TRANSIT SIGNAL PRIORITY: SIMULATION-BASED MODELING, EVALUATION AND IMPROVEMENT

by

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STATEMENT OF DISSERTATION APPROVAL

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ABSTRACT

Traffic congestion is an increasing problem in most urban areas in the United States. One of the sources of this problem is the automobile-oriented development that encourages automobile use and suppresses other transportation modes. A good transit system can satisfy most of the requirements of a transportation system user. A transit system must be efficient, safe, comfortable, and competitive to private cars in order to attract more riders. Transit Signal Priority (TSP) is an operational strategy that facilitates transit vehicles at signalized intersections. It improves transit efficiency and helps transit offer travel times competitive to private cars. A lot of studies conducted in the past 40 years show the major possibilities and benefits of TSP.

The goal of this research is to develop a simulation-based methodology for the evaluation and improvement of TSP strategies. The objectives consist of evaluating existing and future TSP systems, and developing field-ready algorithms that provide adaptive ways for achieving different levels of TSP and improving its operation. The focus of the research is on using traffic microsimulation to evaluate and improve TSP, but it also looks into some field-based implementations and evaluations for additional support.

The analysis of different TSP strategies is performed on existing and future rapid transit mode implementations, namely Bus Rapid Transit (BRT) and Light Rail Transit (LRT). The results from the presented studies show the major benefits of TSP

implementations for transit operations and small disruptions for vehicular traffic. Depending on the selected strategies and level of TSP, the travel time savings for transit can be between 10% and 30%, the reduction in intersection delay can exceed 60%, while running time reliability and headway adherence are greatly improved. These improvements in transit operations can make transit more efficient and competitive to private cars, justifying the TSP implementation.

This research offers significant contributions to the state of TSP practice and research. It provides detailed insights into TSP operations, develops methods for its evaluation, and describes algorithms for achieving different levels of TSP. A significant part of the research is dedicated to the use of Software-in-the-Loop (SIL) traffic controllers in microsimulation. Through this research, SIL is proven to be a powerful tool for simulating complex traffic signal operations and TSP.

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ABBREVIATIONS

AADT	Average Annual Daily Traffic
ADA	Americans with Disabilities Act
ASC/3	Advanced System Controllers series 3
BRT	Bus Rapid Transit
CID	Controller Interface Device
CPN	Colored Petri Network
DOT	Department of Transportation
DSRC	Dedicated Short Range Communications
EIL(S)	Emulator-In-The-Loop (Simulation)
EIS	Environmental Impact Study
GPS	Global Positioning Systems
GUI	Graphical User Interface
HCM	Highway Capacity Manual
HIL(S)	Hardware-In-The-Loop (Simulation)
Hz	Hertz (the unit for frequency)
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
ITS	Intelligent Transportation Systems
LOS	Level of Service

LRT	Light Rail Transit
LRV	Light Rail Vehicle
MAX	Salt Lake City's Bus Rapid Transit system
MOE	Measure of Effectiveness
MPC	Mountain Plains Consortium
NEMA	National Electrical Manufacturers Association
NTCIP	National Transportation Communications for ITS Protocol
OS	Operating System
PPS	Predictive Priority Strategies
PRG	Priority Request Generator
PRS	Priority Request Server
RBC	Ring Barrier Controller
ROW	Right-of-Way
RT	(Bus) Route
SCP	Signal Control and Prioritization
SES	State Environmental Study
SG	Signal Group
SIL(S)	Software-In-The-Loop (Simulation)
TDM	Travel Demand Management
TRAX	Salt Lake City's Light Rail Transit system
TRB	Transportation Research Board
TRR	Transportation Research Record
TSP	Transit Signal Priority

TVM	Ticket Vending Machine
UDOT	Utah Department of Transportation
UTA	Utah Transit Authority
VAP	Vehicle Actuated Programming
VNP	Virtual NextPhase
VISSIM	Verkehr In Stadten SIMulation (Traffic in Towns Simulation)
WFRC	Wasatch Front Regional Council

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CHAPTER 1

INTRODUCTION

This chapter presents the need and methodology for evaluating Transit Signal Priority (TSP) and rapid transit modes. The arguments are made to show the significance of a greater share of public transit in reducing Vehicle Miles Traveled (VMT). TSP methodology and benefits are summarized to support the research problem. The publication-based format of this dissertation and outline of subsequent chapters is presented at the end of the chapter.

1.1. Vehicle Miles Traveled and Transit

VMT has been constantly increasing in the United States since World War II. Those increases have been attributed to a combination of factors, such as enormous growth of metropolitan regions, dramatic increases in private car ownership, and declining importance of transit systems in low-density suburban development (*1*). In the period between 1970 and 2010, VMT in the US has tripled. At the same time, the transit mode share has been decreasing, from about 9% in 1970 to less than 5% in 2000 (*2*). These figures show the predominance of the private car mode, so the increase in VMT and therefore congestions are to be expected. Some of the recognized strategies for reducing VMT are mode shifts from private car to transit, walking or biking, increase in vehicle occupancy through carpools and vanpools, and reduction in travel through telecommuting, combining trips, sliding work time, or compact land development (*1*). Mode shift is the central strategy from the perspective of this research. Shifting modes can work when viable alternatives are available. For transit, viable means frequent, reliable service that connects places people want to go. This type of service can generally only be offered in metropolitan settings where employment and residential concentrations make capital investments and operating costs financially feasible. Increasing transit capacity provides more transportation options among communities, especially in areas where transit service is poor. Furthermore, increased transit capacity reduces VMTs and has a major potential for reducing greenhouse gas emissions and maintenance costs on road infrastructure. The evolving rapid transit modes, such as Light Rail Transit (LRT) or Bus Rapid Transit (BRT), have already been proven as successful solutions capable of attracting and retaining a high share of commuters (*3 – 6*). They have been successfully implemented in large cities and metropolitan areas, such as New York, Washington D. C., Boston, San Francisco, or Portland. However, people are still reluctant to use public transit, because it removes a lot of the convenience, comfort, and the sense of security and safety that a private car offers.

1.2. Transit Signal Priority

The best way to attract more people to use transit and increase ridership is to offer a transit service that is highly competitive to private cars (*3*). This means making transit convenient, comfortable, safe and efficient. High capacity rapid transit modes, such as BRT or LRT, have already been proven to be able to satisfy most of the requirements of a typical transportation system user (*3 - 6*). These transit systems mostly rely upon efficiency, meaning they offer low travel times, high running time reliability and satisfactory schedule adherence. One part of the Intelligent Transportation System (ITS) that helps rapid transit modes in maintaining this efficiency is Transit Signal Priority (TSP). TSP is an operational strategy that facilitates transit vehicles at signalized intersections (*7*). It gives them a certain priority over other traffic, reducing the delays these vehicles experience and improving their travel time and reliability. The main idea behind TSP is to help a transit vehicle go through a signalized intersection without stopping at the red light, or reducing the time this vehicle spends waiting for the green light if it is already stopped. This can be achieved through implementation of different strategies. Green extension/early green are the most common and well-known TSP strategies. Green extension is active when a transit vehicle is approaching a TSP equipped intersection while it is green, but it is estimated that the vehicle will not cross the intersection before the signal changes. Green extension will extend the duration of the green signal for a certain period of time until the vehicle clears the intersection. Early green (or red truncation) is active when a transit vehicle is waiting at the red light. This strategy shortens green durations for conflicting phases to expedite the return to green for the transit vehicle. Phase rotation is a strategy that changes the regular sequence of signal phases in a cycle to serve the transit phase faster. Phase rotation is active only if a transit vehicle is waiting at the red light, or approaching while it is red. It can work independently, or in a combination with the early green strategy. Phase insertion is a strategy that inserts an additional phase into the regular phase sequence to allow green for the transit vehicle. Similarly, dedicated transit phase is a special phase that serves only transit vehicles that are detected at the intersection. Separate TSP strategies are rarely implemented as stand-alone strategies. Usually a combination of strategies is used to provide the optimal priority for transit vehicles. Additional benefits of TSP are reduced operating and maintenance costs and fuel consumption for the transit system, as well as reduced emissions, noise and small impacts to other traffic.

1.3. Transit Signal Priority Evaluations

TSP systems are evaluated to measure their performance, benefits and impact on transit and vehicular traffic (*7*). The majority of TSP assessments is performed through field analysis and evaluation. These are typically before – after studies performed in the field following a TSP implementation. The main traffic and transit parameters, such as speeds, travel times, delays, number of stops, and transit ridership are measured before and after the TSP implementation. Comparing the two datasets can give direct benefits and impacts of the implemented TSP system. This type of analysis is usually time consuming and can be very costly, depending on the research organization and coverage.

Another way of performing TSP analysis is through traffic simulation. Microsimulation is a very powerful tool in different traffic analyses, including TSP. It is a second-by-second simulation of individual vehicles and different driving behaviors. That way, microsimulation can provide very detailed outputs necessary for a reliable TSP analysis and evaluation. The biggest obstacle in using traffic microsimulation for TSP analysis is the simulation of traffic control. The use of inadequate traffic control emulators or user-defined traffic control programs can deteriorate the obtained results. Since TSP is a specific traffic control function, the traffic control simulation is very important. The research presented here also deals with the selection of optimal traffic control programs.

1.4. Research Goal and Methodology

Benefits and impacts of TSP are well documented in existing research. The research that is conducted and presented here supports and contributes to the existing practice by offering detailed insights into TSP, developing methods for its evaluation, and providing algorithms for different levels of TSP and resolving some existing problems. The goal of this research is to develop a simulation-based methodology for the evaluation and improvement of TSP strategies. The objectives consist of evaluating existing and future TSP systems, and developing field-ready algorithms that provide adaptive ways for achieving different levels of TSP and improving its operation. The basic methodology, that also outlines the organization of this dissertation, is given in Figure 1.1.

The analysis of TSP systems can be performed in simulation (which is the focus of this research) and in the field (which was performed to support the research). Before beginning to use microsimulation in TSP analysis, one must make sure that the traffic control systems used in microsimulation are valid. Chapter 2 describes research that evaluates different simulation control types and compares them with a field traffic controller. The goal of this research was to pinpoint the differences in simulation traffic controllers and their limitations. This research also shows the abilities of Software-in-the-Loop (SIL) simulation controllers and their advantages over other simulation controller types.

Chapter 3 provides continuing research that emanated from the previous study. It

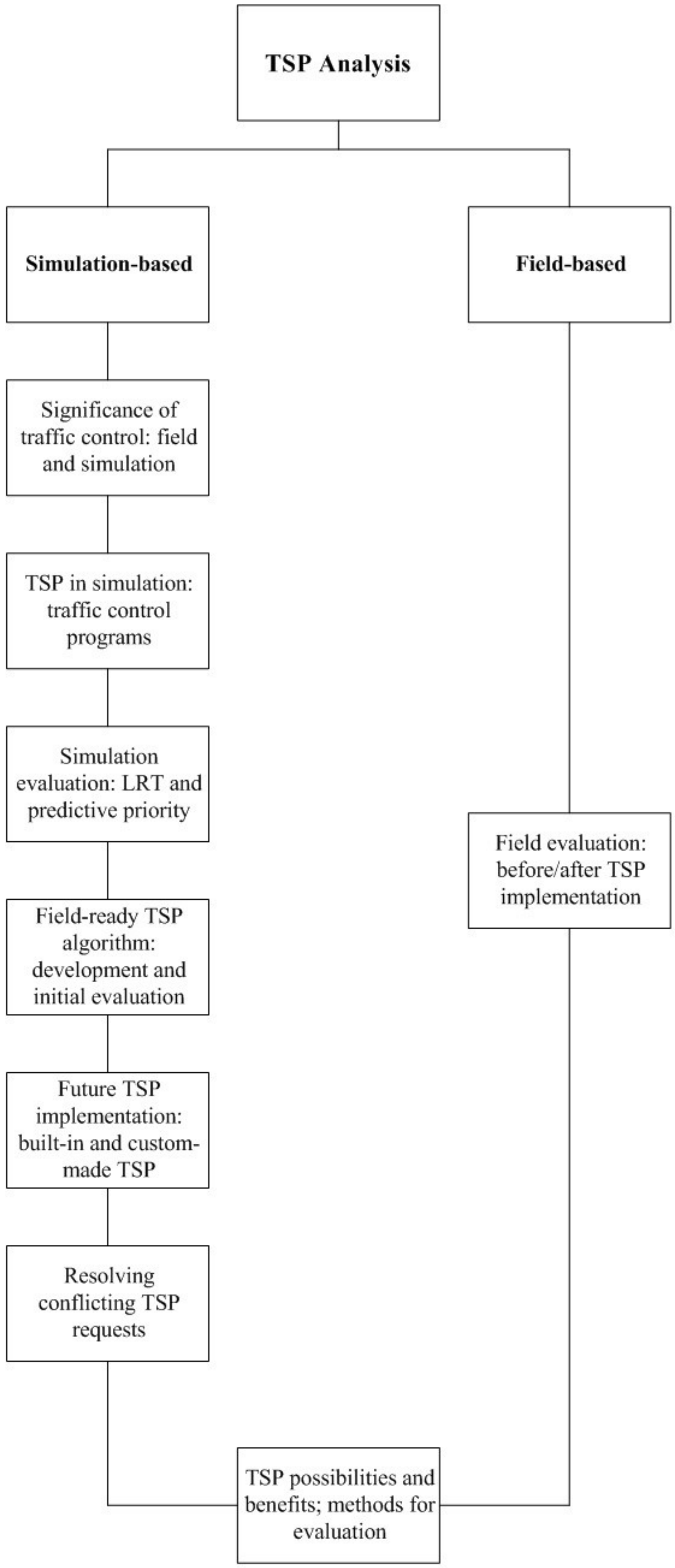

FIGURE 1.1 TSP evaluation methodology.

shows possibilities of a very sophisticated traffic control emulator in providing TSP, and compares it with the SIL controller with the same options. This research also offers detailed insights into TSP operations and the ways they are implemented in traffic controllers.

Chapter 4 describes the only field-based study in this research. This study evaluates the first BRT implementation in Utah and the combined effects of BRT operations and TSP on transit service. It also relates simulation studies of this BRT line described in Chapter 3 to the actual field operations.

Chapter 5 looks into another aspect of TSP called Predictive Priority Strategies (PPS). This chapter describes a simulation study of an existing LRT line and the application of PPS in Siemens traffic controllers. The study shows benefits and impacts of this type of TSP on LRT and traffic operations.

Chapter 6 describes the beginning steps in developing a TSP algorithm that can provide different levels of TSP using traffic controllers' logic processor. The study is based on PPS and its application in a different controller type. However, the study showed the possibilities of the logic processor to provide different levels of TSP that are not necessarily PPS.

Chapter 7 continues with the algorithm described in Chapter 6 and makes a distinction from the PPS algorithm. This study is using traffic and transit data of a future BRT line in West Valley City in Utah. It shows the major possibilities of the described algorithm for achieving different levels of TSP.

Chapter 8 describes an initial development and evaluation of an algorithm for resolving conflicting TSP calls in a SIL simulation environment. This algorithm is being designed to work with actual field traffic controllers, eliminating the need of additional hardware or software installations. Although still in the initial phase, this algorithm shows promising results and sets a path for future TSP research.

Chapter 9 summarizes the contributions of the described research to the current state of practice and research. The main conclusions of the research are presented in the last chapter.

1.5. Format of Dissertation

This dissertation is founded upon seven papers submitted to conferences and publications. Each of the following seven chapters have been individually presented at a conference, submitted to a transportation journal, or both, as indicated in the following list:

Chapter 2: Microscopic Modeling of Traffic Signal Operations: Comparative Evaluation of Hardware-in-the-Loop and Software-in-the-Loop Simulations
Paper submitted to the Transportation Research Board 88th Annual Meeting, January 11-15, 2009, and published in the Transportation Research Record No. 2128, 2009.

Chapter 3: Evaluation of Transit Signal Priority in RBC and ASC/3 Software-in-the-Loop Simulation Environment
Paper submitted and presented at the Transportation Research Board 89th Annual Meeting, January 10-14, 2010.

Chapter 4: 35M MAX: The First Bus Rapid Transit System in Salt Lake County

Paper published in the World Review of Intermodal Transportation Research (WRITR), Inderscience Publishers, 2010.

Chapter 5: Predictive Priority for Light Rail Transit: University Light Rail Line in Salt Lake County, UT

Paper submitted to the Transportation Research Board 90th Annual Meeting, January 21-27, 2011, and published in the Transportation Research Record No. 2259, 2011.

Chapter 6: Implementation of Transit Signal Priority and Predictive Priority Strategies in ASC/3 Software-in-the-Loop Simulation

Paper submitted and presented at the 14th IEEE International Intelligent Transportation Systems Conference (ITSC), October 5-7, 2011, and accepted for publication in the Advances in Artificial Transportation Systems and Simulation book chapter, 2012.

Chapter 7: Evaluation of Transit Signal Priority Options for the Future 5600 W Bus Rapid Transit Line in West Valley City, UT

Paper submitted and presented at the Transportation Research Board 91th Annual Meeting, January 22-26, 2012, and accepted for publication in Transportation Research Record, 2012.

Chapter 8: Development and Evaluation of an Algorithm for Resolving Conflicting Transit Signal Priority Calls

Paper submitted and presented at the Transportation Research Board 91th Annual Meeting, January 22-26, 2012, and accepted for publication in Transportation Research Record, 2012.

Each chapter/paper contains its own abstract, references and other sections required by the conference/journal where they were submitted. The text, figures and tables were not modified from the original submissions, so some overlap of information exists in the chapters. However, the papers were formatted to comply with the University of Utah dissertation guidelines.

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CHAPTER 2

MICROSCOPIC MODELING OF TRAFFIC SIGNAL OPERATIONS: COMPARATIVE EVALUATION OF HARDWARE-IN-THE-LOOP AND SOFTWARE-IN-THE-LOOP SIMULATIONS

From Stevanovic, A., A. Abel-Rahim, M. Zlatkovic, and E. Amin. Microscopic Modeling of Traffic Signal Operations: Comparative Evaluation of Hardware-in-the-Loop and Software-in-the-Loop Simulations. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2128*, pp. 143-151.

2.1. Abstract

Currently, there are three different methods to model traffic signal operations in microscopic simulation models: the simulation model's controller emulator, Hardware-In-the-Loop Simulation, and Software-In-the-Loop Simulation. Although all three methods can be based on the same industry standard code, their different implementations suggest potential operational differences. This study investigates operational differences of the three methods by examining how each method operates in five experimental scenarios. Each of the scenarios differs from the others in network size (one intersection to five intersections) and operational strategies (pretimed, actuated, actuated-coordinated, and two different signal transition logics). Ten 75-minute simulation runs using 100 ms simulation resolution were executed for each experiment using the three signal control modeling alternatives. The results showed that, for basic signal control operations, such as pretimed and isolated-actuated operations, the three alternatives provided similar results as indicated by the average green time allocation and different operational measures of effectiveness. When advanced controller operations are used, such as signal transition logic, the simulation model emulator showed significantly different behavior than that observed in Hardware-In-the-Loop and Software-In-the-Loop Simulations.

2.2. Introduction

Most of the current traffic microsimulation packages, which are used to simulate traffic operations on urban arterials, consist of two components: simulator of traffic flows and generator of traffic signal states. In the simplest case, a generator of traffic signal states sends the current signal status to the simulator (e.g. pretimed traffic control). Two-way communication is used when actuated traffic control is modeled. In this case, the traffic simulator records the activations of virtual detectors and sends the inputs to the traffic control generator. The traffic control generator processes the inputs through its traffic control logic and returns current signal states to the simulator. Interaction between the two components can be more complex when advanced types of traffic control (e.g. adaptive) are modeled. This study focuses on the traffic control component.

The first traffic control logics implemented in traffic microsimulation were generated by internal microsimulation programs, which simply changed traffic signal states at predetermined intervals. This concept was later enhanced to provide for actuated traffic control logic within the microsimulation model. The real enhancements on the traffic control side came when external field controllers were coupled with microsimulation through a concept called Hardware-in-the-Loop Simulation (HILS) (*1*). Recently, the HILS concept has been advanced through its software version known as Software-in-the-Loop Simulation (SILS). Each of the new approaches improved communications between traffic simulator and traffic controller. However, more sophisticated approaches tend to be more expensive, more computationally demanding, and require more expertise, than less sophisticated approaches. Sometimes, when testing basic traffic control functions, it is advantageous to use a simpler and faster approach.

This study investigates three ways of connecting a generator of the traffic control logic with a traffic microsimulator. An internal microsimulation emulator of traffic control is compared with HILS and SILS concepts. VISSIM microsimulation, which supports all three concepts, is used to test a variety of traffic control operations on a case-study network. Operations of the three traffic control concepts and their impact on the traffic performance in the network were analyzed. The differences observed during the tests are discussed at the end of the study.

2.3. Research Background

2.3.1. Emulation-in-the-Loop Simulation (EILS)

As an internal source of traffic control, traffic simulation software uses its own emulator. The simulation software (e.g. CORSIM and VISSIM) may have emulators which are based on NEMA (National Electrical Manufacturers Association) standards. During a simulation, a traffic simulator passes the status of its detectors and signal heads to the emulator of "NEMA Controller" each simulation second and the emulator returns the state of the signal heads for the next simulation second. Considering that this emulator does not have any counterpart used in the field, we decided to use a phrase Emulator-in-the-Loop Simulations (EILS) to refer to this concept in further text. The major disadvantage of using EILS is that this concept does not provide the sophistication and variety of control operations of a field controller. The advantages are higher simulation speed, ease in setting up signal timings, perfect coordination with traffic simulation model, and low installation costs (comes together with main software).

2.3.2. Hardware-in-the-Loop Simulation (HILS)

The basic idea of HILS is as follows: a simulation model generates detector input data, which are then sent through the Controller Interface Device (CID) to the actual traffic controller. CID is piece of hardware which provides the interface from the discrete logic levels of control pins on the controller to the computer running a microscopic traffic simulation. The traffic controller analyzes the detector input data, determines the status of signal control, and sends the data back to the simulation model through the CID. This data exchange between the simulation model, the CID, and the simulation model is done every simulation time step. When using a CID, the real traffic signal controller replaces the internal controller emulation logic of the simulation program. The CID functions as a bridge between the electrical signals of the computer and those of the traffic signal controller.

The concept of Hardware-in-the-Loop Simulation (HILS) was first developed as the package by University of Louisiana (*2*). There is a long list of HILS deployments and testing studies since then (*1-10*). Currently, there are at least half of a dozen university centers across the country where HILS is used for testing, research, and education. The major disadvantages of the HILS are: an inability to run faster or slower than real time, no synchronization between controllers and the computer's clocks, and separate controller hardware is required for each intersection (*2*).

2.3.3. Software-in-the-Loop Simulation (SILS)

Major HILS issues were addressed when SILS was developed. SILS consists of a microscopic simulation model, a virtual traffic controller running on the same computer, along with an interface that allows for communication and exchange of information between the microscopic simulation and the virtual traffic controller. At least two SILS applications were developed in the past: Siemens' NextPhase that is linked to CORSIM and VISSIM (*2*), and Econolite's ASC/3 which connects to VISSIM (the only SILS commercially available).

PTV America and Econolite Control Products, in cooperation with the University of Idaho (the MOST Project), have developed an ASC/3 Software-In-The-Loop Controller embedded in VISSIM. The ASC/3 SILS concept enables use of multiple virtual ASC/3 controllers, all capable of running signal timings faster or slower than real time. The ASC/3 controllers in SILS are NTCIP compliant; they run from the same code base as the ASC/3 hardware controllers, which makes them nearly identical. The major disadvantage of SILS is that it does not have features of a real controller which support communications within a cabinet or centralized traffic signal system (*2*).

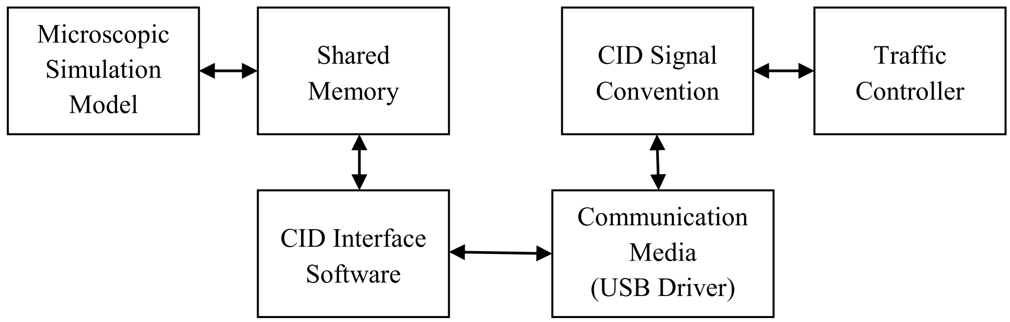
Both EILS and SILS are essentially both emulators and software packages. SILS uses the term Software because it represents the same version of software that is deployed in a field controller. For EILS, the term Emulator is used because its emulation of a (NEMA) traffic controller is much less realistic than that of SILS. In the experiments described below, internal VISSIM EILS and ASC/3 Econolite controllers in SILS and HILS systems were used.

2.3.4. <u>Real-Time Systems</u>

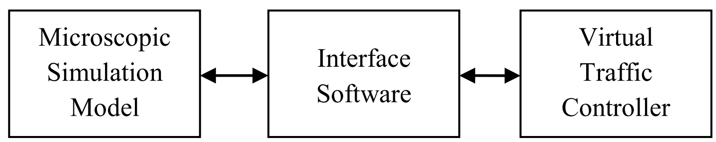
Both HILS and SILS can be considered statically-scheduled real-time systems. Real-time systems can be classified based on their ability to tolerate failures to meet deadlines to hard systems and soft systems. Hard real-time systems cannot tolerate any failures to meet deadlines. Examples of hard real-time systems are aircraft or missile flight control systems. A deadline failure in these systems could cause loss of an aircraft or a missile. Soft real-time systems can tolerate some deadline failures and still function correctly. Both HILS and SILS are examples of soft real-time systems. Here, an occasional missed deadline may affect some Measures of Effectiveness (MOE), but should not cause the simulation to fail completely. Therefore, if the HILS/SILS system is overloaded during a specific simulation time step and unable to finish its tasks on time, the subsequent scheduled time step will be disrupted and will not be initiated at the pre-scheduled time. The latency and any other faults occurring during the simulation update may negatively affect the output of the simulation.

Simulation models using EILS signal control and HILS/SILS represent two different simulation systems. In the EILS system, the signal timing control and detector call the response algorithm, which is included as part of the simulation software. On the other hand, HILS and SILS are real-time systems with additional components, which are described in the previous text. When a simulation model utilizes EILS to provide signal timings, the phase updating and detector responses have no latency, since they are all handled within the simulation model environment. However, the standard HILS implementation of the algorithms requires the integration of four different components. First, the simulation model must be synchronized to run on a real-time basis. Next, the phase and detector information needs to travel back and forth between the four components of the standard HILS system. Data flow for HILS and SILS systems is presented in Figure 2.1. Latency occurs during the generation of the data and the communication of the data between the various HILS and SILS components.

Latencies in HILS can be attributed to either software or hardware. Hardware latency usually results from five sources: USB communication, CID signal conversion, traffic controller, signal transmission, and signal propagation. Software latency most



HILS data flow



SILS data flow

FIGURE 2.1 HILS and SILS data flows.

likely results from four possible factors: simulation model, shared memory, CID Interface software, and USB Driver. Latencies in SILS are attributed to software only. The major sources of latencies in HILS are:

1. Propagation delay – the time it takes a data packet to travel between one point and another (in HILS, via the CID cable to the traffic controller).
2. Transmission delay – the delay introduced by the medium itself. The size of the data packet affects transmission delay. The Universal Serial Bus (USB) maximum packet size for Isochronous IN and OUT endpoint is 1,023 bytes. In the CID system, the maximum packet size is 73 bytes, which will not be a factor that affects the USB communication.
3. CID signal processing delay – the time that it takes each CID to convert data

from digital to analog or from analog to digital.

4. Software processing – the time that software modules take to complete their functions.

2.4. Research Methodology

2.4.1. Study Case Network

To test differences in EILS, HILS, and SILS, a 1.5-mile segment of roadway was used, from 4000 West to 5200 West, of 3500 South (SR 171) arterial in West Valley City, UT. The segment, shown in Figure 2.2, represents one of the major E-W arterials in the County. Levels of service and basic geometry are given for all intersections in Figure 2.2. All intersections have ASC/3 Econolite controllers, which were recently installed to support transit priority operations on the arterial.

A VISSIM model of the study case segment was built, calibrated, and validated based on data from the field. To calibrate the VISSIM model, timings from the field were used. These included speed limits, PM peak 15-minute turning movement counts, and

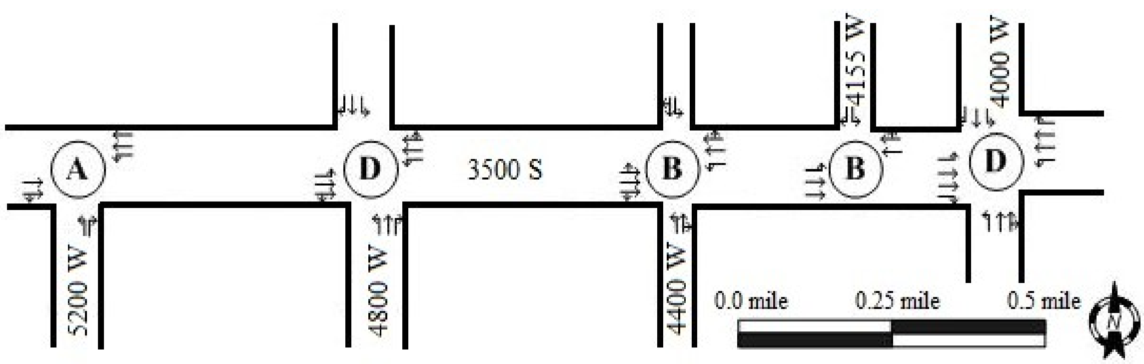


FIGURE 2.2 Study case segment of 3500 South.

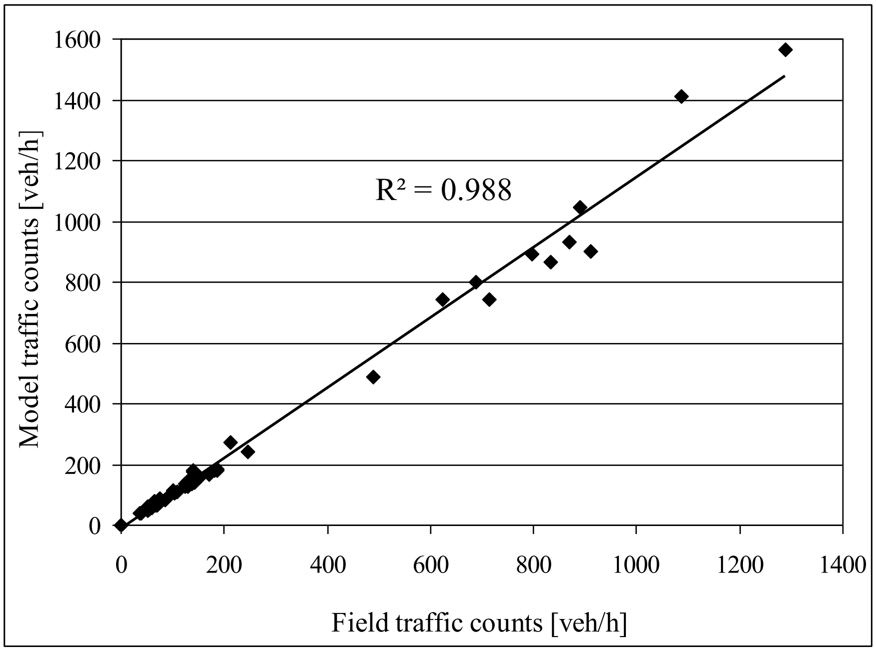
queue lengths at some intersections. To validate the model, travel times (floating car with GPS) along the arterial were measured, while recording passing times at each intersection. Figure 2.3 shows the results of the calibration and validation efforts.

2.4.2. Experimental Scenarios

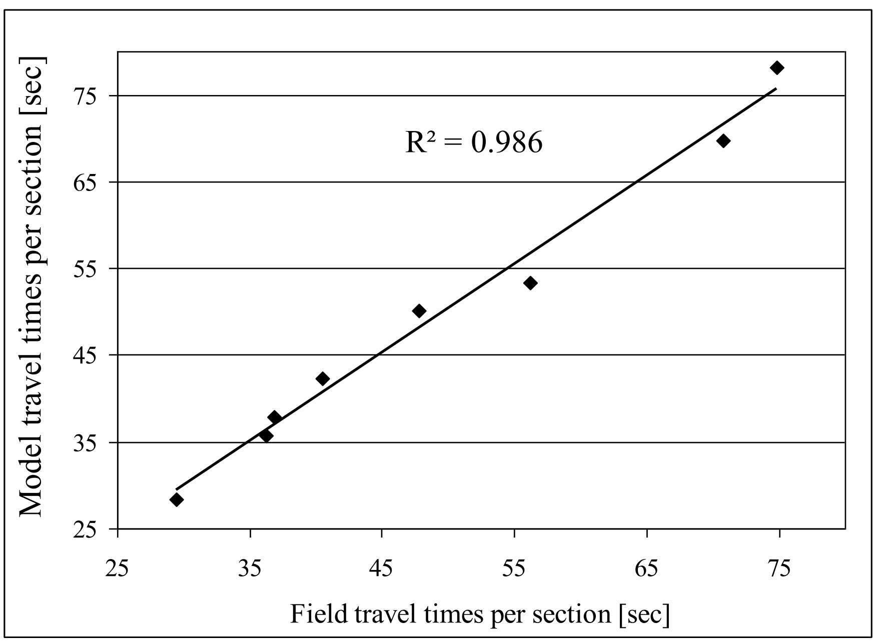
To test consistency between different ways of modeling traffic control, we tested various controllers' operational scenarios. Since EILS does not support advanced and vendor-specific features of HILS and SILS, only operations supported by EILS were tested. UDOT provided signal timing databases from the ASC/3 Econolite controllers in the field. All experiments were performed using VISSIM version 4.30-05. Both HILS and SILS used the same version of ASC/3 controller software - V2.40.04. HILS utilized the ASC/3-2100 hardware version of the controller. For EILS, a standard version of VISSIM's emulation of NEMA controllers was used.

A variety of intersections was used to test five operational scenarios. The first scenario tested operations of an isolated intersection. The second and the third scenarios tested Smooth and Max Dwell transitions, on two and three intersections, respectively. The last two scenarios tested pretimed and actuated-coordinated operations on four and five intersections, respectively. When one or more intersections was removed from the original VISSIM model, new traffic inputs were created to recreate the traffic flows observed in reality. Each reduced model was checked for consistency and validity.

To run a certain timing plan, the date and time in VISSIM were set up so that the SILS clock (which is synchronized with VISSIM) selects a corresponding timing plan. EILS was continuously synchronized with VISSIM. On the other hand, HILS had to be



a)



b)

FIGURE 2.3 Validity of the VISSIM model of 3500 South Street: a) Calibration; b) Validation.

run either at the corresponding time of day or its plan scheduler would need to be adjusted. In addition, controller and simulation model needed to be started manually at the same time to achieve their clock synchronization in HILS. Although this manual procedure does not precisely mimic synchronization of the SILS process, this was the only feasible way to start the two components at the same time.

2.5. Results

There are many ways of testing the consistency of EILS, HILS, and SILS performance and their operations. Signal timings generated by these systems were examined through the VISSIM's performance measures. Phase average green times (Table 2.1), as recorded by VISSIM, were compared to investigate whether signal timings from the three systems were identical. However, slightly different signal timings can sometimes have the same effect on traffic performance. To identify this effect, we examined the set of VISSIM network outputs. In addition to these, the changes in cycle lengths were observed during the transition periods to identify how each system performs the transitions. Finally, VISSIM's Signal Changes Protocols and Signal Changes/Detectors Records were analyzed. This analysis was crucial to explaining differences and inconsistencies in the performance of the three control systems.

The MOEs reported here represent 60-simulation-minute averages from 10 randomly seeded runs. All simulations were 60 minutes long with 15 minutes of warm-up time. Each scenario was simulated in EILS, SILS, and HILS for the same ten random seeds. HILS took exactly 1 hour and 15 minutes to finish each simulation. On the other hand, EILS and SILS took on average 5.5 and 39 minutes to complete the same

TABLE 2.1 Average Green Times (sec) for Free-Running Intersection

4000 West	**EILS**		**SILS**		**HILS**	
Signal Group	MEAN	SD	MEAN	SD	MEAN	SD
1 - EBL	6.13	0.258	5.74	0.275	5.81	0.298
2 - WBT	39.66	1.574	37.01	1.001	36.71	0.940
3 - SBL	8.85	0.794	8.32	0.573	8.39	0.674
4 - NBT	21.69	1.630	19.97	1.210	20.15	1.230
5 - WBL	11.95	0.707	11.37	0.704	11.37	0.559
6 - EBT	28.26	0.921	26.37	0.748	26.26	0.776
7 - NBL	9.59	0.785	9.00	0.581	9.08	0.737
8 - SBT	19.99	1.020	18.33	1.095	18.26	0.938

simulation, respectively.

2.5.1. Free-Running Operations – A Single Intersection

To perform a basic test of controller's "timing plan-free" operations, we selected the intersection of 4000W and 3500S, which was for this purpose "cut" from the rest of the network. The controllers in EILS, SILS, and HILS used original free-running settings from the field. To support EILS (which operates only integer values) the fractional values for some of the field controller's settings were removed. More specifically, red clearance times for certain phases were modified from 1.5 to 2 seconds. This type of adjustment was later repeated for all experimental scenarios and other settings (amber, vehicle extension, etc.).

The analysis of outputs for the free-running intersection, shown in Table 2.1, presents some differences in the way that each system reports phase greens. The phase greens for HILS and SILS are more similar than those reported by EILS.

Table 2.2 shows intersection MOEs for the three traffic control systems. Two-tail t tests for paired samples tested the null hypotheses ($\alpha = 0.05$) that all performance measures from Table 2.2 are the same for each pair of the controls. The test results show that EILS MOEs are statistically different than MOEs from any other system for six out of nine MOEs. Differences between HILS and SILS are not statistically significant for any MOE.

2.5.2. Smooth Transition – Two Intersections

To test the second scenario, Smooth transition strategy, two intersections (4400W and 4800W) were used. The purpose of this scenario was to investigate whether various

TABLE 2.2 MOEs for Free-Running Operations

Performance Measure	Statistic	EILS	SILS	HILS
Total Number of Vehicles	Mean	4010.60	4011.40	4008.80
	SD	11.46	10.79	9.85
Average Delay/Vehicle (s)	Mean	23.93 [1]	23.15	23.00
	SD	1.04	0.96	1.13
Total Delay (h)	Mean	26.66 [1]	25.79	25.61
	SD	1.16	1.10	1.29
Average Number of Stops per Vehicle	Mean	0.647	0.648	0.647
	SD	0.014	0.016	0.017
Total Number of Stops	Mean	2594.90	2598.30	2592.40
	SD	53.97	67.13	70.47
Average Stopped Delay/Vehicle (s)	Mean	14.57 [1, 2]	13.77	13.64
	SD	0.89	0.75	0.88
Total Stopped Delay (h)	Mean	16.23 [1, 2]	15.35	15.19
	SD	0.99	0.86	1.00
Average Speed (mph)	Mean	23.17 [1]	23.36	23.41
	SD	0.26	0.26	0.30
Total Travel Time (h)	Mean	106.08 [1]	105.21	105.03
	SD	1.28	1.14	1.21

[1] Value is significantly different from corresponding SILS value.

[2] Value is significantly different from corresponding HILS value.

ways of modeling traffic control make differences when transitioning between two signal timing plans. It was assumed that Shortway Offset Seeking in VISSIM EILS functions the same as Smooth Transition in the ASC/3 SILS operations (*11*). Shortway Offset Seeking in EILS runs the clock 20% slower or faster during any phase until correct offset is reached, meaning that at most 2½ cycles are needed to get back in sync (*12*). In ASC/3, Smooth Transition is accomplished by adding a maximum of 20% or subtracting a maximum of 17% of cycle length per cycle (*13*). The two intersections were running actuated-coordinated operations with 96-second cycle length for the first 30 minutes, 120-second cycle length for the rest of the simulation.

Results of the Smooth transition experiments show high similarity between the SILS and HILS average green times, although the EILS average green times are within the same range. The differences in average green times between any two traffic control models were less than one second in most cases. When network performances are observed (Table 2.3) there is no statistical significance in differences between the three ways of modeling traffic control for all but one, MOE.

However, transition logics were not identical in the experiments. Figure 2.4 shows that Shortway and Smooth transition logics worked differently, especially for the intersection of 4800W and 3500S, in which case EILS transition was inverted. Figure 2.4 also shows that all three systems at 4400W synchronized almost simultaneously, while the 4800W EILS took longer to synchronize. In spite of the differences in transitioning between cycle lengths, the VISSIM's traffic performance measures and average signal timings were unaffected.

TABLE 2.3 MOEs for Smooth Transition

Performance Measure	Statistic	EILS	SILS	HILS
Total Number of Vehicles	Mean	4042.50 [2]	4046.00	4045.60
	SD	15.68	15.08	16.85
Average Delay/Vehicle (s)	Mean	38.16	37.46	37.46
	SD	4.31	3.54	2.53
Total Delay (h)	Mean	42.86	42.10	42.10
	SD	4.85	4.04	2.89
Average Number of Stops per Vehicle	Mean	0.994	0.983	0.975
	SD	0.094	0.066	0.049
Total Number of Stops	Mean	4017.50	3977.30	3942.20
	SD	379.73	275.00	202.51
Average Stopped Delay/Vehicle (s)	Mean	25.02	24.39	24.53
	SD	2.91	2.42	1.75
Total Stopped Delay (h)	Mean	28.10	27.42	27.57
	SD	3.27	2.76	2.00
Average Speed (mph)	Mean	25.21	25.33	25.32
	SD	0.81	0.68	0.49
Total Travel Time (h)	Mean	152.26	151.54	151.50
	SD	4.97	4.57	3.39
Total Distance Travelled (mi)	Mean	3834.51	3835.51	3834.04
	SD	23.98	22.23	22.88

[1] Value is significantly different from corresponding SILS value.

[2] Value is significantly different from corresponding HILS value.

2.5.3. Max Dwell Transition – Three Intersections

Another operational strategy that was interesting for comparison (because it was implementable in all three systems) was Max Dwell transition. This strategy was tested at three intersections on 3500S: 4400W, 4800W, and 5200W. Max Dwell transition adjusts the start of a cycle by extending the green time of the coordinated phase for a limited amount of time in each cycle (*11*). As appropriate, settings for Max Dwell times were adjusted in VISSIM EILS and ASC/3 SILS and HILS to 20 seconds. As with the previous experiment, the transition from 96-second to 120-second cycle length was executed at the 30th minute of the simulation time, for all three intersections.

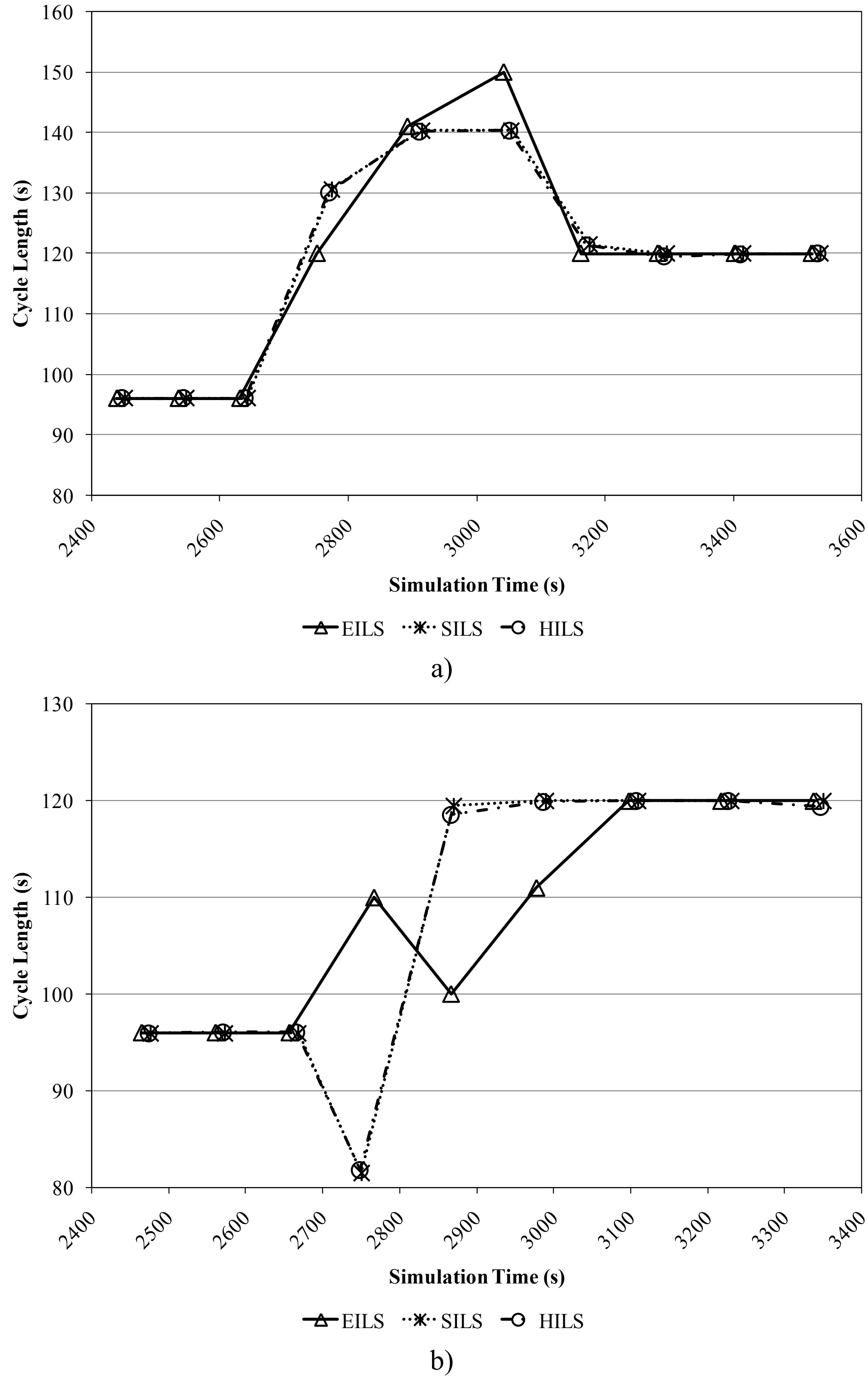


FIGURE 2.4 Cycle lengths during the Smooth transition: a) 4400 W; b) 4800 W.

The Max Dwell transition experiment yielded some unexpected results. Analysis of green times does not show that differences in their averages are practically significant. Here, we refer to practical significance if the difference is large enough to be observed as a significant difference even without statistical tests (e.g. differences in delay of HILS and others in Table 2.4). However, Table 2.4 reveals differences which are significant, statistically and practically. Two-tailed t tests show that most of the differences in MOEs between SILS and EILS are not statistically significant. All other differences show the opposite trend. Figure 2.5 provides additional information about these differences; it shows that of all three systems, HILS was consistently the first one to get back in sync during transition for any of the three intersections. For this reason, when in transition HILS does not run 120-second cycle as long as the other two systems, which evidently reduces overall delay and improves traffic performance in the three-intersection network.

2.5.4. Pretimed Operations – Four Intersections

A segment with four intersections, from 4000W to 4800W, was selected to test the consistency of pretimed controller operations. For all three systems, the actual signal timings from the field were modified to operate with a pretimed control. The motivation for this experiment was investigation of differences in the systems' performances in the least responsive traffic control environment. When pretimed control is selected in ASC/3 controllers, the ASC/3 automatically calls all pedestrian signal groups, with pedestrian phases. Pedestrian signal timings in VISSIM's EILS needed to be adjusted to mimic the pedestrian operations from ASC/3 controllers.

The analysis of the pretimed operations at the four intersections shows no

TABLE 2.4 MOEs for Max Dwell Transition

Performance Measure	Statistic	EILS	SILS	HILS
Total Number of Vehicles	Mean	4279.60 [1, 2]	4274.80 [2]	4265.70
	SD	10.29	10.38	13.76
Average Delay/Vehicle (s)	Mean	43.10 [2]	41.80 [2]	37.87
	SD	6.44	4.72	4.06
Total Delay (h)	Mean	51.24 [2]	49.64 [2]	44.88
	SD	7.67	5.62	4.83
Average Number of Stops per Vehicle	Mean	1.159 [2]	1.126 [2]	1.050
	SD	0.143	0.101	0.076
Total Number of Stops	Mean	4960.30 [2]	4811.80 [2]	4478.80
	SD	613.88	435.58	326.33
Average Stopped Delay/Vehicle (s)	Mean	26.81 [2]	26.37 [2]	23.78
	SD	3.81	2.84	2.75
Total Stopped Delay (h)	Mean	31.88 [2]	31.32 [2]	28.17
	SD	4.54	3.38	3.27
Average Speed (mph)	Mean	25.67 [2]	25.87 [2]	26.51
	SD	1.01	0.75	0.67
Total Travel Time (h)	Mean	194.36 [2]	192.65 [2]	187.68
	SD	8.21	5.84	5.39
Total Distance Travelled (mi)	Mean	4982.79 [2]	4979.86 [2]	4972.47
	SD	33.62	27.98	33.37

[1] Value is significantly different from corresponding SILS value.

[2] Value is significantly different from corresponding HILS value.

difference in average green times between EILS and SILS. There is a very small difference between any of these two systems and HILS. The difference in HILS average green times can be attributed to the latency of the HILS system. Table 2.5 gives a comparison of the network MOEs for the pretimed experiments. With the exception of two cases, when EILS is different from SILS, there was no statistically significant difference in MOEs between any pair of traffic control systems.

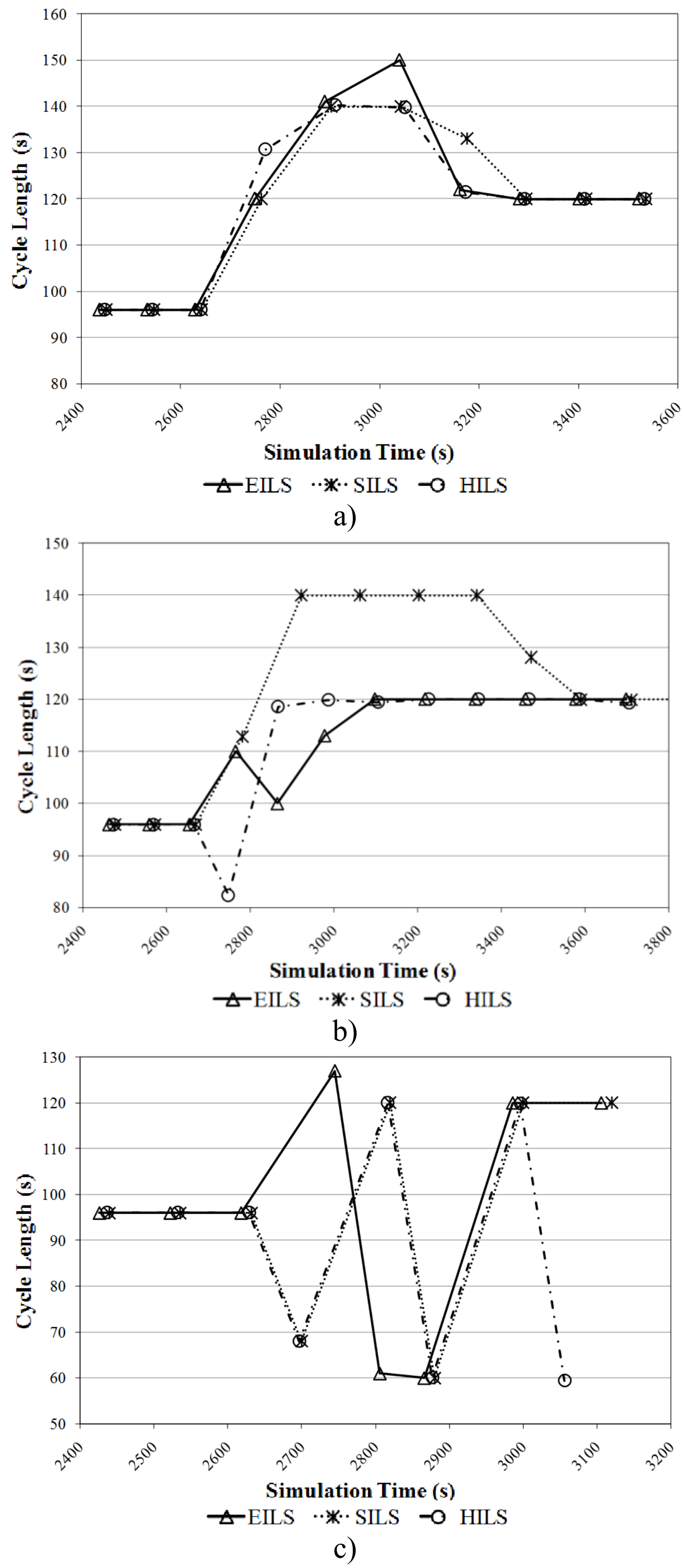


FIGURE 2.5 Cycle lengths during Max Dwell transition: a) 4400 W; b) 4800 W; c) 5200 W.

TABLE 2.5 MOEs for Pretimed Intersections

Performance Measure	Statistic	EILS	SILS	HILS
Total Number of Vehicles	Mean	6041.40	6037.30	6038.70
	SD	17.32	21.39	20.48
Average Delay/Vehicle (s)	Mean	52.79	53.15	53.05
	SD	0.73	0.95	1.17
Total Delay (h)	Mean	88.59	89.13	88.99
	SD	1.20	1.67	2.04
Average Number of Stops per Vehicle	Mean	1.280 [1]	1.289	1.285
	SD	0.011	0.014	0.021
Total Number of Stops	Mean	7733.10 [1]	7780.10	7755.80
	SD	69.70	94.66	133.39
Average Stopped Delay/Vehicle (s)	Mean	34.34	34.57	34.47
	SD	0.57	0.67	0.78
Total Stopped Delay (h)	Mean	57.62	57.98	57.83
	SD	0.92	1.13	1.37
Average Speed (mph)	Mean	23.22	23.18	23.20
	SD	0.08	0.12	0.13
Total Travel Time (h)	Mean	305.69	306.28	306.19
	SD	1.54	2.22	2.61
Total Distance Travelled (mi)	Mean	7098.01	7100.10	7107.97
	SD	37.36	44.40	45.48

[1] Value is significantly different from corresponding SILS value.

[2] Value is significantly different from corresponding HILS value.

2.5.5. Actuated-Coordinated Operations – Five Intersections

Finally, motivation for the fifth experiment was investigation of the basic actuated-coordinated operations. All five intersections from the study network (4000W to 5200W) were used to evaluate the operations of the three control systems when running actuated- coordinated operations. The controller settings were the same as those utilized in the field, except for aforementioned adjustments in fractional signal parameters.

Average phase green times for each intersection again do not reveal enough information – each system looks very similar to the other two. Average MOEs presented in Table 2.6 show that, similarly to the free-running operations, EILS is almost always significantly different from HILS and SILS. However, this time, EILS yields better MOEs than the other two systems.

2.6. Discussion

The analyses of second-by-second signal and detector changes were performed for each of the five experiments to determine potential causes for the observed differences in operations of the three traffic control systems. Three major reasons for

TABLE 2.6 MOEs for Actuated-Coordinated Intersections

Performance Measure	Statistic	EILS	SILS	HILS
Total Number of Vehicles	Mean	6272.60	6273.90	6271.50
	SD	15.27	17.80	12.32
Average Delay/Vehicle (s)	Mean	46.82 [1, 2]	49.51	49.08
	SD	1.01	1.07	1.43
Total Delay (h)	Mean	81.57 [1, 2]	86.28	85.50
	SD	1.78	1.94	2.47
Average Number of Stops per Vehicle	Mean	1.238 [1, 2]	1.268	1.269
	SD	0.022	0.022	0.028
Total Number of Stops	Mean	7768.10 [1, 2]	7953.80	7958.50
	SD	135.24	150.56	172.73
Average Stopped Delay/Vehicle (s)	Mean	29.31 [1, 2]	31.77	31.52
	SD	0.85	0.86	1.10
Total Stopped Delay (h)	Mean	51.07 [1, 2]	55.37	54.92
	SD	1.49	1.54	1.91
Average Speed (mph)	Mean	24.83 [1, 2]	24.48	24.53
	SD	0.15	0.13	0.19
Total Travel Time (h)	Mean	332.77 [1, 2]	337.39	336.50
	SD	1.97	2.35	2.62
Total Distance Travelled (mi)	Mean	8263.43 [1]	8259.53	8254.80
	SD	26.84	26.19	22.58

[1] Value is significantly different from corresponding SILS value.

[2] Value is significantly different from corresponding HILS value.

discrepancies in the operations and generated VISSIM's MOEs were identified:

1. Noticeable differences were observed in the ways that EILS and SILS and HILS react on detector actuations. EILS, which works on a 1 Hz controllers' frequency, has lower sensitivity of detector actuations than SILS and HILS, which work on 10 Hz controller's frequencies. In free-running operations, the consequence of this small delay in reaction will usually cause slightly worse EILS performance than those from the SILS and HILS.

2. The three systems experienced different startup processes. In EILS, start of the controllers is well synchronized with the beginning of simulation. Actual signal timings for each intersection start according to a provided input (e.g. starting phases and offsets). No significant initial delay between a simulator and a traffic control generator was observed and there was no need for subsequent adjustments. In SILS, the controller starts simultaneously with the simulation, but also requires an initialization process (e.g. placing calls on different phases) which can cause a small delay. Usually, the SILS controller needed to adjust signal timings within the first few cycles to synchronize with signal timings from a time-of-day plan. In HILS, this initialization delay was even longer because the HILS controller needed to be powered up at the start of the simulation, and then go through the initialization process similar to SILS. These small delays in controllers' initializations will often cause different signal timing sequences for the three systems. These differences in the signal timing sequence will often have some impact on overall system performance. For example, various signal timing sequences can cause that transition events (e.g. Max Dwell) for the three systems occur at different times throughout coordinated phases. In such a case, depending on when the call for transition

event occurs with respect to cycle time, EILS may find that it is better to extend the cycle length while SILS and HILS may decide the opposite. Such different behavior is observed in experiments with both transition strategies. Corresponding issues related to the initialization processes (and subsequent variations in the signal timing sequences) were sources for discrepancies in all experiments performed in this study.

3. There is latency in SILS and HILS systems. For example, built-in detector actuations in SILS and HILS are 0.1 and 0.2 seconds, respectively. The latencies for other events within SILS and HILS systems may be different and higher than those reported for detector actuations. The sources of latency in real-time systems are described earlier in the text.

2.7. Conclusions

This study investigated three methods for connecting traffic controllers with a traffic microsimulator. A 5-intersection VISSIM model was used to test the following traffic control operations: free-running, Shortway (Smooth) transition, Max Dwell transition, pretimed, and actuated-coordinated. Based on average traffic metrics and signal setting outputs, the following was concluded:

1. The HILS and SILS approaches generate more realistic signal timings than EILS. The EILS inability to work at 10 Hz frequency impacts vehicle actuations and can introduce delay in free-running operations.

2. EILS, HILS, and SILS initialization processes can have a significant impact on sequence of the signal timings implemented by each concept. Initialization is shortest for EILS and the longest for HILS, with SILS in the middle. The difference in sequence,

caused by initialization, introduces randomness in processes when a single event (e.g. transition) places a call on signal operations. In such a situation, it is quite difficult to draw any conclusions about how various systems handle certain events. It seems that most of the differences observed should not be attributed to various ways of applying the same (NEMA) basic logic but to randomness caused by the initialization process.

3. Overall, SILS and HILS performed in a very similar way whereas EILS occasionally performed differently than the other two. Measured traffic metrics show that operational differences were rarely significant, although statistical differences may be present due to small variations of VISSIM's outputs.

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CHAPTER 3

EVALUATION OF TRANSIT SIGNAL PRIORITY IN RBC AND ASC/3 SOFTWARE-IN-THE-LOOP SIMULATION ENVIRONMENT

From Zlatkovic, M., P. Martin, and A. Stevanovic. Evaluation of Transit Signal Priority in RBC and ASC/3 Software-in-the-Loop Simulation Environment. Presented at the 89th Annual Meeting of the Transportation Research Board, January 2010, Washington, D.C.

3.1. Abstract

In recent years, traffic simulation software packages have become powerful tools in developing and studying the impacts of different traffic scenarios. This was formerly impossible, or hardly achievable, in the field. This study presents a use of the VISSIM traffic simulation software in evaluating Transit Signal Priority (TSP) strategies using two types of emulated signal controllers. The first one is the Ring Barrier Controller (RBC), the most sophisticated traffic control emulator presented in the newly developed VISSIM versions. The other one is the Advanced System Controller series 3 (ASC/3) Software-in-the-Loop (SIL) traffic controller which runs from the same code base as the field ASC/3 controllers, thus enabling a high fidelity simulation of signal operations. The two signal control types were evaluated and compared for their abilities to provide TSP, and the impacts TSP causes on the overall traffic. The results have shown benefits of the evaluated traffic controllers within VISSIM in simulating TSP strategies, despite some differences and limitations with controller settings. On the test-case network, the results have shown reductions in transit travel times from 4 to 7%, which are assigned to TSP. Impacts on general purpose traffic along the main corridor were not observed, while TSP causes an increase in delays on side streets of approximately 1%, and an increase in the number of stops of approximately 0.5%. The results also showed some differences in the way the two controller types implement TSP strategies.

3.2. Introduction

Most of the current traffic microsimulation packages, which are used to simulate traffic operations on urban arterials, consist of two components: simulator of traffic flows and generator of traffic signal states. The first models of traffic simulation and traffic control used internal traffic control generators, which simply changed traffic signal states at predetermined intervals. This concept was later enhanced to provide actuated traffic control operations within the internal microsimulation controller, also known as Emulator-in-the-Loop (EIL). The real enhancements within the traffic control came when external real-world controllers were coupled with microsimulation through a concept called Hardware-in-the-Loop simulation (HIL) (*1*). This was a significant advance in traffic simulation, but it also had some disadvantages, such as an inability to run faster or slower than real time, no synchronization between controllers and the computer's clocks, and separate controller hardware required for each intersection (*2*). Major HIL disadvantages were addressed when Software-in-the-Loop (SIL) was developed. The SIL suite provides virtual controllers (controller software) that run from the same code base as the actual hardware controllers. The best known SIL applications developed in the past were Siemens' NextPhase that linked to CORSIM and VISSIM (*2*), and the Econolite's Advanced System Controller series 3 (ASC/3) which connects to VISSIM (the only SIL commercially available). The SIL integration provides many virtual ASC/3 controllers capable of running signal timings faster or slower than real time. The ASC/3 controllers in SIL are NTCIP (National Transportation Communications for ITS Protocol) compliant, and they run from the same code base as the ASC/3 hardware controllers, which make them nearly identical (*3*).

Incorporating Transit Signal Priority (TSP) in simulation models has always been a challenging task. Many of the traffic simulation models available on the market can be used to simulate TSP to a certain level, which depends on the abilities of the models. The most significant limitations include the ability to simulate different characteristics of transit systems, and signal control logic and detection. When it comes to TSP logic in signal controllers, most of the available models demand developing a special programming module, which will control TSP. This process can create problems during the evaluation, because there is no guarantee that the module will perform the same as the real-world controller. Some of the traffic control emulators (e.g. in VISSIM) incorporate TSP settings, but only up to a certain level (such as NEMA control emulators). With an increased use of traffic simulation for estimating TSP, this option has become a very important part, so the vendors are working on developing more sophisticated traffic control modules. The VISSIM developers have made the major contribution to the field, through the development of the Ring Barrier Controller (RBC) emulators and ASC/3 SIL controllers that incorporate complex TSP strategies. Some of the studies that use VISSIM in evaluating TSP strategies can be found in (*4, 5, 6, 7*). These studies use either NEMA controllers, or specially developed programming modules for TSP implementation.

This study investigates abilities of EIL and SIL software in providing TSP. VISSIM microsimulation, coupled with RBC EIL and ASC/3 SIL software, is used to test TSP on a case-study network along 3500 South Street in Salt Lake County, where recently a Bus Rapid Transit (BRT) line was introduced. The goal of the study is to assess the operational implementation of TSP strategies and to compare the abilities of the two controller types (referred to as simulation environments), and their strengths and weaknesses concerning TSP in simulation. The objectives of the study are to evaluate TSP strategies and their benefits and impacts on transit systems and general purpose traffic, in both simulation environments.

3.3. Characteristics of RBC and ASC/3 Controllers

3.3.1. RBC Controller

The RBC is a traffic control emulator integrated into VISSIM and it provides a significant enhancement over the previously used NEMA traffic emulators (*8*). The RBC is NTCIP compliant and supports industry standards for traffic controllers. It is intended to mimic any type of traffic controllers used in North America. The software is mainly based on the D4 ("The Fourth Dimension") traffic controller software, which is recently developed for the 2070 Advanced Transportation Controllers (ATC) (*9, 10*). It supports sixteen signal groups (with complex settings for each group), a four ring structure with up to eight barriers, signal group overlaps, pedestrian signal groups, eight transit signal groups, extent detector features, eight coordination patterns, preemption, and TSP.

3.3.2. ASC/3 Controller

The ASC/3 controller is the last series of Advanced System Controllers offered by Econolite. It combines the requirements of NEMA TS2 and NTCIP, and satisfies all industry and ISO (International Organization for Standardization) quality standards (*11*). It offers sophisticated control features (sixteen phases, eight configurable concurrent groups in four timing rings, all standard NEMA TS1, TS2 and NTCIP functions, sixteen timed vehicle overlaps, sixteen pedestrian phases, etc.), coordination features (120 coordination patterns, 120 split plans, fixed or floating force offs), preemption and TSP features, extent detector features, etc. It is also able to support very complex signal timing settings through Logic Processors, which can emulate external logic that is not included in the default settings. A total of 200 logic commands is available in the controller, and these commands can control and combine all the controller features.

The ASC/3 SIL version of the controller software has been specifically configured to operate as virtual controller within the VISSIM environment (*12*). This allows full ASC/3 controller functionality to be used during simulations under VISSIM. Another benefit of the ASC/3 SIL is that it can run at ten times normal speed during simulation, which greatly reduces the time needed to test a scenario in VISSIM. The ASC/3 SIL is comprised of the Data Manager (or Database Editor), Traffic Control Kernel, Controller Front Panel Simulator, and VISSIM DLL Interface components.

3.4. TSP Simulation Settings

Traffic software developers have been making efforts to incorporate TSP strategies into the traffic controller emulators. Some of the early implementations only allowed simple TSP strategies, or a user had to create a special programming module to control TSP. VISSIM simulation software has incorporated some simple TSP strategies with NEMA controllers. However, due to its simplicity, the use of NEMA TSP was limited for research purposes. Major progress in VISSIM came with the development of RBC controllers, which were much more sophisticated than the NEMA controllers and incorporated many additional options, including comprehensive TSP settings. Also, with the new VISSIM versions came the new ASC/3 SIL versions, with included TSP options. As for all other settings in ASC/3 SIL, the TSP runs from the same code base as the field ASC/3 controllers. The following section gives a description of TSP options and activation in both RBC and ASC/3 SIL controllers.

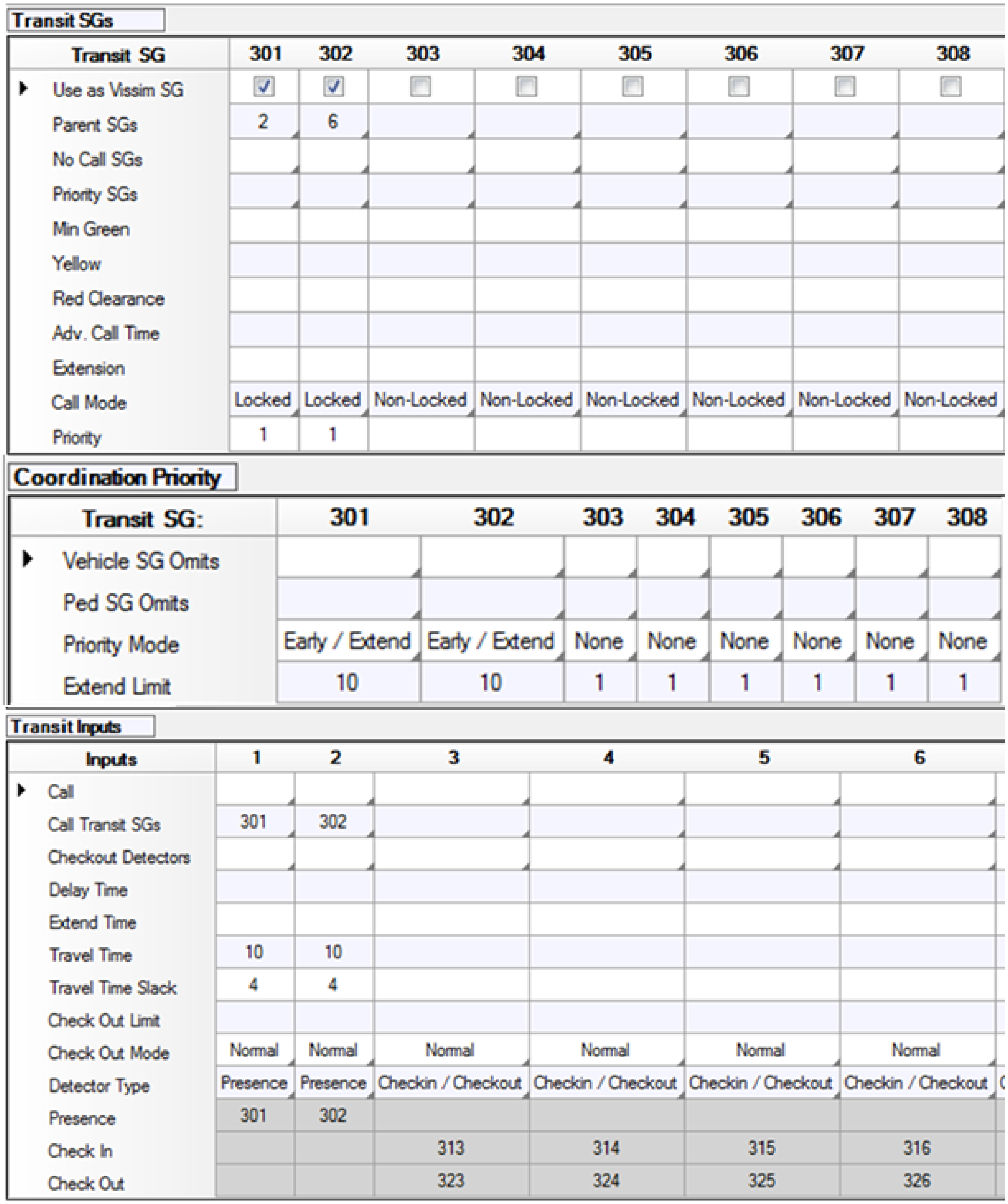
3.4.1. TSP Settings in RBC Controllers

An RBC controller allows TSP settings for up to eight signal groups. Each TSP signal group is tied to a vehicular signal group, defined as the parent signal group (*8*). Priority service for any transit signal group can be enabled. When a transit signal group operates in a priority mode, signal groups that conflict with the parent signal groups of a transit signal group can be abbreviated or omitted based on the defined parameters. The controller will attempt to adjust its operation so that it can have the transit signal group green by the time the vehicle arrives at the intersection. When the signal controller is recovering from a TSP operation, the recovery green is proportional to all upcoming signal groups. It covers all signal groups following the TSP signal groups up through the coordinated signal groups. The proportional recovery green to each signal group is computed as a percentage between the minimum split (based on minimum green) up to the full split.

RBC controllers introduce a user friendly Graphical User Interface (GUI), where the TSP settings are defined step by step: transit signal groups, TSP parameters in a coordinated or free running mode, and TSP detectors and inputs. Figure 3.1 shows the RBC GUI for TSP settings.

3.4.2. TSP Settings in ASC/3 SIL Controllers

The TSP option is introduced within the new ASC/3 SIL version. Same as for all other signal settings, TSP in ASC/3 SIL runs from the same code base as field controllers. The ASC/3 SIL GUI is similar to the controller's interface, making it much easier for practitioners and trainees to handle the software and learn its operations. Figure



Transit SGs

Transit SG	301	302	303	304	305	306	307	308
Use as Vissim SG	[x]	[x]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Parent SGs	2	6						
No Call SGs								
Priority SGs								
Min Green								
Yellow								
Red Clearance								
Adv. Call Time								
Extension								
Call Mode	Locked	Locked	Non-Locked	Non-Locked	Non-Locked	Non-Locked	Non-Locked	Non-Locked
Priority	1	1						

Coordination Priority

Transit SG:	301	302	303	304	305	306	307	308
Vehicle SG Omits								
Ped SG Omits								
Priority Mode	Early / Extend	Early / Extend	None	None	None	None	None	None
Extend Limit	10	10	1	1	1	1	1	1

Transit Inputs

Inputs	1	2	3	4	5	6
Call						
Call Transit SGs	301	302				
Checkout Detectors						
Delay Time						
Extend Time						
Travel Time	10	10				
Travel Time Slack	4	4				
Check Out Limit						
Check Out Mode	Normal	Normal	Normal	Normal	Normal	Normal
Detector Type	Presence	Presence	Checkin / Checkout	Checkin / Checkout	Checkin / Checkout	Checkin / Checkout
Presence	301	302				
Check In			313	314	315	316
Check Out			323	324	325	326

FIGURE 3.1 Graphical User Interface for TSP settings in RBC.

3.2 shows ASC/3 SIL GUI for TSP settings.

The software supports up to six TSP plans, where each plan is linked to a specific TSP input. This way any of the six allowed TSP inputs can be enabled or disabled and specific options for each plan can be set. The connection between VISSIM TSP detectors and ASC/3 SIL TSP settings is established through a separate detector mapping file in VISSIM.

During the programming process, TSP signal phases and the phases that will be

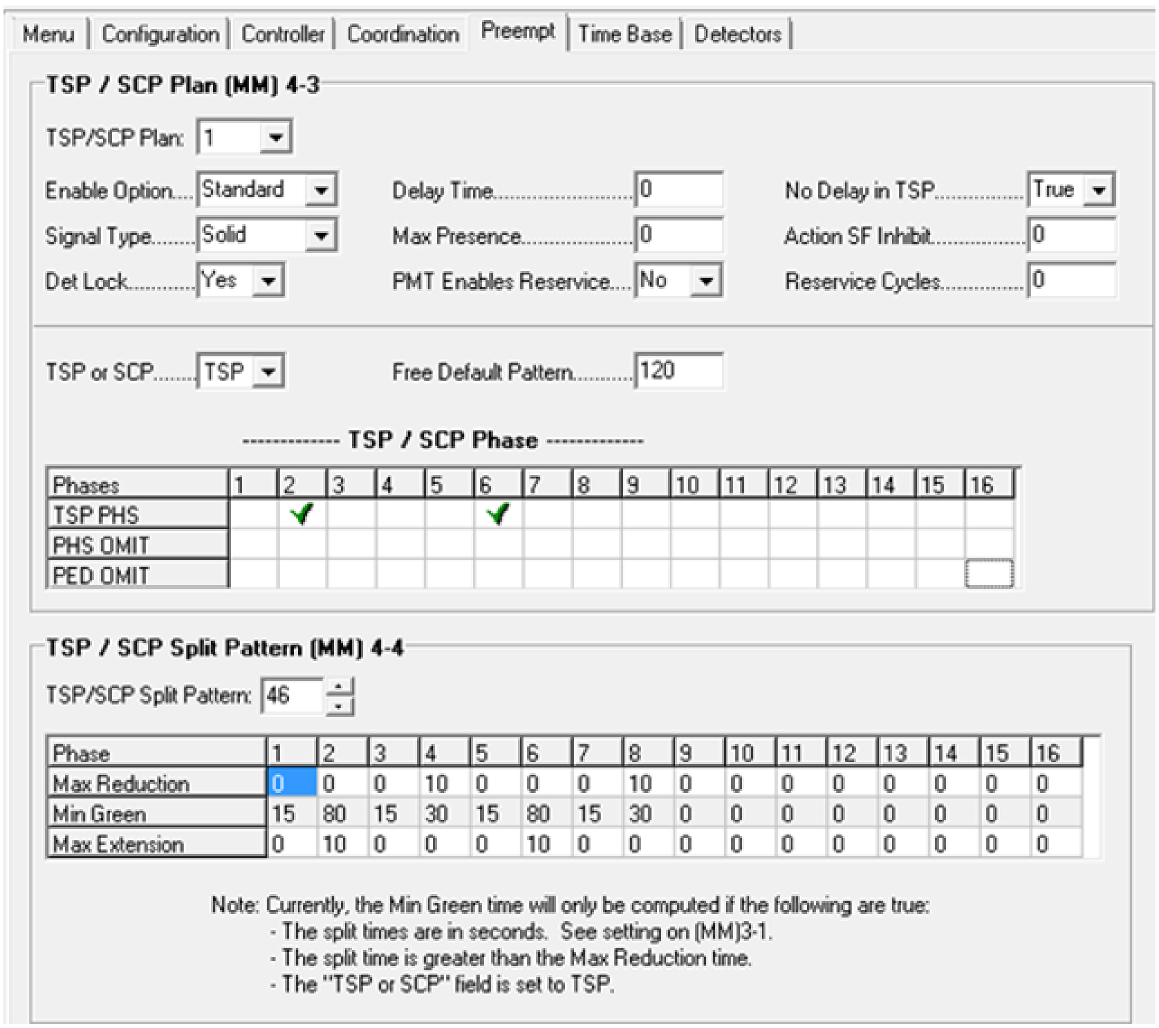


FIGURE 3.2 Graphical User Interface for ASC/3 SIL TSP settings.

omitted during a TSP call, the green reduction/green extension parameters for each phase separately and for the specific split pattern are defined. In general, an ASC/3 controller supports up to 120 split patterns, and each of them can be linked to a TSP pattern. When TSP is activated, the controller will switch from the coordinated pattern to the TSP pattern (*13*).

3.4.3. Differences in TSP Implementation

Both controllers enable comprehensive Green Extension/Early Green strategies. The major difference in TSP implementation is in the way the controller will abbreviate conflicting signal groups after a TSP call. RBC automatically abbreviates and redistributes green times among all conflicting phases proportionally to their splits, within the range between the minimum and the maximum split. For ASC/3 SIL, this option is completely user defined, which means that the user defines which phases will be abbreviated and how much (see Figure 3.2). A graphical representation of Green Extension strategies in RBC and ASC/3 controllers is given in Figure 3.3. In this example, signal groups 2 and 6 are TSP groups, and for ASC/3 SIL only signal groups 4 and 8 can be abbreviated. The Figure shows a different redistribution of recovery green times among the conflicting signal groups in RBC and ASC/3 SIL. The Early Green strategy implementation is similar, only in this case the green time redistribution will occur prior to the TSP signal groups, in order to enable an earlier start.

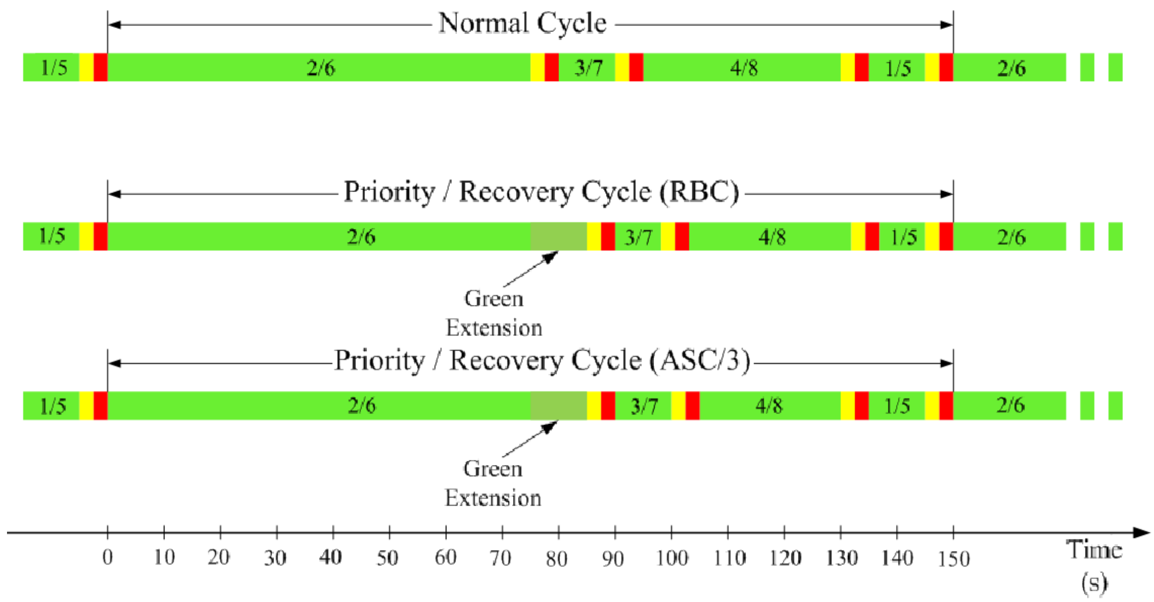


FIGURE 3.3 Green Extension strategies in RBC and ASC/3 SIL.

3.5. Simulation Test-Network Model

For the purpose of the study, a corridor along 3500 South Street in Salt Lake County is chosen as a case-study network. 3500 South is a major East-West arterial and one of the busiest transit corridors, which is the main reason it was chosen for the implementation of the first BRT line, supported by TSP.

The simulation network represents the busiest section of the corridor, from 2700 West to 5600 West Street with a small digression from 2700 West to 2820 West. The modeled section is four miles long with 13 signalized intersections (Figure 3.4), which all operate on coordinated-actuated traffic control (except intersection 3650 S and 2700 W, which operates in a free running mode). The Level of Service (LOS) at intersections along the selected corridor varies significantly.

The case-study network has been modeled in a VISSIM simulation model, with

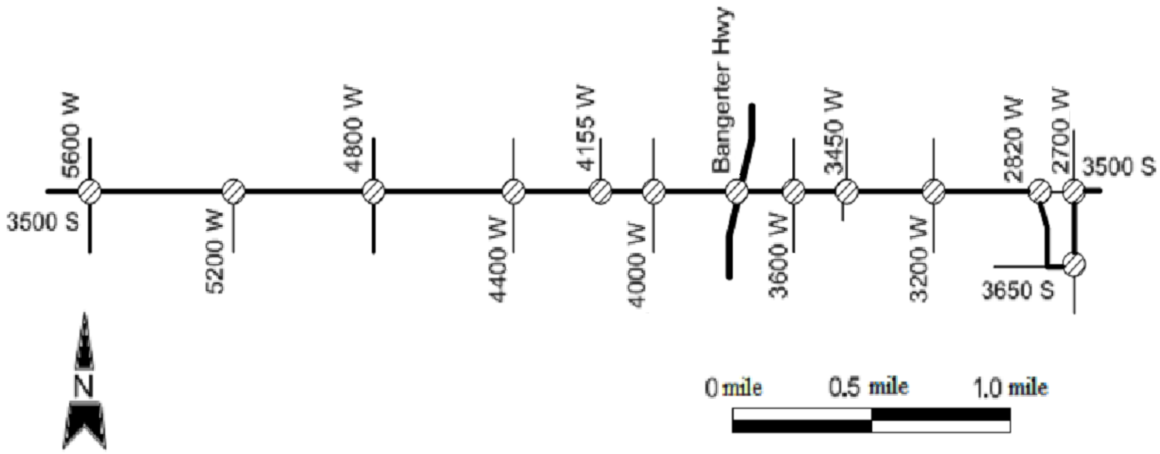


FIGURE 3.4 Study corridor.

existing network geometry, traffic volumes, turning movements at intersections, signal timing data, and transit operations (transit lines along the corridor, the regular bus line RT 35 and the BRT line 35M) for the PM peak period from 4:00 PM to 6:00 PM. The same model was used with RBC and ASC/3 settings. The data coded in the model were based on real data collected either in the field or from relevant transportation agencies, such as Utah Department of Transportation (UDOT) and Utah Transit Authority (UTA).

3.5.1. Calibration and Validation of the 3500 South VISSIM Model

Traffic movements for each signalized intersection were used to calibrate traffic operations in the model. Most of the field traffic counts were collected in 2006, with some exceptions from 2007 and 2008. VISSIM was coded to collect the traffic counts for each movement, as collected in the field. Few traffic flows needed to be adjusted to account for unbalanced traffic counts between some of the intersections. The procedure was performed until a high correlation between the field counts and the data from the simulation was achieved. In both simulation environments, the R-square value between the two data sets was approximately 0.95.

To validate the model, car travel times from the field were compared with those from the model. For this purpose, the studied corridor of 3500 South was divided into 22 smaller segments (11 in each direction) – one between each pair of signalized intersections. PM peak travel times for each segment were measured in the field by using GPS and the floating-car technique. Corresponding travel time measurement points were set in VISSIM. The data from the simulations were averaged from ten simulation runs over a 2-hour peak period, in both RBC and ASC/3 simulation environments. The average R-square value for correlation between the travel times from the field and those from the simulation was close to 0.97 in RBC, and 0.94 in ASC/3.

3.5.2. Simulation Scenarios

The purpose of the study is to evaluate and compare TSP strategies in two simulation environments. In order to achieve that purpose, two simulation scenarios were introduced in each simulation environment: a No TSP scenario and a TSP scenario. In the No TSP scenario, the TSP option is disabled and all intersections operate on the defined PM peak coordinated patterns. In the TSP scenario, TSP is enabled for BRT vehicles only on the following ten intersections: 2700W (westbound left turns only), 3200W, 3450W, 3600W, 4000W, 4155W, 4400W, 4800W, 5200W and 5600W, eastbound and westbound through movements.

In the TSP scenarios, two unconditional TSP strategies are implemented, green extension and red truncation. The values for green extension and red truncation are set to

10 seconds according to the field settings, where none of the conflicting vehicle or pedestrian phases can be omitted. A mismatch between the two controller types appeared when these parameters were set: for the ASC/3 SIL controllers, only the conflicting northbound and southbound through movements could be truncated, according to the field settings, while the RBC controllers did not have that option, but all the conflicting phases were truncated proportional to the duration of the splits.

The analysis compares the obtained results in multiple ways in order to recognize the differences of the two controller types and the way they provide TSP. The two simulation scenarios should provide enough data about traffic and transit operations before and after the TSP implementation in both simulation environments, thus allowing an estimation of TSP strategies and their impacts in both cases and recognizing differences between the two controller types.

3.6. Results

The results, provided in this section for each scenario and each simulation environment, are averaged from ten simulation runs with different random seeds, where the same sequence of random seeds was used in both simulation environments. The main results observed and analyzed are concerning travel times (vehicular and transit) along the main corridor, and delays, stopped delays, and number of stops per vehicle on minor conflicting intersection approaches. These results are aimed to show the benefits of the TSP strategies for BRT vehicles, and impacts on minor intersection approaches. These results allowed a comparative evaluation of the two controller types.

3.6.1. Vehicular Travel Times along the Main Corridor

The analysis of vehicular travel times along the main corridor has two objectives:

1. To compare how these travel times differ based on the controller type that is used within the No TSP scenarios.

2. To evaluate impacts of the TSP implementation on traffic operations along the main corridor, in both simulation environments.

Vehicular travel times along the defined segments from the ten randomly seeded runs from within the RBC and ASC/3 SIL in both scenarios are averaged and presented in Table 3.1. Two-tail t tests for paired samples are used to test the null hypotheses ($\alpha = 0.05$) that these travel times are the same for the two controller types. The segments where the statistical difference is observed are marked.

The differences in travel times are mostly present on segments and intersections with heavier traffic. This is especially emphasized in the westbound direction, because the majority of the traffic in the PM peak period is directed westbound, creating heavier traffic. This is also the reason for longer travel times in the westbound direction. The difference in total travel times along the corridor in the westbound direction within the two simulation environments is insignificant, while in the eastbound direction, RBC recorded lower travel times than ASC/3 SIL. In general, the TSP implementation does not result in significant impacts on vehicular travel times along the main corridor. However, these travel times are more impacted within the RBC simulation environment, especially in the eastbound direction, where the travel times are increased approximately 2.8%.

TABLE 3.1 Vehicular Travel Times along the Main Corridor

		Average Vehicular Travel Times (s)			
		RBC		ASC/3 SIL	
Direction	Segment	No TSP	TSP	No TSP	TSP
EASTBOUND	5600W-5200W	57.9	57.2	58.5	57.8
	5200W-4800W	72.5	69.0*	73.4	72.7
	4800W-4400W	41.2*	41.3*	42.9	42.9
	4400W-4155W	42.6	42.4	42.3	42.3
	4155W-4000W	39.1*	38.1	38.2	37.5
	4000W-Bangerter	72.0	72.6	74.4	73.9
	Bangerter-3600W	20.8	20.9	20.7	20.8
	3600W-3450W	19.8	19.8	19.8	19.8
	3450W-3200W	55.7	57.3*	55.7	55.7
	3200W-2820W	57.5	63.9	58.7	60.6
	2820W-2700W	59.4	70.8	66.7	69.6
WESTBOUND	2700W-2820W	16.1	16.0	16.0	15.9
	2820W-3200W	59.2*	60.1*	59.7	59.3
	3200W-3450W	46.9	47.3*	46.2	46.0
	3450W-3600W	44.8	45.0	45.1	45.3
	3600W-Bangerter	64.4*	65.7*	71.7	71.3
	Bangerter-4000W	30.4	29.9*	30.6	30.6
	4000W-4155W	28.1	27.9	28.4	28.1
	4155W-4400W	43.9*	43.5*	44.5	44.6
	4400W-4800W	67.7*	67.2*	69.4	68.9
	4800W-5200W	53.6*	53.4*	54.7	54.4
	5200W-5600W	117.1*	119.9*	104.8	106.3
TOTAL	EASTBOUND	538.5	553.3	551.3	553.6
	WESTBOUND	572.2	575.9	571.1	570.7

* Travel time in RBC shows a statistically significant difference from the corresponding travel time in ASC/3 SIL simulation environment

3.6.2. Transit Travel Times

The aim of TSP is to facilitate movements of transit vehicles through signalized intersections, thus reducing the transit travel time. The major benefits of the TSP implementation can be assessed by analyzing transit travel times. Table 3.2 shows a comparative evaluation of the BRT line, in BRT No TSP and BRT TSP scenarios, for both simulation environments. The results are averaged from all trips and ten simulation runs. In general, transit travel times for the No TSP scenarios are lower within the ASC/3 SIL simulation environment. This can also point out to the better progression characteristics of ASC/3 SIL.

However, according to the results, the TSP strategies are more effective within the RBC environment. The implementation of TSP in RBC can decrease BRT travel times approximately 3.3% in the eastbound direction and 7% in the westbound direction, compared to the BRT travel times in the No TSP scenario. For ASC/3 SIL, the implementation of TSP can decrease BRT travel times approximately 2.3% in the eastbound direction and 3.6% in the westbound direction, compared to the BRT travel times in the No TSP scenario.

The results show more benefits for transit in the RBC simulation environment. Generally, along this arterial, the TSP implementation was more beneficial in the westbound direction, which was expected considering the direction of the PM peak traffic. A combined implementation of BRT operations and TSP strategies is proven to be beneficial for transit travel times along the corridor.

The main conclusion from the transit travel time results is that the RBC controllers implement TSP strategies more effectively, providing greater travel time

TABLE 3.2 Transit Travel Times

		Average Transit Travel Times (s)			
		RBC		ASC/3 SIL	
Direction	Segment	BRT No TSP	BRT TSP	BRT No TSP	BRT TSP
EASTBOUND	5600W-5200W	62.7	56.0	66.5	61.6
	5200W-4800W	87.2	60.7	87.0	75.7
	4800W-4400W	78.8	79.1	78.3	84.6
	4400W-4155W	34.8	33.4	34.8	37.9
	4155W-4000W	51.4	41.7	37.8	32.5
	4000W-Bangerter	144.1	145.9	137.5	130.2
	Bangerter-3600W	21.9	22.8	21.5	21.6
	3600W-3450W	55.0	55.6	57.3	60.0
	3450W-3200W	59.8	68.9	55.9	47.5
	3200W-2820W	53.8	56.1	51.7	54.5
	2820W-2700W	214.2	216.0	201.4	204.8
WESTBOUND	2700W-2820W	186.7	192.0	182.2	182.6
	2820W-3200W	91.3	92.8	91.3	84.9
	3200W-3450W	42.9	43.1	41.0	40.3
	3450W-3600W	40.8	41.3	42.5	42.1
	3600W-Bangerter	131.9	130.5	135.2	133.0
	Bangerter-4000W	99.4	104.1	106.6	87.1
	4000W-4155W	28.6	24.1	29.8	31.6
	4155W-4400W	46.3	38.0	45.2	48.7
	4400W-4800W	68.9	60.1	69.7	66.3
	4800W-5200W	84.6	81.3	86.0	84.8
	5200W-5600W	127.2	75.2	110.8	104.9
TOTAL	EASTBOUND	863.7	836.2	829.7	810.9
	WESTBOUND	948.6	882.5	940.3	906.3

savings for transit. This can be attributed to the TSP settings in RBC, where the controller will allow the maximum amount of extra time for transit by proportionally truncating green times on all conflicting approaches. The ASC/3 controllers can only truncate conflicting northbound and southbound through movements.

3.6.3. Impacts of TSP on Side Street Traffic

An implementation of TSP along the main corridor can have some impacts on conflicting traffic on side streets. The major impacts can affect delays and stops. In order to address these impacts, the study also included an analysis of delays, stop delays, and number of stops per vehicle on side streets at TSP-equipped intersections. A comparative evaluation of these parameters before and after the TSP implementation can show the effects of TSP on side street traffic.

Table 3.3 shows a comparative evaluation of these parameters for the No TSP scenarios for each TSP-equipped intersection, in both simulation environments, in order to assess possible differences in the parameters depending on the type of the controller used. The data presented in the table are for the 4:00 PM – 5:00 PM peak hour, while the same relationship goes for the 5:00 PM – 6:00 PM hour. Two-tail t tests for paired samples are used to test the null hypotheses ($\alpha = 0.05$) that these parameters are the same for the two controller types. The intersections and movements where the statistical difference is observed are marked. These results correspond to the vehicular travel time differences along the main corridor.

In order to address the impacts of the TSP implementation, the given parameters from the No TSP scenario were compared to the TSP scenario, in both simulation

TABLE 3.3 Comparison of Side Street Parameters

		RBC			ASC/3 SIL		
Side Street	Movement	Delay (s)	Stopped Delay (s)	Average stops per vehicle	Delay (s)	Stopped Delay (s)	Average stops per vehicle
2700 West	NBL	55.9	47.6	0.93	55.0	46.5	0.93
	NBT	44.9*	37.8*	0.79*	47.6	40.1	0.84
	SBL	61.4	51.6	1.01	64.5	54.3	1.04
	SBT	43.4	36.3	0.81	43.6	36.5	0.81
3200 West	NBL	34.7	29.6	1.11	33.4	28.1	1.10
	NBT	42.3*	37.8*	0.84	39.5	35.0	0.82
	SBL	47.5	38.3	1.09	44.8	35.9	1.06
	SBT	54.5	46.5	1.02	51.8	44.2	0.98
3450 West	NBL	58.6	52.3	0.99	59.1	53.0	0.96
	NBT	59.2	53.7	0.86	59.6	54.3	0.86
	SBL	62.5	55.0*	0.92	62.9	55.8	0.93
	SBT	59.2	53. 6	0.85	59.1	53.5	0.85
3600 West	NBL	83.9*	66.4*	2.00*	105. 8	83.8	2.35
	NBT	53.1*	45.0*	0.84*	59.3	50.0	0.89
	SBL	105.4	87.9	1.78	106.5	88.8	1.80
	SBT	139.9*	119.6*	1.65*	146.0	125.3	1.70
4000 West	NBL	52.3*	44.7*	1.21*	55.5	47.3	1.26
	NBT	55.1	49.5	0.89	56.0	50.4	0.89
	SBL	46.9	39.7	0.95	47.8	40.6	0.96
	SBT	57.3*	51.4*	0.88	57.9	52.0	0.88
4155 West	SBL	52.1	46.2	0.88	51.5	45.5	0.91
4400 West	NBL	51.9	42.1	1.87	49.9	40.9	1.69
	NBT	56.1*	46.5*	0.92*	51.8	42.7	0.88
	SBL	80.5*	65.6*	1.74*	64.1	51.3	1.53
	SBT	67.7*	55.9*	1.06*	57.7	47.3	0.96
4800 West	NBL	68.3*	54.2*	3.05	52.5	40.6	2.75
	NBT	35.8	29.4	0.74	36.1	29.7	0.73
	SBL	59.8*	45.9*	2.02*	51.7	39.0	1.78
	SBT	56.9*	45.2*	1.03*	50.7	40.0	0.94
5200 West	NBL	23.7	18.8	0.84	23.8	18.9	0.84
5600 West	NBL	12.8	9.3	0.48	13.4	10.0	0.52
	NBT	13.5*	11.9*	0.44	15.0	13.1	0.47
	SBL	12.4	9.1	0.44	13.5	10.2	0.45
	SBT	14.3*	11.6*	0.45*	16.2	13.1	0.48

* Value in RBC is statistically different from the corresponding value in ASC/3 SIL simulation environment

environments. Table 3.4 presents the results of this comparison. For each TSP-equipped intersection, the parameters are averaged for the 2-hour simulation period and for all side street movements, compared between the two scenarios, and the percentile change is reported.

From the table, the TSP implementation did not necessarily worsen traffic conditions on all side streets. On some side streets, the impacts were insignificant, while in some cases, the TSP scenario even yielded better results. The difference in the intensity of impacts between the two simulation environments was emphasized along three side streets: 3200 West, 4400 West, and 4800 West. In the first case, RBC even caused a significant improvement in these parameters, thus improving side streets movements.

Along the same street, ASC/3 SIL caused the worst case for traffic operations, after the TSP implementation. For the other two side streets, the situation was different: RBC caused major deterioration of traffic conditions (especially along 4400 West), while the impacts in ASC/3 SIL were insignificant. The impacts on side street traffic at the network level were small, and the changes were almost the same in both simulation environments. The delays increased approximately 1%, while the increase in the number of stops was less than 0.50%. On a network level, the TSP implementation would have almost no impacts on side street traffic.

3.7. Discussion

The two controller types, RBC EIL and ASC/3 SIL, operate in slightly different ways during TSP simulation. The results presented in the previous section can support the

TABLE 3.4 Impacts of TSP on Side Street Traffic

Side Street	Parameter	Change (%)	
		RBC	ASC/3 SIL
2700 West	Delay	0.52	0.39
	Stop Delay	0.53	0.45
	Number of stops	0.42	0.50
3200 West	Delay	-9.48	6.56
	Stop Delay	-9.43	6.87
	Number of stops	-5.21	1.96
3450 West	Delay	0.38	-0.17
	Stop Delay	0.41	-0.27
	Number of stops	0.24	-0.34
3600 West	Delay	-2.41	0.86
	Stop Delay	-2.58	0.64
	Number of stops	-1.58	1.37
4000 West	Delay	0.12	0.63
	Stop Delay	0.11	0.75
	Number of stops	-0.78	0.22
4155 West	Delay	0.83	-0.02
	Stop Delay	0.88	0.01
	Number of stops	0.40	0.17
4400 West	Delay	12.11	0.27
	Stop Delay	12.74	0.28
	Number of stops	5.93	0.22
4800 West	Delay	6.64	0.95
	Stop Delay	7.15	1.11
	Number of stops	3.42	1.54
5200 West	Delay	0.00	0.27
	Stop Delay	0.16	0.48
	Number of stops	-0.41	-0.24
5600 West	Delay	0.70	-0.52
	Stop Delay	0.90	-0.37
	Number of stops	-0.39	-0.39
TOTAL	Delay	0.94	0.92
	Stop Delay	1.09	0.99
	Number of stops	0.20	0.50

following discussion about the relationship between the two controller types.

The two controller types have different start up processes, which can have some impacts on the sequence of signal timings later during the simulation. RBC is an emulator encompassed within the simulation software, and its start is well synchronized with the beginning of the simulation. Actual signal timings for each intersection start according to a provided input, such as starting phases and offsets. In ASC/3 SIL, the controller starts simultaneously with the simulation, but also requires an initialization process which can cause a small delay. Usually, this controller takes two to three cycles to adjust signal timings and synchronize them with signal timings from a time-of-day plan. This can cause slight differences in traffic operations, so they are not identical to the traffic operations within the RBC simulation environment.

ASC/3 SIL synchronizes faster than RBC after a disturbance caused by a TSP service, which can be seen from the difference in travel times before and after the TSP implementation. RBC takes more time to restore a coordination pattern after the TSP has been serviced, which causes disturbances in coordination and increases vehicular travel times along the main corridor. This can be caused by the TSP settings and the way RBC implements TSP. As mentioned before, when RBC receives a TSP call, it will truncate green times on all conflicting signal groups proportionally to their splits, including the left turns along the main corridor. On the other hand, ASC/3 SIL settings allow it only to truncate the conflicting northbound and southbound through movements. It makes it easier for ASC/3 SIL to synchronize, because it deals with fewer parameters.

According to the simulation errors reported by VISSIM, when working on a 10 Hz frequency, RBC is prone to minimum green time violations, especially for the noncoordinated signal phases. This can have some impact on general traffic operations, including the travel times.

3.8. Conclusions

An implementation of TSP strategies along a transit corridor can have multiple impacts on transit operations and general purpose traffic. Traffic simulation can be a very powerful tool in evaluating TSP strategies before the field implementation. Different traffic simulation packages provide different types of traffic control emulators, but most of them provide only simple solutions for TSP operations. VISSIM is one of the most widely used simulation software packages, and the latest versions incorporate traffic control emulators with sophisticated and powerful TSP options. This study investigated an implementation of TSP strategies on a case-study network, where VISSIM was coupled with two types of traffic controllers: its traffic emulator, RBC, and software-in-the-loop virtual traffic controller, ASC/3. The study used a simulation model of the 3500 South BRT line in Salt Lake County, and investigated the benefits and impacts of the TSP implementation, as well as differences in the way the two controller types implement these strategies.

Considering the two controller types, the way they operate, and the way they need to be set in order to enable TSP operations, the following can be concluded:

- The startup processes for the two controller types are different, which can cause differences in traffic operations.
- When RBC is working on a 10 Hz frequency, it is prone to minimum green time violations.

- In order to enable TSP strategies (green extension and early green), a RBC controller will truncate all conflicting phases proportionally to their splits, and only one value for green extension/red truncation can be set; ASC/3 SIL allows choosing the phases that are going to be truncated, and different values for green extension/red truncation can be implemented for each phase.
- ASC/3 SIL is getting back into synchronization faster than RBC after a disturbance caused by TSP service.

Both controller types were used to evaluate TSP strategies along the 3500 South BRT line in Salt Lake County, using the settings from the field. However, in order to program both controller types in the same way and make sure that they operate properly, two field settings had to be modified. The TSP detector check-in signals were locked, and the number of reservice cycles were set to zero (instead of three, as it is in the field). All the field controllers were ASC/3 type, which is an advantage for ASC/3 SIL. The analysis of the implemented TSP strategies yielded the following conclusion:

- The implementation of TSP strategies has no significant impacts on general purpose traffic along the main corridor.
- Transit travel times can benefit approximately 3% in the eastbound direction, and 4 – 7% in the westbound direction (depending on the controller type) from TSP during peak hours, when the majority of vehicles travel westbound.
- Impacts of TSP on side street traffic can vary, but on a network level, these impacts are not significant. In general, not more than three out of ten intersections can experience deterioration in traffic conditions with TSP. The individual impacts also depend on the traffic controller, but on the network

level, there were no differences.

This study has shown the benefits of the VISSIM simulation package, coupled with newly developed traffic control emulators and controller software, in researching TSP operations and strategies. This tool has shown its great potential to be used in future studies dealing with traffic control and transit operations.

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CHAPTER 4

35M MAX: THE FIRST BUS RAPID TRANSIT SYSTEM IN SALT LAKE COUNTY

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4.1. Abstract

Bus Rapid Transit (BRT) is becoming one of the most popular transit services in the United States. A total of 106 miles of BRT service is scheduled for deployment in the State of Utah in future years. This research looked at the first BRT deployment in West Valley City, Salt Lake County, Utah. The 10.8 miles long BRT line was launched on July 14, 2008, and shortly after the launching, the first operational data became available. In addition, a series of surveys were conducted to gain feedback from the users of the BRT system. Preliminary results show significant improvements in transit operations, with a 33% increase in ridership, reductions of close to 15% in travel times, and improved reliability. Survey results show a high degree of acceptance among the system users. In general, the BRT system has proven itself to be very successful, bringing significant improvements to transit riders.

4.2. Introduction

With overall traffic growth on urban highways and arterials, congestion is becoming a significant problem with major negative impacts on transit vehicles, which do not have exclusive rights-of-way. These negative impacts often result in increased travel times, poor reliability, unpredictable on-time performance, bus crowding, and longer waiting times at transit stops. In order to overcome these impacts, transit agencies have begun introducing new, high capacity rapid transit modes, such as Bus Rapid Transit (BRT), along with technology and enhanced transit operational strategies.

In recent years, BRT has become one of the most commonly used rapid transit modes. According to the National BRT Institute (2008), BRT is an innovative, high capacity, lower cost public transit solution that can significantly improve mobility. This permanent, integrated system uses buses or specialized vehicles on roadways or dedicated lanes to quickly and efficiently transport passengers to their destinations, while offering the flexibility to meet dynamic transit demands. BRT systems can easily be customized to community needs and incorporate state-of-the-art, low-cost technologies that result in more passengers and less congestion than traditional modes. Levinson et al. (2003) defined BRT as an integrated system with a strong, transit-oriented identity, which consists of running ways (very often exclusive lanes), specially designed rail-like stations, high-capacity low-floor vehicles, improved services, and state-of-the-art Intelligent Transportation Systems (ITS). Further, it provides similar quality of service as rail transit, at much lower construction and operational costs to the transit organization, and retains the flexibility of buses.

Numerous studies and designs, which used buses to provide rapid transit, have been conducted since the 1930s. Some of the notable early implementations were in Chicago in 1937, Washington D.C. from 1956 to 1959, St. Louis in 1959, and Milwaukee in 1970. However, BRT systems installed in the last fifteen years have been shown to be far more advanced than the early BRT systems. Some of these BRT implementations exceeded initial expectations regarding ridership increase, travel time savings, cost effectiveness, safety, attractiveness etc. The Metro Orange Line in Los Angeles County, CA, opened in October 2005, has experienced a large gain in ridership during its first year of operation (Callaghan and Vincent, 2007). In only seven months of operation, the line achieved its 2020 goal in ridership gain, which was more than four times greater than the ridership increase projected for the first year. About 17% of the ridership gain were new riders, while 30% were diverted from cars. The TransMilenio BRT line in Bogota, Columbia, is one of the most massive BRT lines in the world, which carries more than one million passengers per day (Cain et al., 2006). The implemented BRT features have reduced travel times by more than 30% for transit riders along the corridor, and improved safety significantly, reducing traffic accidents along the corridor by 79%. Some other Latin American transit systems had a similar experience after BRT implementations (Menckhoff, 2004). The 98 B-Line in Vancouver, Canada, has recorded almost a 100% ridership increase, where 23% of passengers diverted from private cars to the BRT, while 31% of the ridership increase were new passengers (Spencer et al., 2003). According to the survey that was conducted, this was a result of customer satisfaction with the new service. Table 4.1 shows some benefits of several BRT systems in the USA and Canada, given through the ridership increase and travel time savings, summarized by Levinson et al. (2003), and Kittelson & Associates et al. (2007). Surveys from these studies also showed that approximately 33% of the ridership increase in BRT systems were new riders.

According to the Regional Transportation Plan: 2007 – 2030 (2030 RTP), adopted by the Wasatch Front Regional Council (WFRC), (2007), 106 miles of BRT lines are planned for construction in Salt Lake, Davis, and Weber Counties in Utah. The first implemented BRT line, with a length of 10.8 miles, runs along 3500 South Street in Salt Lake County. BRT was chosen over other alternatives due to lower installation costs than light rail alternatives and its capabilities to meet the transit demand. The BRT also offered additional engineering flexibility over rail.

This study describes the first BRT system deployed along 3500 South in West

TABLE 4.1 Benefits of BRT Systems

City / BRT System	Ridership Increase (%)	Travel Time Savings (%)
Boston, MA	100	20 – 30
Cleveland, OH	13	20
Houston, TX	90 – 100	47
Los Angeles, CA	33	25
Pittsburg, PA	38	41 – 44
Miami, FL	85	30
Oakland, CA	20	17
Vancouver, CAN	100	20

Valley City, Utah and its basic operational characteristics. The objective of the study is to evaluate performance of the BRT system and its impacts on transit service along the corridor. The evaluation is based on operational data from the field collected during the first few months of service, as well as through a series of passenger and operator surveys.

4.3. 3500 South Transit Corridor

The first BRT line in the state of Utah has been implemented along 3500 South in West Valley City, Salt Lake County. 3500 South is the major East-West arterial that connects the fast growing Western part of the county and Magna City with major North-South highways and the Light Rail Transit (LRT) system (called TRAX). The 3500 South arterial carries a significant amount of traffic, with an Average Annual Daily Traffic (AADT) between 33,000 and 51,000 vehicles per day along the busiest arterials' segments in Salt Lake County (UDOT Traffic Maps, 2006).

4.3.1. Transit Lines along 3500 South Corridor

3500 South has always been one of the busiest transit corridors. Historically, the regular bus transit line RT 37 operated along this corridor, on a 30-minute peak and 60-minute off-peak headway. In April 2007, it was replaced with RT 35 and the service frequency was increased. This bus route, which remained in operation even after the BRT line had been introduced, connects Magna City and the 3300 South Millcreek TRAX stations, as shown in Figure 4.1. The length of RT 35 route is 11.9 miles (without the Magna Loop), with 55 eastbound and 52 westbound bus stops. The length of the route through Magna City (Magna Loop) is approximately 4 miles long, with a total of 25 bus stops. Bus stops along the RT 35 route are located on shoulder lanes, with few on-street stops, and they are serviced only if demand exists. Before introduction of the BRT line, the RT 35 was in service for 19 hours during weekdays and buses departed every 15 minutes from 6 a.m. to 9 p.m., and 30 to 60 minutes after 9 p.m., on a time-based schedule. Service hours were reduced during weekends to 17 hours on Saturdays, with 30-minute headways, and 10 hours on Sundays, with 60-minute headways. The time schedule was coordinated with the TRAX line. Fares for RT 35 were collected on-board and only the front door was used for entrance.

After the implementation of the first BRT phase on July 14, 2008, the RT 35 line remained in service, but the service plans were changed. Currently, RT 35 is in service for 20 hours per weekday with operations based on a time-based schedule with 30-minute headways. During weekends, the route is in service 19.5 hours on Saturdays, with 30-minute headways and 11 hours on Sundays, with 60-minute headways.

FIGURE 4.1 Bus Route RT 35.

4.4. History of BRT Implementation

The Utah Transit Authority (UTA), the Wasatch Region's transit agency, started a project called "MAX", which refers to seven planned BRT implementations from the 2030 Regional Transportation Plan. The 3500 South Street corridor has been chosen as the first of the seven BRT lines to be implemented to help alleviate congestion and improve transit service along the corridor. The 3500 South BRT line, known as 35M MAX, runs from Magna City to the 3300 South TRAX station, providing fast and reliable connection for commuters from Magna and West Valley to the LRT TRAX Sandy line. The layout of the line, showing the route, station locations, and TRAX connection, is presented in Figure 4.2.

Planning for 3500 South began by evaluation of transportation needs and consideration of improvements for the corridor based on projected increased travel demand through the year 2030. At the beginning, the project was receiving federal funding, but currently is being funded by the state.

Both UTA and WFRC were involved in planning the transit project with West Valley City. UTA also worked collaboratively with the Utah Department of Transportation (UDOT) and contracted with Carter & Burgess, Inc., to guide the project and prepare the Environmental Impact Study.

In May 2002, UDOT conducted the initial Draft Environmental Impact Study on 3500 South between 8400 West and Redwood Road. This resulted in breaking down the length of roadway into smaller sections, because of the high costs of originally identified alternatives. It was determined that no federal funds would be used for roadway improvements, and as a result, the Environmental Impact Study was discontinued and

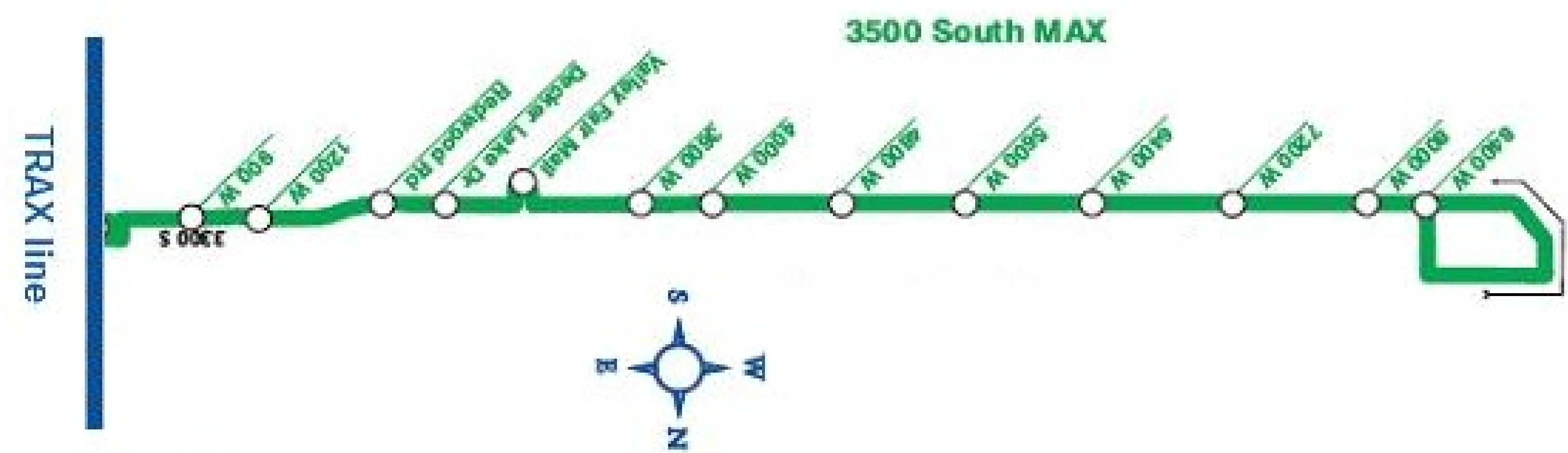

FIGURE 4.2 35M MAX line.

replaced with the current environmental assessment, the State Environmental Study (SES). The SES was submitted to the public for a 30-day comment period, from March 21 to April 22, 2006, and a final version was published in April 2006 on UDOT's official web site.

The Alternative Development Process, as defined by the National Environmental Policy Act (1970), requires that a range of alternatives and a No Action Alternative be presented and evaluated in detail. A public involvement program was developed and has been applied to this project in the planning process.

A total of six alternatives were evaluated: No Build, Transportation Systems Management, Minimum Build, Transit Build, Partial Build, and Full Build. The final screening process evaluated these alternatives under community, environment, and transportation criteria for each zone. After analyzing these alternatives, the Transit Build Alternative was selected as the Preferred Alternative. This alternative would meet most of the project needs while minimizing community impacts.

Upon completion and approval of the SES, UTA introduced the new BRT system, with new stations, station amenities, and vehicles. The first phase of the BRT line was launched on July 14, 2008.

4.5. BRT Elements

Diaz et al. (2004) defined the following major elements of BRT: running ways, stations, vehicles, fare collection, ITS, and service and operation plans. This section provides a description of each of the elements on the 35M MAX line.

4.5.1. Running Ways

In the first phase of the BRT implementation, the 35M MAX buses run in mixed traffic, without utilizing dedicated lanes. This line has the same route as RT 35, with the exception on a segment between 700 W and 900 W, where it continues along 3300 S without turning on side streets. This reduction in the 35M MAX route's length makes the entire route 10.8 miles long from the 3300 South TRAX station to 8400 W.

During the second phase of the implementation, center-running exclusive BRT lanes will be constructed from 2700 W to Bangerter Highway, separating BRT vehicles from other traffic. The third phase will include a construction of exclusive BRT lanes from the 3300 South TRAX station to 2700 W and from Bangerter Highway to 5600 W. This will include new BRT bus stops and pedestrian crossings to connect bus stops to the sidewalks. The layout of the exclusive BRT lanes is shown in Figure 4.3.

4.5.2. Bus Stations

In the first phase of implementation, there are a total of 29 BRT bus stops along the line, 14 westbound and 15 eastbound, located approximately 400 m to 800 m apart. All the bus stops are located on the shoulder lanes, and they have been upgraded to enhance passenger comfort and safety. Most of the stops are sheltered, lighted, and marked with a special MAX bus stop sign, as shown in Figure 4.4. Ticket vending machines are installed at most stops. Passenger information displays with real-time information on bus arrivals will be installed in later phases of BRT implementation.

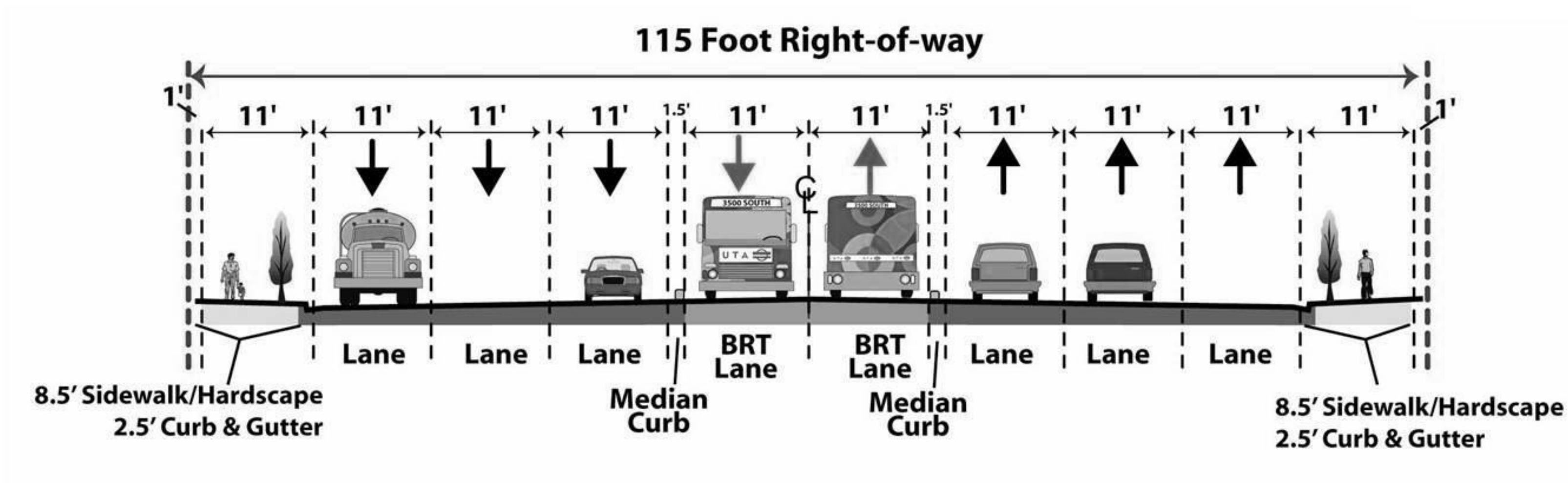

FIGURE 4.3 Exclusive BRT lanes.

FIGURE 4.4 35M Bus stop at 3300 South TRAX station.

4.5.3. Vehicles

UTA has purchased 10 new Belgian Van Hool A300 buses, which are assigned to the 35M MAX line. All buses are customized in order to comply with the U.S. and Utah laws and standards. The buses are equipped with stainless steel frames and body panels, 330 horsepower Cummins ISL diesel motors mounted sideways in the wheelbase, top mounted cooling systems, object detection systems, full low-floor boarding capabilities, a wheelchair ramp located at the center door, wider aisles, and additional doors. In addition, the buses have a unique paint scheme, providing a strong identity to the new BRT system. Each bus can accommodate 60 passengers, with 34 seats and 26 standing places.

According to the Van Hool technical specifications, the A300 bus is 11,995 mm in length, with a width of 2,550 mm, interior height of 2,315 mm, and exterior height of 2,985 mm. The bus has three right-side doors, where the center double-sided door is 950 mm wide, while the front and the rear doors are single sided, with a width of 800 mm. All doors are used both for boarding and alighting, which improves accessibility and reduces bus stop dwell times. The boarding ramp is located at the center door and can be operated only from the inside of the vehicle. A big platform is located at the center door, and it can accommodate two wheelchairs at the same time, with securing straps. Push buttons for stop requesting are located all over the interior of the bus. The center and rear doors can be opened by pushing the door-open buttons, whether from the inside or outside of the bus. For safety purposes, the doors cannot be opened while the bus is in motion, and they are also under the driver's control. The buses are equipped with two bike carrying racks, located at the outer front part of the bus, and there is no additional charge for a passenger who uses them. The cost of each bus is $403,000. A photo of the bus is presented in Figure 4.5.

4.5.4. Fare Collection

The 35M MAX line deploys an off-vehicle fare system that requires all passengers to have a valid proof of payment prior to boarding. The purpose of removing the fare collection from the vehicle is to move fare transaction times to the station areas and thereby reduce station dwell times. Payment verification for riding BRT is based on the honor system, with UTA transit police enforcing fare policies through random checks.

FIGURE 4.5 Customized Van Hool A300 bus assigned to 35M line.

All BRT stations are equipped with Ticket Vending Machines (TVMs), which are presented in Figure 4.6. The TVMs can issue one-way tickets which cost \$2.25 each, senior and reduced one-way tickets for \$1.10, or all-day passes for \$5.50. The TVMs accept cash, credit and debit cards, and they feature audio assistance in both English and Spanish.

Starting from January 2009, UTA introduced a new way of fare collection on most of its lines, including 35M MAX. It is a so-called "Tap on – Tap off" Electronic Fare Collection system, which allows customers to pay the fare using contactless credit cards. When boarding, a passenger needs to tap the card on the card reader installed near each door. When alighting, he/she taps off the same card. The system calculates the distance traveled and charges the credit card. If the card is not tapped off, the full distance of the route will be charged. It also requires those with prepaid passes, such as education

FIGURE 4.6 Ticket Vending Machine.

passes, to tap on and tap off to collect travel data. This system is still in the initial phase, and it will be addressed in detail in future studies.

4.5.5. Intelligent Transportation Systems

ITS components which are currently deployed on the 35M MAX line include: Transit Signal Priority (TSP), object detection, and collision avoidance systems installed on the buses. TSP currently operates on sixteen out of twenty-seven intersections along the corridor. TSP is activated manually when the bus begins service on the route, using a switch installed on the bus. TSP uses 3M OptiCom systems for communication between the buses and traffic controllers, via infrared transmission. The intersections are equipped with newly installed ASC/3 Econolite controllers which include OptiCom receivers. Two unconditional TSP strategies are deployed, green extension and red truncation, and both of them allow a maximum of 10 seconds of additional time for the BRT phases. Once a TSP call is serviced, the controller logic does not allow any TSP services for the next three cycles.

The buses are equipped with object detection and collision avoidance systems which warn bus operators of objects which are too close to the front or the back of the vehicle. These systems improve safety and help avoid damages to the buses.

4.5.6. Service and Operations Plans

35M MAX operates six days a week, with no service on Sundays. During weekdays and Saturdays, buses operate from 5:30 a.m. to 12:30 a.m. on a headway-based schedule with 15-minute headways. The buses skip stations where there are no stop requests for on board passengers and no waiting passengers in the station, and are not subjected to predefined station departure times.

Scheduled travel times for 35M MAX between the 3300 South TRAX station and 8400 W station are approximately 35 minutes during the peak periods and 28 minutes during the off-peak for the eastbound direction, and 42 minutes during the peak periods and 32 minutes off-peak for the westbound. Longer westbound scheduled travel times are attributed to the line characteristics, with several left turns on intersections with heavy traffic. Service and operation plans have also taken into account backup vehicles, in case of a vehicle breakdown along the line.

4.6. Future System Improvements

The basic system enhancements along the 35M MAX line include: traffic signal priority, fixed guideway from 2700 W to Bangerter Highway, and a new light rail spur connecting with the project. Beside these, additional enhancements include the construction of a 300 stall park and ride lot at 5600 W and an intermodal center at the terminus of the light rail line. The intermodal center will include nine bus bays for local buses, a city town square, and a pull out for the BRT buses adjacent to the LRT platform. Finally, due to customer demand, an additional station will be added at 900 W. The intermodal center and added station will be completed in 2009. The first phase of the fixed guideway will be completed in mid-2010. TSP will be added at ten additional intersections. Some of these elements are presented in Figure 4.7.

4.7. Evaluation of System Performance

After the 35M MAX line implementation, UTA started to monitor system performance. The most important performance measures given in UTA's MAX Status Report (2008) for August, September, and the first half of October of 2008 include: transit ridership, headway adherence, travel times, running-time reliability, dwell times, and capital costs. This section gives an analysis of system performance for 35M MAX, as well as for the new RT 35, and compares these performances to the old RT 35, in order to assess the benefits of the new system.

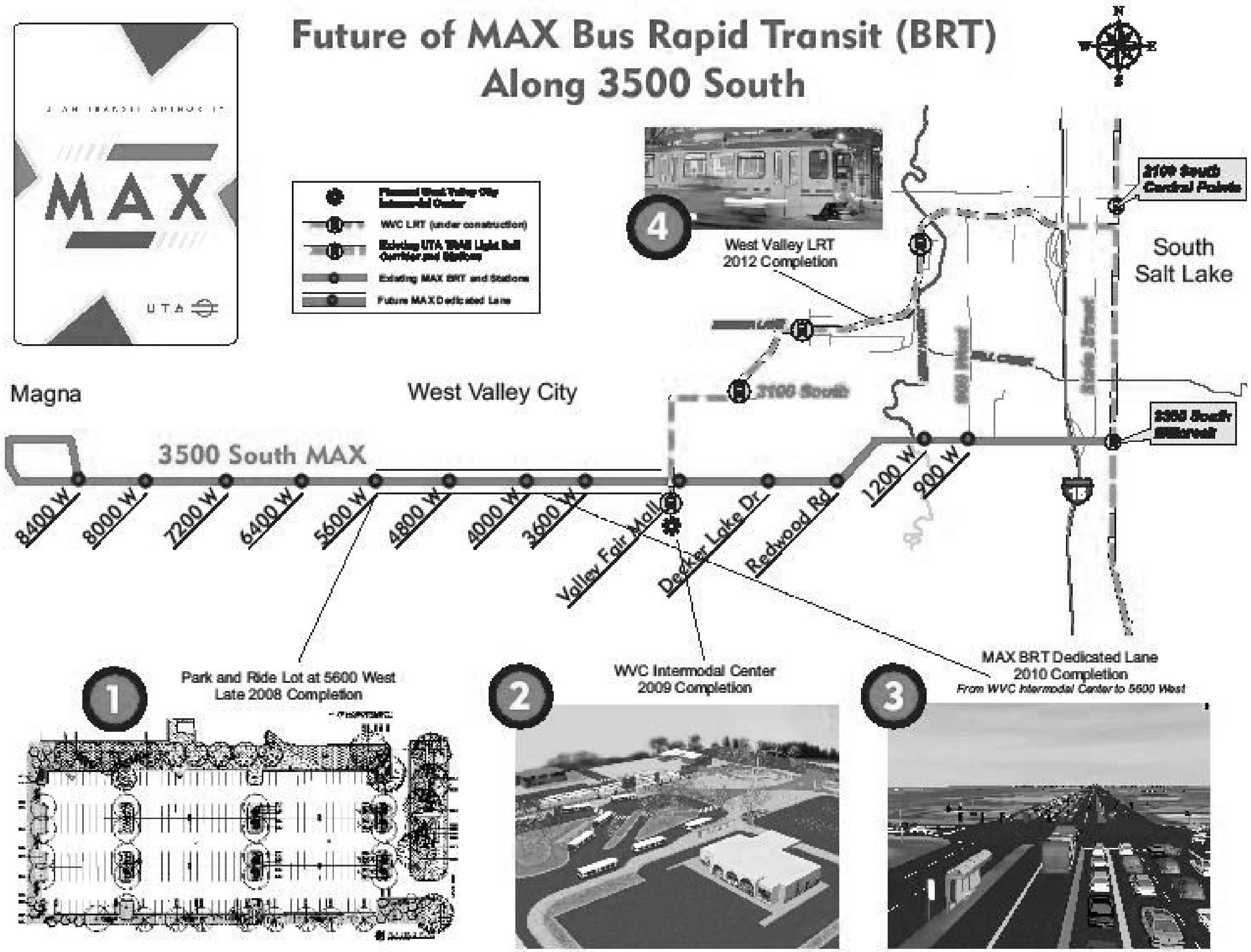

FIGURE 4.7 Future of 35M MAX line.

4.7.1. Transit Ridership

Transit ridership is the main indicator of attractiveness of a transit line. Ridership along the 3500 South corridor has been monitored in order to determine the ability of the new BRT service to attract new customers. Bus operators conduct Operator Counts on the first Tuesday of every month, when boarding on all trips is collected to estimate weekday ridership of the month. Table 4.2 shows estimated weekday ridership based on Operator Counts for both 35M MAX and the new RT 35 and compares them with the old RT 35.

In 2006, UTA operated the existing local bus service on 30-minute headways and the total ridership (estimated from the Operator Counts) was 2600 boardings per day. Leading up to the BRT service, the headways were reduced to 15 minutes, starting August 2007. The 2007 frequency increase was part of a larger redesign of the transit system to improve frequency on key transit corridors to increase ridership. Table 4.2 shows that the total 3500 S corridor ridership increased approximately 33% in 2008, compared to 2007. Ridership increase in 2007, comparing to 2006, was approximately 23%. The increase in ridership is evidential with the new service. 35M MAX carries approximately 70% of the total corridor ridership.

TABLE 4.2 Weekday Ridership (Operator Count)

Line	Ridership (boardings per day)		
	2006	2007	2008
35M MAX			2910
RT 35/37	2600	3200	1336
3500 S Corridor	2600	3200	4246

4.7.2. Headway Adherence

Headway-based control, applied to the 35M MAX line, focuses on maintaining constant headways between successive vehicles, rather than meeting specific schedules. Designed headways on 35M MAX are 15 minutes. On the other hand, RT 35 operates on a schedule-based control with 30-minute headways. Table 4.3 shows actual headways for both 35M MAX and RT 35, and the combined headway along the corridor obtained through field measurements. The old RT 35 line also operated on a schedule-based control, with 15-minute headways. The data recorded on this line are presented for comparison.

Recorded headways for both 35M MAX and RT 35 show a small deviation compared to the designed headways. Partially, this deviation can be attributed to the congestion during the peak periods along some segments of the corridor. When the number of trips and headway adherence are compared to the old RT 35, it is obvious that there has been an improvement in transit service.

TABLE 4.3 Headway Adherence

From 3300 S TRAX to 8400W (Weekday)					
Month	Line	Direction	Number of trips per day	Hours of operation per day	Headway (min)
July 2008	35M MAX	WB	69	20 h 12 m	18
		EB	72	20 h 08 m	17
July 2008	RT 35	WB	34	18 h 59 m	35
		EB	33	18 h 23 m	34
July 2008	3500 S Corridor	WB	103	20 h 12 m	12
		EB	105	20 h 08 m	12
Aug 2007	Old RT 35	WB	59	18 h 59 m	20
		EB	65	18 h 33 m	17

4.7.3. Travel Times

Diaz et al. (2004) pointed out that travel time can be considered the single attribute of a transit system that customers care the most about, especially for trips made for work purposes. It is also the most important factor in selecting the mode of travel (e.g. private cars vs. transit). Recorded travel times for the analyzed lines are presented in Table 4.4.

As expected, 35M MAX records the lowest travel times along the corridor. The westbound direction of 35M MAX experiences lower travel times than the scheduled ones, while in the eastbound direction, the travel times are slightly higher than scheduled travel times. Westbound travel times are scheduled to be higher, due to the line characteristics and several left turns on busy intersections. But as the results show, the actual westbound travel times are approximately 10% lower than the scheduled times. Compared to the old RT 35, the decrease in travel times for 35M MAX is about 15%. The RT 35 travel times are close to the scheduled times in both directions, and there is just a small difference comparing to the old RT 35 travel times. It should also be noted

TABLE 4.4 Travel Times

Travel time (min) from 3300 South TRAX to 8400 West					
Line	Direction	Actual			Scheduled
		Aug	Sept	Oct	
35M MAX (2008)	WB	35	34	32	38
RT 35 (2008)	WB	44	41	40	39
Old RT 35 (2007)	WB	43	41	41	39
35M MAX (2008)	EB	35	36	34	32
RT 35 (2008)	EB	39	39	38	37
Old RT 35 (2007)	EB	41	41	40	38

that the data given in the table represent preliminary results, as there were utility works along some segments, which affected travel times.

4.7.4. Running-Time Reliability

Running-time reliability is defined as ability of BRT service to maintain a consistently high speed in order to provide customers with consistent travel times. This is important from a passenger's perspective because the passenger knows that he/she can depend on the BRT system consistently.

Table 4.5 shows recorded running-time reliability for the analyzed lines. It shows the percentage of consistency of recorded travel times with the scheduled travel times. 35M MAX has the best running-time reliability, with a constant improvement from month to month. Running-time reliability for RT 35 has also increased, contributing to the overall service improvement. A significant improvement in running-time reliability for 35M MAX is achieved compared to the old RT 35.

4.7.5. Dwell Times

The analyzed dwell times consist of bus stop dwell times (the time needed for loading and unloading passengers at bus stops), and dwell times in traffic stops (mostly delays at signalized intersections). Separate data for bus stop dwell times and traffic stop delays are not available. Table 4.6 shows averaged dwell times recorded in September 2008 for 35M MAX and RT 35. These data are not available for the old RT 35, so no comparison was made.

Generally, average dwell times are lower for 35M MAX. On the other hand, in

TABLE 4.5 Running-Time Reliability

From 3300 S TRAX to 8400W				
	Direction	Aug	Sep	Oct
35M MAX (2008)		87%	94%	97%
RT 35 (2008)	WB	64%	77%	82%
Old 35 (2007)		57%	63%	64%
35M MAX (2008)		83%	81%	89%
RT 35 (2008)	EB	78%	77%	83%
Old RT 35 (2007)		74%	77%	79%

TABLE 4.6 Average Dwell Times

Line	Direction	Average dwell times (September 2008) Per trip (min:sec)	Per stopping (sec)
35M MAX	WB	2:47	18
RT 35		3:41	21
35M MAX	EB	3:00	19
RT 35		3:29	20

order to conduct a more comprehensive analysis, data about the average number of stops, as well as separate data for bus stop dwell times are needed, but are not currently available. Comparing these dwell times to the average travel times recorded during the same month, it can be seen that 35M MAX dwell times comprise approximately 8% of the total travel times (in both directions), while the same percentage for RT 35 is approximately 9%.

4.7.6. Capital Cost

As noted in Table 4.7, the total capital cost of the first phase of the BRT project was $7,403,000 in 2007 dollars. The largest component of the budget was the purchase of new buses and supporting parts. The canopies were the next largest expenditure at $1,579,000 with an additional $68,000 for real estate and $49,000 for art in transit.

4.8. Passenger and Operator Surveys

4.8.1. Survey Methodology

A few weeks after launching the first phase of the 35M MAX line, a series of operators' and passengers' surveys were conducted. The purpose of the surveys was to get feedback on the new Van Hool buses and the new BRT service. The survey was deliberately conducted soon after the start of the BRT service. The intention was to survey passengers and drivers before they get used to the new service and forget their experience with the old RT 35 service.

TABLE 4.7 Total 3500 South Phase 1 BRT Project Cost

Element	Cost (2007 dollars)
Canopies	1,579,000
Buses and Parts	4,670,000
Design / Construction Management	272,000
Art in transit	49,000
Signage	8,000
Staff time	125,000
Garbage cans	7,000
Real estate	68,000
Ticket Vending Machines	425,000
Signal priority equipments	150,000
Marketing	50,000
Total	7,403,000

The overall survey was divided into three questionnaires to assess the following concerns:

- How passengers value specific features of transit service in general
- How passengers compare new Van Hool buses with the other UTA buses
- What operators see as differences between the new and the old buses from the driver's perspective

Scales from 0 (no importance) to 10 (the highest importance) were used to record passengers' and operators' responses on given affirmative statements. In addition to the scalar questions, respondents were asked how long they have been affiliated with UTA and how often they used transit. They were also asked to make any comments or suggestions in the provided space at the bottom of the survey forms. Table 4.8 shows the statements that were used in each survey. To avoid confusing passengers, the term "MAX" was used instead of "Van Hool" buses.

4.8.2. Survey Results

The passenger surveys had responses from a total of 426 passengers. The surveyed passengers consisted mainly of regular transit users. Seventy-eight percent of respondents rode more than once per week, and 63% have ridden with UTA for more than one year. The survey on vehicle attributes had 212 respondents. The results from this survey, presented in Table 4.9, show that climate control was considered the most important factor to the surveyed passengers, with a median score of 10. High outside temperatures in mid-July seem to have biased some respondents when grading importance of the various bus features. Fastness of the bus, smoothness of the ride, and

TABLE 4.8 Passenger and Operator Surveys

Passenger Surveys		Operator Survey
Vehicle Attributes	Comparative Survey	
Comfortable seat.	Better seats.	Easier to steer.
Accessible seat.	Smoother ride.	Operates more smoothly.
Fast bus.	Nicer windows/views.	Better acceleration.
Smooth ride.	Better seating option.	Smoother cruising.
Windows/views.	Nicer bus.	Better windows/views.
Nice looking bus.	More standing room.	Easier boarding / alighting.
Leg room.	Quieter bus.	Better heating / air conditioning.
Quiet ride.	Better air conditioning.	Comfortable operator's seat .
Heating/Air conditioning.	Push button over pull cords.	Better mirrors.
Three-door configuration.	Three door configuration.	TSP service as an advantage.
	The MAX is a better bus.	The MAX is a better bus.

TABLE 4.9 Vehicle Attributes Survey

Feature	Median Score
Comfortable seat	8
Accessible seat	8
Fast bus	9
Smooth ride	9
Windows / views	7
Nice looking bus	8
Leg room	8
Quiet ride	8
Heating / Air conditioning	10
Three-door configuration	9

easiness to board/alight to/from buses were also important to passengers. Comfortable and accessible seats, a nice appearance, leg room, and noise control scored relatively high, although distributions of their importance were somewhat increased. Windows and views were considered the least important to the passengers. Some respondents also made unsolicited complaints about an insufficient number of bike racks on the buses.

The comparative survey of passengers included 214 respondents. The results are shown in Table 4.10. Overall, the Van Hool buses scored better than other UTA buses, with a median score of 10. The features of the new bus that received the highest scores are: appearance, the push buttons instead of pull cords, and better accessibility resulting from the three door configuration. The median score for all three was 10. The comfort of the seats, smoothness of the bus' ride, and a face-to-face seating option had a median score of 8. These scores show that the Van Hool bus is a preferred option when compared to the other UTA buses.

TABLE 4.10 Comparative Survey

Statement	Median Score
Better seat	8
Smoother ride	8
Nicer windows / views	9
Better seating option	8
Nicer bus	10
More standing room	9
Quieter bus	9
Better air conditioning	9
Push buttons over pull cords	10
Three door configuration	10
The MAX is a better bus	10

Most of the passengers' comments addressed the limited stops along the route and the bike carrying capacity on the buses. Many riders seemed accustomed to frequent stops along RT 35 and found new service somewhat confusing. Also, multiple respondents would prefer to have more than two bike racks on the Van Hool buses.

The operator survey questioned 20 UTA bus operators, who had an opportunity to operate the new buses. The operators expressed a high opinion of the Van Hool buses, giving the buses a median score of 9, which is shown in Table 4.11. Although most of the statements scored higher than 7, acceleration received a median score of 5.5, while the TSP feature received a median score of 6, with a relatively wide range in scores. Reasons for low scores for TSP implementation seemed to be two-fold. First, most of the drivers were still not familiar with the implementation of TSP, which was active at only six intersections along the route at the time. It is possible that they did not notice TSP benefits at the operating intersections, while they noticed delays at the intersections with no TSP functionality. Second, it is possible that TSP parameters were still not

TABLE 4.11 Operator Survey

Statement	Median Score
Easier to steer	7.5
Operates more smoothly	9.0
Better acceleration	5.5
Smoother cruising	10.0
Better windows / views	9.5
Easier boarding / alighting	10.0
Better heating / air conditioning	10.0
Comfortable operator's seat	10.0
Better mirrors	8.0
TSP service as an advantage	6.0
The MAX is a better bus	9.0

sufficiently fine-tuned to support specific requirements at each TSP-operating intersection. Most of the operators liked the boarding and alighting operations, the big windows, and the operator's seat. The highest-scored bus feature among operators was boarding and alighting of the new BRT buses. Operators' opinions on this subject might be biased by the fact that boarding and alighting through multiple doors release drivers from responsibility of collecting fares. Overall, the operators had more compliments than complaints for the new buses.

4.9. Conclusions

This study describes the BRT system deployed in West Valley City, Utah and its basic operational characteristics. The objective was to assess the performance of the newly introduced BRT system, using operational data collected from the field during the first few months of service. A set of passenger and operator surveys was conducted to assess quality and acceptance of the new BRT buses and system. Based on the operation data analysis and statistics from the surveys, the following conclusions were reached:

- Average transit ridership along the 3500 South corridor increased by approximately 33% in 2008, compared to ridership in 2007. The 35M MAX line carries approximately 70% of the total corridor ridership.
- The 35M MAX line travel times are approximately 15% lower than the travel times of the regular old RT 35, with improvements in running time reliability and headway adherence. The new modified RT 35 also reported lower travel times.
- Dwell times along 35M MAX have been reduced, mostly due to the new fare

collection process and improved accessibility at bus stops. However, more data are needed to conduct a more comprehensive analysis, in order to ascertain the full impact of the BRT system on dwell times.

- The system users (both passengers and bus operators) see the new “MAX” buses, and the system in general, as an improvement over the old service. While passengers appreciate the new three-door configuration and smoother rides the most, operators see the highest benefits in better windows, more comfortable driver’s seats, and the fact that they do not have to deal with fare collection.

Overall, the BRT implementation has a successful start and it has brought significant improvements in transit operations along the 3500 South corridor. Future work should analyze system performance for future phases of the implementation of the whole UTA BRT system.

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CHAPTER 5

PREDICTIVE PRIORITY FOR LIGHT RAIL TRANSIT: UNIVERSITY LIGHT RAIL LINE IN SALT LAKE COUNTY, UT

From Zlatkovic, M., P. Martin, and A. Stevanovic. Predictive Priority for Light Rail Transit: University Light Rail Line in Salt Lake County, Utah. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2259*, pp. 168-178.

5.1. Abstract

The goal of this paper is to assess the operational implementation of predictive light rail priority strategies through microsimulation. The field of study consists of a 2-mile corridor in Salt Lake County, where the University light rail line operates. The study uses VISSIM microsimulation models to analyze light rail operations, and the impacts that light rail priority has on transit and vehicular traffic.

The results show that the existing priority strategies have no impacts on vehicular traffic along the corridor, while at the same time reduce train travel times 20% to 30%. Left turns along the main corridor are slightly affected by the priority. The priority strategies can cause minor to major impacts on vehicular traffic along side streets through increased delays, while at the same time reduce train delays by 2.5 minutes along the corridor. Enabling priority at the 700 E intersection (where the priority is currently not active) would help reduce delays for trains by an additional 10%, with a small increase in vehicle delays. However, the coordinated north-south through movements would experience minimum impacts.

Three recommendations have emerged from the study. The first is to enable priority at 700 E to improve transit, without major impacts on vehicular traffic. The second is to reset priority parameters at intersections adjacent to light rail stations so that the priority call encompasses station dwell times. The third recommendation is to consider removing the queue jump strategies, so to reduce delays for the corridor through movements and help preserve coordination patterns.

5.2. Introduction

Light Rail Transit (LRT) is the fastest growing rail transit mode in the US (*1*). LRT has been operating in Salt Lake County for more than ten years, with a great share of transit riders. Utah Transit Authority's (UTA) goals are to maintain LRT operations on a high quality level and make this transit mode more competitive to private cars. UTA's LRT priority control is integrated into the Areawide Traffic Management System, developed separately by the Utah Department of Transportation (UDOT) in conjunction with Salt Lake County and Salt Lake City. This system uses tiered progression techniques to provide priority service for LRT vehicles (LRV) with minimal disruption to traffic-signal operation. It uses a combination of techniques, such as background timing plans, virtual preemption, and priority control (*2*).

Benefits and impacts of the LRT and its priority strategies could not be assessed through field measurements, because experimenting with controller settings in the field would bring major traffic disruptions, and the results could not be guaranteed. For that reason, we began a study in which we use traffic simulation to evaluate LRT and traffic operations on a part of the University LRT line. The main methodology and results are described in this paper.

The research question is whether the LRT priority is justified, from transit and general purpose traffic perspectives. The goal of the paper is to assess the operational implementation of the LRT predictive priority strategies. The objective is a trade-off analysis between transit preferences and traffic impacts. The field of study consists of a 2-mile corridor with twelve signalized intersections along the 400 S/500 S corridor, where the University line operates. The study uses VISSIM microsimulation models and

Siemens NextPhase Software-in-the-Loop (SIL) traffic controllers to analyze LRT operations and impacts that LRT priority has on transit and vehicular traffic.

The paper is organized in seven sections. The next section gives a review of the literature for LRT, Transit Signal Priority (TSP), and use of traffic simulation in these fields. It is followed by the description of the project and data collection processes. The methods of creating, calibrating, and validating simulation models are given in the Modeling Methodology section. It is followed by the results obtained through microsimulation, and the discussion of the results. Finally, the major conclusions of the study are presented in the last section.

5.3. Literature Review

LRT was developed from other rail transit modes in the 1950s. It was introduced as a separate rail transit mode in North America in 1972. The Transportation Research Board (TRB) Committee on LRT defines LRT as a metropolitan electric railway system which can operate single cars or short trains along exclusive rights-of-way (ROW) at ground level, on aerial structures, in subways or in streets, and it can board and discharge passengers at track or car-floor level (*1*).

To make LRT faster, safer, and more reliable, it is necessary to provide certain priority or preemption to LRVs. Depending on the specific location, traffic operations, and safety requirements, either TSP or preemption for LRT are implemented. TSP is an operational strategy that facilitates the movement of in-service transit vehicles through signalized intersections. It makes transit faster, more reliable, and more cost-effective (*3*). The most important benefits are improved schedule adherence and reliability and reduced travel time for transit. Potential negative impacts consist primarily of delays to vehicular traffic, and these delays have proven to be minimal (*3*).

Preemption is conceptually different from TSP. TSP only modifies the normal signal operations to facilitate transit. Preemption interrupts the normal process for special events, such as emergency vehicles or trains, and serves these vehicles without any delay. A study of the Downtown Baltimore LRT line showed that preemption is not the best option to provide priority for LRT (*4*). This strategy has major negative impacts on vehicular traffic, especially in highly congested areas. The authors proposed an upgrade of the system that would accommodate TSP possibilities enabled in the National Transportation Communications for ITS Protocol (NTCIP) 1211 standard, which allows a number of priority alternatives. The same conclusions were drawn for the Hudson–Bergen LRT line in New Jersey, where preemption was proposed to be substituted by TSP software based on the NTCIP 1211 standard (*5*).

Priority treatment for LRVs follows detection and subsequent priority request activation. Because of the complexity of the LRT priority treatment, a new approach, called predictive priority concept, has been developed to provide priority for LRT on a network level (*6*). The predictive priority concept uses TSP strategies and peer-to-peer communications among intersections. It provides requests for priority service in advance and uses detection information to reduce uncertainty. There are three major goals of this concept (*7*). The first is to provide additional LRV service phase opportunities within the existing signal phasing. The second is to provide communication between intersections that sends information about approaching trains. The third goal is to prepare the intersections for the train without causing additional delay to vehicle or pedestrian traffic, and serve the train quickly, maintaining coordinated signal operation.

Traffic simulation is a powerful tool to analyze different aspects of traffic and transit operations. A study of the Central Phoenix/East Valley LRT Project used VISSIM microsimulation to evaluate three different alternatives for providing priority for LRT: NEMA TS/2 Railroad Preemption, NEMA TS/2 Transit Priority (Green extension/Early green), and Type 2070/VS-PLUS predictive priority (*8*). The study results showed advantages of the predictive priority concept that gave the best balance between LRT benefits and impacts on vehicular traffic. A follow-up study of the same LRT line used VISSIM simulation coupled with Siemens NextPhase virtual traffic controllers to estimate predictive priority abilities of the software that would be implemented in the field (*9*). Another integration of VISSIM simulation software and Siemens NextPhase virtual traffic controller was used to simulate predictive priority for a LRT line in Houston, Texas (*7*). This study showed benefits of this concept and justified its implementation in the field. A study of the 3rd Street LRT in San Francisco, California, compared four options of providing priority for LRVs (*10*). Two options were with fixed time conditions (optimized for LRVs and vehicular traffic, respectively), the third was NextPhase software, and the last was VS-PLUS software. The study showed numerous advantages of NextPhase and VS-PLUS over fixed signal timings. Predictive priority was also tested on the Huntington Avenue LRT corridor in Boston, Massachusetts, using VISSIM and Vehicle Actuated Programming (VAP) (*11*). The advanced detection and subsequent cycle adaptation were proven to provide improvements to light rail travel time and regularity with negligible impacts on other traffic. It was also found to be more effective than simple preemption.

This paper explains how predictive priority works and how different TSP strategies can be combined within this concept. It uses microsimulation and NextPhase SIL traffic controllers to analyze benefits and impacts of LRT operations and predictive priority strategies.

5.4. Project Description

The University LRT line (called the TRAX) connects the University of Utah Campus and Downtown Salt Lake City, providing further transit connections. The line is 5.7 miles long with fourteen stations. The terminals of the line are the Medical Center station, and Salt Lake Central Station. The University TRAX line is shown in Figure 5.1.

This project addresses a University line corridor along the 400 S/500 S streets, from Main Street to 1300 East (Stadium station). This corridor is two miles long with twelve signalized intersections.

During the peak hours, the intersections operate in a coordinated pattern. Along the studied corridor, the eastbound and westbound through movements are coordinated (except at 700 E). During the studied PM peak period, intersections operate on a 120-second cycle. On weekdays, LRT trains operate 18 hours a day on 15-minute headways. Unconditional predictive train priority is enabled at all intersections, except at 700 E. This is a major north-south arterial in this part of the County, and it is estimated that train priority at this intersection would disturb main street coordination. The LRT priority is achieved using overlap intersection phasing, and a series of logical commands defined within the controllers. For every intersection controller, the signal settings have nine major parts:

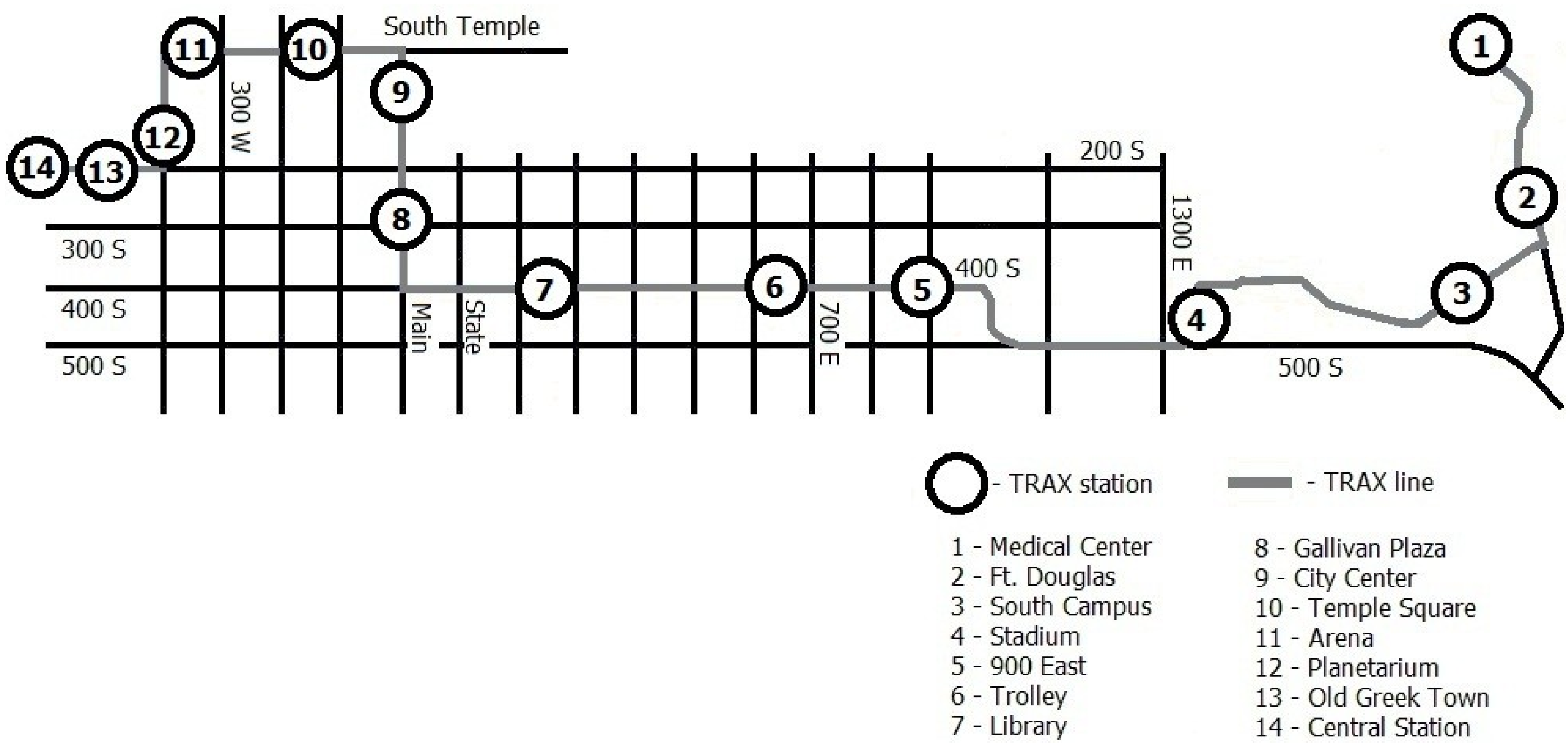


FIGURE 5.1 University TRAX line.

1) General intersection setup
2) LRT priority setup
3) Green extend / Insertion phases
4) Early phase termination
5) Phase rotation strategy
6) Queue jumping
7) Peer-to-peer calls
8) LRT signage
9) Shared lane logic

The general intersection setup defines general inputs (detector actuations), outputs (phases and overlaps), and NEMA TS/2 cabinet functions. LRT priority setup defines basic LRT inputs, such as eastbound and westbound LRT check-in and check-out actuations, LRT advanced and midblock calls. The outputs in this case are so-called state phases (generally, they turn the train approaching and/or "Stay off track" signs on), and they serve as inputs for priority logic activation.

Green extend / Insertion phases logic allows extra green time for LRVs once they have been detected approaching an intersection. There are several phases in phase rings used by the LRT overlap phases, depending on the moment within a cycle when an LRV has been detected. General logic for an intersection in this case is to extend the LRT phase overlaps until the train has cleared the intersection (reached the check-out point). However, this maximum time allowed for the LRVs is limited by the maximum phase time for the inserted phases, or until the LRT detectors have timed out. Usually, if the LRT detector is activated more than 90 seconds, it will be turned off automatically, which prevents LRT calls in a case of a detector failure (such as check-out failure).

If the LRT overlap is timing red when a train is approaching, the Early phase termination logic will terminate all the conflicting phases that are timing green at that moment to allow the LRT overlap to be served with priority. This logic turns the conflicting phases' detectors off, allowing these phases to be terminated once they have reached the minimum green time.

The intersections along this corridor, from State Street to 1300 E, operate with leading left turns and lagging through movements. If the LRT overlap is timing red when a train is approaching an intersection, the Phase rotation strategy will rotate phases for through movements and left turns. This allows the through movements with concurrent LRT overlaps to be served first, and the left turns after that. This is achieved by using additional left turn phases within the ring, which are activated through the Phase rotation strategy.

The LRT overlaps are timing concurrently with the vehicular through movements along the main corridor. However, if a train, and through vehicles, are waiting at the red light at an intersection, the Queue jumping logic allows an earlier start for the train. The start of the through movements will be delayed for 5 seconds, allowing the train to clear the intersection before the vehicles. The intention of this strategy is to improve safety, so that there would be no confused drivers which would attempt a left turn once the through movements get green, and directly conflict the train.

A peer-to-peer call is information about the presence of trains that is being sent between intersections. In that way, an intersection can start the preparation for the approaching trains, turning the train approaching and/or “Stay off track” signs on and going into the transition to allow train priority.

Special outputs from the controller logic settings are dedicated to the LRT signage. They turn the train approaching and/or "Stay off track" signs on when a train is approaching an intersection, and turn them off once the train has cleared it.

The Shared lane logic is a special type of functions active at the shared lane sites. Those are the sites where the left turns and trains share the same lane within the ROW. Along this corridor, those are 1300 E, 1100 E (westbound), 700 E (where the priority is not active), and State Street. This logic activates track clearance, by allowing left turns before the train, if there are left turning vehicles in the shared lane. The "Stay off track" signs are aimed to inform drivers not to enter the sharing left turn lane if a train is approaching. However, it often happens that there are some vehicles in the lane in front of the train. This logic allows discharging of the left turning vehicles, and then allows the train to clear the intersection.

All these strategies are aimed to facilitate LRT along the corridor, with minimum impacts on vehicular traffic. The true benefits and impacts cannot be measured in the field, so they are addressed in this paper through microsimulation.

5.5. Data Collection

A series of data collections were performed along the corridor. These measurements were used to analyze current traffic and transit operations and to develop microsimulation models. The data collected in the field were intersection movement counts for three major intersections (1300 E, 700 E, and State Street), vehicular travel times, and LRT travel times. Intersection movements for other intersections were obtained from VISSIM models of this area that Fehr & Peers created in 2002. These flows were balanced to match the flows collected at the three intersections.

Travel time was measured for both TRAX and vehicular traffic. It was used to determine the Level of Service (LOS) for the vehicular traffic along the corridor. The Highway Capacity Manual (HCM) (*12*) defines LOS on urban streets according to the urban street class and the average travel speed along segments and corridors. The studied corridor belongs to the 3rd urban street class with a typical free-flow speed of 35 miles per hour (speed limit). Table 5.1 shows average travel speeds and travel times for vehicular traffic and TRAX along the corridor and its segments. LOS is calculated for vehicular traffic and given in the table. The data collected in the field were used to create microsimulation models, and to calibrate and validate model parameters.

5.6. Modeling Methodology

LRT operations and the benefits and impacts of the train priority were evaluated through VISSIM microsimulation models. Modeling and evaluations were performed for the PM peak period, from 4:00 to 6:00 PM. Three model scenarios were used in the process: Base Case model, No Priority model, and 700 E Priority model. The simulation network consists of the corridor along 400 S/500 S from 1300 E to Main Street. This corridor is two miles long with twelve signalized intersections.

5.6.1. Base Case Model

The existing network was modeled, calibrated, and validated for field data (network geometry, traffic, and transit operations). The final output from this process was

TABLE 5.1 Arterial Travel Speed, Travel Time and Level of Service: a) Eastbound; b) Westbound

Segments	Vehicular Traffic			TRAX
	Average Speed (mph)	Average Travel Time (s)	LOS	Average Travel Time (s)
Main St. - State St.	14.36	57	D	59
State St. - 200 E	28.37	20	B	26
200 E - 300 E	19.86	49	C	93
300 E - 400 E	27.90	22	B	21
400 E - 500 E	17.61	34	D	25
500 E - 600 E	20.99	30	C	26
600 E - 700 E	17.15	61	D	99
700 E - 800 E	29.32	18	B	22
800 E - 900 E	20.37	39	C	79
900 E - 1100 E	23.72	66	C	56
1100 E - 1300 E	17.92	78	D	114
Total:	**16.17**	**474**	**D**	**620**

a)

Segments	Vehicular Traffic			TRAX
	Average Speed (mph)	Average Travel Time (s)	LOS	Average Travel Time (s)
1300 E - 1100 E	29.68	40	B	48
1100 E - 900 E	24.34	63	B	66
900 E - 800 E	16.28	46	D	64
800 E - 700 E	15.62	45	D	91
700 E - 600 E	28.67	21	B	63
600 E - 500 E	17.16	50	D	26
500 E - 400 E	18.70	39	C	18
400 E - 300 E	15.03	51	D	27
300 E - 200 E	18.64	37	C	81
200 E - State St.	12.12	63	E	47
State St. - Main St.	12.93	64	E	62
Total:	**14.50**	**519**	**D**	**593**

b)

a calibrated and validated simulation model of the existing conditions for the 2-hour PM peak period, with 15-minute build-up time. The same network model was later used in hypothetical scenarios. All VISSIM simulations were run for five random seeds and all the results represent averaged values from five measurements.

The network was created and loaded with traffic according to the data collected in the field in 2008 and 2009. The traffic was generated and distributed on the network using static assignment. The traffic composition was defined as 98% passenger cars and 2% heavy vehicles. The speed distribution for vehicles along the corridor was defined according to the posted speed limits (35 mph along the main corridor) and field observations and measurements.

The field traffic controllers at intersections are Siemens NextPhase 1.7.4 controllers, which determined the choice of the signal control emulator within the VISSIM model. In this research, Siemens NextPhase 1.4.4 SIL Virtual NextPhase (VNP) was used to model the actual traffic control, because it uses the same traffic control algorithm as NextPhase 1.7.4. However, there were some limitations with the VNP controllers. Some of them resulted from the different NextPhase versions, and some were the limitations within the VNP itself. The solution for some of the problems was suggested by the UDOT engineers. For example, the peer-to-peer calls could not be modeled as they are in the field, so for this purpose, the advanced/midblock train detectors were used.

The biggest limitations were at the intersections where left turns and LRT share the same ROW. VNP allows a maximum of fourteen detectors per controller, while at these sites, more detectors are needed. In the field, some of these detectors are not physical detectors, but they are mapped through the controller logic. VNP demands that all VISSIM detectors be physical detectors which exist in the modeled network. In the model, this problem was overcome by defining maximum recall for the main coordinated phases, thus eliminating the need for detection for these phases. Also, the advanced and midblock train detectors (which should be two different calls at these sites) were set to be the same. These actions fixed problems for the shared lane sites.

Controller's operations and structure at the Main Street intersection are very complex, mostly due to the fact that this controller handles eight phases for vehicular traffic, three conflicting LRT movements, and pedestrian operations in the downtown area. VNP was not equipped with all facilities of such complex controllers, so operations of this controller could not be modeled in VNP in the same way as executed in the field. For this reason, the traffic controller for Main Street in the VISSIM model operated slightly different than the field controller. However, considering that this intersection represents a bordering intersection of the model, and that its controller operates in free mode, operations of Main Street traffic controller did not have impacts on other intersections in the model.

The signal timing settings for the intersections were downloaded using UDOT's i2 software, which enables a direct communication link to the field controllers. The controller logic settings were obtained from UDOT. LRT operations were also modeled using field data. Arrivals and departures of the trains were modeled according to the real UTA train schedules for the University line. Also, the passenger boarding and alighting at each LRT station were modeled based on field data, obtained from UTA.

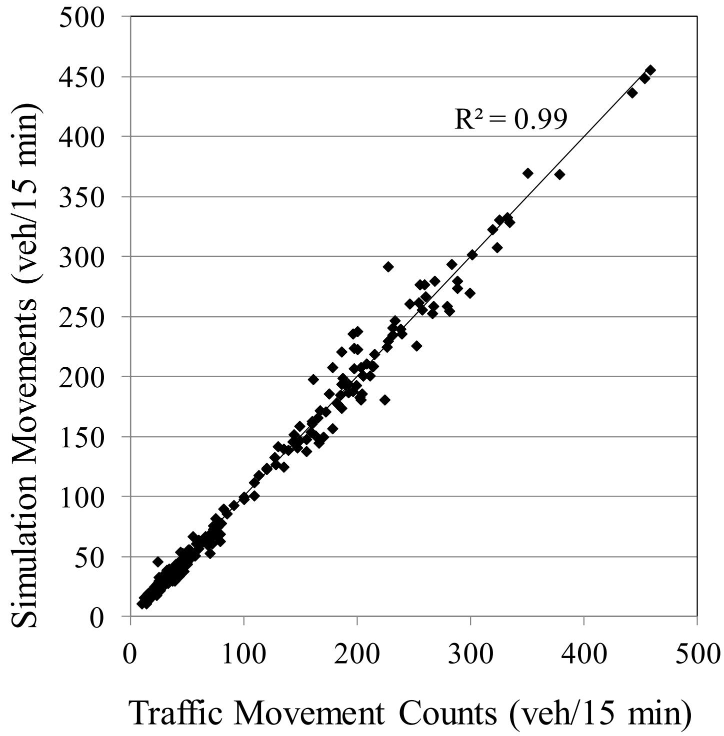
5.6.2. Calibration and Validation of the Base Case Model

Calibration and validation of the simulation model were based on the field traffic data. The model was calibrated for recorded traffic movements at the three major signalized intersections in the network: 1300 E, 700 E, and State Street. Travel times between each pair of signalized intersections were used to validate the model.

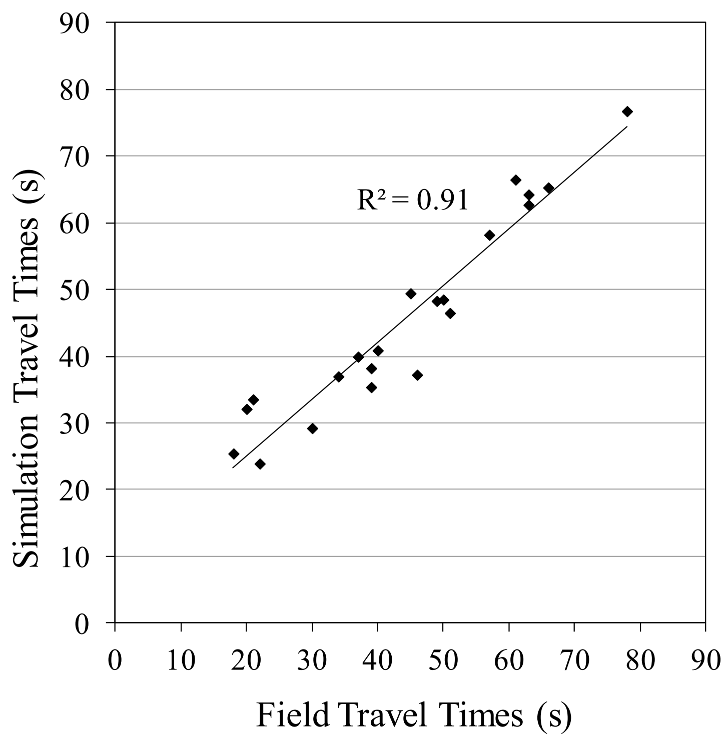
Intersection movements were compared for eight 15-minute intervals. The comparison gave a high R Square value of 0.99, showing a good correlation between the two data sets. The results were checked using a two-tailed T test for paired samples, with a 5% level of confidence (α=0.05). The traffic movements from the field and the simulation were tested, resulting in a T test value of 0.87, which proves good calibration efforts.

The 400 S/500 S corridor was divided into eleven eastbound and ten westbound segments, between each pair of signalized intersections. The field travel times were averaged from fourteen eastbound and fifteen westbound car runs and compared to the simulation travel times. For both directions, the R square value between the two sets was 0.91. The T test value of 0.86 in the westbound and 0.09 in the eastbound direction shows that there was no statistically significant difference between the field and simulation travel times. Figure 5.2 shows calibration and validation results.

To validate TRAX travel times from the simulation, we compared modeled travel times with those from the field for each segment. The R Square value between the two data sets was 0.93. The T test value of 0.48 in the westbound and 0.85 in the eastbound direction shows no statistically significant difference between the data sets.



a) Calibration



b) Validation

FIGURE 5.2 Model calibration and validation.

5.6.3. No Priority Model

The No Priority model was developed to assess impacts of the LRT priority on transit and vehicular traffic. The results from the No Priority model were compared to the Base Case model to justify the use of LRT priority and show that the LRT priority does not have significant negative impacts on vehicular traffic, while bringing significant benefits to LRT operations. The No Priority model represents a copy of the Base Case model, with the only difference that the train priority is turned off. In the VISSIM model, this was accomplished by removing train detection at the intersections.

5.6.4. 700 E Priority Model

In the existing conditions, train priority exists at all intersections along the studied corridor, except at the 700 E intersection. 700 E is a major north – south arterial in this part of the county, and it carries more traffic than 400 S. For this reason, intersection of 400 S and 700 E facilitates coordinated traffic progression in the north – south direction. The LRT priority that was originally designed for this intersection is not active, to prevent major coordination disruptions and increase in delays for the major traffic flows. Train priority strategies for this intersection have been defined by UDOT, while phase splits for the LRT phases were defined as a part of this research’s efforts. For the purpose of evaluating priority strategies at 400 S and 700 E, a VISSIM model with enabled train priority strategies at this intersection was developed. The results from the simulation were compared to the existing conditions to assess all benefits and impacts that such a LRT priority would bring.

5.7. Results

5.7.1. Vehicular Travel Times

Usually, a change in intersection signal timings, and/or providing priority for transit vehicles, can have some impacts on vehicular travel times along a corridor. A comparison of travel times for the three described model scenarios is given in Figure 5.3.

5.7.2. Transit Travel Times

Transit travel time can be considered the single attribute of a transit system about which the LRT riders care the most. It is also important to transit agencies, as an indication of the level of service offered to the LRT riders. The TRAX travel times along the corridor were modeled in the three scenarios and their comparison is shown in Figure 5.4.

5.7.3. Intersection Delays and Level of Service

The best way to assess performance of a signalized intersection is by investigating control delays at the intersection. Table 5.2 shows intersection delays per vehicle and the changes in delays for the two hypothetical scenarios compared to the Base Case.

To further investigate specific impacts of the LRT priority at the 700 E intersection, simulation results for each intersection movement were analyzed individually. This type of analysis can help to identify how the LRT priority impacts individual intersection movements and decide whether it should be enabled at this intersection, or not. Table 5.3 shows movement delays per vehicle and the corresponding LOS for current conditions, the priority scenario, and the change in delays.

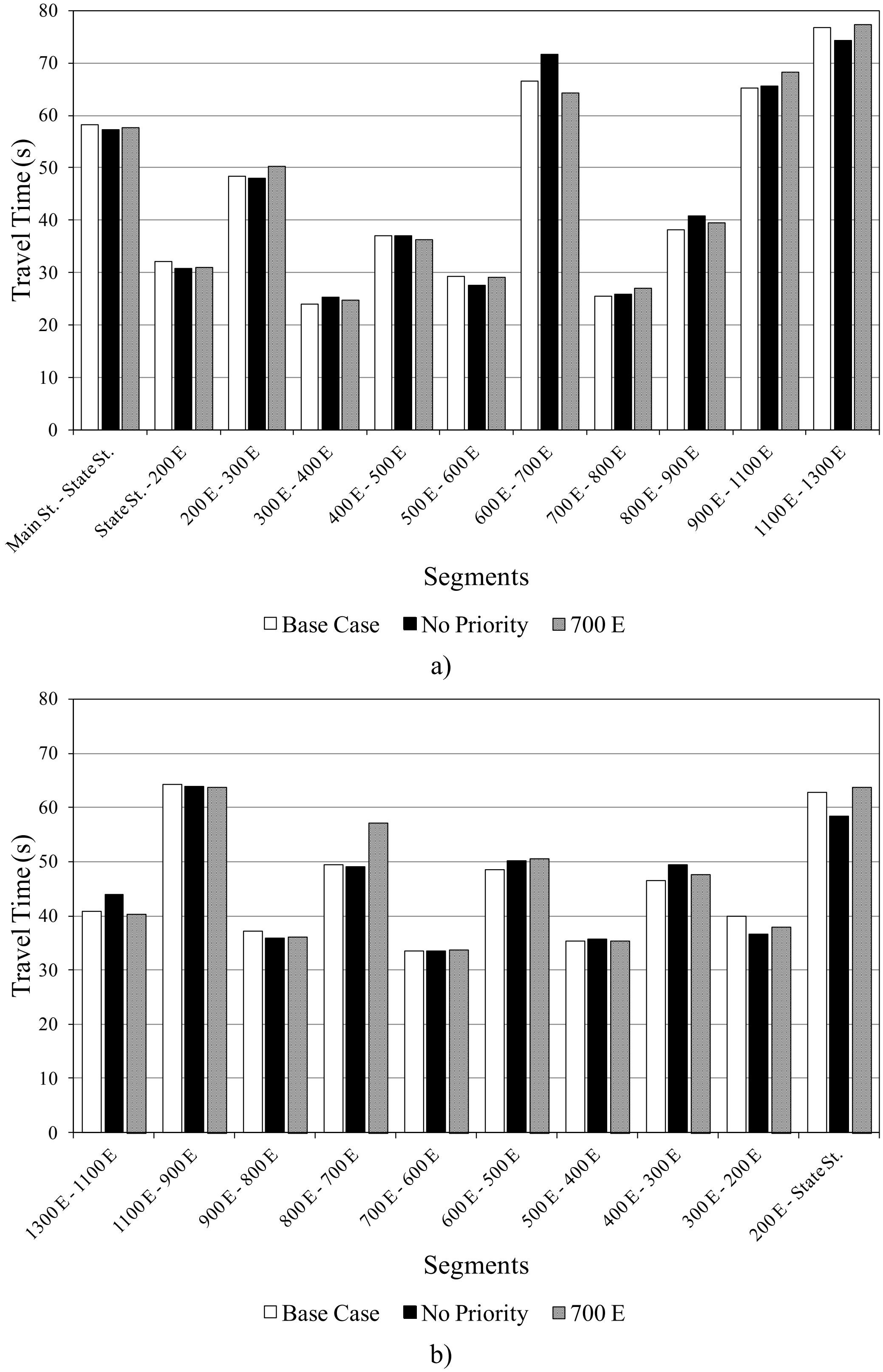
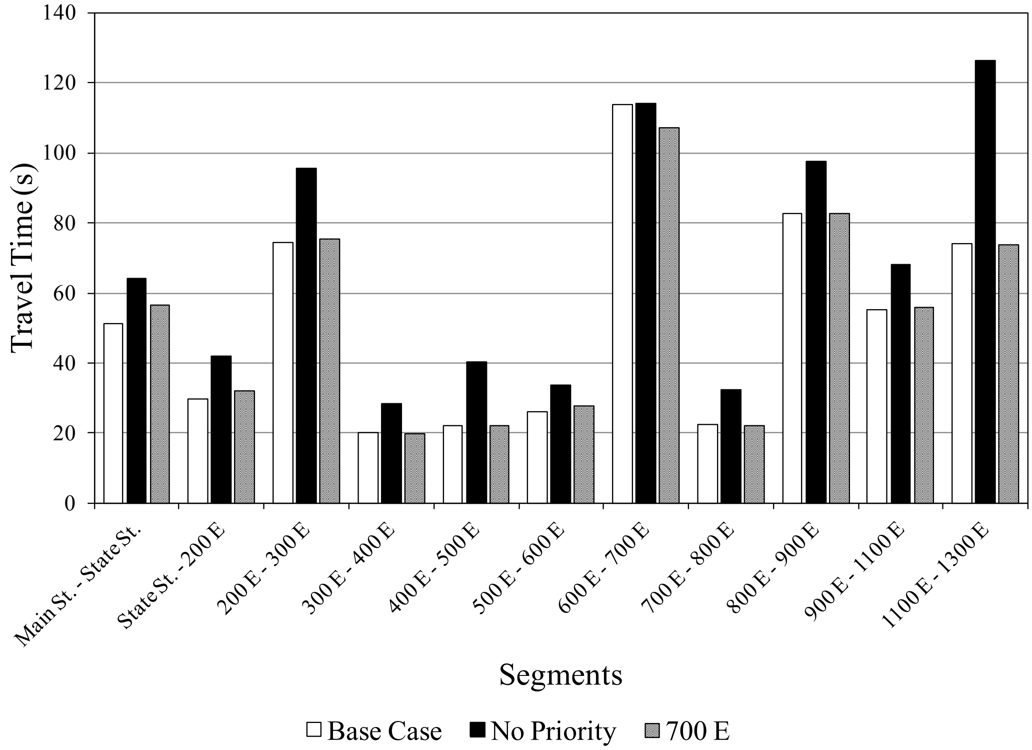
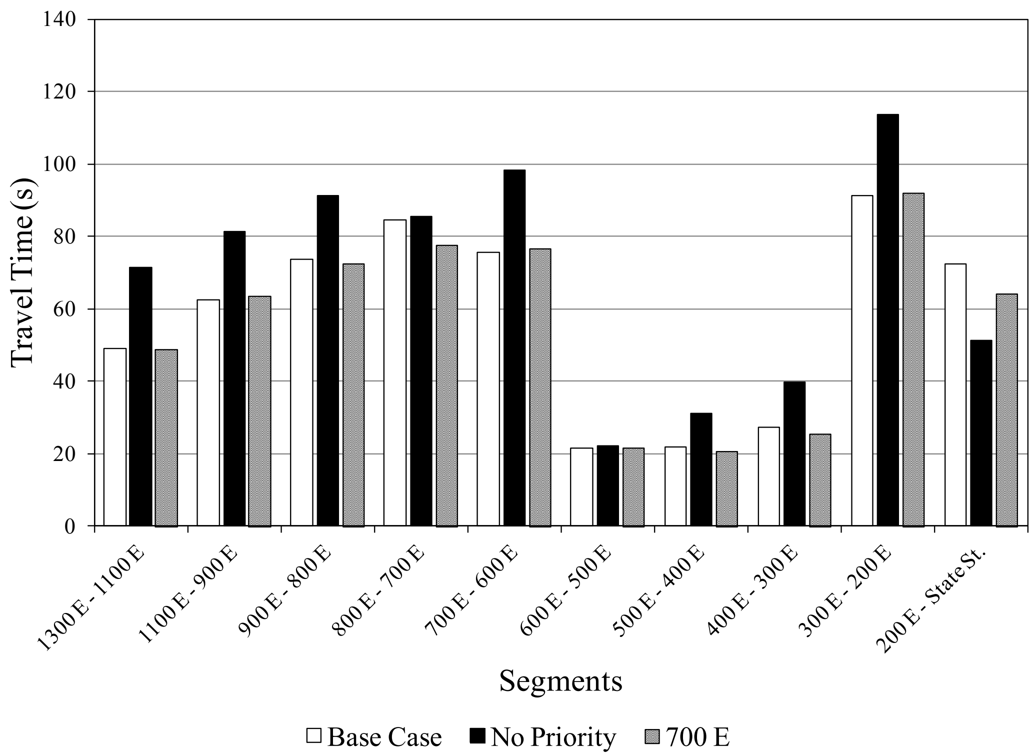


FIGURE 5.3 Vehicular travel times comparison:
a) Eastbound; b) Westbound.



a)



b)

FIGURE 5.4 Transit travel times comparison:
a) Eastbound; b) Westbound.

TABLE 5.2 Average Intersection Delays

Intersection	Mode	Base Case		No Priority			700 E		
		Delay (s)	LOS	Delay (s)	Change (s)	Change (%)	Delay (s)	Change (s)	Change (%)
State St.	Car	39.1	D	34.6	-4.5	-11.5	38.0	-1.1	-2.8
	LRT	37.0	D	36.1	-0.9	-2.4	35.3	-1.7	-4.6
	All	38.8	D	34.8	-4.0	-10.3	37.6	-1.2	-3.1
200 E	Car	30.8	C	27.4	-3.4	-11.0	31.3	0.5	1.6
	LRT	16.5	B	36.9	20.4	123.6	17.3	0.8	4.8
	All	28.6	C	28.8	0.2	0.7	29.2	0.6	2.1
300 E	Car	39.0	D	36.8	-2.2	-5.6	38.7	-0.3	-0.8
	LRT	14.5	B	31.8	17.3	119.3	14.3	-0.2	-1.4
	All	35.5	D	36.1	0.6	1.7	35.2	-0.3	-0.8
400 E	Car	14.1	B	13.7	-0.4	-2.8	14.1	0.0	0.0
	LRT	4.2	A	11.3	7.1	169.0	3.1	-1.1	-26.2
	All	12.7	B	13.3	0.6	4.7	12.5	-0.2	-1.6
500 E	Car	39.4	D	38.6	-0.8	-2.0	41.3	1.9	4.8
	LRT	2.2	A	11.3	9.1	413.6	2.0	-0.2	-9.1
	All	34.1	C	34.7	0.6	1.8	35.7	1.6	4.7
600 E	Car	22.6	C	20.4	-2.2	-9.7	22.0	-0.6	-2.7
	LRT	12.2	B	22.8	10.6	86.9	13.2	1.0	8.2
	All	21.0	C	20.8	-0.2	-1.0	20.7	-0.3	-1.4
700 E	Car	35.1	D	36.9	1.8	5.1	37.7	2.6	7.4
	LRT	63.1	E	56.6	-6.5	-10.3	56.7	-6.4	-10.1
	All	39.1	D	39.7	0.6	1.5	40.4	1.3	3.3
800 E	Car	25.1	C	21.9	-3.2	-12.7	25.2	0.1	0.4
	LRT	11.8	B	25.1	13.3	112.7	11.2	-0.6	-5.1
	All	23.2	C	22.4	-0.8	-3.4	23.2	0.0	0.0
900 E	Car	28.3	C	26.5	-1.8	-6.4	28.2	-0.1	-0.4
	LRT	12.1	B	25.6	13.5	111.6	12.4	0.3	2.5
	All	25.8	C	26.4	0.6	2.3	25.8	0.0	0.0
1100 E	Car	26.1	C	24.8	-1.3	-5.0	26.0	-0.1	-0.4
	LRT	5.8	A	23.0	17.2	296.6	6.2	0.4	6.9
	All	23.0	C	24.5	1.5	6.5	22.9	-0.1	-0.4
1300 E	Car	41.3	D	41.6	0.3	0.7	41.3	0.0	0.0
	LRT	36.3	D	88.5	52.2	143.8	31.5	-4.8	-13.2
	All	40.6	D	48.3	7.7	19.0	39.9	-0.7	-1.7
Total	**Car**	**340.9**	**N/A**	**323.2**	**-17.7**	**-5.2**	**343.8**	**2.9**	**0.9**
	LRT	**215.7**	**N/A**	**369.0**	**153.3**	**71.1**	**203.2**	**-12.5**	**-5.8**
	All	**322.4**	**N/A**	**329.8**	**7.4**	**2.3**	**323.1**	**0.7**	**0.2**

5.8. Discussion

This section provides major findings which are based on the results presented in the previous section. The results are discussed in the same order as they are presented.

5.8.1. Vehicular Travel Times

A comparison of vehicular travel times along the corridor given in Figure 5.3 shows that the general purpose traffic is not affected by the existing LRT priority strategies. Furthermore, it would not be affected if the train priority was given at the 700 E intersection. Some smaller changes in travel times along certain segments are caused by the changes in coordination patterns, as results of presence or absence of train priority. A two-tailed T test for paired samples, with a 5% level of confidence (α=0.05), was used to compare vehicular travel times among the three scenarios for both directions. Test results vary between 0.44 and 0.98, and they show that there is no statistically significant difference among the vehicular travel times.

5.8.2. Transit Travel Times

Opposite from the vehicular travel times, the LRT travel times would experience major impacts if no priority is given. Without the existing priority, LRT travel times would increase approximately 30% in the eastbound and 20% in the westbound direction. The 700 E scenario results show that the eastbound LRT travel times would not be affected, while in the westbound direction, the travel times would decrease approximately 3%. Overall, from the aspect of LRT travel times, providing LRT priority is justified.

TABLE 5.3 Intersection Delay and LOS: Base Case vs. 700 E

Movement	Base Case		700 E		Change in seconds	Percentage Change
	Delay (s)	LOS	Delay (s)	LOS		
EBR	22.0	C	21.2	C	-0.8	-3.6
EBT	48.4	D	46.5	D	-1.9	-3.9
EBL	67.0	E	66.2	E	-0.8	-1.2
WBR	5.9	A	6.4	A	0.5	8.0
WBT	34.4	C	42.6	D	8.2	23.9
WBL	60.9	E	67.9	E	7.0	11.5
NBR	5.2	A	5.4	A	0.2	2.9
NBT	25.9	C	27.8	C	1.9	7.4
NBL	55.2	E	57.9	E	2.7	4.8
SBR	9.9	A	11.9	B	2.0	19.2
SBT	30.3	C	34.4	C	4.1	13.7
SBL	56.4	E	63.8	E	7.4	13.2
EBT LRT	61.1	E	55.6	E	-5.5	-9.1
WBT LRT	65.2	E	57.7	E	-7.5	-11.4
Car	35.1	D	37.7	D	2.6	7.2
LRT	63.1	E	56.7	E	-6.4	-10.3

5.8.3. Intersection Delays and Level of Service

The results on the average intersection delay and changes, given in Table 5.2, can provide an overall assessment on the intersection delays along the corridor. The existing train priority increases delays for vehicles at intersections by approximately 18 seconds (5%) along the entire corridor. The majority of the delay increase is experienced by vehicles on side streets, but some delay is also experienced by vehicles on through and left movements along the main corridor. The increase in delays on side streets is caused by earlier phase terminations/later phase starts when the LRT priority is active. Left turns along the main corridor are impacted by the phase rotation strategy, which delays the start of left turns. The through movements along the main corridor are impacted by the queue jump strategy, which delays the phase starts when this strategy is active, but also by the impacts on coordination. When the LRT priority is active, it forces signal controllers to go through the transition process, which can impact the coordination along the corridor.

The real extent of the priority strategies can be seen when train delays at intersections are analyzed. The existing priority reduces LRV intersection delays by approximately 2.5 minutes (71%) along this corridor. If the train priority was introduced at 700 E, it would slightly increase delays for vehicular traffic at this intersection. The main corridor would be affected by the phase rotation strategy (left turns), and the queue jump strategy (through movements). Along the entire studied corridor, priority at 700 E has almost no impacts on vehicular traffic (0.9% increase in delays), and it slightly decreases intersection delay for trains (approximately 6%).

Detailed delay analysis for 700 E, given in Table 5.3, can give a clearer picture of priority impacts on each intersection movement individually. The results show that the southbound and westbound movements would experience a certain increase in delays (from 8% to 24%). The LOS would remain unchanged, except for the westbound through movement, where it would drop from C to D. Another movement with a slight increase in delays would be the northbound through movement, while changes in delays for all other movements would be unnoticeable. Both light rail movements would experience a decrease in delays from 9% to 11%. Overall, priority at 700 E would increase delays for vehicular traffic approximately 7%, while decreasing delays for trains approximately 10% at this intersection.

5.9. Conclusions

The main conclusion of the study is that the existing priority brings major improvements to LRT, reducing both travel times and delays. Being the major transit line in this part of the County, and carrying a lot of passengers throughout the day, the fast and reliable functioning of this line is essential. This justifies the implemented priority strategies, and impacts it causes to the vehicular traffic are minimal when compared to the benefits it brings to transit.

A big concern of traffic and transit officials is the impacts of train priority at the 700 E intersection. The analysis shows that certain impacts could be expected, but they are minor for the coordinated north-south through movements, so impacts on coordination along 700 E should be minimal. On the other hand, it would bring certain benefits for LRT, so our recommendation is that enabling priority at this intersection should be considered. Two more recommendations have emerged from the study. One is related to the priority calls at those intersections which are adjacent to train stations. The priority call for a certain intersection is placed when the train is at the previous one. However, the train dwells at the station for a certain amount of time (30 to 50 seconds, depending on the station and direction), so the priority call comes too early. This causes the intersection to prepare for the train priority, and the priority is active even if the train is stopped at the station. This minimizes benefits that trains have from the priority, while at the same time impacts all conflicting traffic flows. Sometimes it can even cause the priority to be active during two consecutive cycles, further increasing impacts to vehicular traffic. That is why it is recommended to delay the priority call for those intersections for at least 30 seconds, which would give more time to serve conflicting traffic. This would minimize impacts for vehicles, and the trains would get priority once they clear the station and approach the intersection.

The last recommendation is about the queue jump priority strategy. When trains and vehicles are waiting at the red light, this strategy gives an earlier start to trains through delaying the through movements for 5 seconds. The intention of this strategy is to improve safety, so that there would be no confused drivers which would attempt a left turn once the through movements get green, and directly conflict the train. However, all the left turns along the main corridor are protected, with an improved signage in a case of an approaching train. Also, this line has been in service for a long time, and most of the regular drivers along the corridor are familiar with the traffic patterns. These reasons can justify the idea of removing the queue jump strategy. It would decrease delays for the through movements, and improve coordination along the corridor that is disrupted by the priority. These recommendations should be considered from traffic and transit officials. If there is an agreement to apply these recommendations in the field, we believe it would be beneficial for both vehicular traffic and LRT.

Future work should follow any changes in traffic and transit patterns, such as changes in traffic volumes, signal retiming, transit ridership, train schedules etc. The microsimulation models which were developed for the study can be used to test any priority strategy, changes in signal timings, or even design changes prior to their implementation in the field. It can help to decide whether or not the proposed changes are justified.

5.10. Acknowledgements

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CHAPTER 6

IMPLEMENTATION OF TRANSIT SIGNAL PRIORITY AND PREDICTIVE PRIORITY STRATEGIES IN ASC/3 SOFTWARE-IN-THE-LOOP SIMULATION

6.1. Abstract

This paper presents an application of the Advanced System Controller series 3 (ASC/3) Software-in-the-Loop (SIL) simulation in Transit Signal Priority (TSP) implementation and analysis. Two options of the ASC/3 controller software are examined: built-in TSP features, and the controller logic processor as a means to develop custom-defined Predictive Priority Strategies (PPS). The study is using a VISSIM simulation model of a planned transportation network with a Bus Rapid Transit (BRT) line in West Valley City, UT. The results show major possibilities for SIL simulation for transit priority analysis. Since the logic processor is not available in the simulation software's traffic control emulators, SIL simulation can offer many options for custom-defined traffic control strategies beyond the standard operations. All of the described strategies can be implemented in the field controllers, without the need for new hardware or software.

6.2. Introduction

Microsimulation software packages are successfully applied for all types of traffic signal control simulation. Implementation of traffic control logics in traffic microsimulation provides modeling of both pretimed and actuated traffic control. In most traffic microsimulation packages, the traffic control system is emulated within the software. This is called Emulator-in-the-Loop (EIL), because this emulator does not have any counterpart in the field. EIL can also be achieved through the Vehicle Actuated Programming (VAP) interface. In this case, the traffic control mechanism is developed in a programming language (Visual Basic, C++, Java, and alike) and is called through the microsimulation interface. VAP allows for a more customized traffic control than the built-in EIL controllers can offer.

Emulated control is later replaced with the real traffic control hardware. One or more signal controllers are integrated with the traffic microsimulation software. This enhancement of communication between the traffic simulator and traffic controller requires that an actual hardware controller be driven by the simulation through a process called Hardware-in-the-Loop simulation (HIL) (*1*).

The most advanced form of traffic simulator and traffic controller interface is Software-in-the-Loop simulation (SIL) (*2*). The SIL concept allows the simulation of several virtual controllers under simulation software without the cost and complexity of physical controllers and controller-interface devices. SIL can also run in a mode that is faster than real-time, facilitating simpler and less time-consuming simulation runs, something that HIL concept cannot provide.

6.2.1. HIL Concept

In the HIL concept, the data generated from the simulation model vehicle detectors are first sent to the controller interface device (CID) (*2*, *3*). The CID provides the interface between the computer that is running the traffic microsimulation and the discrete logic levels of the control pins in the traffic controller. After receiving the data through the CID, the traffic controller analyzes the input, determines the status of signal control according to its control logic, and sends the data about the signal control status back to the simulation model through the CID. During every simulation time step, the data exchange is conducted between the simulation model, the CID, and the traffic controller. The CID functions as a bridge between the electrical signals of the computer and those of the traffic signal controller. The real traffic controller determines the status of traffic signals through the CID integration, replacing the internal control logic emulated in the simulation software. Figure 6.1 shows the HIL concept of the Econolite's Advanced System Controller series 3 (ASC/3) traffic controller and VISSIM microsimulation.

6.2.2. <u>SIL Concept</u>

The SIL concept is developed to overcome the major HIL problems related to the complexity of physical controllers and CID devices. The main idea of the SIL is that both the simulation program and virtual traffic controller are running on the same computer, with an interface that allows communication between them.

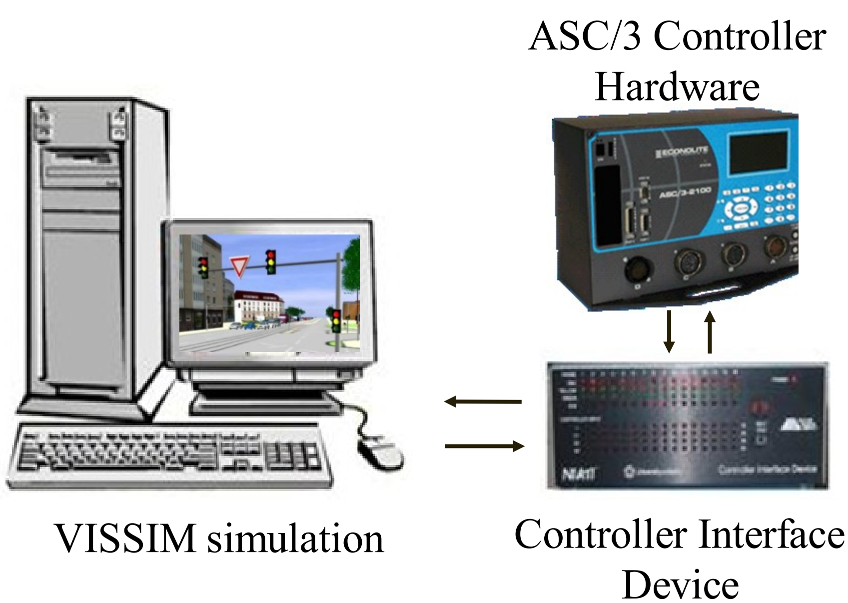

FIGURE 6.1 ASC/3 – VISSIM HIL concept.

Two well-known SIL applications have been developed in recent years: Siemens's NextPhase, which is linked to CORSIM and VISSIM, and ASC/3 which connects to VISSIM (*2, 3*). PTV America and Econolite Control Products, in cooperation with the University of Idaho (the MOST Project), have developed an ASC/3 SIL controller embedded in VISSIM (*2*).

Several virtual ASC/3 controllers can be integrated with VISSIM. These controllers are compliant with the National Transportation Communications for Intelligent Transportation Systems Protocol (NTCIP) and operate from the same code base as the ASC/3 hardware controllers, making them nearly identical. This is a big advantage over emulators and custom-developed VAP simulation traffic controllers, because all the features and options are the same in both versions.

However, SIL does not have the features of a real controller that supports the communications within a cabinet or centralized traffic signal system. This is the major disadvantage of the SIL concept. The ASC/3 – VISSIM SIL concept is given in Figure 6.2.

6.2.3. Priority Strategies

Transit Signal Priority (TSP) is an operational strategy created to improve service and decrease costs of public transit (*4*). It is a control strategy that facilitates the movement of in-service transit vehicles through signalized intersections. In the simplest type of TSP, called passive TSP, the priority operates continuously, based on the knowledge of transit routes and ridership patterns. Passive TSP does not require a transit detection or priority request, and it does not need any special hardware or software

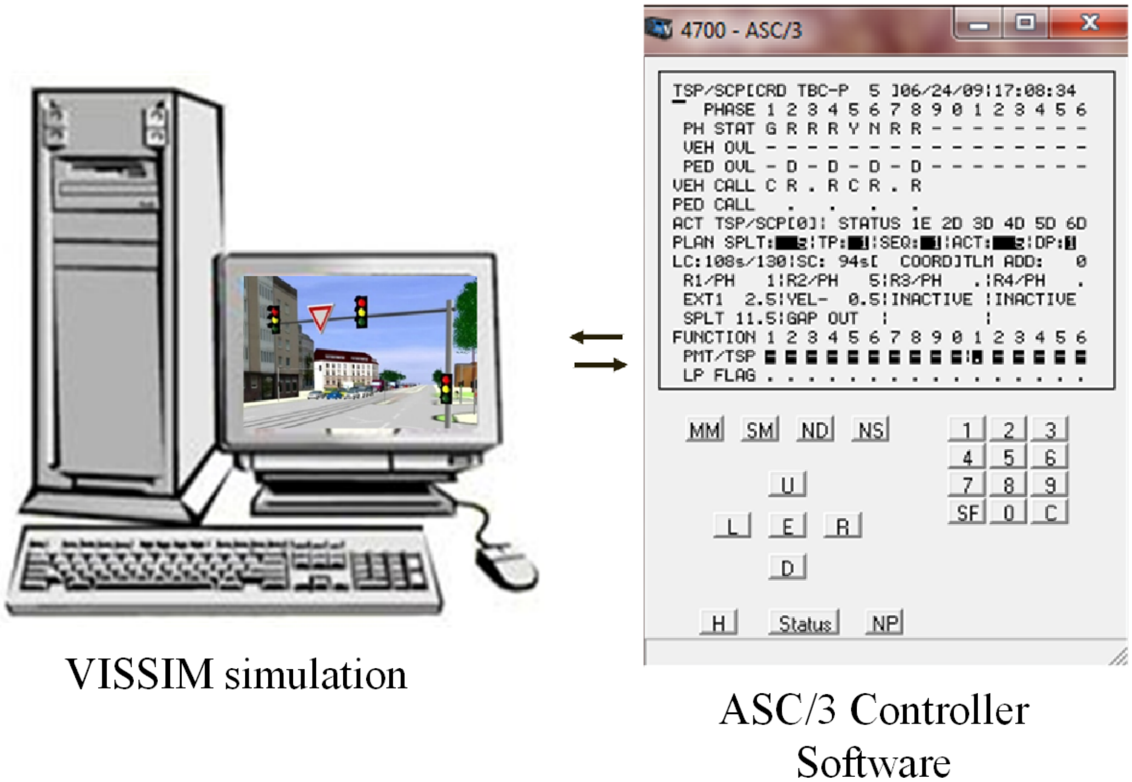

FIGURE 6.2 ASC/3 – VISSIM SIL concept.

installations. It can be very efficient when transit operations are predictable.

The priority treatment can also be provided for transit vehicles following detection and subsequent priority request activation. This type of TSP is called active priority and it can be deployed in different manners within the specific traffic control environment. Active TSP can be achieved as unconditional or conditional. Unconditional active TSP provides priority treatment for every transit vehicle that sends a TSP request. Conditional TSP provides priority only to transit vehicles that meet certain conditions, such as running behind the schedule, or having a certain number of passengers on board. Active TSP can be implemented through the green extension, where the green time for the TSP movement is extended when a TSP equipped vehicle is approaching. This strategy only applies when the signal is green for the approaching transit vehicle. Another common strategy is the early green or red truncation strategy, which shortens the green time of the preceding phases to expedite the return to green for the transit phase. This strategy only applies when the signal is red for the approaching transit vehicle. Some other active TSP strategies in use are phase rotation, phase insertion, actuated transit phase, or a combination of strategies.

The most comprehensive TSP strategy is adaptive TSP. It takes into consideration the trade-offs between transit and traffic delay and allows adequate adjustments of signal timing by adapting the movement of the transit vehicle and the prevailing traffic condition. It can also consider some other transit inputs, such as whether the transit vehicle is running on time or is late, the headway between two successive transit vehicles, and the number of passengers on board.

Another way to improve transit progression is to use some of the Predictive Priority Strategies (PPS) (*5 - 7*). In general, PPS combines different TSP strategies and the communication between intersection controllers to provide a high level of priority for transit vehicles with minimum disruptions for other traffic. This form of signal control for transit priority was first developed for trains on urban transportation networks. PPS uses a series of advanced detectors to track the vehicle that needs to be prioritized and allows a green signal progression for that vehicle at intersections. The signal controller in this case functions in accordance with the set of control logic commands that are activated once the transit vehicle is detected approaching the intersection. This is an adaptive traffic signal control strategy that allows the adjustment of signal phases to transit vehicles present in the intersection area. PPS application to rapid transit modes (Light Rail or Bus

Rapid Transit) could achieve uninterrupted progression of these vehicles through the intersections, without waiting for the signal changes. So far, PPS has only been used for rail transit modes.

The ASC/3 controller software has built-in TSP features for green extension and early green strategies. Custom defined TSP strategies can be achieved through the application of the ASC/3 logic processor. Control logics can be adjusted for different types of priorities for public transit.

This paper presents the application of ASC/3 SIL in VISSIM simulation for an evaluation of TSP and PPS for Bus Rapid Transit (BRT), compared to the transportation network without any type of priority for transit vehicles. The goal of the paper is to explore the capabilities of ASC/3 SIL software in providing different transit priority strategies. This is achieved through back to back comparisons and analysis of three different microsimulation model scenarios of a base case network, which is a planned BRT line in West Valley City, Utah. The paper is organized in six sections. The following section describes the ASC/3 controller and its SIL applications in more details. The third section describes the network and simulation models. It is followed by the results and discussion sections. Finally, the major conclusions of the study are given in the last section.

6.3. ASC/3 Controller and Software-in-the-Loop Applications

ASC/3 controller is the latest series of Advanced System Controllers manufactured by Econolite Control Products (*8*). It offers a vast array of control, coordination, preemption and TSP features, extent detector options, and communication abilities. It is also able to support very complex signal timing settings through the Logic Processor. A total of 100 logic commands can be accessed directly in the controller, and additional 100 logic commands can be enabled through a special extension file. These commands can control and combine all the controller features and emulate external logic that is not included in the default settings.

The ASC/3 controller has been frequently used for HIL simulations. However, since HIL simulation is very time and resource demanding, a better solution is found in ASC/3 SIL application developed for VISSIM simulation software (*2, 3*). ASC/3 SIL runs from the same code base as the hardware controllers, and they perform identically. This application provides many opportunities for evaluating and analyzing traffic control strategies that could be performed within a simulation environment. Once all the tests have been done in the simulation, the control strategies can be easily transferred to the field controllers by simply uploading the data base file created during the simulation. This saves time, effort, and costs that could be induced if the changes and testing are performed on a field controller. Another big advantage of the ASC/3 SIL is that it can run ten times faster than the real time during simulation, which greatly reduces the time needed to test a scenario in VISSIM. The ASC/3 SIL is comprised of the Data Manager (or Database Editor), Traffic Control Kernel, Controller Front Panel Simulator, and VISSIM DLL Interface components (*9*). The Data Manager is an application for managing the controller timing data of the simulated controllers while in the Operating System (OS) environment. This software is more intuitive and easier to use than the controllers' normal front panel data entry screens. The database file for the ASC/3 SIL and an actual ASC/3 controller are identical. The Traffic Control Kernel is the virtual

ASC/3 core software that operates under OS. It encompasses all internal processing that occurs between the mapped field inputs that are passed from VISSIM and subsequent calculation of commanded field outputs that are passed to VISSIM. This interface guarantees consistency in traffic control operation between the simulated ASC/3 SIL running under VISSIM and a physical ASC/3 controller. The Controller Front Panel Simulator is a Graphical User Interface (GUI) designed to simulate the 16 line x 40 character display and keypad found on the ASC/3 physical controller. This GUI permits the display of status and data along with the changing of all user data settings within the simulated ASC/3 controllers running under VISSIM. Any changes made to the controller settings are stored in the simulated controller's database. The VISSIM DLL interface couples the ASC/3 simulated controllers to VISSIM. It allows VISSIM to pass detector and other Input/Output functions to the simulated ASC/3 controllers and to receive controller status information back.

The ASC/3 controller offers built-in preemption and TSP functions. The latest version of the ASC/3 SIL has these options too, making it possible to test different priority strategies in simulation. Studies that looked into the ASC/3 SIL priority showed the capabilities of the software (*9 - 11*).

Another ASC/3 option that has just begun to emerge in the SIL application is the logic processor. Logic commands offer additional external control logic that does not exist in the default settings. A study that used ASC/3 SIL logic processor to evaluate phase termination based on traffic flow data under recurring congestion showed advantages of external control logic and the ability of ASC/3 SIL to apply user-defined logic controls (*12*).

This study explores the capabilities of the built-in TSP strategies, but also in a greater manner the use of the logic processor for custom-defined PPS. A series of logic commands was developed in order to define extensive priority strategies, beyond those that are offered within the controller software.

6.4. Project Description

6.4.1. Project Network

A network selected for this study is a part of a future BRT line along 5600 W street in West Valley City, Utah. The planned 5600 W BRT line involves five miles of dedicated center-running BRT lanes from 2700 S to 6200 S, with a total of six BRT stations, as shown in Figure 6.3. This type of layout with center-running transit lines is convenient for analyzing different aspects of TSP, from both operational and safety points of view. The network was originally developed as a part of a research project to analyze traffic and transit impacts for the target year 2030, when big changes in land development, traffic, and transit patterns are expected (*13*). VISSIM models were developed, calibrated, and validated for current traffic conditions in 2009, and projected traffic volumes for 2030. Here we apply the 2030 estimates, with some small changes in traffic and transit patterns to make them more suitable for the focus of the research. Three modeling scenarios were used for the study: No TSP scenario, TSP scenario, and PPS scenario. All scenarios are customized to work in the ASC/3 SIL simulation environment.

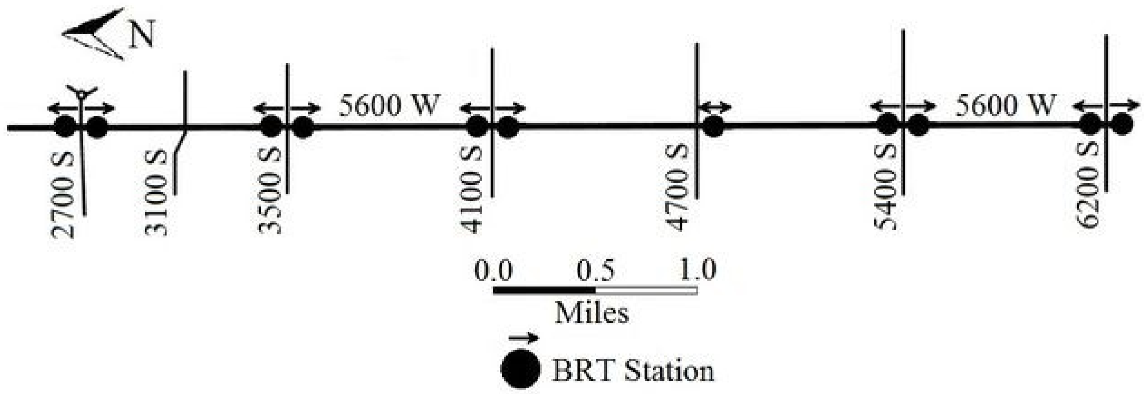

FIGURE 6.3 5600W Base case network

6.4.2. <u>No TSP Scenario</u>

This scenario introduces the center-running BRT line without any special control treatment. The seven traffic signals are optimized in SYNCHRO for the 2030 volumes and road design, and these signal timings are incorporated in ASC/3 SIL. The headway for the BRT buses is set to 8 minutes in each direction. This is less than the planned 10-minute headways, but it was changed in order to assess priority strategies in more details. The duration of the VISSIM simulation was 2 hours, for the 4:00 to 6:00 PM peak period, with a 15-minute build-up time. The outputs from the simulation were averaged from ten simulation runs with different random seeds. All the same settings were used for the other two scenarios, with an addition of TSP or PPS.

6.4.3. <u>TSP Scenario</u>

This is an extension of the No TSP scenario. Green extension and early green (red truncation) strategies were defined using the built-in ASC/3 TSP features. For each intersection, the TSP settings were as follows:

- Maximum green extension for BRT phases: 10 s
- Maximum red truncation for conflicting through movements: 10 s
- Maximum red truncation for (all) conflicting left turns: 5 s

With these TSP strategies, the total gain for BRT buses was up to 20 seconds, depending on the moment during a cycle when the bus approached the intersection. TSP was defined as unconditional priority, which means that every BRT bus that was in the network sent a TSP request and was serviced accordingly.

6.4.4. PPS Scenario

This scenario is using custom-developed priority strategies achieved through a series of logic commands defined within the ASC/3 SIL logic processor. Four basic strategies were defined and simulated:

- Intersection communication
- Green extension
- Early phase termination
- Phase rotation

The main postulate of PPS was that none of the phases (vehicular or pedestrian) could be omitted, no matter which strategy was active at the time. This would provide normal intersection functions, with some modifications in operations when the priority was active.

Intersection communication is one of the postulates of the predictive priority. It means that the information about the presence of transit vehicles is sent from one intersection to the adjacent ones, giving them enough time to prepare for the approaching transit vehicle and serve it with minimum delay, and minimum impacts on vehicular traffic. The intersection communication could not be achieved directly with the ASC/3 SIL controllers. Instead, detectors for the downstream intersection were set at the previous one, simulating a signal that would be sent between the intersections. This signal was then delayed based on the spacing between the intersections, which is half a mile to one mile for the given network, and the presence of transit stops in the midblock section. This signal would become active when the transit vehicle was 200-300 feet from the intersection. It would then activate one (or a combination) of priority strategies, depending on the moment within a cycle when the vehicle appeared and the current phase timings at the intersection.

Green extension provides extra green time for a transit vehicle which is approaching an intersection, and it is estimated that it will not clear the intersection before the green ends. The built-in TSP strategies for green extension work the same way, but in this case, this was achieved through control logic. This logic works as follows:

IF

BRT detected AND

BRT phases timing green

THEN

Turn off minimum recall for all phases

Turn off detectors for conflicting phases

Call MAX 2 maximum green time for BRT phases

Set coordination free

Set green for BRT phases

The IF condition for this strategy is that a BRT bus is detected approaching the intersection, and the green time for BRT phases is currently on. The logic makes sure that the bus will clear the intersection before the green ends. The first step is to turn off detector actuations for all conflicting phases, and to turn off minimum phase recalls (if any). This will clear calls for conflicting phases and give an opportunity to the BRT phases to continue timing green. However, the duration of this green time can be constrained by the maximum phase green time, or the coordination offset. The ASC/3 controller has an option of defining three maximum green times, where MAX 1 is the standard maximum green, while MAX 2 and MAX 3 are optional, and they can be activated through the control logic. For the purpose of green extension, the logic refers to the MAX 2 time for the BRT phases, which is in this case defined large enough to allow the BRT bus to clear the intersection on green. To maintain the coordination offset, the controller can also end the green time of the coordinated phases at a certain point during the cycle. For the analyzed network, the coordinated phases at each intersection are the same as the BRT phases. This can conflict with the green extension, so the logic sets coordination to "free-running" until the bus has cleared the intersection. Setting the control logic to dwell in green ensures that the BRT phases will remain green while the conditions are satisfied. When the bus crosses the stop bar, this logic will become inactive and the intersection will return to normal operations.

Early phase termination is the same strategy as early green or red truncation. If a BRT bus is detected approaching an intersection, and some of the conflicting phases are timing green at that moment, this strategy will terminate those phases to provide an earlier start for the BRT green phases. The logic that drives this strategy is as follows:

IF

BRT detected AND

Conflicting phase is timing green

THEN

Turn off detectors for that conflicting phase

When the detectors for the conflicting phase are turned off, the call for that phase will end and it will stop timing green once it reaches the minimum phase green time. It should also be noted that this strategy will not omit any phase, whether or not that phase is on a minimum recall. The logic becomes active once the phase green starts timing, which ensures minimum green for that phase. If one of the conflicting pedestrian phases, which time concurrently with the through movements, is active at the same time as this logic, the conflicting phases will end when the pedestrian phase turns red. It means that active pedestrian phases will not terminate earlier. Turning the conflicting phases' detectors off is a better option than forcing their green time to end (which can also be achieved through the control logic), because in this case the conflicting phases will gap out, which will not disturb intersection coordination, and is more fair to the vehicles on the conflicting movements.

Phase rotation is a strategy that changes the phase sequence in order to serve a transit phase faster. In this case, only the phases on the same intersection approach (within the same control barrier) can be rotated. Along the studied BRT corridor, the phase sequence is defined as leading left turns and lagging through movements for all intersections. All BRT phases time concurrently with vehicular through phases. If a BRT vehicle is detected at the intersection while the side street through movements have green, phase rotation will change the sequence for left and through phases at the main approach, allowing the through movements to be served first, and left turns after that. This strategy reduces delays for transit vehicles, but it can also have safety benefits in a case of a transit lane that is positioned in the middle of the roadway (especially for exclusive BRT or Light Rail Transit - LRT lanes). It reduces conflicts between transit and left turning vehicles. The logic behind this strategy is as follows:

IF

BRT detected AND

Left turns on BRT approach timing red

THEN

Select alternative sequence with leading through and lagging left phases

If a BRT bus is detected, the second IF command checks the timing for the left turn phases on the main (BRT) approach. If these left turn phases are red at the moment, two options are possible: either the through phases on the main approach (and BRT phases) are green, or any phases (left or through) on the side approach are green. In the first case, if the BRT phases and the concurrent through movements are green, the bus will clear the intersection and deactivate phase rotation. However, if some of the side street phases are green at the moment, it means that both left turns and through (and BRT) movements on the main intersection approach are timing red. The normal phase sequence on the main approach in this case would start with leading left turns on the main approach, and will lag through and BRT phases. But in this case, the logic will be active and it will select an alternative sequence, which is defined as leading through phases and lagging left turns, serving the BRT phases first. This alternative sequence has to be predefined in the ASC/3 SIL configuration and referred to through a proper logic command. The early phase termination strategy will always be active along with phase rotation.

Depending on the moment when a BRT vehicle is detected approaching an intersection and current phase timings, either one or a combination of strategies will become active, giving a certain priority to the BRT vehicle. As in the previous scenario, priority for the BRT vehicles was unconditional. Figure 6.4 shows an example of applying ASC/3 logic processor in PPS programming.

6.5. Results

For the purpose of evaluating different priority strategies, VISSIM was coded to record travel times (vehicular and BRT), intersection performance, signal phase timings, and overall network performance. The results were collected for each scenario and then compared.

6.5.1. Travel Times

Travel times for vehicles and BRT buses were measured for segments between each pair of signalized intersections, in the northbound and southbound direction. A comparison of the average travel times for the 2-hour simulation period between scenarios is given in Table 6.1.

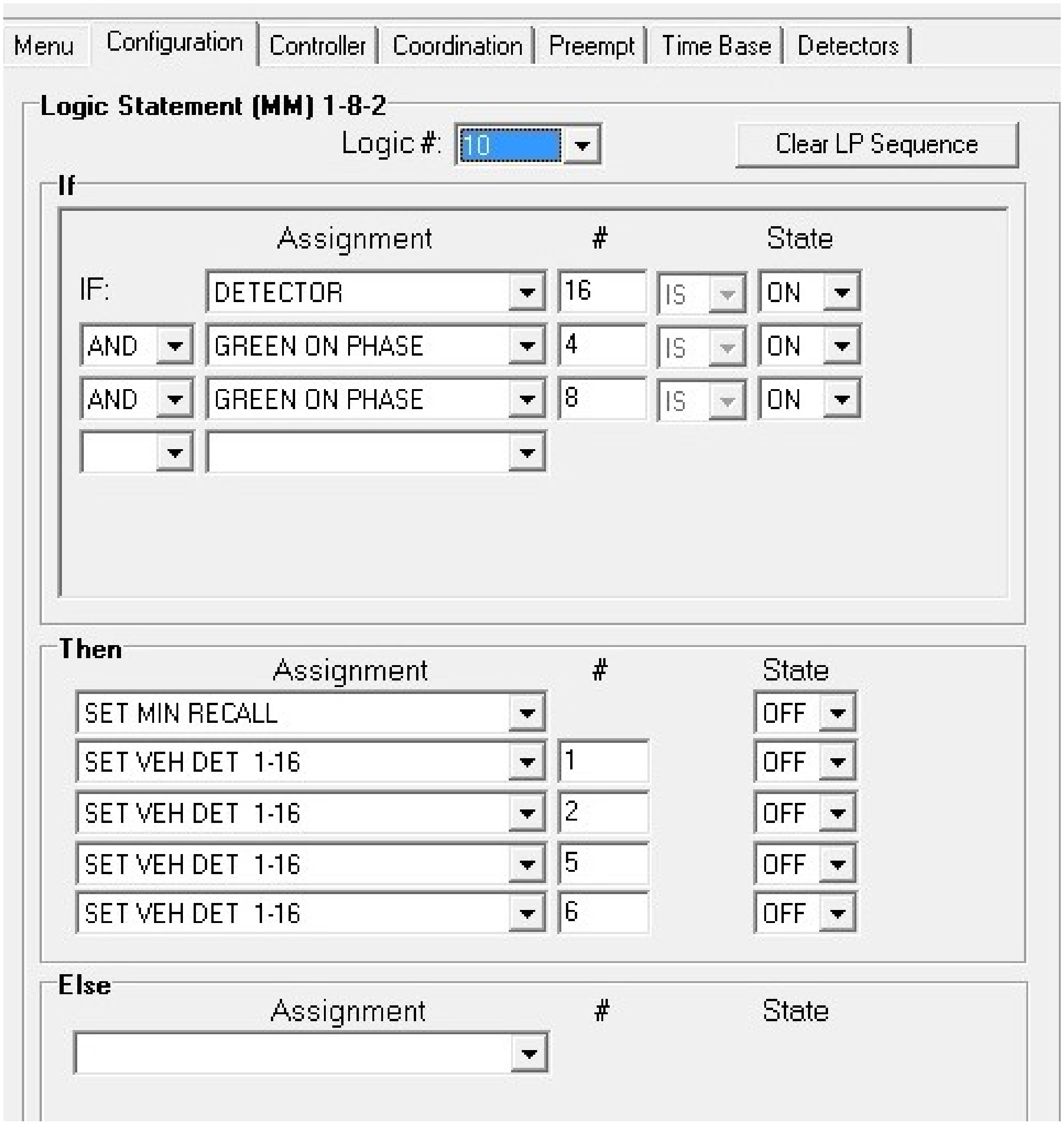

FIGURE 6.4 ASC/3 logic processor GUI: PPS application example.

TABLE 6.1 Travel Times for BRT and Vehicles in Seconds

SB	NO TSP		TSP		PPS	
Segment	BRT	Cars	BRT	Cars	BRT	Cars
2700 S - 3100 S	135	61	114	61	109	64
3100 S - 3500 S	69	71	66	71	59	81
3500 S - 4100 S	209	111	193	111	173	130
4100 S - 4700 S	199	113	173	113	175	132
4700 S - 5400 S	187	127	184	127	171	128
5400 S - 6200 S	196	119	181	119	169	128
Total	**995**	**602**	**912**	**602**	**856**	**663**

NB	NO TSP		TSP		PPS	
Segment	BRT	Cars	BRT	Cars	BRT	Cars
6200 S - 5400 S	141	135	141	136	145	139
5400 S - 4700 S	223	118	207	119	177	132
4700 S - 4100 S	136	136	125	134	111	131
4100 S - 3500 S	163	160	164	162	145	147
3500 S - 3100 S	87	64	87	64	91	71
3100 S - 2700 S	59	70	58	70	58	72
Total	**809**	**683**	**782**	**685**	**727**	**692**

6.5.2. <u>Intersection Performance</u>

The intersection performance parameters, such as vehicle and person delays, stop delay, number of stops, and average and maximum queues were measured for each movement at each intersection. The example shown in Table 6.2 is for the intersection of 5600 W and 4100 S, which is the intersection in the middle of the network. The comparison is given for the number of vehicles, vehicle delays, and number of stops per vehicle for the 5:00 – 6:00 PM peak hour. Table 6.3 shows weighted performance measures on the intersection level for all intersections in the network and the entire analysis period (4:00 – 6:00 PM). The results are given separately for private cars and BRT vehicles.

TABLE 6.2 4100 S Intersection Performance Comparison

	NO TSP			TSP			PPS		
Movement	Veh.	Delay (s)	Stops	Veh.	Delay (s)	Stops	Veh.	Delay (s)	Stops
NBT	334	29.5	0.79	333	28.1	0.79	333	27.6	0.64
NBL	131	44.0	0.90	130	49.1	0.93	130	64.6	1.00
SBT	926	12.2	0.24	923	10.9	0.22	918	24.9	0.50
SBL	186	80.0	1.06	187	77.7	1.06	189	70.4	1.00
EBT	824	41.5	0.80	823	43.1	0.82	832	46.3	0.86
EBL	174	40.9	1.14	174	42.8	1.16	176	43.2	1.18
WBT	895	41.8	0.81	894	43.2	0.82	905	46.4	0.85
WBL	169	37.5	1.09	168	39.8	1.11	170	41.0	1.15
BRT NB	8	46.7	0.81	8	37.0	0.63	8	21.8	0.11
BRT SB	7	64.7	0.99	8	47.7	0.85	8	28.5	0.36
Total	**3653**	**34.9**	**0.71**	**3647**	**35.4**	**0.71**	**3669**	**40.7**	**0.79**

SB – southbound; NB – northbound; WB – westbound; EB – eastbound;
L – left movement; T – through movement;

TABLE 6.3 Network Level Intersection Performance

Mode	Intersection	Number of vehicles			Delay per vehicle (s)			Stops per vehicle		
		No TSP	TSP	PPS	No TSP	TSP	PPS	No TSP	TSP	PPS
Cars	2700 S	7805	7805	7802	28.1	28.2	29.6	0.82	0.82	0.82
	3100 S	7104	7105	7100	31.6	32.1	32.9	0.67	0.68	0.70
	3500 S	10173	10170	10121	35.9	36.7	43.9	0.86	0.86	0.92
	4100 S	8713	8708	8740	31.9	32.6	38.5	0.73	0.73	0.83
	4700 S	7237	7236	7233	29.7	30.0	33.4	0.74	0.76	0.88
	5400 S	8313	8316	8305	32.4	33.2	36.1	0.81	0.82	0.83
	6200 S	7896	7902	7919	30.2	30.4	33.3	0.75	0.75	0.77
BRT	2700 S	30	30	30	29.0	25.3	21.8	0.32	0.27	0.13
	3100 S	30	30	30	17.5	7.0	6.5	0.31	0.17	0.15
	3500 S	30	30	30	35.4	35.0	21.9	0.71	0.62	0.14
	4100 S	30	31	31	54.6	41.5	25.5	0.88	0.72	0.25
	4700 S	30	30	30	60.7	40.4	25.6	0.61	0.35	0.34
	5400 S	30	30	30	31.7	30.9	25.9	0.32	0.38	0.26
	6200 S	29	29	29	49.4	35.3	24.9	0.62	0.47	0.26

6.5.3. Signal Phase Timings

TSP strategies can impact phase timings, especially green time durations. In order to assess these impacts for each of the three examined strategies, VISSIM was coded to provide signal status during each 0.1 seconds. Table 6.4 shows an example of average phase time durations during a cycle for each scenario for the intersection of 5600 W and 4100 S.

6.5.4. Network Performance

Impacts and benefits of the different priority strategies can be assessed on a network-wide level. Table 6.5 presents a network performance comparison for the most relevant parameters.

TABLE 6.4 Signal Phase Durations in Seconds

	No TSP			TSP			PPS		
Sig. group	Green	Yellow	Red	Green	Yellow	Red	Green	Yellow	Red
1 - SBL	14.5	3.0	112.5	14.2	2.9	112.9	15.9	3.2	110.8
2 - NBT	47.3	4.5	78.1	48.9	4.5	76.5	47.1	4.9	78.0
3 - WBL	8.5	2.9	118.6	8.5	3.0	118.5	8.4	2.9	118.7
4 - EBT	38.3	4.0	87.7	36.9	4.0	89.1	36.4	4.0	89.6
5 - NBL	11.2	2.9	115.9	10.7	2.8	116.5	9.9	2.9	117.2
6 - SBT	50.8	4.5	74.7	52.6	4.5	72.8	54.1	4.6	71.3
7 - EBL	8.1	2.9	118.9	7.8	2.8	119.4	8.8	2.9	118.3
8 - WBT	38.6	4.0	87.4	37.9	4.0	88.1	36.0	4.0	90.0

TABLE 6.5 Network Performance

Parameter	NO TSP	TSP	PPS
Average delay per vehicle (s)	57.9	58.7	65.2
Average stopped delay per vehicle (s)	42.0	42.7	48.2
Average number of stops per vehicles	1.4	1.4	1.5
Average speed (mph)	23.7	23.6	22.7

6.6. Discussion

6.6.1. Travel Times

The travel time results for each scenario show greater BRT travel times in the southbound than in the northbound direction. This is expected, because southbound is the PM peak direction with more transit riders and greater station dwell times. An implementation of different TSP strategies improves BRT travel times. The results show that the green extension/early green strategies reduce BRT travel times by 8% in the southbound and 3% in the northbound direction when compared to the No TSP scenario. PPS strategies result with even more travel time savings for BRT vehicles: 14% in the southbound and 10% in the northbound direction.

Green extension/early green strategies have no impact on vehicular travel times along the main corridor. However, PPS strategies tend to increase vehicular travel times in the southbound direction by approximately 10%. These travel times are impacted by the phase rotation and disturbances in intersection coordination caused by some of the PPS strategies.

6.6.2. Intersection Performance

An analysis on the intersection level shows that the green extension/early green strategies have certain benefits, while PPS offers significant savings in delays and number of stops for BRT in both directions (see Tables 6.2 and 6.3). Built-in TSP reduces BRT delays in the range between 1% (at 3500 S) and 60% (at 3100 S). Reductions in BRT delays in the PPS scenario vary from 18% (at 5400 S) to 63% (at 3100 S).

TSP strategies have minimal impacts on vehicular traffic along the main corridor and on side streets. Along the main corridor, PPS causes increase in delays mostly for vehicles on southbound through movements and some left turns. These movements are affected by the phase rotation and impact that PPS has on coordination. Some smaller impacts of PPS are noticed on side street movements. The increase in car delays caused by PPS varies from 4% (at 3100 S) to 22% (at 3500 S).

6.6.3. Signal Phase Timings

TSP and PPS have no major impacts on green phases' durations, as given in Table 6.4. However, the distribution of green times changes slightly with different strategies. Both TSP and PPS increase green times for through movements along the corridor. Green times are generally decreased for all other movements along the corridor and on side streets. It can also be observed that the green phase durations for some left turns are impacted by the phase rotation strategy in PPS.

6.6.4. Network Performance

Network performance results given in Table 6.5 are similar to the single intersection results. It can be seen that TSP has no major impacts on the network-wide level performance, while PPS increases average delays per vehicle by about 12%. The reason for this is the same as in the case of a single intersection (phase rotation and impacts on coordination).

All the compared parameters show the same impacts/benefits that different strategies have on vehicular traffic and BRT.

6.7. Conclusions

The main goal of this paper is to explore the capabilities of the ASC/3 SIL software in analyzing different types of transit priority strategies, through the built-in ASC/3 TSP features and custom-developed priority achieved through the logic processor. This paper shows that the ASC/3 SIL has proven to be a very powerful tool for this type of analysis. It means that for a real network, these analyses can be performed in a simulation environment, removing the risk of any errors that could be made in an on-site controller programming. The ASC/3 SIL has an option of creating a data base file that can be directly transferred into a field controller.

The results from the base case network are hypothetical, because they are given for assumed transit operations. In order to record different aspects of the defined priority strategies, transit frequencies were increased beyond those that would be implemented in the planned network. This increased the impact that transit and TSP had on vehicular traffic. However, the results are significant because they can offer some guidelines for defining optimal priority strategies. In this paper, they are used to show the extent of the ASC/3 TSP features and user-programmable priority strategies. It is demonstrated that SIL can be applied to real-life transportation networks and used for traffic optimization purposes.

The main contribution of this work is that it provides a set of instructions for different levels of TSP that can be directly programmed into the field traffic controllers, without the need to install new hardware or software. The analysis was performed for ASC/3 controllers, but it can be easily customized for any other type that supports TSP options and/or logic processor.

Some of the topics for future research in this area can be as follows:

- A combination of built-in TSP features and logic processor to optimize transit priority strategies for a given transportation network
- Application of the logic processor to conditional and adaptive transit priority
- Application of the logic processor in resolving two or more conflicting priority requests
- Application of the logic processor in analyzing traffic control strategies that are beyond standard operations

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CHAPTER 7

EVALUATION OF TRANSIT SIGNAL PRIORITY OPTIONS FOR THE FUTURE 5600 W BUS RAPID TRANSIT LINE IN WEST VALLEY CITY, UT

From Zlatkovic, M., A. Stevanovic, P. Martin, and I. Tasic. Evaluation of Transit Signal Priority Options for the Future 5600 W Bus Rapid Transit Line in West Valley City, Utah. Presented at the 91st Annual Meeting of the Transportation Research Board, January 2012, Washington, D.C., and accepted for publication in the 2012 series of the *Transportation Research Record: Journal of the Transportation Research Board* (forthcoming)

7.1. Abstract

This paper presents an analysis of different Transit Signal Priority (TSP) strategies for a future Bus Rapid Transit (BRT) corridor in West Valley City, UT. The goal is to find the optimal TSP strategy for estimated and planned traffic and transit operations. The study uses VISSIM microsimulation software in combination with ASC/3 Software-in-the-Loop (SIL) simulation. Four different models were used in the analysis: No TSP, TSP, TSP with phase rotation, and Custom TSP. The results show that TSP with phase rotation and Custom TSP can both be considered for implementation. TSP with phase rotation brings significant benefits for BRT, with minimum impacts on vehicular traffic. Custom TSP brings major benefits for BRT in terms of travel times, delays, and stops. However, this strategy has more impacts on vehicular traffic. Custom TSP is an advanced strategy that still needs examination and improvement. The study provides a set of instructions on how the described strategies can be implemented in the field traffic controllers.

7.2. Introduction

With overall traffic growth on urban highways and arterials, congestion is becoming a significant problem with major negative impacts on transit vehicles. These negative impacts often result in increased travel times, poor reliability, unpredictable on-time performance, bus crowding, and longer waiting times at transit stops. Transit agencies have introduced new, high capacity rapid transit modes, such as Bus Rapid Transit (BRT), and enhanced transit operational strategies.

Transit signal priority is an operational strategy that facilitates the movement of in-service transit vehicles through signalized intersections. It makes transit faster, more reliable, and more cost-effective (*1*). The most important benefits are improved schedule adherence and reliability and reduced travel time for transit, which increase the quality of transit service. Potential negative impacts consist primarily of delays to the vehicular traffic. These delays have proven to be small (*1*).

The goal of the paper is to identify the optimal TSP strategy for planned traffic and transit operations for a future BRT corridor in West Valley City, UT. The objective is a trade-off between transit preferences and traffic impacts in terms of travel times and delays. This is achieved through analysis and comparison of four different models: No TSP, TSP, TSP with phase rotation, and Custom TSP. The study is using VISSIM microsimulation software in combination with ASC/3 Software-in-the-Loop (SIL) traffic controllers.

The paper is organized in six sections. The following section provides a literature review on TSP strategies. The third section describes the modeling methodology and project network. It is followed by the results and discussion sections. Finally, the major conclusions of the study are given in the last section.

7.3. Literature Review

TSP is an operational strategy created to improve service and decrease costs of public transit (*1*). In the simplest type of TSP, or passive TSP, the priority operates continuously, based on knowledge of transit route and ridership patterns. Passive TSP does not require a transit detection or priority request, and it does not need any special hardware or software installations. It can be very efficient when transit operations are predictable.

The priority treatment can also be provided for transit vehicles following detection and subsequent priority request activation. This type of TSP is called active priority strategy and it can be deployed in different ways within the specific traffic control environment. An active TSP can be implemented through the green extension. A green time is extended for the TSP movement when a TSP-equipped vehicle is approaching. This strategy only applies when the signal is green for the approaching transit vehicle. There is also an early green or red truncation strategy, which shortens the green time of preceding phases to expedite the return to green for the transit phase. This strategy only applies when the signal is red for the approaching transit vehicle.

The most comprehensive TSP strategy is adaptive TSP. It takes into consideration the trade-offs between transit and traffic delay and allows adequate adjustments of signal timing by adapting the movement of the transit vehicle and the prevailing traffic condition. It can also consider some other inputs, such as whether the transit vehicle is running on time or late, the headway between two successive transit vehicles, and the number of passengers on board.

A TSP implementation is not a straightforward process. Each TSP deployment faces certain problems, which depend on the actual traffic and transit system. Factors which affect a TSP implementation can be categorized in two major categories: traffic-related factors and transit-related factors (*2, 3*).

The detection technology is another important part of a TSP system (*3*). It must detect a transit vehicle and transfer the information to the traffic controller in real time. The communication technology can be light, sound, laser, and radio frequencies. The most widely used are Dedicated Short Range Communication (DSRC) technologies. GPS can also be very effective because it can provide quality data about transit operations.

The effects of TSP are proven in the field and documented in numerous studies. TSP has been shown to reduce transit travel times, vehicle delays, and person delays. This leads to an increased reliability and on-time performance, and a reduction in fuel consumption and emissions (*1* - *3*).

Another way to improve transit progression is to use some of the advanced transit vehicle detection strategies such as Predictive Priority Strategy (PPS) (*4* - *6*). This form of signal control for transit priority was first developed for trains on urban transportation networks. PPS uses a series of advanced detectors to track the vehicle that needs to be prioritized and allows a green signal for that vehicle at the intersections. The signal controller in this case functions in accordance with the set of control logic that is usually activated once the transit vehicle is detected approaching the intersection. This is an adaptive traffic signal control strategy that allows the adjustment of signal phases to transit vehicles present in the intersection area. PPS application to rapid transit modes (Light Rail or BRT) could achieve uninterrupted progress of these vehicles through the intersections, without waiting for the signal changes. So far, PPS has only been used for rail transit modes.

The ASC/3 controller software has built-in TSP features for green extension and early green strategies. The latest version of the ASC/3 SIL has these options too, making it possible to test different priority strategies in simulation. Custom defined TSP strategies can be achieved through the application of the ASC/3 logic processor. Control logic can be adjusted for different types of priorities for public transit. Studies that looked into the ASC/3 SIL priority show the capabilities of the software (*7 - 9*).

This paper provides a comparison of different TSP strategies that can be applied to a test location: a future BRT line along the 5600 W corridor in West Valley City, UT. The study considers delays for BRT and passenger cars and determines the optimal strategy from both aspects. It also provides a set of instructions for different levels of TSP that can be directly programmed into the field traffic controllers. Although the tests were performed in the ASC/3 controller, these strategies can be programmed into any traffic controller that supports TSP and/or logic processor features.

7.4. Modeling Methodology

7.4.1. Test-Case Network

A network selected for this study is a part of a future BRT line along 5600 W street in West Valley City, Utah. The planned 5600 W BRT line involves 5 miles of dedicated center-running BRT lanes from 2700 S to 6200 S, with a total of 6 BRT stations, as shown in Figure 7.1. There are 7 signalized intersections along this corridor that operate in actuated-coordinated mode. Traffic control and signal timings were optimized for predicted traffic volumes for the year 2030. Detailed information on predicted traffic volumes and planned transit operations can be found in (*10*). All intersections introduce one separate right and left turn lane, and two lanes for through movements along the corridor. Since the planned BRT line will be positioned in the center of the roadway, for the purpose of safety, all left turns along the corridor were designed as protected only. This type of layout with center-running transit lines is convenient for analyzing different aspects of TSP, from both operational and safety

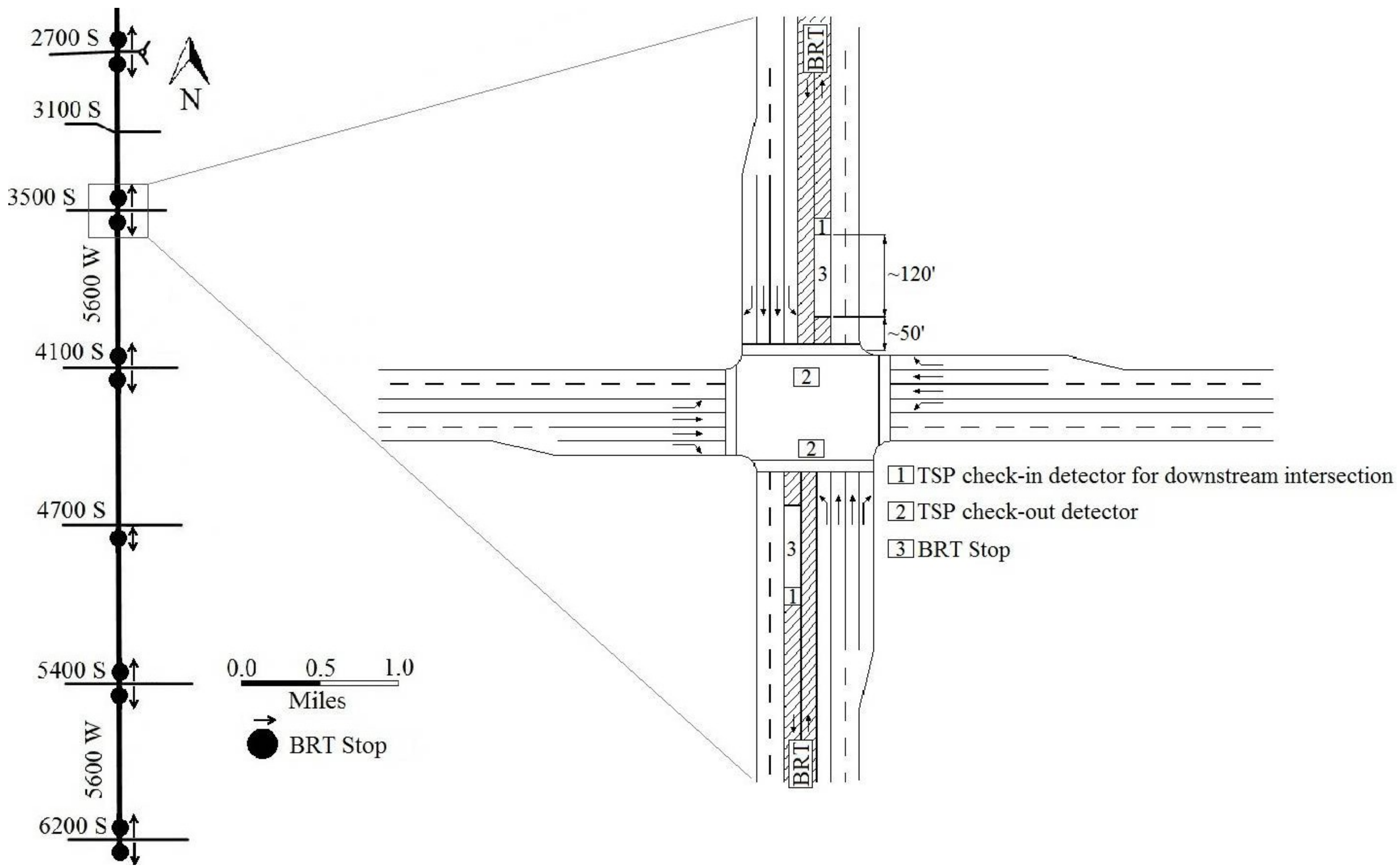


FIGURE 7.1 5600W Test-case network.

points of view. This study evaluates future BRT and traffic operations along the segment from 2700 S to 6200 S, where the full phase BRT is planned for implementation. Four models were developed for the purpose of this study: No TSP model, TSP model, TSP model with phase rotation, and Custom TSP model. All scenarios were customized to work in the ASC/3 SIL simulation environment.

7.4.2. Calibration and Validation

VISSIM models were developed, calibrated, and validated for current traffic conditions in 2009, and projected traffic volumes for 2030. Here we apply the 2030 traffic estimates, and the planned service frequency for the BRT line.

The calibration results are shown in Figure 7.2, where the estimated intersection movements are plotted against the movements obtained from the simulation. The R-square value of more than 0.99 shows a good correlation between the data sets.

7.4.3. No TSP Model

This scenario introduces the center-running BRT line without any special control treatment. The seven traffic signals were optimized in SYNCHRO for the 2030 volumes and road design, and these signal timings were incorporated in ASC/3 SIL. The headway for the BRT buses was set to 10 minutes in each direction, according to the planned frequency for this line. Passenger activity was also modeled according to the estimated data. The duration of the VISSIM simulation was 2 hours, for the 4:00 to 6:00 PM peak period, with a 15-minute build-up time. The outputs from the simulation were averaged from 5 simulation runs with different random seeds. All the same settings were used for

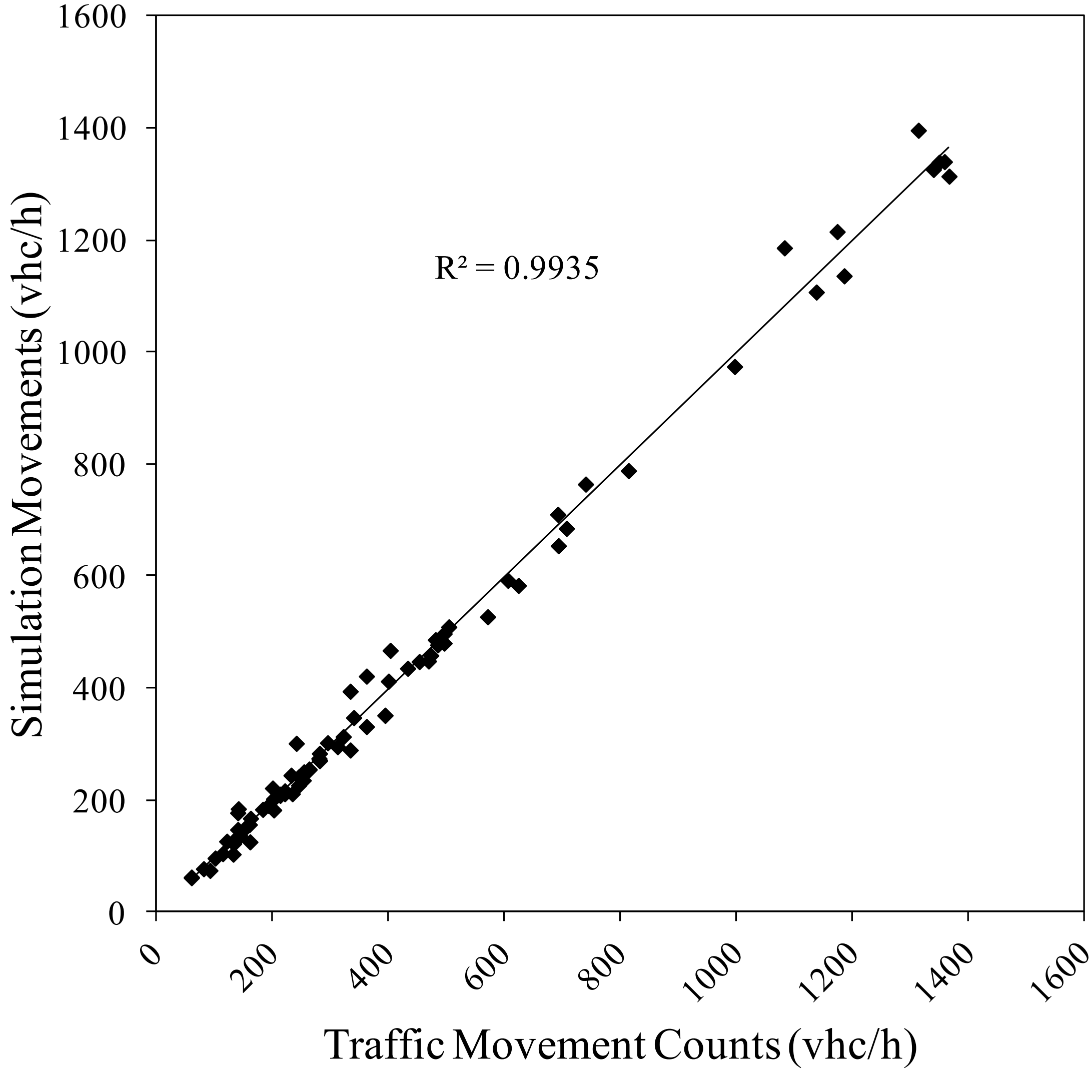


FIGURE 7.2 VISSIM model calibration.

the other two scenarios, with an addition of different TSP strategies, as described below.

7.4.4. TSP Model

This is an extension of the No TSP model. Green extension and early green (red truncation) strategies were defined using the built-in ASC/3 TSP features. For each intersection, the TSP settings were as follows:

- Maximum green extension for BRT phases: 10 s
- Maximum red truncation for conflicting through movements: 10 s
- Maximum red truncation for (all) conflicting left turns: 5 s

With these TSP strategies, the total gain for BRT buses was up to 20 seconds, depending on the moment during a cycle when the bus approached the intersection. TSP was defined as unconditional priority, which means that every BRT bus that was in the network sent a TSP request and was served accordingly.

Intersection communication is one of the postulates of the advanced transit vehicle detection. It means that the information about the presence of transit vehicles is sent from one intersection to the adjacent ones, giving them enough time to prepare for the approaching transit vehicle and serve it with minimum delay, and minimum impacts on vehicular traffic. The intersection communication could not be achieved directly with the ASC/3 SIL controllers. Instead, detectors for each downstream intersection were set at its respective upstream intersection, in that way simulating a signal that would be sent between the intersections. All transit stops, except 4700 S northbound, are located on the far side of intersections. The transit detectors were located at transit stops, and were activated once the BRT bus left the stop (see Figure 7.1 for typical intersection layout). In that way, the transit detection accounted for the station dwell time, which was 30-60 seconds, depending on the stop. The detection signal was then delayed based on the spacing between the intersections, which is half a mile to one mile for the given network. This signal would become active when the transit vehicle was 200-300 feet from the intersection. It would then activate one (or a combination) of priority strategies, depending on the moment within a cycle when the vehicle appeared and the current phase timings at the intersection. Advanced detection was also used in the other two TSP models.

7.4.5. TSP Model with Phase Rotation

This model is set up as the previous TSP model with the addition of phase rotation. This strategy changes the phase sequence in order to serve a transit phase faster. In this case, only the phases on the same intersection approach (within the same control barrier) can be rotated. Along the studied BRT corridor, the phase sequence is defined as leading left turns and lagging through movements for all intersections. All BRT phases time concurrently with vehicular through phases. If a BRT vehicle is detected at the intersection while the side street through movements have green, phase rotation will change the sequence for left and through phases at the main approach. This allows the through movements to be served first, and left turns after that. This strategy reduces delays for transit vehicles, but it can also have safety benefits in a case of a transit lane that is positioned in the middle of the roadway (especially for exclusive BRT or Light Rail Transit - LRT lanes). It reduces conflicts between transit and left turning vehicles. The logic behind this strategy is as follows:

IF

BRT detected AND

Left turns on BRT approach timing red

THEN

Select alternative sequence with leading through and lagging left phases

If a BRT bus is detected, the second IF command checks the timing for the left turn phases on the main (BRT) approach. If these left turn phases are red at the moment, two options are possible: either the through phases on the main approach (and BRT phases) are green, or any phases (left or through) on the side approach are green. In the first case, if the BRT phases and the concurrent through movements are green, the bus will clear the intersection and deactivate phase rotation. However, if some of the side street phases are green at the moment, it means that both left turns and through (and BRT) movements on the main intersection approach are timing red. The normal phase sequence on the main approach in this case would start with leading left turns on the main approach, and will lag through and BRT phases. But in this case, the logic will be active and it will select an alternative sequence, which is defined as leading through phases and lagging left turns, serving the BRT phases first. This alternative sequence has to be predefined in the ASC/3 SIL configuration and referred to through a proper logic command. The early green strategy will always be active along with phase rotation.

7.4.6. Custom TSP Model

This scenario is using custom-developed priority strategies created through the ASC/3 SIL logic processor. This model does not use built-in TSP, but the priority is achieved through a series of logic commands. Four basic strategies were defined and simulated:

- Advanced transit vehicle detection
- Green extension
- Early green
- Phase rotation

The main principle is that none of the phases (vehicular or pedestrian) could be omitted, no matter which strategy was active at the time. This would provide normal intersection functions, with some modifications in operations when the priority was active.

The green extension strategy was achieved through the following logic commands:

IF

BRT detected AND

BRT phases timing green

THEN

Turn off minimum recall for all phases

Turn off detectors for conflicting phases

Call MAX 2 maximum green time for BRT phases

Set coordination free

Set green for BRT phases

The IF condition for this strategy is that a BRT bus is detected approaching the intersection, and the green time for BRT phases is currently on. The logic ensures that the bus clears the intersection before the green ends. The first step turns off detector actuations for all conflicting phases, and any minimum phase recalls. This clears calls for conflicting phases and enables the BRT phases to continue timing green. However, the duration of this green time can be constrained by the maximum phase green time, or the coordination offset. The ASC/3 controller has an option of activating three maximum green times. MAX 1 is the standard maximum green, while MAX 2 and MAX 3 are optional. For the purpose of green extension, the logic refers to the MAX 2 time for the BRT phases, which in this case is large enough to allow the BRT bus to clear the intersection on green. To maintain the coordination offset, the controller can also end the green time of the coordinated phases at a certain point during the cycle. This can conflict with the green extension. The logic sets coordination to "free running" until the bus clears the intersection. Setting the control logic to dwell in green ensures that the BRT phases remain green while the IF conditions are satisfied. When the bus crosses the stop bar, this logic deactivates and the intersection returns to normal operations. The travel time of any BRT bus from the time when the TSP call becomes active to the intersection is about 10 seconds. This corresponds to the previously defined TSP settings. However, if a BRT bus is delayed along the midblock section for a longer time period than predicted, this logic will still hold the green time for that bus until it reaches the intersection.

If a BRT bus is detected approaching the intersection while the conflicting phases are timing green, the early green strategy terminates those phases and provides an earlier start for BRT. The logic that drives this strategy is as follows:

IF

BRT detected AND

Conflicting phase is timing green

THEN

Turn off detectors for that conflicting phase

When the detectors for the conflicting phase are turned off, the call for that phase will end and it will stop timing green once it reaches the minimum phase green time. It should also be noted that this strategy will not omit any phase, whether or not that phase is on a minimum recall. The logic becomes active once the phase green starts timing, which ensures minimum green for that phase. If one of the conflicting pedestrian phases, which time concurrently with the through movements, is active at the same time as this logic, the conflicting phases will end when the pedestrian phase turns red. It means that active pedestrian phases will not terminate earlier. Turning the conflicting phases' detectors off is a better option than forcing their green time to end (which can also be achieved through the control logic), because in this case, the conflicting phases will gap out, which will not disturb intersection coordination, and is more fair to the vehicles on the conflicting movements.

Phase rotation strategy is also a part of the custom TSP model and it is explained in the previous model description. It works for custom TSP in the exact same way and the same logics are applicable.

Depending on the moment when a BRT vehicle is detected approaching an intersection and current phase timings, either one or a combination of strategies will become active, giving a certain priority to the BRT vehicle. As in the previous scenario, priority for the BRT vehicles was unconditional.

Table 7.1 provides a comparison of TSP strategies for the three TSP scenarios. It

TABLE 7.1 Comparison of TSP Strategies

Scenario	TSP	TSP PR	Custom TSP
Max green extension (s)	10	10	29 – 60* (47)
Max red truncation for conflicting through movements (s)	10	10	18 – 45* (34)
Max red truncation for conflicting left turns (s)	5	5	5 – 36* (16)
Phase rotation	No	Yes	Yes

PR – Phase Rotation

* depending on intersection; values in parenthesis are average values

shows a big difference between Custom TSP and the other two scenarios. Custom TSP provides a much higher level of priority for transit vehicles.

7.5. Results

For the purpose of evaluating different priority strategies, VISSIM was coded to record travel times (vehicular and BRT), intersection performance, BRT time-space positions, signal changes, and overall network performance. The results were collected for each scenario and then compared.

7.5.1. Travel Times

Travel times for vehicles and BRT buses were measured for segments between each pair of signalized intersections, in the northbound and southbound direction. A comparison of the average travel times for the 2-hour simulation period between scenarios is given in Table 7.2.

7.5.2. Intersection Performance

The intersection performance parameters, such as the number of vehicle, average delay per vehicle, and number of stops per vehicle were measured for each movement at

TABLE 7.2 Travel Times for BRT and Passenger Cars

Segments	No TSP		TSP		TSP Phase rotation		TSP Custom	
	Travel times (s)							
SB	**BRT**	**Cars**	**BRT**	**Cars**	**BRT**	**Cars**	**BRT**	**Cars**
2700 S - 3100 S	140	61	120	61	116	62	113	66
3100 S - 3500 S	68	67	67	68	60	68	59	75
3500 S - 4100 S	213	110	201	111	183	117	180	128
4100 S - 4700 S	219	113	184	114	179	116	180	130
4700 S - 5400 S	183	127	197	126	185	127	181	129
5400 S - 6200 S	205	119	184	120	186	121	175	130
Total	**1029**	**598**	**952**	**600**	**909**	**611**	**889**	**658**
NB	**BRT**	**Cars**	**BRT**	**Cars**	**BRT**	**Cars**	**BRT**	**Cars**
6200 S - 5400 S	141	132	142	132	146	134	147	138
5400 S - 4700 S	228	119	198	121	182	122	175	128
4700 S - 4100 S	130	134	114	131	111	131	112	131
4100 S - 3500 S	166	163	161	163	152	161	149	152
3500 S - 3100 S	90	64	89	64	91	69	94	72
3100 S - 2700 S	57	70	56	69	59	70	59	69
Total	**812**	**682**	**760**	**681**	**741**	**687**	**735**	**689**

each intersection. The results are averaged for the whole 2-hour PM peak period. Aggregated results on an intersection level are given in Table 7.3.

7.5.3. BRT Time-Space Diagrams and Service Rate

The simulations recorded BRT positions and speeds for every simulation step. These data were used to plot time-space diagrams and compare BRT vehicle trajectories for the four scenarios. There were ten BRT vehicles in each direction that started and completed their trips during the evaluation interval. The example diagrams for one randomly seeded simulation are given in Figure 7.3. The diagram shows three consecutive southbound BRT vehicles for the four scenarios and their progression between 3500 S and 6200 S intersections.

TABLE 7.3 Aggregated Intersection Performance Measures

Mode	Intersection	Average delay per vehicle (s)				Average number of stops per vehicle			
		No TSP	TSP	TSP PR	TSP Custom	No TSP	TSP	TSP PR	TSP Custom
Passenger cars	2700 S	33	34	34	35	0.8	0.8	0.6	0.8
	3100 S	35	36	36	37	0.7	0.7	0.6	0.7
	3500 S	37	38	39	46	0.8	0.8	0.8	0.9
	4100 S	34	35	36	41	0.7	0.7	0.8	0.8
	4700 S	35	36	38	39	0.7	0.7	0.7	0.8
	5400 S	35	36	36	41	0.8	0.8	0.7	0.8
	6200 S	35	35	35	38	0.7	0.8	0.6	0.8
BRT	2700 S	28	25	26	25	0.3	0.2	0.6	0.2
	3100 S	20	9	8	8	0.4	0.2	0.6	0.2
	3500 S	35	33	25	22	0.7	0.6	0.8	0.2
	4100 S	51	37	27	26	0.9	0.6	0.8	0.3
	4700 S	68	35	25	22	0.7	0.3	0.7	0.2
	5400 S	26	33	30	28	0.2	0.5	0.7	0.4
	6200 S	49	35	35	25	0.7	0.4	0.6	0.2

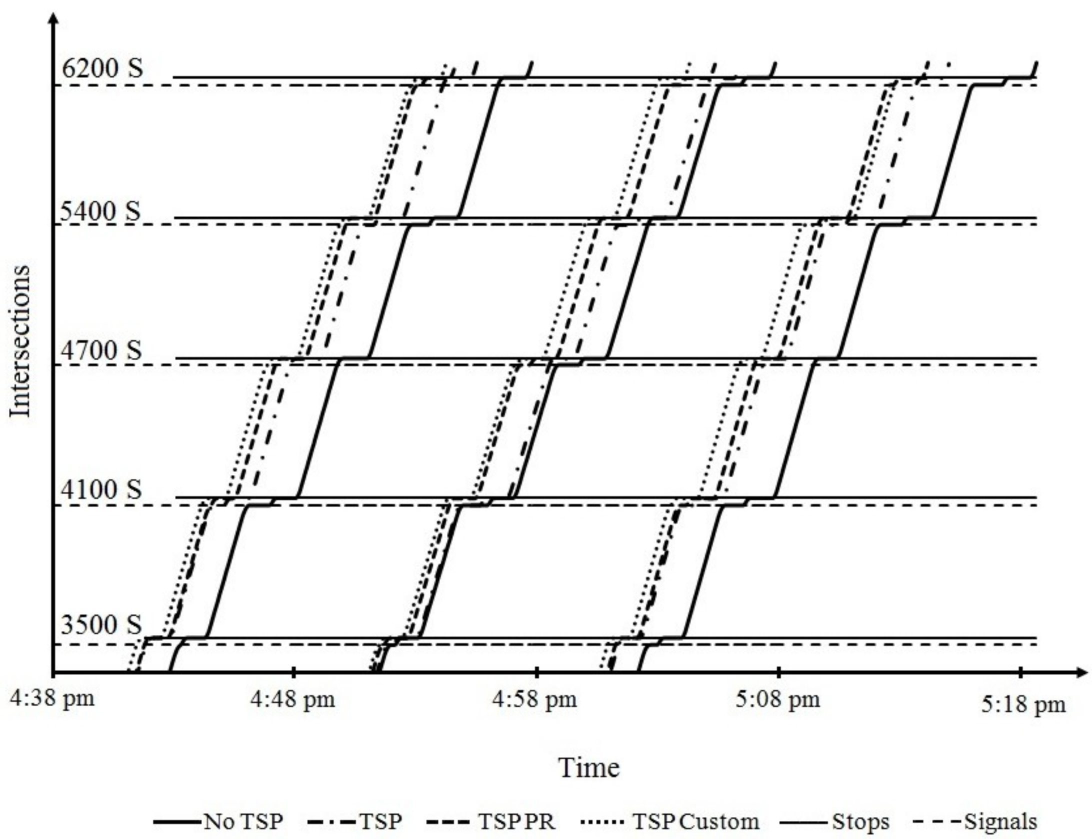


FIGURE 7.3 BRT time-space diagram: three SB BRT vehicles.

Table 7.4 summarizes stopping percentages and times that BRT vehicles spent waiting at the red light at intersections. The BRT data are extracted for ten southbound and ten northbound vehicles for one randomly seeded simulation. The signal changes data are also extracted for the same simulation run and compared against the vehicle positions at intersections. This provided detailed information on how the signals responded to the oncoming BRT vehicles in each scenario. The example is for only one random seed, but similar patterns exist for all simulation runs. Additional information extracted from the time-space diagrams was BRT running-time reliability. Running-time reliability can be defined as the ability of the BRT service to maintain consistent travel times with minimum variability. Figure 7.4 shows the comparison of average BRT running times along the corridor and their standard deviations for the four scenarios.

7.5.4. Network Performance

Impacts and benefits of the different priority strategies can be assessed on a network-wide level. Table 7.5 presents a network performance comparison for the most relevant parameters. The data are given separately for passenger cars and BRT vehicles.

7.6. Discussion

7.6.1. BRT Travel Times

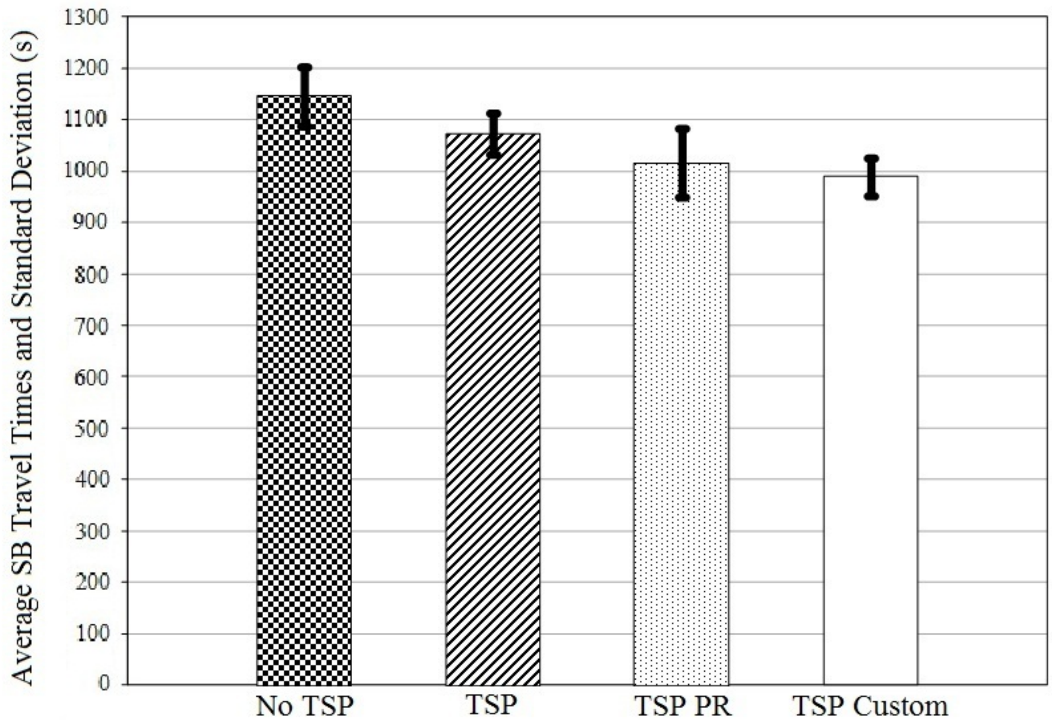
The travel time results show larger BRT travel times in the southbound direction. This is expected, because southbound is the PM peak direction with more transit riders and greater station dwell times. An implementation of different TSP strategies improves BRT travel times. The results show that the green extension/early green strategies reduce

TABLE 7.4 BRT Stopping Percentages and Waiting Times

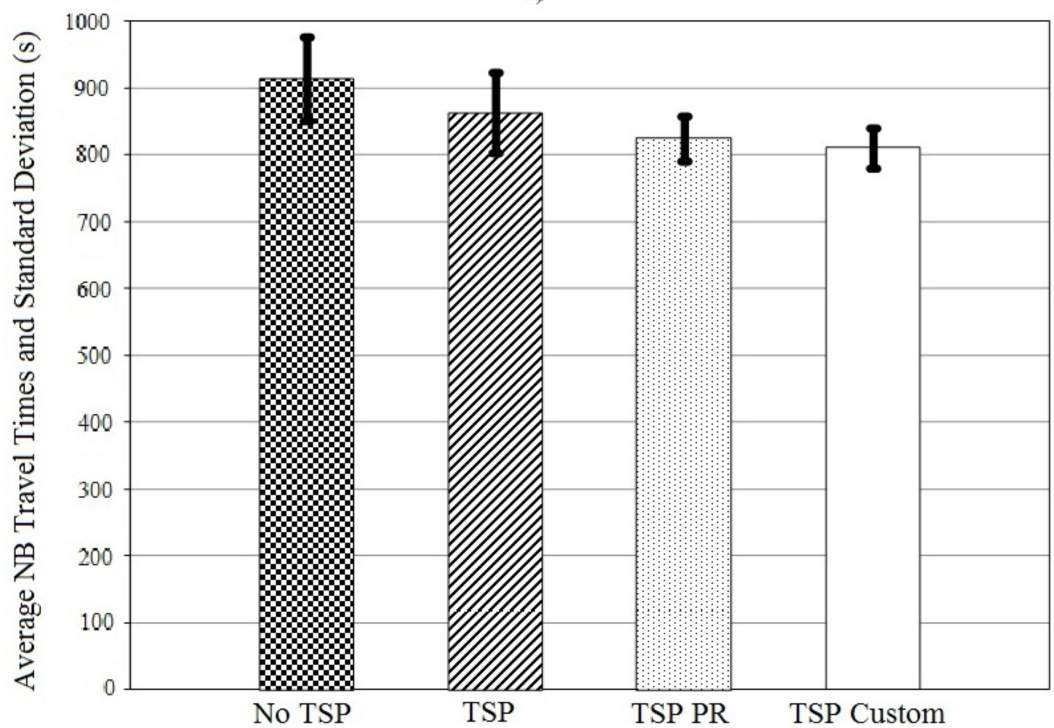
SB	No TSP		TSP		TSP PR		TSP Custom	
	Stop %	WT (s)	Stop %	WT (s)	Stop %	WT (s)	Stop %	WT (s)
2700	40	92	40	88	40	70	30	70
3100	80	295	60	186	40	68	30	45
3500	60	74	50	62	40	13	10	20
4100	100	419	90	262	30	48	30	31
4700	60	286	20	93	30	52	10	3
5400	40	144	70	223	30	70	30	81
6200	60	211	20	68	60	147	10	1
Average /total	**63**	**1521**	**50**	**982**	**39**	**468**	**21**	**251**

NB	No TSP		TSP		TSP PR		TSP Custom	
	Stop %	WT (s)	Stop %	WT (s)	Stop %	WT (s)	Stop %	WT (s)
6200	60	239	60	219	60	126	30	72
5400	20	16	30	30	40	27	40	46
4700	80	545	40	260	20	95	10	32
4100	80	131	30	24	20	25	10	8
3500	90	161	90	142	50	39	10	9
3100	0	0	0	0	0	0	10	13
2700	0	0	0	0	0	0	0	0
Average /total	**47**	**1092**	**36**	**675**	**27**	**312**	**16**	**180**

Stop % – percentage of stopped BRT vehicles at red light
WT – BRT waiting time at red light at intersection



a)



b)

FIGURE 7.4 Average BRT running times and standard deviation: a) Southbound; b) Northbound.

TABLE 7.5 Network Performance

Passenger cars	No TSP	TSP	TSP PR	TSP Custom
Total number of vehicles	33789	33795	33793	33827
Average delay time per vehicle (s)	57	58	59	64
Average stopped delay per vehicle (s)	41	42	43	47
Average number of stops per vehicles	1.3	1.4	1.4	1.5
Average speed (mph)	23.9	23.7	23.6	22.9

BRT vehicles	No TSP	TSP	TSP PR	TSP Custom
Total number of vehicles	27	27	27	27
Average delay time per vehicle (s)	244	184	155	139
Average stopped delay per vehicle (s)	111	61	35	21
Average number of stops per vehicles	8.7	7.8	7.2	6.7
Average speed (mph)	18.6	19.9	20.6	21.0

BRT travel times approximately 7% in the southbound and 6% in the northbound direction when compared to the No TSP scenario. Green extension/early green strategies combined with phase rotation reduce BRT travel times by 12% in the southbound and 9% in the northbound direction. The Custom TSP results in a 14% travel time saving in the southbound and 9% in the northbound direction. This shows that BRT benefits most from the Custom TSP strategies.

7.6.2. Vehicular Travel Times

Green extension/early green strategies have no impact on vehicular travel times along the main corridor. Combination of these strategies with phase rotation slightly increases travel times for vehicular traffic. This increase is about 2% in the southbound direction, and less than 1% in the northbound direction. Custom TSP strategies tend to increase vehicular travel times in the southbound direction by approximately 10%, and about 1% in the northbound direction. These travel times are impacted by the phase rotation and disturbances in intersection coordination caused by some of the implemented strategies.

7.6.3. Intersection Performance

An analysis of the intersection performance measures shows that green extension/early green strategies do not have impacts on passenger cars, while significantly decrease delays for BRT (20 - 50%). The addition of phase rotation causes some changes in the way that left turns operate, which can result in impacts on vehicular traffic. However, the results show that this impact is not significant (the maximum increase in intersection delay is experienced at 4700 S and is about 3 seconds or 8%). On the other hand, BRT delays decrease significantly at the majority of intersections (the maximum decrease of about 60% is also observed at 4700 S). Custom TSP causes greater increases in passenger car delays than other strategies (an increase of 6% to 24% depending on intersection). However, Custom TSP shows the greatest benefits for BRT vehicles at all intersections. It can decrease BRT delays by 70% in some cases. The results on the average number of stops follow the same pattern as the delays for passenger cars and BRT.

7.6.4. BRT Time-Space Diagrams and Service Rate

The progression of BRT vehicles through the network is best observed on the time-space plots and from additional data extracted from them. When no TSP is implemented, vehicle trajectories vary significantly from vehicle to vehicle. Stopping percentage is quite high at the busiest intersections with a lot of time spent waiting at red lights. The average running times also vary significantly, with a standard deviation of more than a minute in each direction. Similar patterns are observed in both directions, although the impacts are larger in the peak southbound direction. TSP strategies improve BRT performance. Green extension/early green strategies reduce the stopping percentage and intersection waiting time by 20% and 35%, respectively. The running-time reliability is higher, with lower variations in the average running times. The inclusion of phase rotation further reduces the stopping percentage and intersection waiting times, which are in this case respectively 38% and 70% lower when compared to No TSP. However, these strategies yield higher running-time variations then green extension/early green in the southbound direction, although the variations are lower than for No TSP. Custom TSP yields the highest decrease in the stopping percentage and intersection waiting time, which are about 67% and 83% (respectively) lower than for the No TSP scenario. The running-time reliability is the highest in this case, with low running-time variations. The BRT vehicle speeds are consistent throughout the evaluation period. Once again, Custom TSP provides the most benefits for the BRT service.

7.6.5. Network Performance

Network performance results given in Table 7.5 show the same trend as the single intersection results. It can be seen that TSP and TSP with phase rotation have no major impacts on the network-wide level performance and they increase delays for passenger cars 2% and 4%, respectively. Custom TSP increases average delays approximately 12%. The reason for this is the same as in the case of a single intersection (phase rotation and impacts on coordination). On the other hand, each TSP strategy provides certain benefits for BRT. Green extension/early green strategies reduce network-wide BRT delays approximately 25%, while their combination with phase rotation reduces these delays more than 35%. Custom TSP again offers the greatest delay reduction for BRT, which is around 45%. The results for the average number of stops per vehicle on the network-wide level follow similar distribution as the delays for passenger cars and BRT.

7.7. Conclusions

The goal of this paper is to find the optimal TSP strategies for the future transit corridor along 5600 W in West Valley City, UT. This was achieved through the comparison of four different TSP options in the VISSIM – ASC/3 SIL microsimulation environment. The analysis was conducted for travel times, intersection performance, and network performance. The study was using estimated and planned traffic and transit operations for the tested network.

Each of the tested strategies brings certain benefits for BRT vehicles. The obtained results show that TSP with phase rotation and Custom TSP can both be considered for implementation. TSP with phase rotation brings significant benefits for BRT (9 – 12% reduction in travel times, and over 60% reduction in delays at some intersections), with minimum impacts on vehicular traffic. It significantly improves BRT progression through the corridor and offers acceptable running time reliability. Custom TSP brings major benefits for BRT (9 – 14% reduction in travel times, over 60% reduction in delays at some intersections, and major reductions in intersection stopping percentage and waiting times). The progression of BRT vehicles through the corridor is significantly improved, with consistent speeds and high running-time reliability. On the other hand, Custom TSP brings higher impacts on vehicular traffic than the other strategies. One of the drawbacks of this advanced strategy is that it brings disturbances to intersection coordination. It could be successfully applied to corridors which are transit-oriented, with low traffic volumes for passenger vehicles.

This study could be used as a road map that shows how to increase the level of TSP with an increase in BRT ridership. It gives a range of benefits and impacts (for BRT and passenger cars) associated with various levels of TSP. Based on the expansion of the BRT mode, an agency may decide which of the TSP scenarios will be the best to fit the current situation.

The study also provides a set of instructions for different levels of TSP that can be directly programmed into the field traffic controllers. The analysis was performed for ASC/3 controllers, but it can be easily customized for any other controller type that supports TSP options and/or logic processor.

Some of the topics for future research in this area can be as follows:

- Investigate how the Custom TSP could be improved in order to provide more benefits for transit and less impact to vehicular traffic
- Examine the impact of TSP strategies on larger networks and different transit systems
- Apply these TSP strategies to conditional and adaptive transit priority
- Resolve problems with two or more conflicting TSP requests.

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CHAPTER 8

DEVELOPMENT AND EVALUATION OF AN ALGORITHM FOR RESOLVING CONFLICTING TRANSIT SIGNAL PRIORITY CALLS

From Zlatkovic, M., A. Stevanovic, and P. Martin. Development and Evaluation of an Algorithm for Resolving Conflicting Transit Signal Priority Calls. Presented at the 91st Annual Meeting of the Transportation Research Board, January 2012, Washington, D.C., and accepted for publication in the 2012 series of the *Transportation Research Record: Journal of the Transportation Research Board* (forthcoming)

8.1. Abstract

The goal of this paper is the development and evaluation of an algorithm for resolving conflicting Transit Signal Priority (TSP) requests. This algorithm was designed to work with actual traffic controllers, without the need of new hardware or software installations. It was tested in VISSIM microsimulation and ASC/3 Software-in-the-Loop (SIL) controllers on an actual intersection which will be upgraded to serve two conflicting Bus Rapid Transit (BRT) lines. The ASC/3 logic processor was used to control built-in TSP in the case of conflicting requests, and to develop custom TSP strategies that do not rely on built-in TSP. Custom TSP provides a much higher level of TSP for transit vehicles then the built-in TSP, and it creates opportunities for more adaptable TSP control.

The results show that the widely used first-come first-served policy for resolving conflicting TSP requests is not the best solution. It can perform worse than if no priority is provided. For the analyzed intersection, this option even increased BRT delays by 13% over the No TSP option. The presented algorithm can help resolve the problem of the conflicting TSP requests. It works best when combined with several TSP strategies. For the custom TSP strategies, the application of the algorithm reduces BRT delays more than 30%, with minimal impact on vehicular traffic. The algorithm shows promising results, and with small upgrades, it can be applied to any type of TSP.

8.2. Introduction

Transit Signal Priority (TSP) is a traffic control strategy for facilitating transit vehicles that is becoming more and more popular among transit agencies. Although it has been in use for more than 40 years (*1*), recent achievements in detection, communication, and traffic control technologies enable its implementation on a much wider level and in many different forms. Many worldwide implementations of TSP have shown the benefits it brings to transit, without impacting other users of the traffic networks (*1, 2*). For that reason, it is very popular among researchers and practitioners.

One of the recognized problems of the expanding implementation of TSP is the conflict between two or more TSP requests. With an increasing number of prioritized transit lines within the same network, the probability of having two or more conflicting requests at the same time is also increasing. The current standards for TSP implementation do not offer a good solution to this problem (*3*). Several research studies have identified some of the possible ways to overcome the problem (*4 - 7*), but the actual implementation of these methods in the field has not yet been resolved.

The goal of this paper is the development and evaluation of an algorithm for resolving conflicting TSP requests that can be implemented within the existing traffic controllers. The algorithm was tested in VISSIM microsimulation and ASC/3 Software-in-the-Loop (SIL) controllers on an actual intersection which will be upgraded to serve two conflicting Bus Rapid Transit (BRT) lines. The ASC/3 logic processor was used to control built-in TSP in the case of conflicting requests, and to develop custom-made TSP strategies that do not rely on built-in TSP.

The paper is organized in six sections. The next section provides a review of the literature that presents methods for resolving conflicting TSP requests. It is followed by the description of the proposed Multi-TSP algorithm. The methods of creating and calibrating simulation models, and the implementation of the algorithm in some of them are given in the Modeling Methodology section. It is followed by the results obtained through microsimulation, and the discussion of the results. Finally, the major conclusions of the study are presented in the last section.

8.3. Literature Review

TSP is an operational strategy that facilitates the movement of in-service transit vehicles through signalized intersections (*1*). The most important benefits are improved schedule adherence and reliability and reduced travel time for transit, which increase the quality of transit service. Potential negative impacts consist primarily of delays to vehicular traffic, or in some cases impacting pedestrian crossing opportunities. TSP can be implemented as passive, active, or adaptive priority (*1*). Passive TSP does not require transit detection or priority request. It offers a simple progression for transit vehicles along corridors where transit operations are predictable. Active TSP follows a transit vehicle detection and subsequent priority request activation. It is usually implemented as the green extension and/or early green strategy, providing a wider green time bandwidth for transit vehicles. Active TSP can be implemented as unconditional and conditional. Unconditional TSP provides priority for each transit vehicle that sends a request. Conditional TSP provides priority only for transit vehicles that satisfy certain conditions, such as running behind schedule or having more passengers on board. Adaptive TSP considers the trade-offs between transit and traffic delay and allows adequate adjustments of signal timing by adapting to the movement of the transit vehicle and the prevailing traffic condition.

Transit agencies are expanding the use of TSP, which leads to an increasing number of prioritized transit lines within the same network. This increases the probability of two or more transit vehicles approaching an intersection concurrently and sending TSP requests that are in conflict (*2*). The traffic controller's Priority Request Server (PRS) must decide which vehicle will be given preference. Most TSP implementations are not able to determine the optimal order in which individual requests should be served. The solution for the conflicting requests was found in the first-come first-served policy, where the first vehicle requesting priority is served first. Within this policy, the next TSP request may or may not be served in the following cycle.

The Los Angeles Department of Transportation (LA DOT) TSP software assigns a higher priority level to the transit line on which TSP was first implemented (*2*). Although not optimal, this method is consistent in resolving conflicting calls. This is one solution for classifying unconditional priority requests.

It is easier to determine the service preferences in the case of conditional TSP. This type provides priority only to transit vehicles that are behind schedule, or carry passenger loads higher than the defined threshold. The National Transportation Communication for Intelligent Transportation Systems Protocol (NTCIP) standards 1211 for Signal Control and Prioritization (SCP) classify TSP requests into the Request Class Types and Request Class Levels (*3*). A Priority Request Message that is sent from the Priority Request Generator (PRG) to the PRS contains information on vehicle I. D., vehicle class type, and vehicle class level. Once the PRS receives this message, it determines the order in which to allow priority for conflicting requests based on the class type and class level. However, it cannot provide the best solution in the case of two or more requests of the same type and same level.

Resolving conflicting TSP requests has become an emerging topic in TSP research studies. Different optimization methods have been proposed by different researchers. A study that used Colored Petri Network (CPN) models for transit priority and preemption looked into the way to improve conditional conflicting TSP requests (*4*). The proposed method determines the best order to serve conflicting requests in three steps. The first step is to determine the priority level of transit vehicles on conflicting approaches. The second step takes into consideration the status of the operation of transit vehicles. In the third step, the algorithm decides the priority type, priority degree, and service sequence. The requests with higher priority preempt those with lower priority, creating an order in which to serve the requests.

A different study proposed a decision model for multiple priority control based on precedence graphs (*5*). The precedence graph model is formed by representing each phase by an "activity on arc", following the defined phase sequence and phase barrier constraints. The priority control problem is presented as a mathematical programming formulation with an objective function that minimizes total priority delay. The model is subjected to the precedence, phase duration, and service phase selection constraints. The problem is defined as a mixed-integer mathematical programming model that can be solved by using readily available tools. It was tested and compared to the first-come first-served policy. The results showed the potential benefit in developing strategies that are not simply first-come first-served in which priority requests can be received with sufficient lead time to allow intelligent service planning.

A dynamic programming model was also used to optimize TSP strategies in the case of conflicting requests (*6*). The objective function of the model is to minimize the total weighted transit delay. The model outputs are the optimal serve sequence of multi-bus priority requests and corresponding signal timings. The model was tested for a case of conditional priority where schedule deviation, the number of passengers on board, and the overall traffic were considered. It was compared to a No TSP model and first-come first-served TSP model. The results showed an advantage of the proposed model over the other two in terms of reduced transit delay and impacts on overall traffic.

A recent study proposed a heuristic algorithm for optimizing multiple priority requests at isolated intersections in the context of vehicle-to-infrastructure communications (*7*). The basic concept of this algorithm is to separate the assignment of priority requests to a cycle and phase from the optimization of signal durations. The algorithm was tested in microscopic traffic simulation and compared to the exact mixed-integer linear programming solution, as well as to traditional priority algorithms. The results showed that the proposed algorithm was able to provide near-optimal solutions in terms of transit delays and impacts on traffic.

These studies show that the problem of conflicting TSP requests can be successfully solved by using some of the available optimization methods. However, the question of actual implementation of these methods in the field still remains. Each of them requires separate calculation/optimization software that would cause some difficulties and costs for actual implementation. This paper describes an algorithm for resolving conflicting TSP calls and its implementation within existing controller software using logic processor. The algorithm focuses on finding the best way to serve conflicting TSP requests within the existing signal timing plan. It can be used for unconditional or conditional TSP calls of the same type and same level. Although the research was using

ASC/3 controller software, the principles and commands can easily be transferred to any other software that supports logic commands.

8.4. Multi-TSP Algorithm

The proposed algorithm for resolving conflicting TSP requests is given in Figure 8.1. The main postulate of this algorithm is that none of the phases (vehicular or pedestrian) can be omitted during a cycle. The algorithm is defined for unconditional priority, meaning that any transit vehicle can place a TSP call and will be served accordingly. Since the network that was used to test the algorithm consists of two conflicting BRT lines, the calls for these lines in the algorithm are referenced as BRT 1 and BRT 2. In this test-case network, both lines are served with the corresponding through movements, but in general, the algorithm can be applied to any other movement. The algorithm works the same way, no matter which BRT line requests TSP first.

The two most important parameters in the algorithm that set the course of action are: 1) the moment when a TSP call is placed by one or more transit vehicles, and 2) the current signal phase at that moment. When a TSP call is received from BRT 1, the algorithm checks the current signal phase. If the phase that corresponds to BRT 1 is timing green at that moment, the algorithm will give priority to that BRT line. Then it checks for a TSP call from the conflicting line. If there are no conflicting calls, the TSP works as in a case of a single line with the green extension strategy: if BRT 1 does not check out during the normal green phase, the BRT phase will be extended until it checks out, or until that phase reaches its maximum green time. If there is a conflicting call from BRT 2, that call will be canceled until BRT 1 has cleared the intersection. Once BRT 1

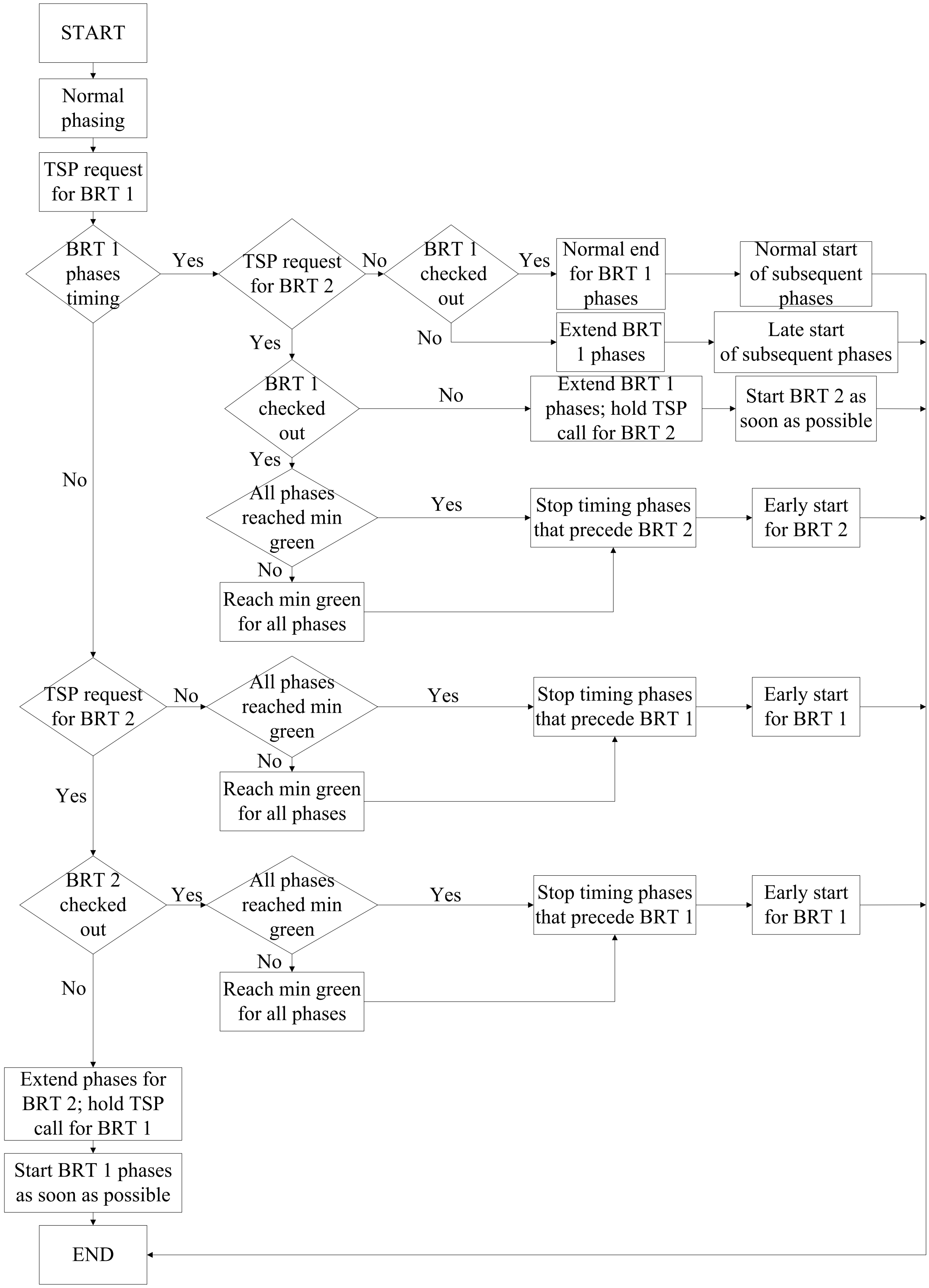

FIGURE 8.1 Multi-TSP algorithm.

checks out, the call for BRT 2 will be placed again. In this case, the early green strategy will become active to provide an early start for BRT 2. Early green can also be combined with phase rotation, which will rotate the regular sequence of phases to service BRT 2 first, if that is not the case within the normal phase sequence.

If the phase that corresponds to BRT 1 is timing red at the moment when BRT 1 checks in, it means that some of the conflicting phases are timing green. The algorithm then checks for a call from BRT 2. If there is no call from BRT 2, the early green strategy (with a potential combination with phase rotation) will become active, shortening the green time for conflicting phases and giving an early start to BRT 1. If there is a call from BRT 2, the algorithm checks which phase is currently timing green. If that is the phase that corresponds to the BRT 2 movement, than the BRT 1 call will be canceled and BRT 2 served with green extension, as previously described. If phases that do not correspond to either BRT 1 or BRT 2 are timing green, generally it does not matter which TSP call is active: those phases will be shortened according to the early green settings. Then the phasing will go into the next sequence, serving either BRT 1 or BRT 2 depending on which phases are next in the phase ring. Potentially, phase rotation can come into play in this case too. When one BRT line is served, the call will again be placed for the other one, which will also be served according to the early green strategy.

There is a significant difference in the way this algorithm works from already available software that uses priority Request Class Type and Request Class Level defined in NTCIP 1211. The algorithm classifies TSP calls on a case-to-case basis during each cycle according to the current intersection operations. Priority Request Class Type and Request Class Level in existing controllers “predefine” which transit vehicles will be given priority, and this is fixed from cycle to cycle. In that way, the algorithm presented here provides a more adaptable way of controlling conflicting TSP calls.

8.5. Modeling Methodology

8.5.1. Test-Case Network

The proposed algorithm and its benefits and impacts on traffic and transit operations were evaluated through VISSIM microsimulation, coupled with ASC/3 SIL controllers. The algorithm was tested for one intersection, 3500 S and 5600 W in West Valley City, UT, which was modeled according to the existing traffic conditions (traffic counts and signal timings). This intersection was selected because in the future it will serve two conflicting BRT lines, one along 3500 S (which is already operational) and the other along 5600 W (the construction will start in 2015). Both BRT lines are modeled as center-running lines, according to the design plans (*8*). The layout of the (future) intersection is given in Figure 8.2. The intersection operates on an actuated-coordinated pattern, with coordinated north-south movements and a 130 seconds cycle length. All approaches have two through lanes and separate left and right turn lanes (except the east approach, which has a shared through-right turn lane). TSP check-in detectors are placed at each intersection approach at about 600 ft from the intersection. The check-out detectors are placed after the intersection stop bars. All BRT stops are located on the far sides of the intersection. They are approximately 50 ft away from the intersection, and their length is about 120 ft. In addition to this intersection, six surrounding intersections were also modeled with existing signal timing plans to create more realistic traffic demand for the analyzed intersection.

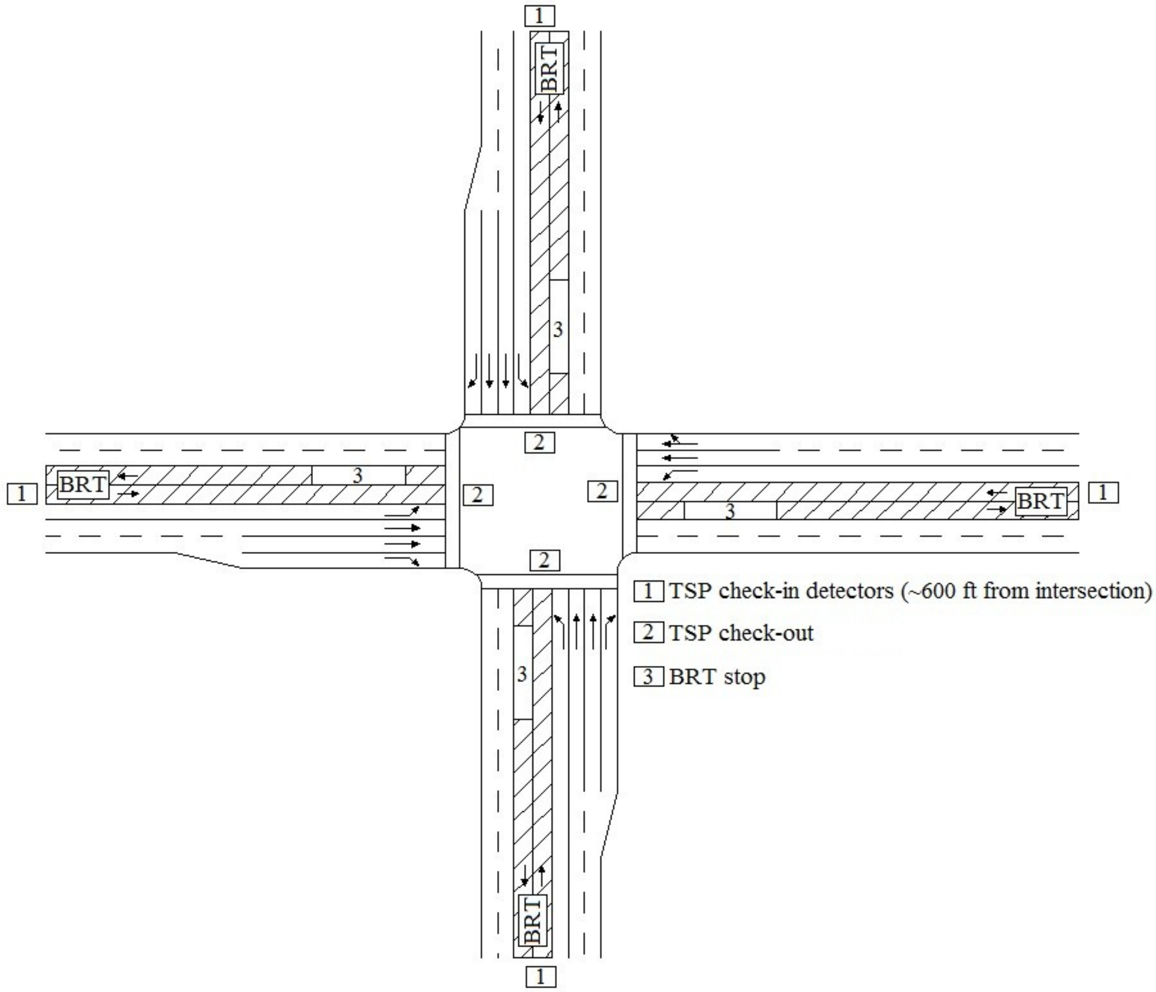

FIGURE 8.2 Intersection layout.

The network was loaded with traffic according to the PM peak period (4:00 – 6:00 PM) traffic counts for the 3500 S and 5600 W intersection, collected in the fall of 2008. The simulation model was then calibrated according to the traffic counts for this intersection. The results of the model calibration are presented in Figure 8.3. A high R-square value shows a good correlation between the two data sets. The focus of the model calibration was on the second hour (5:00 – 6:00 PM), since this was the peak hour. The calibration results were the same for the first hour of the simulation (with an R-square

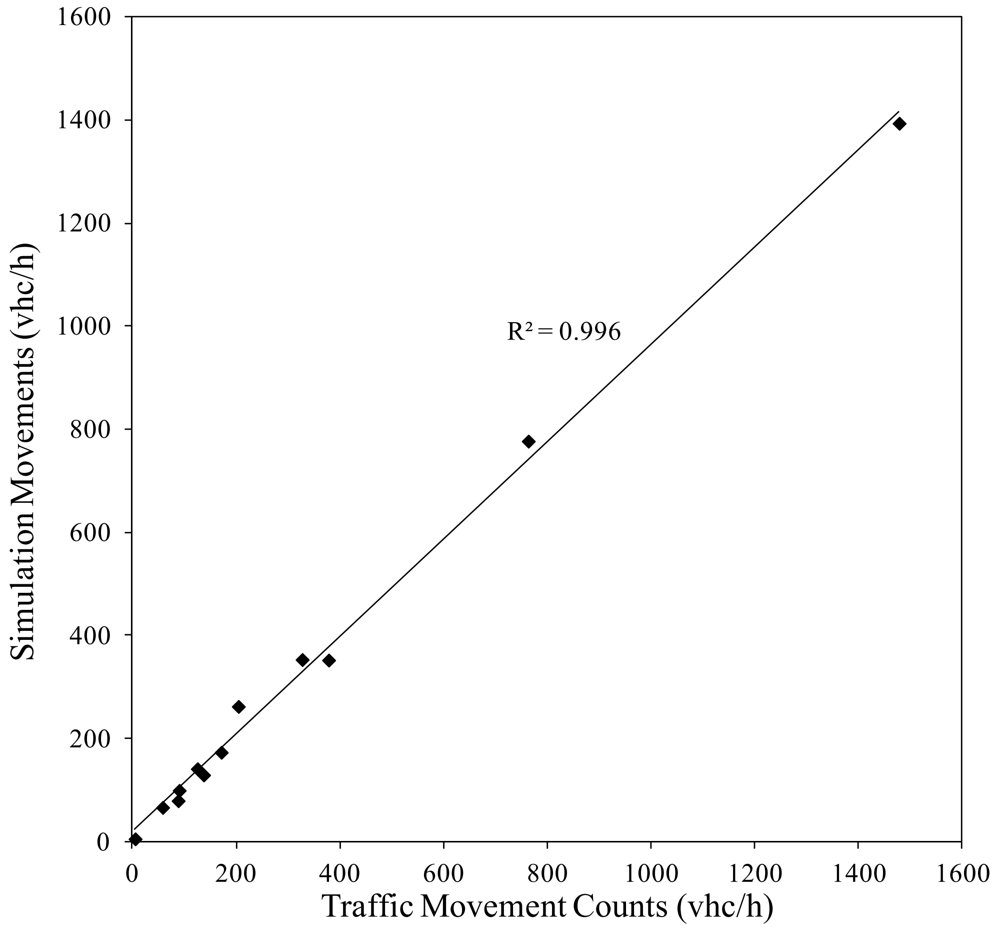

FIGURE 8.3 VISSIM model calibration.

value of 0.995).

Four model scenarios were used in this research: No TSP model, TSP model, Multi-TSP model, and Custom Multi-TSP model. Each of the TSP scenarios was implemented through ASC/3 software-in-the-loop (SIL) controllers with actual signal timings from the field. The models were created using built-in TSP strategies and logic processor, as described below for each model individually. Each model was run for 2 hours, with a 15-minute build-up time. The results for each model are averaged from ten randomly seeded simulation runs.

8.5.2. No TSP Model

This model introduces two center running BRT lines along 5600 W (North-South) and 3500 S (East-West) that conflict each other at the analyzed intersection. In this case, the BRT lines did not have any special control treatment. The headway for both BRT lines was set to 10 minutes in each direction, which is the planned service frequency for the future (currently the 3500 S BRT line operates on 15-minute headways). Bus stops for both lines were located on the far sides of the intersection. Passenger activity at bus stops was also modeled according to the existing (or estimated) data. Traffic control for the surrounding intersections was modeled according to the actual signal timing data. No special control treatment was introduced for BRT lines at those intersections (this also goes for other TSP models; TSP was only modeled at the analyzed intersection). This model served as a basis to create other TSP models, which differed from the base one only by their TSP logics.

8.5.3. TSP Model

This model introduces TSP at the analyzed intersection for both BRT lines. In this case, the built-in TSP strategies of the ASC/3 controller software were used. These strategies allow for green extension/early green according to the parameters that the user defines. The TSP check-in detectors were placed about 600 feet from the intersection. Since the speed of the BRT buses is between 40 and 45 mph, it would take them about 10 seconds to reach the intersection once they were detected. This fact was used to define the TSP parameters, which were set as follow:

- Maximum green extension for BRT phases: 10 s

- Maximum red truncation for conflicting through movements: 10 s
- Maximum red truncation for (all) conflicting left turns: 5 s

The built-in TSP strategies work on a first-come first-served policy. This means that the BRT bus that was detected first will be served first.

8.5.4. Multi-TSP Model

This is an extension of the TSP model. The same built-in TSP strategies and settings were used as in the previous case. In Multi-TSP, the TSP calls were controlled by the logic processor based on the proposed algorithm. This logic was defined in the controller as follows:

IF

BRT 1 detected AND

BRT 1 phases timing green AND

BRT 2 detected

THEN

Cancel TSP call for BRT 2

Apply green extension for BRT 1 (if needed)

At the same time, the controller checks if BRT 1 has cleared the intersection. This was achieved through the following set of logic commands:

IF

BRT 1 checked out AND

BRT 2 detected AND

TSP call for BRT 2 not active

THEN

Call TSP for BRT 2

These sets of logic commands were also controlling TSP calls in a case when none of the BRT 1 or BRT 2 phases was active at the time they were detected approaching the intersection. In this case, the early green strategy becomes active by shortening the green times for conflicting phases according to the TSP settings. Any active TSP call can activate this strategy. Once the conflicting phases were forced-off, the controller would start those BRT phases that were next in the phase sequence. Let us assume that the BRT 1 phases are next in the sequence to be served, and BRT 2 is waiting at the intersection, so both TSP calls are active. Once the BRT 1 phases start, the same defined logic will deactivate the TSP call for BRT 2. But as soon as BRT 1 checks out, the call for BRT 2 will be placed again, so the early green strategy will reactivate in order to prioritize BRT 2.

8.5.5. Custom Multi-TSP Model

This is a multi-TSP model, without the built-in TSP options. TSP was achieved through a series of logic commands using the ASC/3 logic processor. The result was a custom made priority that allowed a higher level of TSP treatment for BRT. Three TSP strategies were defined: green extension, early green, and phase rotation.

The green extension strategy was achieved through the following logic commands:

IF

BRT detected AND

BRT phases timing green

THEN

Turn off minimum recall for all phases

Turn off detectors for conflicting phases

Call MAX 2 maximum green time for BRT phases

Set coordination free

Set green for BRT phases

The IF condition for this strategy is that a BRT bus is detected approaching the intersection, and the green time for BRT phases is currently on. The logic ensures that the bus clears the intersection before the green ends. The first step turns off detector actuations for all conflicting phases, and any minimum phase recalls. This clears calls for conflicting phases and enables the BRT phases to continue timing green. However, the duration of this green time can be constrained by the maximum phase green time, or the coordination offset. The ASC/3 controller has an option of activating three maximum green times. MAX 1 is the standard maximum green, while MAX 2 and MAX 3 are optional. For the purpose of green extension, the logic refers to the MAX 2 time for the BRT phases, which in this case is large enough to allow the BRT bus to clear the intersection on green. To maintain the coordination offset, the controller can also end the green time of the coordinated phases at a certain point during the cycle. This can conflict with the green extension. The logic sets coordination to “free running” until the bus clears the intersection. Setting the control logic to dwell in green ensures that the BRT phases remain green while the IF conditions are satisfied. When the bus crosses the stop bar, this logic deactivates and the intersection returns to normal operations. The travel time of any BRT bus from the check-in detector to the intersection is about 10 seconds. So in the worst case, the BRT phases will be extended by 10 seconds at most. This corresponds to the previously defined TSP settings.

If a BRT bus is detected approaching the intersection while the conflicting phases are timing green, the early green strategy terminates those phases and provides an earlier start for BRT. The logic that drives this strategy is as follows:

IF

BRT detected AND

Conflicting phase is timing green

THEN

Turn off detectors for that conflicting phase

The call for the phase ends when the detectors for the conflicting phase are turned off, and it stops timing green once it reaches the minimum phase green time. It should also be noted that this strategy does not omit any phase, whether or not that phase is on a minimum recall. The logic activates once the phase green starts timing, which ensures the minimum green for that phase. If one of the conflicting pedestrian phases is active at the same time as this logic, the conflicting phases will end when the pedestrian phase turns red. It means that active pedestrian phases will not terminate earlier. Turning the conflicting phases' detectors off is a better option than forcing their green time to end (which can also be achieved through the control logic), because in this case, the conflicting phases gap out, which does not disturb intersection coordination.

Phase rotation changes the phase sequence in order to serve a transit phase faster. Only the phases on the same intersection approach (within the same control barrier) can be rotated. At the analyzed intersection, the phase sequence is defined as leading left turns and lagging through movements. All BRT phases time concurrently with vehicular through phases. If a BRT vehicle is detected at the intersection while some of the movements on the other approach time green, phase rotation will change the sequence for left and through phases. This allows the through movements to be served first, and left turns after that. This strategy reduces delays for transit vehicles, but it can also have safety benefits in the case of a transit lane that is positioned in the middle of the roadway. It reduces conflicts between transit and left-turning vehicles. The logic works the same for both BRT lines and is defined as follows:

IF

BRT detected AND

Left turns on BRT approach timing red

THEN

Select alternative sequence with leading through and lagging left phases

If a BRT bus is detected on one intersection approach, the second IF command checks the timing for the left turn phases on that approach. If these left turn phases are red at the moment, two options are possible: either the through phases on that approach (and BRT phases) are green, or any phase on the other approach is green. In the first case, the bus will clear the intersection and deactivate phase rotation. The second case means that both left turns and through (and BRT) phases on the approach in question are timing red. The normal phase sequence in this case would start with leading left turns and lagging through and BRT phases. However, to facilitate BRT operations, the logic will select an alternate sequence, which is defined as leading through phases and lagging left turns, serving the BRT phases first. This alternate sequence has to be predefined in the ASC/3 controller configuration and referred to through a proper logic command. The early green strategy is always active along with phase rotation.

In this case, the TSP parameters were set as follows:

- Maximum green extension for BRT phases: 27 – 54 s depending on phase; average 39 s
- Maximum red truncation for conflicting through movements: 6 – 28 s depending on phase; average 19 s
- Maximum red truncation for (all) conflicting left turns: 3 – 18 s depending on phase; average 9 s
- Phase rotation active

The same logic that controls multi-TSP calls was also active here. The logic was set to control TSP calls in cases of green extension and early green according to the algorithm.

8.6. Results

8.6.1. Number of Conflicting Requests

The main input for the analysis is the number of conflicting TSP requests that appeared during the evaluation period. VISSIM was coded to record BRT detectors activation for the 2-hour period (simulation seconds 900 – 8100). The results on the number of conflicting requests were obtained through filtering those TSP calls that appeared during the same cycle on conflicting approaches. Table 8.1 shows simulation time when two conflicting calls appeared and the conflicting directions. These results were extracted for one simulation run for each scenario, but the results were similar for all runs.

8.6.2. Intersection and Network Performance

The analysis was focused on one intersection. So, the best way to assess the impacts and benefits of the tested scenarios is through intersection performance parameters. The main parameters used in this case were the number of vehicles, delay per vehicle, and the number of stops per vehicle for through, left, and BRT movements (right turns were not analyzed, since they are allowed on red). The results for the second hour (5:00 – 6:00 PM) for each scenario are given in Table 8.2. Table 8.3 shows the aggregated values of these parameters for the whole 2-hour period, calculated on the intersection level separately for vehicles and BRT.

Some of the most important performance parameters were observed on a network-wide level. This analysis can show the impacts that the tested strategies have on the surrounding network. These parameters, aggregated for the 2-hour period, are given in Table 8.4.

8.7. Discussion

8.7.1. Number of Conflicting Requests

It can be seen from Table 8.1 that conflicting requests appeared at approximately the same time in each scenario. However, the number of those requests was not the same for each scenario. Seven conflicting requests were recorded for the No TSP and Multi-TSP scenarios, eight for the TSP scenario and six for the Custom Multi-TSP scenario.

TABLE 8.1 Conflicting TSP Requests: Simulation Time and Directions

No TSP		TSP		Multi-TSP		Custom Multi-TSP	
Simulation time (s)	Directions of TSP calls	Simulation time (s)	Directions of TSP calls	Simulation time (s)	Directions of TSP calls	Simulation time (s)	Directions of TSP calls
1058	↓ ←	1058	↓ ←	1058	↓ ←	1058	↓ ←
2871	↓ ←	2340	→ ↓	2340	→ ↓	2870	↓ ←
4055	↓ ←	2870	↓ ←	2870	↓ ←	4055	↓ ←
5336	→ ↓	4055	↓ ←	4055	↓ ←	5872	↓ ←
5872	↓ ←	5336	→ ↓	5872	↓ ←	7139	→ ↓
7140	→ ↓	5872	↓ ←	7139	→ ↓	7691	↓ ←
7693	↓ ←	7140	→ ↓	7695	→ ↓		
		7693	↓ ←				

TABLE 8.2 Intersection Performance Parameters

Scenario	No TSP			TSP			Multi-TSP			Custom Multi-TSP		
Movement	Veh.	Delay (s)	Stops	Veh.	Delay (s)	Stops	Veh.	Delay (s)	Stops	Veh.	Delay (s)	Stops
NBT	773	32	0.8	772	34	0.8	769	34	0.8	777	27	0.7
NBL	130	47	0.9	128	50	0.9	128	50	0.9	128	61	1.0
SBT	1393	11	0.3	1396	11	0.3	1393	11	0.3	1388	19	0.6
SBL	262	69	1.1	262	69	1.1	263	67	1.0	259	64	1.2
EBT	353	49	0.9	353	49	0.9	353	49	0.9	358	47	0.8
EBL	5	65	0.9	5	58	0.9	5	65	0.9	5	74	1.0
WBT	353	43	0.9	353	42	0.9	354	43	0.9	363	44	1.0
WBL	141	74	1.3	141	82	1.3	141	79	1.3	143	77	1.3
BRT NB	6	29	0.5	6	34	0.6	6	37	0.6	6	8	0.1
BRT SB	6	31	0.4	6	33	0.5	6	29	0.4	6	43	0.8
BRT EB	6	43	0.7	6	48	0.7	6	49	0.7	6	21	0.4
BRT WB	6	52	0.8	6	60	0.7	6	50	0.8	6	41	0.7
Total vehicles	**3410**	**32**	**0.7**	**3410**	**32**	**0.7**	**3406**	**32**	**0.7**	**3421**	**34**	**0.8**
Total BRT	**24**	**39**	**0.6**	**24**	**44**	**0.6**	**24**	**41**	**0.6**	**24**	**28**	**0.5**

TABLE 8.3 Aggregated Intersection Performance Parameters

Scenario	No TSP			TSP			Multi-TSP			Custom Multi-TSP		
Mode	Veh.	Delay (s)	Stops	Veh.	Delay (s)	Stops	Veh.	Delay (s)	Stops	Veh.	Delay (s)	Stops
Vehicles	6660	32	0.7	6649	33	0.7	6646	32	0.7	6650	34	0.8
BRT	49	42	0.7	49	47	0.7	49	45	0.7	48	29	0.6

TABLE 8.4 Aggregated Network Performance Parameters

Parameter	No TSP	TSP	Multi-TSP	Custom Multi-TSP
Total number of vehicles	21172	21168	21170	21173
Average delay time per vehicle (s)	67	69	69	71
Total delay time (h)	394.8	407.7	408.2	416.0
Average stopped delay per vehicle (s)	44	45	45	46
Total stopped delay (h)	259.2	265.7	265.5	270.9
Average number of stops per vehicle	1.6	1.6	1.6	1.7
Total number of stops	33266	34398	34564	35664
Average speed (mph)	24.6	24.3	24.3	24.2

Changes in the treatment of BRT vehicles at the intersection introduced in each scenario caused changes in transit operations, such as the number of passengers on board, the number of alighting and boarding passengers at BRT stops, or waiting time at the intersection. For that reason, some of the BRT vehicles appeared during a different cycle in different scenarios. It can also be observed that the majority of conflicts occurred between the peak directed BRT vehicles (southbound and westbound) in each scenario. Some of the conflicts occurred between the southbound and eastbound vehicles, while the northbound vehicles did not cause any conflicts.

8.7.2. Intersection and Network Performance

A comparison of the intersection performance parameters given in Table 8.2 shows that the defined TSP strategies have little impact on vehicular traffic. Each scenario has certain impacts on all intersection movements. In general, all scenarios increase delays for left turns and reduce delays for through movements. However, there is little or no impact on delays on the intersection level. Table 8.3 shows that TSP and Multi-TSP have no impacts on vehicular traffic, while for the Custom Multi-TSP the impact is minimal (about 2 seconds increase in delays, or around 6%).

The models perform differently from the standpoint of BRT performance. It can be observed that the built-in TSP performs even worse than when No TSP is implemented. In this case, it even increased BRT delays by 13% compared to No TSP. This shows that the first-come first-served policy is not a good choice for conflicting TSP calls. Also, the TSP scenario had the highest number of conflicting requests compared to the other scenarios. Multi-TSP performs better, but still does not show much improvement over No TSP. However, the peak period transit directions (southbound and westbound for the given network) show some improvement with this strategy. Considering that the majority of conflicts occurred between the southbound and westbound BRT vehicles, the algorithm did bring some improvements over the conventional TSP. The Custom Multi-TSP yields the best BRT performance. During the 2- hour period, the average reduction in delays for each BRT vehicle was about 13 seconds, which is an improvement of more than 30% over No TSP. The improvements are substantial for all BRT movements. These results show that Custom Multi-TSP is the best of the four strategies for resolving conflicting TSP calls. It also offers the highest level of TSP among the strategies.

The impacts of the tested strategies are also minimal on the network-wide level. In this case, the Custom Multi-TSP has the biggest impacts on network-wide delays (the increase in delays is also around 6%).

8.8. Conclusions

The main contribution of the paper is the development of an algorithm for programming field traffic controllers to implement conflicting TSP requests. This procedure can utilize the existing hardware and software, therefore reducing the costs associated with new installations. The paper also shows the benefits of using microsimulation to test various real-world controllers' strategies through the ASC/3 SIL platform.

The conclusions of the study are:

1. The widely used first-come first-served policy for resolving conflicting TSP requests is not the best option. It can perform worse than if no priority is provided for any of the conflicting BRT lines.
2. The algorithm presented in the paper can help resolve the problem of the conflicting TSP requests. The algorithm works best when combined with several TSP strategies.
3. The logic processor (which exists in most traffic control software) can be successfully used in defining custom TSP strategies, which can perform better than the built-in TSP options. It can also help to better control built-in TSP.

Future work should focus on networks with several intersections and more conflicting TSP requests to find the best option for resolving those conflicts. The proposed algorithm shows advantages when applied to a single intersection with two conflicting TSP requests. It should be upgraded to allow for more than two requests and optimized for coordinated networks. The algorithm should also be upgraded to include conditional and adaptive TSP, and combined with some already available TSP software that classifies multiple TSP requests.

8.9. References

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CHAPTER 9

RESEARCH CONTRIBUTIONS

This research is focused on TSP strategies, algorithms, and evaluation methodology. It offers detailed insights in TSP, develops methods for its evaluation, and provides algorithms for achieving different levels of TSP. The goal of this research is to develop a simulation-based methodology for the evaluation and improvement of TSP strategies. The objectives consist of evaluating existing and future TSP systems, and developing field-ready algorithms that provide adaptive ways for achieving different levels of TSP and improving its operation.

The first contribution of the research is the assessment of SIL traffic controllers operations, which is the underlying methodology of all simulation-based studies in this research. A detailed study described in Chapter 2 compares different levels of traffic control operations between SIL and field traffic controllers. Since the study did not find differences in their operations, it confirmed that SIL can be used for analyzing complex traffic controls in simulation. Also, experimenting with ASC/3 SIL controllers showed that traffic control databases are interchangeable between field and SIL controllers. This means that the traffic control database created in the simulation can easily be uploaded to a field traffic controller, simplifying the programming process.

TSP is usually an add-on module in most traffic controllers, and it supplements the regular controller operations. TSP operations in traffic controllers are compliant with NTCIP 1211 standards, but there are still differences in the ways different controller software achieve TSP. For that reason, it is important to have simulation traffic control software that provides the same TSP operations as the field controllers. Utah Traffic Lab had a chance to be one of the beta-testers of the ASC/3 SIL TSP feature in 2008 and 2009, and these evaluations are part of this research. The study described in Chapter 3 is the beginning of the ASC/3 SIL TSP assessment that is continued in the follow-up studies. This study looked into detailed TSP operations of the ASC/3 SIL and the RBC traffic control emulator. Although the emulator showed satisfying TSP features, the use of SIL controllers is recommended, since it mimics the field control operations in the exact way. This study showed that a separate database file for TSP can be created in simulation and uploaded to a field controller. The study also pinpointed some details when it comes to TSP programming and evaluation in simulation.

This research also showed a successful implementation of a different SIL controller type, in this case, Siemens NextPhase. The advantage that this controller type offers is the easy controller communication and a vast array of complex traffic control features. The study described in Chapter 5 gives a method of using NextPhase SIL in achieving and evaluating predictive priority. Although NextPhase SIL has all the control features as a field controller, there are some limitations that can affect its implementation in simulation. The study describes these limitations and offers some practical solutions for overcoming them.

The study described in Chapter 6 offers a simplified algorithm for achieving predictive priority in other controller types that support logic processor. This algorithm was tested in ASC/3 SIL, but the presented set of logic rules allows for an easy customization. Because of the easy programming, this algorithm can be used for other TSP strategies other than predictive priority. So the algorithm was upgraded to allow for the programming of different levels of TSP, as described in Chapter 7. The algorithm even showed certain advantages over the built-in TSP, which can be especially beneficial for rapid transit modes. These studies showed that TSP can be achieved in traffic controllers that do not have the TSP feature, if they support the logic processor.

The study given in Chapter 8 offers a field-ready algorithm for resolving conflicting TSP requests, which is an emerging problem in TSP implementations. Although the existing standards and some studies offer certain solutions to this problem, they are not completely satisfactory and easy to implement. The presented study offers a practical solution for overcoming this problem. Although only at the beginning of its development, this algorithm shows major possibilities.

This research supports and extends the current state of TSP practice. It offers detailed insights in TSP operations, giving the practitioners useful tools for the selection of strategies for an actual implementation. Furthermore, the research offers a simulation-based methodology for TSP evaluation, which can be used to evaluate and fine-tune TSP strategies before their implementation in the field.

CHAPTER 10

CONCLUSIONS

The best solution for ever-increasing traffic congestions in urban areas cannot be found only in adding new capacities. Shifting to high-capacity transit modes can significantly reduce vehicle miles traveled, relieving the road infrastructure of excessive traffic. Transit systems must be efficient, safe, and comfortable to be competitive to private automobiles and attract riders. TSP is an operational strategy that helps with this efficiency and competiveness.

10.1. Review of Research Goal and Objectives

The goal of this research is to develop a simulation-based methodology for the evaluation and improvement of TSP strategies. The objectives consist of evaluating existing and future TSP systems, and developing field-ready algorithms that provide adaptive ways for achieving different levels of TSP and improving its operation. The focus of the research is on using traffic microsimulation to evaluate and improve TSP, but it also looks into some field-based implementations and evaluations for additional support.

10.2. Summary of Research Conclusions

The research first looked into the different ways of implementing complex traffic control strategies in microsimulation, as the basis for TSP implementation. The results of the study presented in Chapter 2 showed that SIL traffic controllers generate realistic signal timings and perform the same way as the field traffic controllers. This makes SIL the best solution for evaluating complex signal operations. The continuation of this study presented in Chapter 3 looked into detailed TSP features of a SIL controller and an advanced traffic control emulator. Although the emulator showed promising results, the TSP operations of the SIL controller were closer to what can be expected in the field implementation. This study also evaluated the TSP implementation of a BRT line along the 3500 S corridor in West Valley City, UT. It was backed up by a field study of this transit line described in Chapter 4. Although the field study was focused on the overall performance of the BRT system, it still justified the TSP implementation and supported the findings of the simulation study. The biggest benefits of the combined BRT/TSP systems are reduction in travel times and delays, improved running time reliability and headway adherence, and acceptance among the system users.

Predictive priority for LRT was analyzed and described in Chapter 5. This study again showed the benefits of the simulation-based approach in the analysis of complex TSP operations. The actual implementation of these priority strategies in the field brings major benefits to the transit system. It reduces the LRT travel times by 20% to 30% and intersection delays by more than 70%, with minimal impact on vehicular traffic. The study justified the implemented TSP strategies along the analyzed corridor.

Predictive priority strategies can be simplified and implemented in different controller types and for different types of transit, as shown in Chapter 6. Major benefits for the analyzed BRT line, with small impacts on vehicular traffic, are again supported by this study. The algorithm developed for predictive priority in this study is proven to be adjustable for TSP strategies that do not rely on intersection communication. It was further developed and customized to allow for higher priority for transit. The implementation of this algorithm to a future BRT line along the 5600 W corridor in West Valley City, Utah, is described in Chapter 7. The results showed that different levels of TSP can save 9 – 14% in BRT travel times, and reduce intersection delays by more than 60% with minimal impact on vehicular traffic. This study also provided the optimal combination of strategies for this future transit corridor.

The implementation of TSP on the greater number of transit lines increases the chance of having two or more conflicting TSP requests at one intersection. The existing solutions that resolve conflicting TSP calls are either inefficient, or difficult for implementation in the field. The study presented in Chapter 8 offers a possible solution to this problem. The advantage of the presented algorithm is in the ease of field implementation, without the need for additional hardware or software. The results from this study showed that the built-in TSP options are not a good solution for conflicting TSP calls. The implementation of the presented algorithm, in combination with advanced TSP options developed in the previous studies, offer significant improvements. The study of two (future) conflicting BRT lines resulted in the BRT delay reduction of about 30% for both lines, with minimal impact on vehicular traffic.

The results from all studies show major benefits of TSP implementations for transit operations and small disruptions for vehicular traffic. Depending on the selected strategies and level of TSP, the travel time savings for transit can be between 10% and 30%, intersection delay reduction can exceed 60%, while running-time reliability and headway adherence are greatly improved. These improvements in transit operations can make transit more efficient and competitive to private cars, justifying the TSP implementation.

10.3. Future Research

TSP is a successful solution for improving transit operations and alleviating traffic congestions in urban areas, which makes it an attractive topic for research. The advances in ITS and traffic simulation technology are of a great help for any TSP-related research, which is shown in this dissertation. The biggest possibilities for future research are in the development and evaluation of TSP algorithms presented in Chapters 6, 7 and 8. These algorithms are in the starting phases of development, but they show major possibilities. Some of the topics for future research can be as follows:

- Fine tuning the TSP algorithms to reduce negative impacts on vehicular traffic.
- Combining the TSP algorithms with built-in TSP features.
- Implementing the TSP algorithms on larger scales and for different transit systems.
- Designing, implementing, and evaluating algorithms for conditional and adaptive TSP.

- Implementing the developed TSP algorithms in the field.

Developing SIL applications of other traffic controllers that are being used by transportation agencies can also be a significant part of the future research. This can be important from the complex traffic control and TSP standpoints. Simulation-based methodology for traffic control evaluation using SIL controllers is proven to be a powerful tool in any traffic control related research.