissive	0.0
Coordinated	☐	MaxInhibit	☑
AutoCalc Splits	☑	CycleReference	0.0

Nema Editor Help Panel

Click on a label to view help contents.

Figure 23. NEMA Controller Settings for LRT in Median Scenario

Appendix B. Calculation of Saturation Flow Rates

Saturation flow rate, from the Highway Capacity Manual:

$$s = (s_o)(N)(f_w)(f_{HV})(f_g)(f_p)(f_a)(f_{bb})(f_{Lu})(f_{RT})(f_{LT})$$

For the 2-lane isolated intersection:

s_o = 1900
N = 1
f_w = 0.967 (11 ft widths)
f_{HV} = 0.980 (2% trucks)
f_g = 1
f_p = 1
f_a = 1
f_{bb} = 1
f_{Lu} = 1
f_{RT} = 1
f_{LT} = 1

s = (1900)(.967)(.980) = **1800 vphg**

For the 4-lane isolated intersection:

s_o = 1900
N = 2
f_w = 0.967 (11 ft widths)
f_{HV} = 0.980 (2% trucks)
f_g = 1
f_p = 1
f_a = 1
f_{bb} = 1
f_{Lu} = 1
f_{RT} = 1
f_{LT} = 1

s = (1900)(2)(.967)(.980) = **3600 vphg**

For the LRT in median intersection, through and right turning movements:

s_o = 1900
N = 2
f_w = 0.967 (11 ft widths)
f_{HV} = 0.980 (2% trucks)
f_g = 1
f_p = 1

f_a = 1
f_{bb} = 1
f_{Lu} = 0.95
f_{RT} = 0.970 for NB, EB, WB; 0.940 for SB
f_{LT} = 1

no pedestrians

s = (1900)(2)(.967)(.980)(0.970) = **3318 vphg NB, EB, WB**
s = (1900)(2)(.967)(.980)(0.940) = **3216 vphg SB**

For the LRT in median intersection, left turning movements:

s_o = 1900
N = 1
f_w = 0.967 (11 ft widths)
f_{HV} = 0.980 (2% trucks)
f_g = 1
f_p = 1
f_a = 1
f_{bb} = 1
f_{Lu} = 1
f_{RT} = 1
f_{LT} = 0.95 (protected left turns)

no pedestrians

s = (1900)(.967)(.980)(0.950) = **1710 vphg**