EVALUATION OF TRANSIT SIGNAL PRIORITY STRATEGIES FOR SMALL-MEDIUM CITIES

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ABSTRACT

Transit Signal Priority (TSP) has mainly been applied in larger metropolitan areas where demand for transit service is moderate to high and bus headways are less than 15 minutes. TSP in larger metropolitan areas is implemented to expedite the movement of buses with high occupancy, thus justifying any negative impacts on other traffic and lowering the overall person-delay at intersections. Transit agencies in small-medium size cities, on the other hand, have fewer users and operate at less frequency (i.e., headway greater than 30 minutes). During peak periods, traffic congestion causes missed connections at transfer points and can increase the transit rider's total trip time by as much as one hour. Therefore, TSP could be used in small-medium size areas to alleviate missed connections, enhance service, and attract more transit riders. This study provides a theoretical evaluation of TSP strategies in a small-medium size urban area. Several scenarios are evaluated, involving two TSP strategies; existing and reduced bus headways; and two traffic peak periods. The study findings could give practitioners information concerning TSP implementation in a small-medium size city. The microscopic traffic simulation model, VISSIM, was used to accurately model a downtown region of Fargo, ND, with several bus routes. Results indicated potential bus travel time savings as high as 14 percent, with a decrease in bus stopped delay as high as 38 percent. Impacts to the local system were investigated as well; side-street person-delay increased as much as 14 percent during the afternoon peak.

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BNSF	Burlington Northern Santa Fe Railroad
CBD	Central Business District
CORSIM	FHWA CORridor SIMulation Model
FHWA	Federal Highway Administration
GPS	Global Positioning System
GTC	Ground Transportation Center
HCM	Highway Capacity Manual
ITS	Intelligent Transportation Systems
LOS	Level of Service
MAT	Metro Area Transit
Mn/DOT	Minnesota Department of Transportation
MOE	Measure of Effectiveness
NEMA	National Electrical Manufacturers Association
TSP	Transit Signal Priority
UTCS-1	Urban Traffic Control System-1
VAP	Vehicle Actuated Programing
VISSIM	Traffic in Towns - Simulation (German Acronym)

CHAPTER I. INTRODUCTION

Transit agencies often use technologies to improve service to their customers and reduce their operating costs. Some examples include automated fare collection, real-time traveler information, kiosks with route information, buses which operate on alternative fuels, and transit signal priority. These types of technologies are implemented to attract more customers through improved service while possibly reducing operating costs.

Background

Transit Signal Priority (TSP) includes traffic signal enhancement strategies that allow for the rapid, safe, and efficient movement of transit vehicles through signalized intersections. Although these strategies have been applied since the 1970s, only recently have their use increased. The majority of TSP applications are primarily in areas with extensive transit service (i.e., short headways and heavy ridership) and moderate to heavy traffic conditions. TSP may require the detection of the transit vehicle in order to alter the normal traffic signal operations to benefit the transit vehicle. TSP strategies generally decrease transit vehicle travel times, but they tend to increase delays for other vehicles in non-priority movements. However, TSP can potentially improve traffic conditions in the area where it is implemented, for both transit and non-transit vehicles.

Local transit agencies can benefit from TSP strategies as well when more auto users decide to switch to transit as a result of improved service. Therefore, the demand on roadway capacity is reduced, and traffic operation is enhanced. Through proper evaluation and implementation, TSP can be integrated into existing systems at relatively low costs.

Problem Identification

Large transit agencies often experience unique problems and characteristics associated with very high ridership and operation on a more congested transportation system. In response, there has been an increased use of advanced technologies suited for such problems. For example, the majority of Intelligent Transportation Systems (ITS) have been implemented in the largest 75 metropolitan areas. Smaller urban areas, in turn, rely on those experiences to address transportation problems of their own. However, some of these larger system solutions may not be appropriate for smaller systems.

Furthermore, larger transit agencies implement TSP as a solution to reduce travel times and, therefore, increase capacity through traffic signal enhancement. By increasing capacity, routes can be eliminated to serve the same demand, or the same number of buses can be used to serve more users through decreased headways. Thus, the problem is excessive delay and limited capacity, and the solution is to decrease travel times through signal enhancements to increase capacity and customer service.

Conversely, when looking at smaller transit agencies, the aforementioned problems differ. Smaller transit agency difficulties are more related to adequately servicing its constituents given limited resources, with some implications on system efficiency. For instance, missed connections can be a critical problem for transit agencies in smaller metropolitan areas where headways are greater than 30 minutes. Individuals who rely on bus transit service as their sole mode of transportation are at the mercy of this service for their everyday activities, such as getting to work, shopping, and healthcare. The schedules of these individuals must be carefully planned around the bus schedule. For a 30- or 60-minute headway, a considerable amount of time is needed to plan and complete a trip. It is then easy to appreciate the problem of missed connections due to delay on a transit route, especially as the headway of the route increases.

Another consideration is the competing and attractive auto mode. Consider the automobile passenger traveling the same route as the transit vehicle. This individual experiences the same delay as the bus and reaches his/her destinationin less time, when taking boarding/deboarding time or transfers into consideration. In addition, auto users have flexible schedules and do not have to adhere to a 30-minute headway schedule. The automobile traveler does not see a significant benefit to use transit.

The limited resources of small-medium size cities may impede or limit how agencies develop, test, and evaluate new technologies, including TSP. The resources required to evaluate and deploy these systems may be beyond the ability of these agencies. Since traffic congestion is not as severe as it is in large areas, the benefits and cost may be diluted upon initial evaluation. Regardless, the traffic engineer may be hesitant to provide one mode of transportation (transit) greater priority at the expense of system performance.

Studies have shown, as will this study, that non-priority movements may experience increased delay contributed to the application of TSP strategies. Further, TSP strategies are needed most to the transit user when the negative impacts to other traffic are greatest (i.e., during peak traffic conditions). TSP implementation, when increasing non-transit user costs (longer travel times), becomes one of policy that must be addressed by the traffic engineer, transit officials, policymakers, and the community at large.

Research Objectives

This study will generate information concerning the performance characteristics of TSP strategies and their impacts on local transportation networks relative to small-medium size cities. Specifically, the objectives are as follows:

- identify current TSP strategies,
- perform a literature review of TSP evaluations and applications,
- develop an evaluation framework,
- develop a case study for the evaluation,
- analyze possible scenarios, and
- evaluate the results.

The methodology applied will investigate the impact of TSP on traffic and transit operations, and provide insights on the effects of varying levels of operation for two TSP strategies. Measures of effectiveness (MOEs) will be investigated for both traffic and transit operations.

Proposed Methodology

The TSP strategies will be evaluated using a microscopic traffic simulation model, VISSIM. The base case model will be developed and calibrated using common methods and available data. Traffic and bus transit system characteristics will be investigated, and the impacts of applied TSP strategies will be evaluated using several MOEs. The main MOEs chosen for the analysis are side-street person-delay, network person-delay, and bus travel time. Several scenarios will be developed for midday and afternoon periods, representing each TSP strategy and at differing levels of bus operation.

Organization

This study is divided into six chapters, including the current Introduction chapter. This chapter gave an introduction to TSP, the problem faced by smaller bus transit agencies, research objectives, and proposed methodology. Chapter II reviews currently available TSP systems, including different types of priority strategies. Chapter III presents a literature review of TSP evaluations and real-world applications. It summarizes studies evaluating TSP strategies using traffic simulation and conventional analyses, and five TSP applications throughout the nation. Chapter IV details the research approach and methodology. Chapter V describes the case study used for the methodology, building a network for the simulation model, and results. Finally, Chapter VI summarizes the study findings and provides insights for applications of TSP to small-medium size cities based on the results from this methodology.

CHAPTER II. TRANSIT SIGNAL PRIORITY

Transit signal priority is not a new concept, with applications dating back to the 1970s. In fact, there was an experiment in 1962 conducted in Washington, D.C., to adjust the offsets of a signalized network to better match the lower average speed of buses (Sunkari et al., 1995). Similar projects have continued for the last 30 years, mainly in large metropolitan areas.

Transit Objectives

Clearly, the objectives of the transit agency for transit priority systems are twofold: improve service and decrease costs. Implementing TSP for transit service gives the customers a more dependable service through greater schedule adherence, reduced travel times, and a more comfortable ride by reducing the number of stops and braking for signals. Furthermore, transit users' perceptions of customer service are enhanced by giving a greater emphasis on their modal choice. Through customer service enhancements, the transit agency could ultimately attract more customers.

The financial objectives of the transit agency are to lower the operating costs through reduced maintenance (by decreasing the number of stops caused by signalized intersections) or eliminating the need for additional vehicles while maintaining required headways through TSP enhancements. Greater fuel economy and reduced maintenance costs can be achieved through these strategies, resulting in increased economies of utilization. Economies of utilization can also be gained through TSP by providing a larger service area while maintaining the same size of transit fleet and personnel.

Priority Strategies

There are generally two classes of TSP strategies, passive and active. Passive priority strategies give priority to transit vehicles without the need for transit vehicle detection. Conversely, active priority strategies provide priority to transit vehicles after a transit vehicle is detected and priority conditions are met. The selection of an appropriate strategy depends on the characteristics of the transportation network, objectives of the transit agency, cost considerations, and factors associated with the performance of the traffic signal controller.

Passive Priority

Passive priority strategies mainly consist of signal timing modifications favoring the transit vehicle, but may also include geometric or infrastructure enhancements. These strategies include phase splitting, progression/coordination to favor priority vehicle movements, increasing the priority phase split, or queue jumps. Passive priority strategies are useful for applications where the transit service is moderate to heavy and uniform throughout the day, and overall traffic conditions are light to moderate. The advantages of passive priority are ease of implementation, low costs, and the ability to change plans dependent upon changing conditions of traffic and transit operations. Disadvantages may include increased delay to side-street traffic, excessive allocation of green time to priority movement, increased signal maintenance, or dissatisfaction from the general public. Furthermore, if the transit headways are large, as is generally the case in small-medium size cities, these strategies may induce unnecessary delay to the entire system when busses are not present. The other TSP strategy class, active priority, can address some of the disadvantages of a passive priority strategy, however, at different expenses.

Active Priority

Active priority strategies are dynamic signal timing enhancements, where the signal phases are modified upon the detection of a transit vehicle. This strategy provides for an efficient operation of the signal by responding to the transit call and then returning to normal operations after the call has expired or serviced. Active priority strategies are further classified into two types: conditional and unconditional. Conditional priority is awarded to a detected bus when conditions are met, such as the number of passengers, the schedule adherence of the route, or the time since last priority was awarded. Urbanik and Holder (1977) describe unconditional active transit priority as a strategy where transit vehicles receive green extensions or red truncations whenever needed, regardless of cross street queue lengths or the time since priority was last granted (as cited in Garrow and Machemehl, 1997). Active transit signal priority strategies include the following types:

- Early Green (Early Start or Red Truncation of Priority Phase),
- Extended Green (or Phase Extension of Priority Phase),
- Phase Insert (or Special Phase), and
- Phase Suppression.

Early green strategy is the process indicating a green light prior to the normal start of a priority movement phase. This process is done by shortening the green time of the opposing phase, without violating the minimum green time, pedestrian movements, or clearance intervals, and returning to the priority phase. Extended green is similar to early green in the sense that the opposing phases are shortened after the priority phase was extended. Both methods are intended to allow for the passage of the transit vehicle in the most efficient manner, dependent upon the arrival time within the cycle. These strategies are the most common methods applied, as will be discussed in Chapter III. However, each strategy should be evaluated depending on the type of transit movement and characteristics of the signalized intersection. Figure 2.1 provides a graphical comparison between early green and extended green strategies.

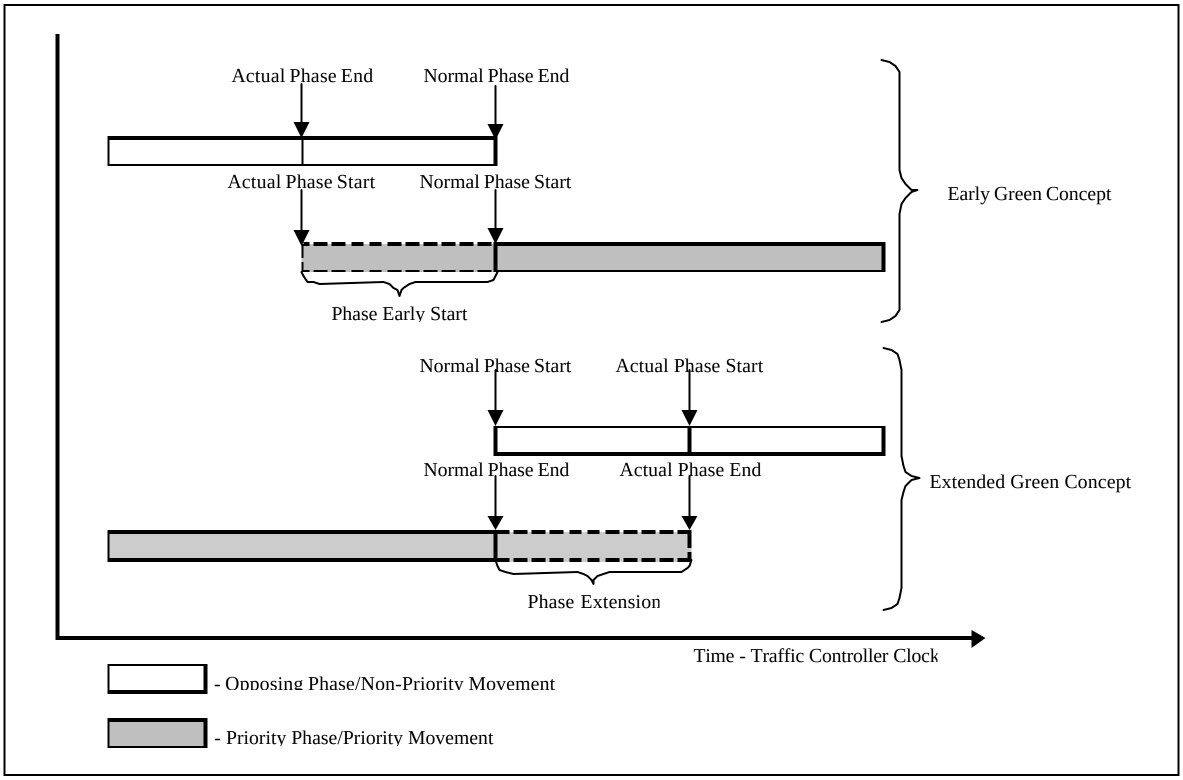

Figure 2.1. Illustration of Early Green and Extended Green Strategies.

Phase insert is the application of a special "transit only" phase introduced into the normal signal operations. This strategy may be applied through exclusive turning movement phases or through an additional phase for the transit movement. Phase insert is applicable for long cycle lengths where there is adequate room for the minimum green times and clearance intervals for the inserted phase. Similarly, phase suppression is the process of allowing phases to be skipped, permitting the transit phase to be serviced. This strategy may be suitable where there are several turning movement phases, such as leading left-turn phases.

Signal Controller Operations

Typically, TSP is implemented using hardware and software enhancements to the current traffic controller assembly. Some traffic controller manufacturers provide low-priority preemption or transit priority routines as part of the controller software. However, the detection of transit vehicles still requires additional hardware components to the existing system to process the priority call. Most active priority TSP applications require “check-in” and a “check-out” detection. These routines operate in the same manner as regular preemption but have additional parameters which control the impact of the preemption routine. Bus preemption usually occurs on a first-come, first-served operation, while yielding to emergency vehicle preemption or railroad preemption. There are several different types of transit vehicle detection, which will be discussed next.

Detection Requirements

The hardware requirements for transit signal priority are dependent upon the characteristics of the surrounding area and/or available technologies. There are several methods of detecting and processing transit vehicle information, including

- Inductive Loop,
- Radio Frequency,
- Infrared Detection,
- Audio Detection, and
- Global Positioning System.

This chapter provided a general overview of the types of TSP strategies and their characteristics. The next chapter will provide an overview of the findings from research and real-world applications of these types of systems.

CHAPTER III. LITERATURE REVIEW AND PRACTICE

The literature review will provide a general overview of the current bus priority systems and applications throughout the country. The objectives of this research are to identify what studies have been performed using microscopic simulation for analysis, the TSP strategies applied, the characteristics of the transportation system where TSP was applied, and the results from these studies. As stated previously, this technology has been analyzed since the early 1970s, as is discussed in the first review with Ludwick (1975).

Evaluations of TSP

Washington, District of Columbia

The work of Ludwick in 1975 was among the first TSP studies in the United States. This evaluation was built from the initial Urban Traffic Control System - Bus Priority System (UTCS-BPS) in Washington, D.C., and used a microscopic simulation model, UTCS-1. Using the UTCS-1 model, Ludwick simulated a network with unconditional preemption for transit buses, applying early green or extended green logic.

Several scenarios were evaluated by varying the headways of 1 transit route from 30 seconds to 4 minutes, and moving the bus stops to represent far-side or near-side stops. The model uses bus detection zones 210 feet upstream from the instrumented intersection and extended to within 5 feet of the intersection (Ludwick, 1975). In addition, the algorithm provides immediate reaction to a transit call and determines appropriate action. Any signal synchronization (coordination) in the network is, thus, maintained after the departure of all buses from the detection zone (Ludwick, 1975). The major findings from this report may be summarized as follows:

- mean bus travel times experienced a decrease from 22 percent to 32 percent,
- cross street traffic travel time increased from 6 percent to 30 percent for far-side stops, and
- cross street traffic travel time increased from 9 percent to 66 percent for near-side stops.

Another interesting finding was an improvement in mean bus travel times, within 15 percent of the theoretical minimum travel time for the transit vehicle. The theoretical minimum travel time was calculated from the distance traveled and the average running speed of the transit vehicle.

College Station, Texas

Sunkari et al. (1995) developed a model to evaluate a bus priority strategy for one signalized intersection in a coordinated signal system. The model used the *1985 Highway Capacity Manual* delay equation for signalized intersections and adapted the equation to calculated person-delay for cases with and without priority strategies. Priority is provided by early green and green extensions of the priority phase at regular intervals, coordinating to the estimated bus arrival interval. Five cases were identified: (1) no priority, (2) priority phases receive a minimum extension, (3) priority phases receive a maximum extension, (4) priority phases provided a minimum early start, and (5) priority phases provided maximum early start.

The benefits of the priority strategies were compared on a cycle-by-cycle basis by calculating the delay for buses and other vehicles. A weighted normal delay was then calculated for a non-priority scenario and a priority scenario. The model was compared to field evaluation to test the reliability of results. A site was chosen in College Station, TX, and the controller was modified to accept manual inputs to simulate a bus approach. Approximately 10 sample priority cycles were obtained for Case 3 and Case 5. It was determined that the other cases would not be compared due to the small impact they had on the side-street traffic.

Comparison of the model to the field evaluation resulted in delay predicted by the model slightly higher than delay observed in the field (Sunkari et al., 1995). The model is a good predictor for delay when volume to capacity ratios are less than .85 but overestimates at higher ratios. A linear regression indicates that the model overestimates total delay by approximately 41 percent. This overestimation was identified as a limitation of the model to measure correctly protected-permitted left-turn operation. Another linear regression was developed with the elimination of delays for left-turn phases and phases with high v/c ratios. The results again show a good linear relationship but a 25 percent overestimation of delay (Sunkari et al., 1995).

Ann Arbor, Michigan

Al-Sahili and Taylor (1996) performed an analysis of Washtenaw Avenue in Ann Arbor, MI, in 1996 using the NETSIM microscopic model. Washtenaw Avenue is located in a central business district (CBD) with volumes exceeding design capacity. The analysis included six signal preemption (commonly referred as low-priority preemption, a TSP strategy) schemes representing six case simulation runs. The signal preemption schemes for this study are as follows: (1) green extension, early green, no compensation; (2) green extension, early green, compensation (compensation determined empirically based on full queue discharge after preemption); (3) skip phase, no compensation; (4) skip phase with compensation; (5) selective plans (the optimal scheme determined for each intersection separately using schemes 1-4); and (6) conditional preemption (scheme 5 but only allowed if bus was behind schedule).

Prior to conducting the evaluation, traffic signal timing plans for Washtenaw Avenue were optimized using the TRANSYT-7F model and used for a base case. Three constraints were then placed in the NETSIM model: (1) no preemption is allowed during two consecutive cycles; (2) the minimum green time for any signal phase is 10 sec; and (3) the maximum extension or advance of the green signal phase is 10 sec (Al-Sahili and Taylor, 1996).

The research approach used an animation viewer for visual inspection to detect bus positions in the network and then manually determine timing plans based on the criteria described above. The use of several time periods in NETSIM allowed the authors to change the timing plans, based on the visual inspection of bus arrivals, to emulate the reaction of the traffic controller. This approach also allowed for the collection of MOE for each time period, representing the appropriate scheme. The MOEs for the case study were vehicle trips, total delay, and average delay.

The study found few benefits of preemption to the corridor given the traffic volume and bus headway characteristics of Washtenaw Avenue. The maximum benefit found was a 6 percent savings in travel time for a single bus. The authors concluded that bus headways would have to be less than 15 minutes to justify the implementation of preemption (TSP). Further, the authors suggested that the most suitable preemption plan for each intersection should be evaluated and implemented together as a system.

Austin, Texas

Garrow and Machemehl (1997) evaluated the 2.5 mile Guadalupe-N. Lamar arterial in Austin, TX. The main objective of this study was to evaluate different TSP strategies for off-peak and peak time periods, and investigate the different saturation levels for side-street and main-street approaches. The study used the NETSIM model and a graphical animator to determine appropriate times for transit arrival and response intervals. Utilizing the time period function in NETSIM, the authors were able to simulate active priority strategies by changing the signal timing parameters for time periods when a transit vehicle was traversing an intersection.

The off-peak analysis consisted of two passive priority strategies and an unconditional priority strategy. Passive priority strategies were evaluated using an optimized lower cycle length and phase splitting. The benefits of reducing the cycle length from 100 seconds to 70 seconds resulted in bus travel time savings of 11 percent. Likewise, phase splitting resulted in a bus travel time savings of 10 percent. Results from the analysis of unconditional active priority suggest bounded lengths of priority for green extension and early green strategies for various cross-street saturation levels. Specifically, the cross-street saturation levels of < 0.25, 0.25 to 0.35, and 0.35 to 0.70 should have unbounded, 20 second maximum, and 10 second maximum priority lengths, respectively (Garrow and Machemehl, 1997).

This section provided an overview of studies using simulation models to evaluate TSP strategies. Table 3.1 summarizes studies, which may not have been identified in the literature review, that used simulation models for TSP analysis. The next section provides an overview of five TSP applications throughout the United States.

Table 3.1. Summary of Simulation Models Used for TSP Analysis

Study	Simulation Model
Development and Evaluation of Transit Signal Priority Strategies	TRAF-NETSIM
Simulation of an Unconditional Preemption Bus Priority System	UTCS-1
Model to Evaluate the Impacts of Bus Priority on Signalized Intersections	1985 HCM
Evaluation of Bus Priority Signal Strategies in Ann Arbor, Michigan	NETSIM/TRANSYT-7F
NETSIM-Based Approach to Evaluation of Bus Preemption Strategies	TRAF-NETSIM
The Cermak Road Bus Preemption Study, Summary Report	TRAF-NETSIM

Implemented TSP Systems

This section identifies five applications of TSP systems throughout the United States. These projects were chosen arbitrarily from successful TSP applications for evaluation or permanent implementations. Applications for small-medium sized agencies were preferred and are identified in two studies from Pierce Transit, Tacoma, WA, and St. Cloud Metropolitan Transit Commission, St. Cloud, MN.

Cermak Road Bus Preemption Study, Illinois

The Cermak Road bus preemption study in the Chicago area was one of the first applications identified in this literature review (Illinois Department of Transportation [IDOT], 1993a). This project was divided into three parts: a feasibility study, the design and implementation of the system, and the evaluation of the system's operations (Weesner and Meyerkord, 1999). The feasibility study began in 1991 and ended with a summary report published in 1993. The design and implementation occurred between 1995 and 1997. While the term "preemption" was initially used, the actual logic applied in the project is more representative of "low-priority preemption" of traffic signal controllers.

The Cermak Road encompasses 15 signalized intersections along 2.5 miles. This corridor serviced three bus routes for two transit agencies. The corridor spanned multiple jurisdictions responsible for traffic operations as well, resulting in several different signal controllers. Therefore, to provide uniformity throughout the corridor, the existing traffic controllers were replaced with Econolite ASC-2 series controllers equipped with controller software modified to conform to the functional specifications determined by the design phase.

The feasibility study used a simulation analysis of the corridor using TRAF-NETSIM. In order to provide unbiased results, traffic signal timing plans were optimized before evaluating the effectiveness of priority strategies. TRANSYT-7F was used for signal split and offset optimization to develop the base-case timing plans. Results indicated a 20 percent increase in average bus travel speeds over the existing conditions as a result of signal timing improvements (without priority). An additional 24 percent increase in average bus travel speeds was experienced through the application of priority strategies. This increased speed resulted in a 30 percent reduction in total bus trip time along the corridor, from 15 minutes to 10.5 minutes.

The simulation analysis found that only 36 percent of the signal cycles which had buses present actually required preemption (IDOT, 1993b). Furthermore, the effect of the preemption on the cross-street traffic delay was insignificant. Field-delay measurements collected after the implementation of the priority strategies found that stopped delay increased on all but one cross street and ranged from 0.4 to 37.9 sec/veh during the PM peak hour studied, with an average increase of 8.2 sec/veh (Weesner and Meyerkord, 1999). Studies conducted after implementation also indicated an average bus travel time decrease of 83 seconds for eastbound buses and 12 seconds for westbound buses when compared to optimized corridor travel time studies (Weesner and Meyerkord, 1999). The average bus travel time decreases were a savings of approximately 8 percent for eastbound buses and 1 percent for westbound buses (IDOT, 1993b).

City of Phoenix Advanced Bus Detection Demonstration Project, Arizona

The City of Phoenix conducted a TSP demonstration project using the 3M Opticom system. Travel time and speeds were analyzed before and after the deployment of an Opticom Advanced Detection system (Parsons Brinckerhoff, 1998). The study evaluated a six mile section of Roeser Road that included six intersections with arterials in the southern Phoenix area. This study was conducted to address concerns with increased bus travel times experienced by the City of Phoenix public transit department. The authors of the demonstration project identified the following factors contributing to the increased bus travel times:

- increased number of wheelchair accessible routes,
- addition of bike racks,
- bus bay turnouts and re-entering traffic concerns,
- traffic signal system progression timed for autos without consideration to bus operations, and
- quickly growing traffic congestion.

The Opticom system was used for transit vehicle detection to provide two priority strategies, early green and green extension. The operating range of the Opticom emitters was between 800 and 1200 feet. This study also identified 3 of the 6 intersections with green extensions limits from 6 seconds to 9.5 seconds. Information was not available on specific timing parameters or manufacturer of the traffic controller.

The major findings from this study included delay time at an intersection, schedule reliability, benefit/cost ratio, and the LOS of each intersection. Time spent waiting at red lights, or the approach delay for buses, declined 16 percent and was statistically significant (Parsons Brinckerhoff, 1998). Transit benefits per intersection were calculated at $5,932 annually, resulting in a benefit/cost ratio of 1.57 over a 10-year life cycle. In addition, this study concluded that total intersection delay increased 1.4 percent during both AM and PM peak periods using a Highway Capacity Manual analysis and the signal timing parameters of the traffic controller.

King County Demonstration Project, Washington

The King County Demonstration Project involves several agencies and stakeholders, including the Washington State Department of Transportation, King County Transit and Roads Divisions, City of Seattle, City of Shoreline, and City of Bellevue, among others (Dale et al., 2000) Two arterial roadways, Aurora Avenue (SR99) and Rainier Ave, are being studied in the King County Demonstration Project. The demonstration is evaluating TSP for buses equipped with automatic vehicle identification (AVI) tags. Three local jurisdictions developed specific TSP strategies tailored to their own needs, mainly employing minor variations of the green extension and early green/red truncation strategies (Dale et al., 2000). The TSP strategies must also obey any minimum or clearance intervals, and may not skip any phases or break coordination. Upon final implementation, a total of 26 signalized intersections along the two arterials will be AVI/TSP equipped.

The results from the Rainier Avenue South TSP Field Evaluation, conducted by King County Metro, SEATRAN, and Innovative Transportation Concepts, Inc., suggest improved system operations. The Rainier Avenue South corridor is approximately 2.1 miles in length with 5 of 9 signalized intersections equipped with TSP devices. Field data were collected from three TSP intersections and extrapolated for the analysis. The analysis included both AM peak and midday-peak periods.

Several MOEs were gathered for transit and non-transit traffic. Impacts on non-transit traffic delay (seconds/vehicle) ranged from a 13 percent reduction in the AM to a 9 percent increase for the midday period. Intersection (stopped + approach) bus delay was reduced by an average of 34 percent for the AM peak period and 24 percent for the midday-peak period. The estimated travel time saving for buses was 8 percent through the corridor. Finally, the average person-delay, which provides a comprehensive measurement of delay when comparing different modes, ranged from a 13 percent reduction for the AM period to an 8 percent increase for the midday-peak period (Innovative Transportation Concepts [ITC], 2000a). These values suggest a high number of non-transit vehicles through the intersection.

Pierce Transit Demonstration Project, Washington

Pierce Transit Agency, Tacoma, WA, conducted a study to evaluate the effectiveness of TSP for a 3.1 mile segment of South 19th Street in the City of Tacoma (Funkhouser et al., 1996). The study corridor consisted of 11 signalized intersections which ran on actuated free mode or actuated traffic responsive coordination. Fifteen transit vehicles were equipped with Opticom emitters and/or other priority hardware for two routes traveling the study corridor. A project committee was formed and assigned five primary objectives: (1) determine transit travel time savings for participating buses, (2) determine impacts on cross street traffic, (3) document steps taken and lessons learned, (4) evaluate the effectiveness of several signal control strategies and equipment, and

(5) evaluate data collection capabilities of TSP systems.

An external logic control was used to evaluate two TSP strategies: (1) green extension, and (2) green extension and/or early green. The following guidelines were established for the control strategies: pedestrian movements and timing would not be skipped or truncated; signal coordination would be maintained; vehicle phase skipping would not be permitted; and wiring modifications to the signal cabinet would be kept minimal (Funkhouser et al., 1996).

The results for the green extension suggest that reductions in bus travel time ranged from 5.8 to 9.7 percent, with one direction having most statistically significant results. The results for the green extension and/or early green included only one statistically significant result, a travel time savings of 8.2 percent. It was also noted that, under certain conditions, TSP could reduce bus travel time up to 13.4 percent (Funkhouser et al., 1996).

The side-street movements did not experience statistically significant impacts, but field studies indicated that an average of 1-4 seconds of additional delay per vehicle was experienced. The side-street delay was sampled at 4 intersections along the corridor, with increases ranging from 5 to 12 percent, however, the variances in stopped delay between the control period and the task period were not statistically significant. An interesting observation made by the committee was the use of loop occupancy to measure delay. It was concluded by the committee that collecting and comparing loop occupancy data can be used as an additional indication of vehicle delay when making adjustment to signal timing.

The Opticom system allowed for the sampling of approximately 2,200 bus trips. The detection zone settings ranged from 150 feet to 800 feet. Interactions of the Opticom system among various jurisdictions in the Tacoma area resulted in the need to allow the drivers to manually control the emitters, although the policies were not discussed.

Finally, a survey of the driver perceptions was conducted. Bus operators were surveyed to determine whether they perceived a reduction in travel time; 48.3 percent responded yes. When asked about their perception for the use of the equipment permanently, 61.4 percent of surveyed bus operators favored permanent use. The general public was not surveyed, however, operators were asked if customers had any difficulties during the demonstration due to removal of the fixed schedule. Of the surveys received, 70.5 percent responded no to customer difficulties experienced.

St. Cloud Transit Priority Evaluation Project, Minnesota

The St. Cloud Metropolitan Transit Commission conducted a transit priority evaluation project in November 2000. The Cermak Roads transit priority software used for Econolite ASC/2 traffic controllers was utilized for this test (Westwood Professional Services, 2000). The study was a cooperative effort involving the Metropolitan Transit Commission, City of St. Cloud, Stearns County, and Mn/DOT. This study evaluated the Southwest/Crosstown bus route, which is approximately 15.7 miles in length and crosses 11 signalized intersections.

Five intersections were evaluated before and after the implementation of the TSP. The detection zones for these intersections were set at approximately 300 feet, with an observed 50-foot variation in the zones. The analysis was conducted for three periods representing an AM-peak, off-peak, and a PM-peak period. The results from the comparison indicate a 43 percent savings in the overall average bus delay caused by signalized intersections for all periods (Westwood Professional Services, 2000).

Another observation was a reduction in the average bus running speed for the route. The reduction in intersection delay allowed the drivers to maintain schedules without the need to "catch up" by increasing travel speeds. A comparison was made between the increase in person-delay for non-transit traffic and the decrease in person-delay for transit. This comparison resulted in an average bus occupancy of 24 required to balance the delay (Westwood Professional Services, 2000).

Transit Priority for Small-Medium Cities

Only a few studies were found to address the evaluation of TSP for small-medium size cities. The Pierce Transit Demonstration Project and St. Cloud Transit Priority Evaluation Project were the only projects identified to provide an implementation of TSP for small-medium size cities, which was unexpected. The resources available to these agencies for implementation and the general lack of information on TSP strategies suggest very few applications or evaluations for small-medium size cities. While other small-medium size cities and transit agencies may have evaluated or implemented a transit signal priority system, resources were not available to identify those locations.

Summary

The studies identified in the literature review provide insight on the impacts of implementing multiple TSP strategies under various traffic conditions. Most of the studies reviewed primarily focused on the extended green and early green TSP strategies, in addition to some passive priority strategies. The 3M Opticom detection system was the most widely used transit vehicle detection method, followed by inductive loop detectors. Installation and purchase costs of a standard 3M Opticom system with new traffic controllers is estimated at approximately $30,000 per intersection (Westwood Professional Services, 2000).

Table 3.2 illustrates the TSP strategies used for the five applications reviewed. The studies indicate a range of bus travel time savings of 8 percent to 30 percent. The most common measure between the studies, bus control delay, indicates a range of savings between 16 percent and 34 percent.

Table 3.2. Summary of TSP Application Strategies

Application	TSP Strategies
Pierce Transit Demonstration Project, Washington	Extended Green, Early/Extended Green
Cermak Road Bus Preemption Study, Illinois	Extended Green, Early Green, Extended/Early Green
City of Phoenix Advanced Bus Detection Demonstration Project, Arizona	Extended Green, Early Green
King County Demonstration Project, Washington	Extended/Early Green
St. Cloud Metropolitan Transit Commission Transit Priority Evaluation Project, Minnesota	Extended/Early Green

CHAPTER IV. METHODOLOGY

This chapter provides an overview of the methodology used for the development and evaluation of TSP strategies. The study examines two TSP strategies: early green and extended green. The method for evaluating these TSP strategies will also be discussed, along with an overview of the microscopic simulation model, VISSIM, which was used for the evaluation.

Objectives

The overall objective of this methodology is to assess potential impacts of implementing TSP strategies in small-medium size cities. Therefore, TSP strategies and applications appropriate for small-medium size cities were considered. The two TSP strategies examined in this study, early green and extended green, are consistent with other studies and applications previously conducted. The information generated from this study should provide useful information on the impacts of TSP strategies to transit service and traffic conditions representative of small-medium size cities.

Specifically, the methodology will compare key MOEs (e.g., approach delay) between normal operations and TSP strategy implementation using a microscopic simulation model (VISSIM). It will also investigate the impacts of varying bus headways using the same evaluation method for two traffic peak periods. Therefore, the main components of the methodology are as follows:

- identify TSP strategies for evaluation,
- develop TSP strategy logic,
- collect data,
- construct a simulation model,
- calibrate model,
- evaluate TSP strategies, and
- compare MOE.

A technical steering committee was formed to assist in the data collection and provide guidance throughout the study. Figure 4.1 shows a general flowchart of the methodology.

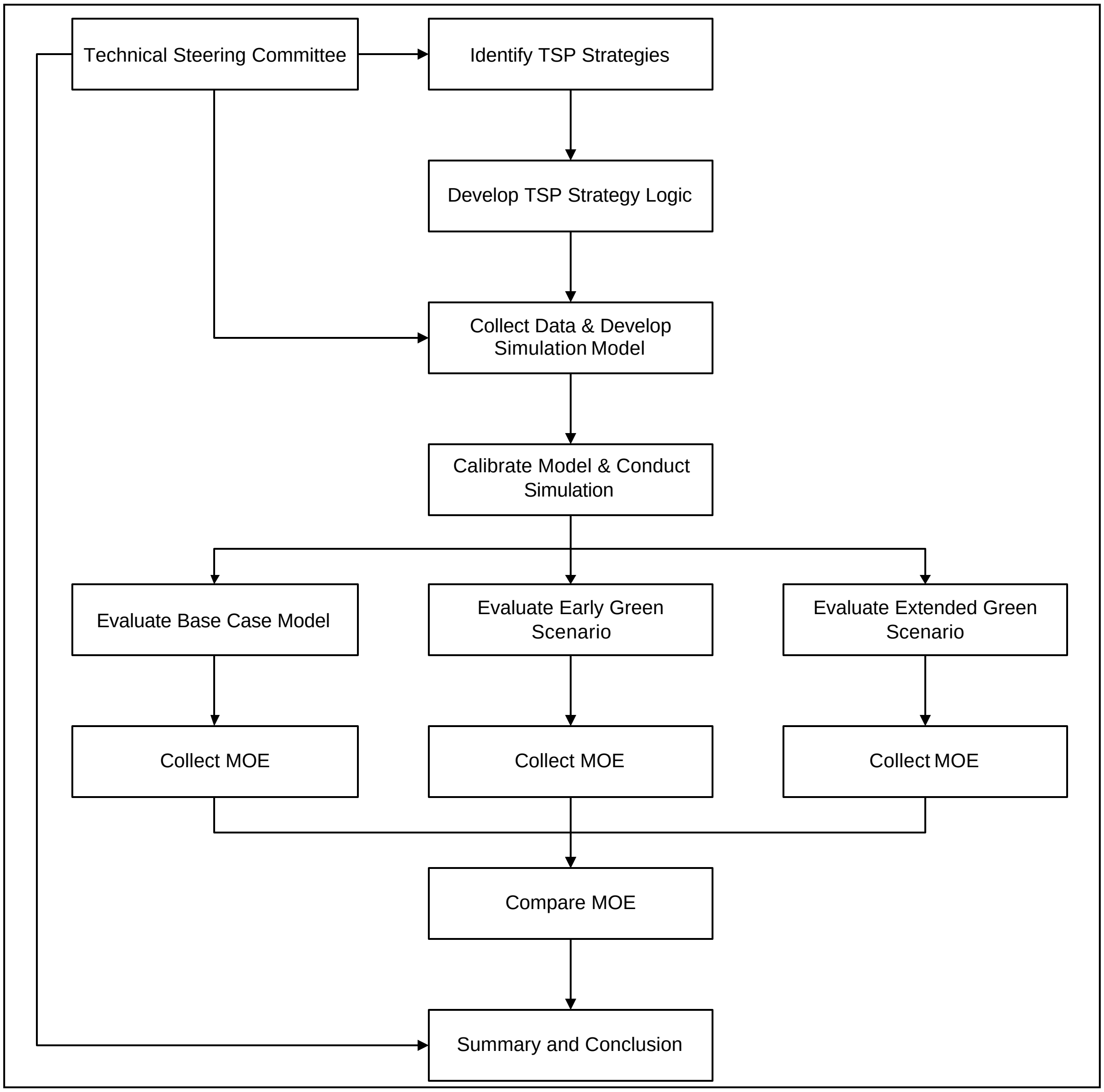

Figure 4.1. Methodology Flowchart.

The next section will describe the use of a case study design for the methodology application. The remainder of this chapter will look at the rest of the methodology, i.e., the development of TSP strategies, evaluation of TSP strategies, and a description of the VISSIM traffic simulation model.

Case Study Design

A case study design will be applied to illustrate the impacts of the TSP strategies. Each evaluation scenario will represent an application of a TSP strategy compared to the calibrated base case. The scenarios will be simulated for a midday period and an afternoon period. Likewise, each application and peak period will be simulated with 2 levels of transit operations, 15-minute and 30-minute headways, as will be discussed in the next chapter.

Modeling of TSP Strategies

The literature review summarized in Chapter II identified the most common TSP strategies used throughout the country. The review showed that early green and extended green TSP strategies were the most used methods. These strategies were also tailored to meet agencies' preferences, implementation requirements, and location restrictions. Therefore, this study utilizes these two strategies for the case study with emphasis on minimizing disruption of coordinated traffic signal operations. This feature was especially important to the case study area, where the two main corridors are one way streets in a central business district (CBD).

The next section will describe the TSP application framework developed for the methodology. This framework dictates the details of TSP implementation and, therefore, directly impacts the results of the evaluation. As a result, the evaluation of early green and extended green strategies under a different framework would yield different results. The framework for applying TSP strategies in this methodology may be described as follows:

- obey minimum green and pedestrian timing requirements for all signal phases,
- minimize interruptions to traffic signal coordination,
- provide the maximum benefit to the transit vehicle,
- utilize one detection zone and a timer or clearance interval for the transit vehicle, and
- provide priority to the transit vehicle on a first-come, first-served basis.

As described in Chapter II, the early green strategy is the process of giving a green indication to a priority vehicle earlier than normal traffic signal controller operations. In the same manner, the extended green strategy is the process of extending the green indication for the priority vehicle movement longer than the normal traffic signal controller operations. Some general information and definitions will be given here to help clarify the discussion to follow. Phases refer to the set of signal indications for a movement of vehicles. Logic refers, generally, to software coding for the traffic signal controllers. Finally, bus clearance interval or bus clearance time is a variable used for detecting buses for the TSP strategy. It refers to the time required for the bus to travel from the point of detection to the stop bar of the signalized intersection (i.e., an 80 meter detection zone equals 8 seconds).

Early Green

There are two unique rules which handle main-street and side-street early green calls. An early green call for the main-street movement can be recognized within one cycle length, whereas an early green call for the side-street movement is recognized during the transition to a new cycle. Figure 4.2 illustrates the time segments during which an early green call can be recognized for main-street and side-street priority movements.

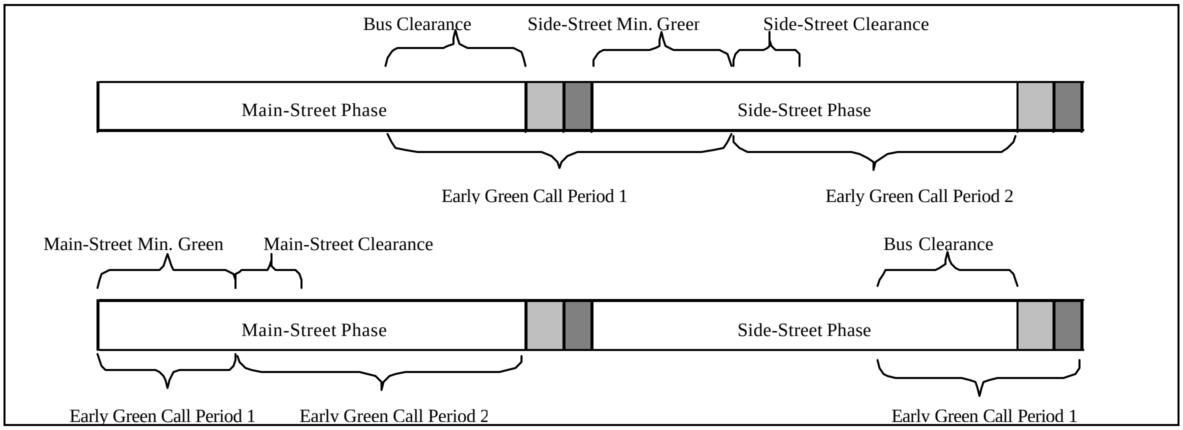

Figure 4.2. Illustration of Early Green Logic Concept.

Early green call period 1, illustrated in Figure 4.2, is the period of time which a call from a bus can be recognized, thus causing an early return to the priority movements. Calls received during early green call period 1 will cause the signal control to recognize a forceoff at the end of the minimum green time or minimum pedestrian clearance time for the opposite phase, whichever is greater. Likewise, calls received during early green call period 2 will cause the signal control to recognize a forceoff at the time of the bus actuation. This method provides for maximum priority for the transit vehicle by servicing the clearance interval for the opposing movement and providing a startup time for any queues which may have developed within the bus clearance interval.

Both of these rules accept the transit vehicle actuation and apply the new forceoffs within the current time step. Also, once green is given to the priority phase, the phase will remain green until the original forceoff is reached. The next section will build upon this discussion for extended green strategy.

Extended Green

The extended green strategy is similar to the early green strategy in the use of bus clearance intervals and truncation of green times of opposing phases by adjusting the forceoffs of the priority phases. Similarly, the extended green logic for the main-street phases are handled within one cycle length, whereas the side-street phases are handled during a transition to a new cycle. The main difference is the amount of time available within the cycle length for the acceptance of an extended green call. This time is equivalent to the clearance time for the transit vehicle (bus clearance interval). Multiple actuations can be recognized, however, resulting in greater benefits for buses arriving in platoons. Figure 4.3 illustrates the appropriate extended green call periods and extension periods for main-street phases and side-street phases.

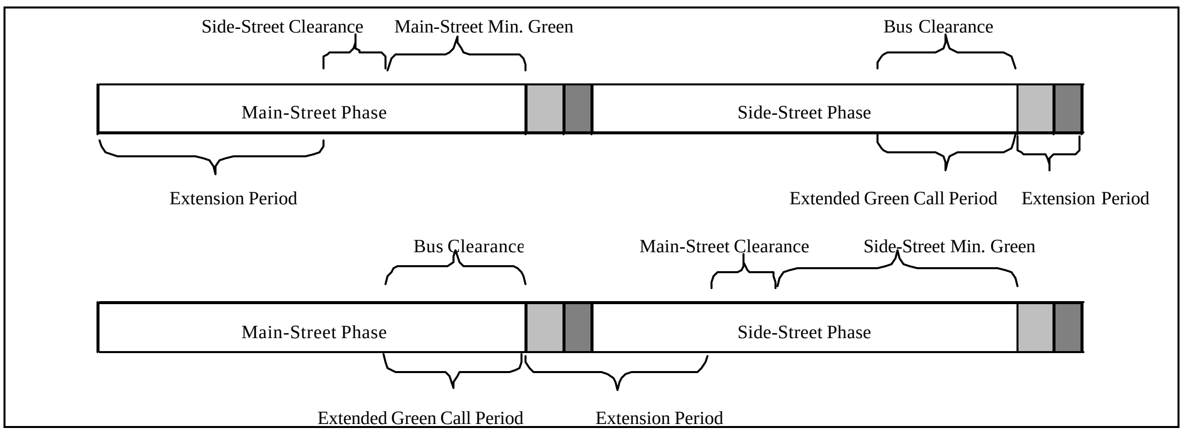

Figure 4.3. Illustration of Extended Green Logic Concept.

Upon a call by the bus, the current forceoff for the priority phase will be extended by an interval equal to the bus clearance time. In the case of multiple calls, if the transit phase is being extended, additional calls will extend the green only if there is enough time to service the bus clearance time. The extended green method for the side-street approach does allow for interruption of traffic coordination. This method seemed like an acceptable practice since there are few occurrences of multiple buses on side-street movements and the green band for the main-street movements was large. The number of bus routes on the side streets will be illustrated in Chapter V.

It is expected that the early green strategy will provide greater benefits than the extended green strategy. This expectation is due to the greater time window an early green call can be recognized, which can be greater than one-half cycle length. In comparison, the extended green strategy can only recognize a call for a period equal to the bus clearance interval. The next section will provide a description of the method for evaluating the different strategies.

Evaluation of TSP Strategies

As stated in the case study design, the two TSP strategies are compared to the base case for the varying levels of traffic and transit operations. A statistical test will be applied to 30 simulation runs performed for each TSP strategy and the base case. The high number of samples should compensate for differences between the simulation runs due to the stochastic nature of the traffic and transit generations, and the reactions to the TSP strategy. This high number of samples also allows for greater statistical confidence when conducting the statistical analysis.

Operational Factors

In order to provide a comprehensive representation of TSP strategy impacts, a sensitivity analysis was developed. There are two main variables which could affect the performance of TSP strategies: traffic volumes and transit service characteristics (i.e., headways and ridership). The traffic volumes for both main street and side street directly affect the benefits or disbenefits which are realized. By analyzing peak and off-peak conditions, a greater understanding of the impacts associated with time of day can be realized. Furthermore, other measures or system states which are directly related to traffic volumes, such as LOS or cycle lengths, can be associated with the results. Transit service characteristics can also affect the performance of TSP strategies. By varying the bus transit headways, the impacts of the TSP strategy associated with the service level can be investigated. The combination of these two variables results in six scenarios which are discussed in the case study description in the next chapter.

The levels of transit operation used are representative of typical small-medium city transit operations. These levels are assumed to have greater than 15-minute headways. For this study, two levels were chosen: one to represent the existing headways and one that uses half of the existing headways (i.e., doubles bus frequency). For the case study area, the current and double levels of transit service represent a 30-minute and 15-minute headway, respectively.

Measures of Effectiveness

The MOE chosen for evaluating the impacts of TSP strategies are side-street person-delay, network person-delay, bus travel time, and bus delay. In addition, bus stopped delay and bus total delay have been collected to give a more detailed representation of the impacts to the transit service. Stopped delay measures the time the bus had a velocity of zero waiting for a signalized intersection approach. Total delay measures the time the bus was below the desired velocity for a signalized intersection approach. To clarify the term approach in this study, it is most commonly referred to as the area from approximately one block upstream from the stop bar location. The MOEs used here are consistent with the reviewed studies and should provide a good representation of the TSP impacts to general traffic and transit operations.

Side-Street Person-Delay

The largest negative impacts associated with TSP strategies are expected to be increased side-street person-delay. Since the majority of the traffic travels on the main street, side-street delay is representative of the "worst case" scenario. The case study, however, includes bus movements on the side streets. Therefore, vehicle delay will also be analyzed to provide a better understanding of the impacts to non-transit vehicles on the side streets.

Network Person-Delay

Network person-delay is an aggregate measure of the delay on all approaches in the case study network. This MOE will give insight into the cumulative effect of the TSP strategy applied on the entire network or system included in the model. The network person-delay impacts are expected to be less than side-street delay impacts due to the large number of TSP calls which can occur. This difference is caused because benefits to transit and traffic on the main-street approach will offset negative impacts on opposing approaches. As green times for the main-street are increased, capacity is increased, thus lower approach delay times are expected.

Bus Travel Time

Bus travel time is an aggregate measurement of travel times on all bus routes included in the analysis. Therefore, this measure will include benefits received by some bus movements and losses received by others arriving near the transition to or from a TSP strategy. As discussed earlier, the TSP in this methodology uses a first-come, first-served rule. Therefore, a bus arriving on a side street before a bus arriving on the main street will receive priority, causing delay to the main movement. It is also important to realize that multiple buses in the same direction may incur increased delay due to the transition from TSP strategies. Therefore, this MOE will provide a good representation of the performance of the entire system and the applied TSP strategy.

Bus Delay

Bus delay is reflected in the bus travel time, but it is also a measurement of the effectiveness of the TSP strategy since it specifically examines delay due to traffic signal operations. A large decrease in bus delay equates to an increased number of priority calls received and processed by the traffic signal controller. This measure will also capture the effects from opposing priority bus movements.

Microscopic Simulation Model

The VISSIM microscopic simulation model was used for the analysis. VISSIM was selected because of its capability to provide detailed information on the MOE identified; it has a strong emphasis on modeling transit, and it allows the user to evaluate traffic signals through fixed time controllers or through explicitly defined controller logic. This section will give a general overview of the characteristics of the model, its data requirements, and the calibration method applied to the model.

VISSIM was developed in Germany through research originating at the University of Karlsrhue, Karlsrhue, Germany. VISSIM, a German acronym for "traffic in towns - simulation" is a stochastic microscopic simulation model. There are two main components of the VISSIM model: a traffic simulator and a signal state generator.

The traffic simulator model primarily consists of a car following and a lane changing logic. This model uses a psychophysical driver behavior model developed by Wiedemann (1974) (ITC, 2000b). Basically, this model uses perception thresholds for drivers approaching a moving vehicle and the reaction of the driver once a reaction must be taken. This reaction is then an iterative process of acceleration and deceleration of the vehicle until passing of the vehicle takes place or the paths of the two vehicles diverge (ITC, 2000b). The model can process vehicle locations up to 10 time steps per second.

The signal state generator operates by acquiring detector information and signal head status from the traffic simulator, processes the data, and then returns a new value for a signal head (i.e., green, yellow, or red). This process allows for greater flexibility when creating simulation networks. The signal state generator uses a language called VAP, an English acronym for Vehicle Actuated Program. This language is similar to BASIC in using an IF-THEN logic structure. The VAP polls information and returns signal status to the traffic simulator once per second.

The data requirements of the model consist of mainly four categories: geometric, traffic characteristics, traffic signal control, and transit information. Signal control data include parameters such as green times, clearance intervals, maximum and minimum green times, offsets, and permissive periods. Traffic characteristics include parameters such as speed distributions, volumes, turning percentages, percentage of heavy vehicles, vehicle classifications, acceleration/deceleration distributions, etc. Examples of geometric and traffic control data are number of lanes, grades, reduced speed areas, pavement markings, detector locations, yield areas, stop signs, and parking areas. Finally, transit information includes routes, schedule, ridership levels, transit vehicle characteristics, and bus dwell times.

The calibration of the model is an important process in the methodology which provides credibility to the results by closely representing the actual conditions. There are several methods of calibrating a simulation model, mainly by changing generated traffic, turning movement percentages, or altering driver behavior characteristics. Simulation models can over- or underestimate measures such as delay, travel times, or effective green time. Therefore, the user can manipulate model input to compensate for any shortcomings observed through output or animation. Model inputs, such as traffic volumes or turning percentatges, can be adjusted to represent the highest intersection count or the maximum queue observed. Examples of driver behavior modifications can include speed distributions, acceleration/deceleration distributions, headway, or driver reaction times. Typical calibration measures consist of volume, delay, and travel speeds. Other measures such as lane usage, headways, and start-up lost times can be adjusted in some simulation models to represent driver behavior.

The methods of calibration are directly related to the nature of the application, scale of the network, and availability of data. The larger the network, the more tolerance is accepted for driver behavior characteristics. In some cases, traffic volumes may be the only method of calibration and acceptance. Likewise, the MOEs extracted from the model also determine the level of calibration.

Calibrating detailed measures of traffic conditions, such as delay, stopped delay, or travel speeds would require more field data.

This section provided a brief overview of the simulation model, the components of the model, and the data requirements for proper model development. It provided an understanding of the capabilities of this model when applied to the methodology. However, for a detailed description of the simulation model used, readers are encouraged to refer to the VISSIM User Manual (ITC, 2000b).

CHAPTER V. CASE STUDY AND RESULTS

This chapter will discuss the details of the case study network and simulation model, the evaluation of the TSP strategies, and the results obtained from VISSIM. The important characteristics of the case study network are described. The results of the simulation analysis are summarized in this chapter as well.

Overview

Metro Area Transit (MAT), which serves the areas of Moorhead, MN; and Fargo, and West Fargo, ND, was selected for the case study. The location where TSP was evaluated is in the vicinity of the ground transfer center (GTC) in the Fargo downtown area. The network mainly consists of two one-way corridors and four two-way crossing streets. The Fargo downtown area consists of banking services, professional firms, and some service industries. There is adequate side-street parking, diagonal or parallel, and there are several public and private parking lots in this area.

Figure 5.1 shows an aerial view of the case study area. The east-west streets consist of 1^{st} Ave N, NP Ave, and Main Ave. Similarly, the north-south streets consist of 5^{th} St N, 4^{th} St N, 3^{rd} St N, and 2^{nd} St N. The Red River of the North, which is shown in the upper right corner of Figure 5.1, separates the cities of Fargo, ND, and Moorhead, MN. In addition, a major Burlington Northern Santa Fe Railroad (BNSF) line transects the case study network directly north of Main Ave.

The GTC is located at the intersection of NP Ave and 5^{th} St. This transit center serves as a transfer point for both Moorhead and Fargo routes. This location also serves a regional bus transit service, Greyhound.

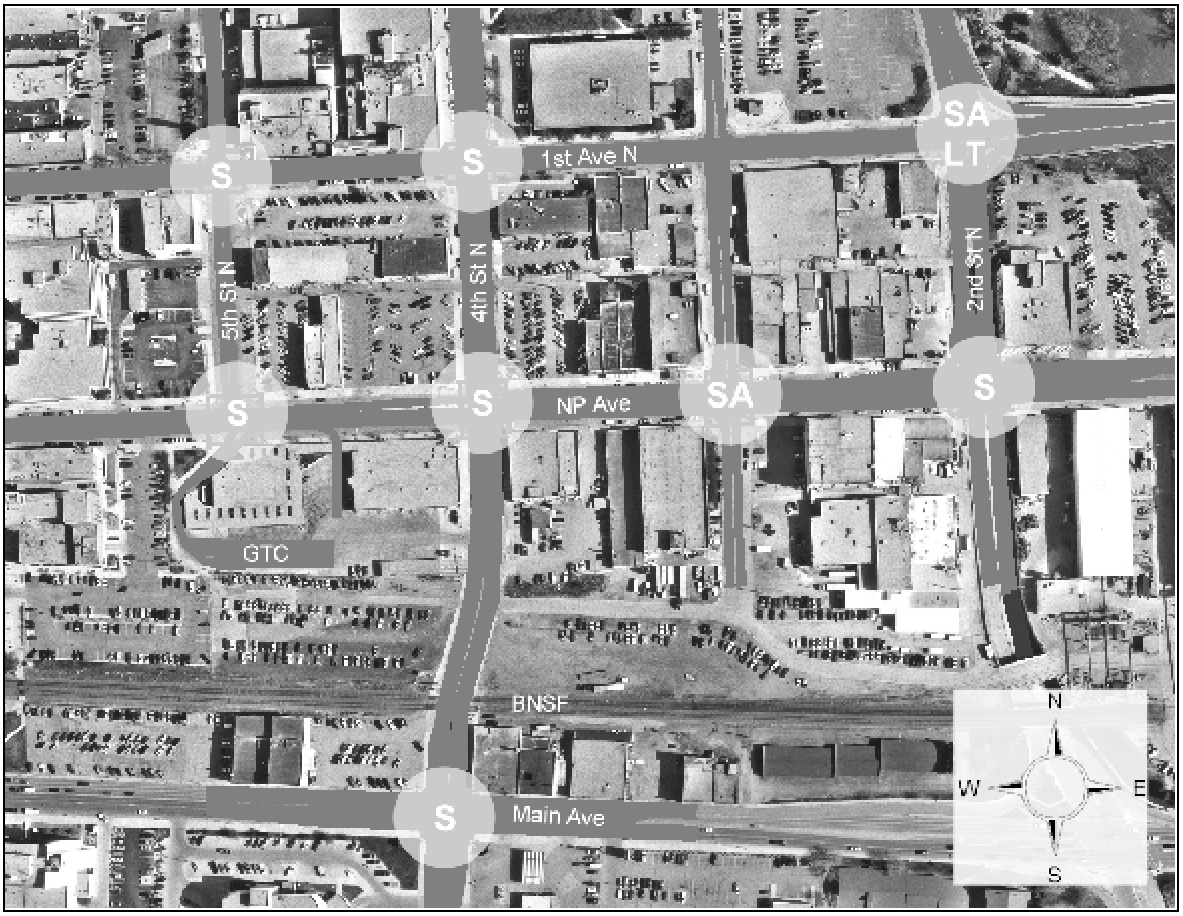

Figure 5.1. Case Study Location.
S - Signalized Intersection.
SA - Semi-Actuated Signalized Intersection (LT - Left-turn Only).

Network Characteristics

Main Ave, NP Ave, and 1st Ave N serve as major collectors for the east-west movements for the downtown regions of Fargo and Moorhead. A small retail shopping mall is located between NP Ave and 1st Ave N in Moorhead. Moreover, these avenues are the only river crossings for 10 blocks north and 20 blocks south.

NP Ave operates as a three-lane, one-way collector to 4th Ave N where it becomes a four-lane, two-way collector. NP Ave continues past 2nd St N and crosses the Red River of the North into

Moorhead. The other east-west arterial, 1^{st} Ave N, is a three-lane, westbound, one-way arterial from 2^{nd} St and a four-lane, two-way collector to the east of 2^{nd} St. Main Ave operates as a four-lane, two-way arterial.

The BNSF mainline serves approximately 70 trains daily through the case study network. While these trains are very frequent, there is only one route affected in the network. Furthermore, from field observations, the number of actual conflicts caused by trains would be minimal. As will be discussed in the next section on policy issues, drivers are allowed to alter routes. In this case, the driver would proceed to 2^{nd} St N to an underpass and return to the route to avoid waiting for a train, thus reducing the travel time.

The case study network includes eight signalized intersections and one unsignalized intersection. These traffic signals operate in a dual coordinated, fixed-timed mode. The intersection of 1^{st} Ave N and 2^{nd} St N has actuated left-turn movements for the northbound and southbound movements while the intersection of NP Ave and 3^{rd} St N has semi-actuated operation. The semi-actuated intersection did not require any modifications to the TSP logic, however, the intersection with actuated left-turn movements required some modifications to achieve the desired TSP operation.

The City of Fargo operates these signals on four timing plans:

- AM-peak period: 6:00 am-8:30 am,
- midday or off-peak period: 8:30 am-3:30 pm and 6:00 pm-2:00 am,
- PM-peak period: 3:30 pm-6:00 pm, and
- flash operation: 2:00 am-6:00 am.

The periods included in this study are the midday and PM (afternoon) peak periods.

The midday period operates on a 60-second cycle length, with typical splits of 50-50 and 60-40 favored to the one-way movements. The afternoon period operates on a 90-second cycle length, with slightly higher splits for the one-way movements.

Transit Characteristics

The MAT operates several transit routes in the downtown area near the GTC. MAT operates seven Fargo routes and four Moorhead routes within the case study network. These routes are scheduled on 30-minute headways, with 2 routes alternating on a 60-minute headway. In addition, several routes have seasonal variations when they are reduced to 60-minute headways. These routes serve the extreme northern and southern regions of Fargo, as well as extending east and west to major shopping centers and other transfer points in both Fargo and Moorhead. Figures 5.2 and 5.3 illustrate the routes originating and terminating at the GTC within the case study network, respectively.

MAT operates with flexible guidelines for route adherence practices based on passenger boardings/deboardings. While bus stops are typically located at mid-block locations, both near-side and far-side stops exist. Regardless, riders may be picked up or dropped off anywhere along a route by signaling the bus driver. Drivers are also allowed to take special requests from riders and may divert slightly from the route if the bus is within schedule.

Figure 5.2. MAT Routes Originating at GTC. Numbers above routes show total number of buses traveling route.

Drivers of routes originating or terminating at the GTC maintain communications on schedule adherence and inform riders if missed connections should be expected. In case of the potential for a missed connection, a departing bus at the GTC may wait for the late bus if it will arrive within an acceptable time frame. Missed connections occur mainly during the afternoon period. MAT also allows bicycle loadings on the front of the bus. Handicap accessible ramps are also available on all MAT buses.

Figure 5.3. MAT Routes Terminating at GTC. Numbers above routes show total number of buses traveling route.

This section gave an overview of the operational aspects of the case study location, mainly traffic and transit characteristics. The next section will give an overview of the design of the case study simulation model.

Simulation Model Design

This section provides a description of the simulation model and the appropriate parameters. There are five topics which will be discussed: data requirements, simulation characteristics, calibration, base-case design, and TSP scenario designs. The test procedure and results are discussed in the next section.

Data Requirements

There are mainly three categories of data requirements: geometry, traffic operations, and traffic control. The geometric data were obtained from 1999 aerial photos supplied by the Fargo-Moorhead Council of Governments. The photos were scaled and then used to develop the network geometry. Some detailed geometric attributes, such as turning bays and stop bar locations, were obtained from field observations.

Traffic operation data consist of traffic volumes, turning movement percentages, and observed speed and lane usage. In addition, approach bus delay was gathered for potential model calibration. These data were obtained through traffic counts conducted between April 4, 2000, and May 25, 2000, using video detection equipment. The video observations were reviewed manually to collect traffic volume, turning movements, and bus delay measurements. Finally, travel time studies were conducted to determine appropriate travel speeds for vehicles, which could also be used for calibration purposes.

Traffic control data consist mainly of signal timing plans which were obtained from the City of Fargo. The signal timing plans were recently updated in 1999. These data were verified with field observations. Stop bar locations, actual lane usage, yield signs, and detector placements were collected from field observations as well.

Network Model Characteristics

This section will discuss some of the aspects of the case study simulation model which are critical to evaluating the performance of the base case and TSP strategies. Transit vehicle generation, vehicle occupancies, detector locations, signal control logic, and the parameters of the signal controller which were modified to evaluate proper TSP strategies are the main items discussed in this section.

The manner of transit vehicle generation into the network is an important aspect of the simulation model development. First, bus arrival times were extracted from the video data and used to develop bus arrival distribution times for various intersection approaches. Next, minimum and maximum arrival times were determined for each street approach with bus routes and then used to calculate a normal distribution for bus arrivals for that approach. However, the model does not allow the use of a statistical distribution of bus arrival times. Therefore, an artificial bus stop was utilized with a normal distribution applied to a dwell time. Due to the nature of the network, multiple routes on one approach were assumed to have the same dwell time distribution. This assumption is safe given the stochastic nature of the boardings/deboardings and delays experienced at signalized intersections through the entire route.

Bus routes begin at the GTC every 15 minutes from the start of the simulation period, depending on the TSP scenario. Returning routes begin at the minimum observed time and dwell at the artificial stops for the calculated normal distribution. The normal distribution was approximated by determining the standard deviation from the minimum and maximum times, and using the properties of a normal distribution to gain 99 percent confidence of the distribution. For example, if the difference between the minimum and maximum arrivals was six minutes, the mean distribution would be three minutes with a standard deviation of one minute.

VISSIM allows two methods of modeling transit bus stops through on-street stops or bus bays. Bus stops are addressed here because a method was needed to obtain the appropriate bus arrival distribution mentioned previously. Bus bays would have been an acceptable method of generating the buses, but it was desired to try to keep the model visually similar to the actual conditions. On-street stops were hence used for each route and were “superimposed” onto the network using dummy links. As a bus leaves the bus stop, the other traffic yields to the bus to introduce the bus into the network correctly.

Another important issue related to the significance of the results is vehicle ridership. Vehicle occupancy values were assigned for both bus and other traffic. Bus ridership was generated from data obtained from the MAT agencies. The average values were obtained for both simulation periods resulting in 12 passengers/hour per route for the midday period and 17.5 passengers/hour per route for the afternoon period. The assumption was made that the ridership level would double to justify the decrease in headways. Thus, the same values were used for passengers per bus for each scenario. Other traffic was assumed to have a vehicle occupancy of 1.3, consistent with local agency standards.

Bus detection is needed for active TSP strategies and may be accomplished in several ways. As identified in the literature review, the Opticom detection system is a common method of TSP detection. The Opticom system uses a coded infrared signal that has configured detection areas for each signalized intersection. In the case study network, the Opticom system is installed at some signalized intersections. Therefore, it was desired to emulate a typical Opticom detection area by using 5 m detectors in the simulation model. Several locations were tested: mid-block upstream, one block upstream, and two blocks upstream. Due to the nature of the case study network, detection locations one block upstream performed better and thus were used in the case study simulation model. Most detectors are located 90 m ($\approx$295 ft) upstream from the signalized intersection. Depending on the network geometry and due to the method of bus generation, some detectors were placed 60 m ($\approx$197 ft) upstream.

The signal control logic, discussed earlier in the methodology, was obtained from Innovative Transportation Concepts, Inc., the North American distributor of VISSIM. The logic replicates a NEMA type controller with all functions required for the case study simulation model. Modifications were made to this logic to perform the desired TSP strategy, which will be discussed next.

The parameters which were altered for the proper operation of the signal control are briefly mentioned here. The methodology addressed the procedures developed and used for the early green and extended green strategies. Recall the modification of forceoffs by extending the green time or truncating the green time. To correctly replicate this type of operation, other factors were adjusted dynamically with the forceoffs. The factors which were adjusted were the maximum green time, permissive start time, and permissive end time. The maximum green time was adjusted for both TSP strategies. This value was calculated by determining the worst case scenario, which was equal to cycle length minus minimum green time for opposing priority phase minus both phase clearance intervals. The permissive start and permissive end periods were also adjusted to allow the logic to recognize a forceoff call.

Calibration

The potential calibration variables used for the case study network required field observations for bus delay, traffic volumes, and turning percentages. The Autoscope video detection system was used for most data collection. Manual reviews of the video allowed the collection of bus delay values, traffic volumes, turning percentages, and traffic composition.

In order to have a good representation of the field delay compared to the simulation delay, the acceleration and deceleration of the buses were adjusted slightly. Travel speeds were also modified to provide a closer representation of stopped delay and total delay. It is important to note that the field delay values were calculated for 2 one-hour intervals during 1 observation; the simulation delay is an average of 30 simulation runs. The method of vehicle generation may also contribute to some inaccuracies. Buses that would usually arrive in coordination arrive stochastically through the simulation parameters. Due to the nature of human error, methods of collection, and the comparison of averages, the base case was accepted as a valid representation of the actual field delay.

Another important measure of calibration is traffic volumes. Since the traffic counts were done over several weeks, there are some expected variations between the values. In addition, a detour which affected the intersections of NP Ave and 5th St N, and 1st Ave N and 5th St N was created during the traffic count period. Comparisons were made, and traffic generation areas lacking volumes were adjusted by a maximum of 10 percent to reach the desired volumes. Turning percentages were not altered to maintain the desired representation of traffic movements. Tables 5.1 and 5.2 compare field traffic volumes to simulation traffic volumes for the midday period and afternoon period, respectively. The approaches identified in Tables 5.1 and 5.2 represent the approaches with the greatest interaction with bus routes.

Table 5.1. Selected Midday Field Traffic Volumes vs. Simulation Traffic Volumes

Intersection	Direction of Travel	Field Volumes	Simulation Volumes	Percentage Difference
1st Ave N & 5th St N	WB	579	611	5.5
1st Ave N & 4th St N	WB	529	560	5.9
1st Ave N & 2nd St N	WB	716	716	0
NP Ave & 5th St N	EB	800	821	2.6
NP Ave & 4th St N	EB	587	636	8.3
NP Ave & 3rd St N	EB	546	610	11.7
NP Ave & 2nd St N	EB	541	603	11.5
Main Ave & 4th St N	SB	398	361	-9.3

The acceptable level of difference between the field volumes and simulation volumes should be within approximately 15 percent. This level takes into account the variations between the traffic counts due to fluctuations in traffic volumes for differing days. As can be seen from Tables 5.1 and 5.2, the majority of the approach volume differences are below this level. The accuracy of the simulation model to generate vehicles is also shown with 1st Ave N and 2nd St N westbound approach.

Table 5.2. Selected Afternoon Field Traffic Volumes vs. Simulation Traffic Volumes

Intersection	Direction of Travel	Field Volumes	Simulation Volumes	Percentage Difference
1st Ave N & 5th St N	WB	620	658	6.1
1st Ave N & 4th St N	WB	536	606	13.1
1st Ave N & 2nd St N	WB	881	881	0
NP Ave & 5th St N	EB	1166	1185	1.6
NP Ave & 4th St N	EB	935	1081	15.6
NP Ave & 3rd St N	EB	965	1072	11.1
NP Ave & 2nd St N	EB	1018	1133	11.3
Main Ave & 4th St N	SB	809	579	-28.4

Base Case

Four base cases were used to compare the TSP strategies: a midday period with 15- and 30-minute headways, and an afternoon period with 15- and 30-minute headways. The operational characteristics of these periods were discussed previously. Once the base cases were calibrated, they were then simulated for one-hour intervals. Each simulation period included a five-minute network loading interval to obtain equilibrium and get a representation of the peak period vehicle interactions before calculating the MOE.

TSP Scenarios

There are several TSP scenarios representing the sensitivity analysis framework. The only changes made among the strategies were the controller logic modifications for the appropriate TSP strategy and the detector locations for buses. All other parameters remained the same. Specifically, the scenarios are as follows:

- Early Green Strategy, 30-Minute Transit Headway, Midday Period,
- Early Green Strategy, 30-Minute Transit Headway, Afternoon Period,
- Extended Green Strategy, 30-Minute Transit Headway, Midday Period,
- Extended Green Strategy, 30-Minute Transit Headway, Afternoon Period,
- Early Green Strategy, 15-Minute Transit Headway, Midday Period,
- Early Green Strategy, 15-Minute Transit Headway, Afternoon Period,
- Extended Green Strategy, 15-Minute Transit Headway, Midday Period, and
- Extended Green Strategy, 15-Minute Transit Headway, Afternoon Period.

As with the base cases, each simulation period was simulated for five minutes before collecting MOE. Since the simulation parameters were constant between the base cases and the TSP scenarios, it is, therefore, expected that these scenarios would have the same traffic volumes. However, due to the TSP strategies, vehicles enter decision points at different simulation times. Since these elements are based on stochastic variables, the turning percentages change slightly from the base-case results and, thus, alter the approach volumes. Regardless, this small change between the scenarios is not significant enough to alter the results.

Results

Traffic volumes and delay data were gathered for each intersection approach in the simulation model. In addition, travel times were calculated for the entrance and exit points of the transit routes in the simulation network. These values were aggregated for each simulation run, averaged for the all simulation runs, and were converted into the appropriate MOE identified in the methodology. This section will summarize the results obtained and the statistical significance of the results.

A statistical paired t-test was used to examine the differences between the base cases and the TSP strategies. Thirty simulation runs were performed for each scenario, thereby giving a good statistical representation. The test procedure follows (Ott, 1984):

Null Hypothesis:

H_o: $\mu_d = D_o$

Alternative Hypothesis:

H_a: $\mu_d \neq D_o$

Test Statistic:

$$t = \frac{\bar{d} - D_o}{s_d / \sqrt{n}},$$

where $\bar{d}$ is the sample mean difference

D_o is the desired difference

s_d is the standard deviation of n differences

n is the number of differences

μ_d is the two sample mean difference

Rejection Rule:

α=0.05 and degrees of freedom = 29, reject H_o if $|t| > t_{\alpha/2}$

The t-value for 29 degrees of freedom is 2.054. The α value of 0.05 sets the probability level at 95 percent. The results showed high t-values in several cases, suggesting a higher probability level. Tables 5.3-5.6 show the results from the simulation runs for the two strategies and base case values as a relative measurement. Each table shows the impacts on selected MOE of the TSP strategies relative to the base case for each analysis period and bus headway combination. The next sections will examine the results for each MOE in more detail.

Table 5.3. Comparison of TSP Strategies, Midday Period, 15-Minute Headway Scenario

MOE	Early Green Strategy	Extended Green Strategy	Base Case Values
Side-Street Approach Delay†, vehicle-hr	-1.78%	+0.15%††	17.22
Side-Street Approach Person-Delay, person-hr	-16.86%	-14.79%	25.29
Network Approach Delay†, vehicle-hr	+2.68%	+2.87%	31.61
Network Approach Person-Delay, person-hr	-8.54%	-8.28%	44.78
Bus Travel Time, sec	-13.87%	-12.41%	6132
Bus Total Delay, vehicle-sec	-28.00%	-27.84%	2657
Bus Stopped Delay, vehicle-sec	-36.93%	-34.24%	1781

†Excluding buses.
††Shaded areas indicate statistically insignificant results at the 95% confidence level.

Table 5.4. Comparison of TSP Strategies, Midday Period, 30-Minute Headway Scenario

MOE	Early Green Strategy	Extended Green Strategy	Base Case Values
Side-Street Approach Delay†, vehicle-hr	+0.26%††	+0.39%††	16.77
Side-Street Approach Person-Delay, person-hr	-7.61%	-8.86%	23.28
Network Approach Delay†, vehicle-hr	+2.64%	+2.61%	30.95
Network Approach Person-Delay, person-hr	-3.05%	-4.61%	41.79
Bus Travel Time, sec	-13.06%	-14.20%	3082
Bus Total Delay, vehicle-sec	-26.06%	-31.25%	1351
Bus Stopped Delay, vehicle-sec	-33.40%	-38.21%	911

†Excluding buses.
††Shaded areas indicate statistically insignificant results at the 95% confidence level.

Table 5.5. Comparison of TSP Strategies, Afternoon Period, 15-Minute Headway Scenario

MOE	Early Green Strategy	Extended Green Strategy	Base Case Values
Side-Street Approach Delay †, vehicle-hr	+24.42%	+16.16%	28.12
Side-Street Approach Person-Delay, person-hr	+10.66%	+11.08%	39.78
Network Approach Delay †, vehicle-hr	+22.59%	+9.18%	56.27
Network Approach Person-Delay, person-hr	+13.64%	+6.49%	79.09
Bus Travel Time, sec	-10.61%	-2.41%	6442
Bus Total Delay, vehicle-sec	-18.88%	-5.15%	2984
Bus Stopped Delay, vehicle-sec	-31.75%	-7.10%	2105

†Excluding buses.

Table 5.6. Comparison of TSP Strategies, Afternoon Period, 30-Minute Headway Scenario

MOE	Early Green Strategy	Extended Green Strategy	Base Case Values
Side-Street Approach Delay †, vehicle-hr	+18.66%	+16.34%	27.86
Side-Street Approach Person-Delay, person-hr	+12.86%	+14.12%	39.78
Network Approach Delay †, vehicle-hr	+15.42%	+8.50%	55.46
Network Approach Person-Delay, person-hr	+11.84%	+7.40%	74.25
Bus Travel Time, sec	-9.49%	-1.80%††	3147
Bus Total Delay, vehicle-sec	-16.11%	-4.04%††	1394
Bus Stopped Delay, vehicle-sec	-29.24%	-5.72%	973

†Excluding buses.

††Shaded areas indicate statistically insignificant results at the 95% confidence level.

Side-Street Approach Person-Delay

The side-street approach person-delay is an important measure of the TSP strategy impacts. While vehicle delay is a common measure, person-delay is more accurate when comparing different modes of transportation. Total delay was calculated when the vehicle speed was below the desired speed, including stopped delay. Stopped delay was measured as any time the velocity of the vehicle is zero. Delay values were calculated for each intersection approach approximately from the stop bar to about two-thirds of the approach length.

Figure 5.4 illustrates the percentage change in person-delay between the base case and the two TSP strategies. Several trends can be identified from Figure 5.4: benefits decrease (increasing person-delay) with increased headways, increased side-street volumes, and longer cycle lengths. The later trend is more complicated to identify due to the cycle length difference between TSP strategies.

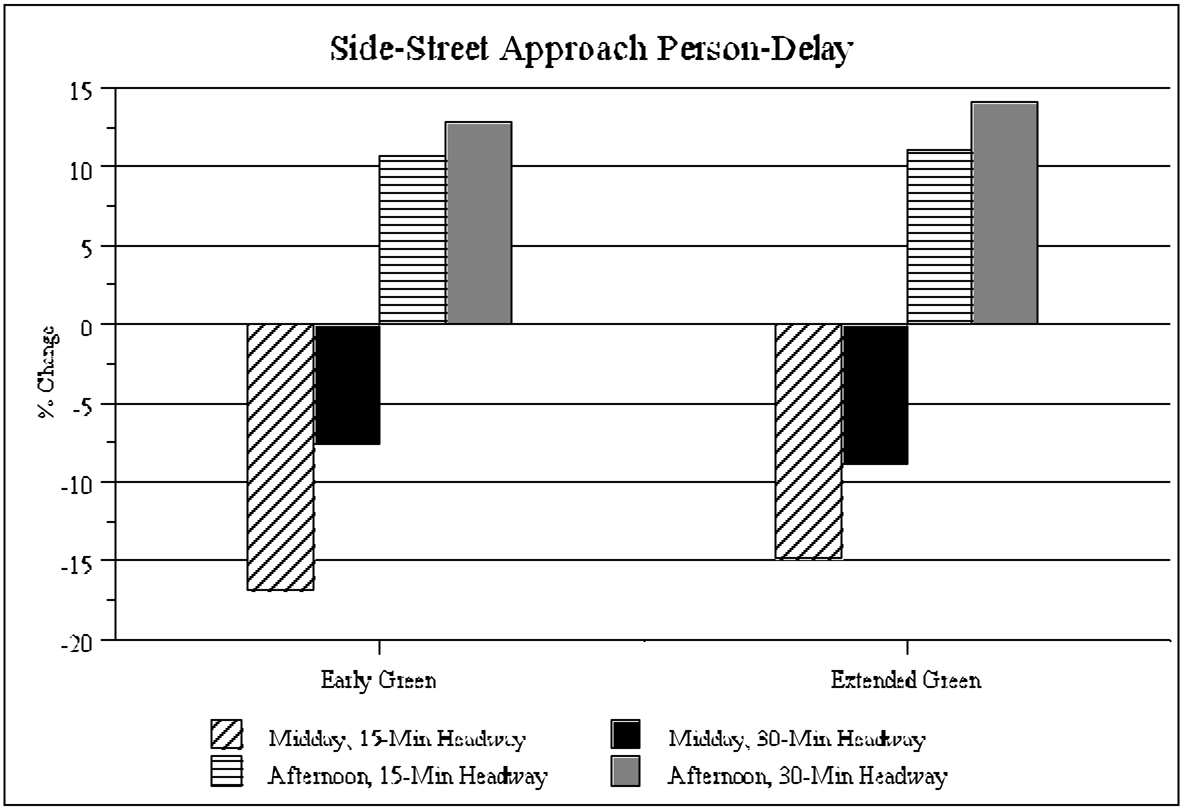

Figure 5.4. Side-Street Approach Person-Delay.

When comparing the two TSP strategies, early green performs slightly better than extended green. This performance suggests that the transit vehicles using the side streets received priority more often with the early green strategy, the main-street priority had less impact with the early green strategy, or both. This performance is also expected due to the dual coordination of traffic signal operations in the case study network.

As headways increase, a negative impact is noticed. This impact suggests that person-delay on the side-street increases at a greater rate than the positive impacts received from the TSP strategy applied to the main-street movements. While the values suggest that midday periods provide the least impact to side-street movements, transit vehicles receive modest benefits during this period as well.

Network Person-Delay

Similar to the side-street approach person-delay, network person-delay is another important measure for evaluating TSP strategies. Network person-delay aggregates all intersection approaches in the case study network. Figure 5.5 shows that the midday period experiences positive impacts from both TSP strategies. The early green strategy results in larger impacts than the extended green strategy, noticeably more in the afternoon period.

Network person-delay is lower than side-street person-delay for both TSP strategies and for both periods, except the afternoon, 30-minute period for early green strategy. The percentage reduction for all extended green strategies and the midday period's early green strategies suggests the main street experiences a negative impact in person-delay for the midday period and a positive impact for the afternoon period. Likewise, there is relatively little change between the side-street person-delay percentage change and the network person-delay percentage change for the afternoon period, early green strategy, suggesting a greater impact on the main-street movements caused by side-street priority movements.

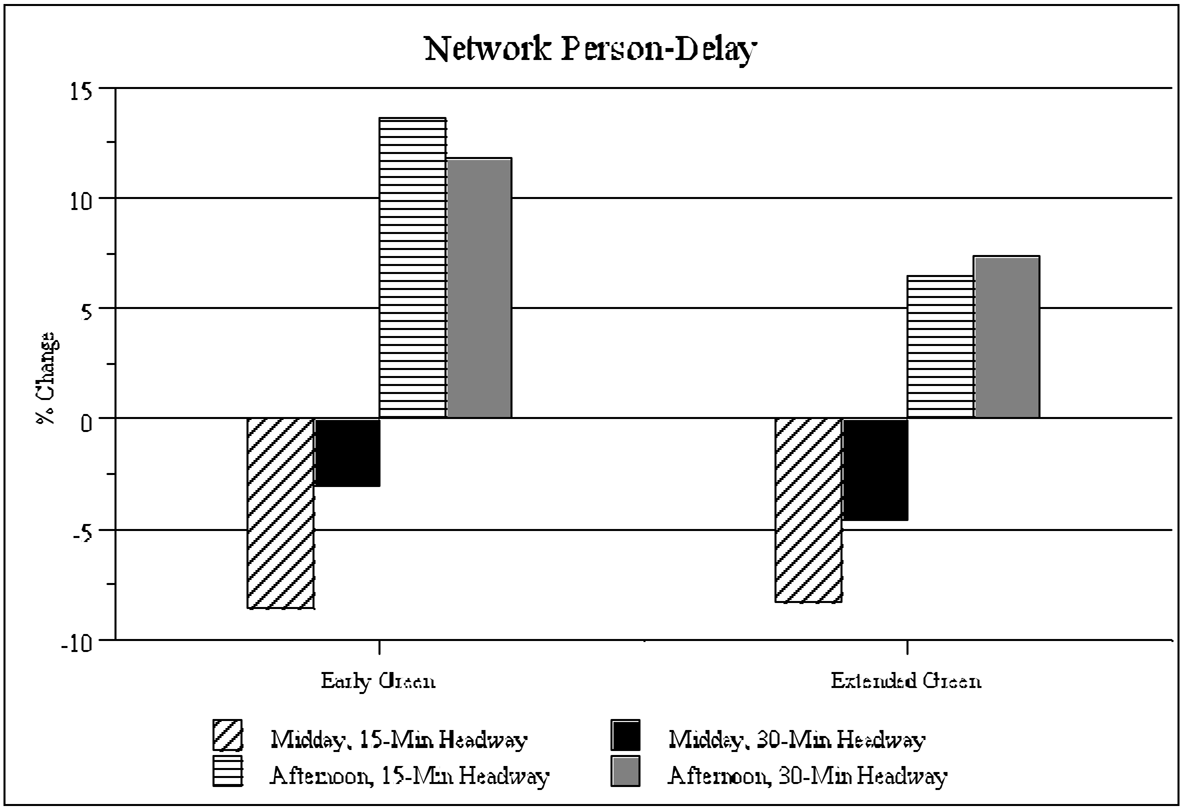

Figure 5.5. Network Person-Delay.

Bus Travel Time

Bus travel time was measured from the point of entry of the bus into the case study network to the bus destination at the GTC, and from the GTC to the corresponding exit point from the network. As illustrated in Figure 5.6, all of the TSP strategies provided a reduction in total bus travel time with the exception of the afternoon period with 30-minute headways, which was statistically insignificant. Both the early green and extended green strategies provided reductions in bus travel time greater than 12 percent for the midday periods while the afternoon period realized greater benefits from the early green strategy.

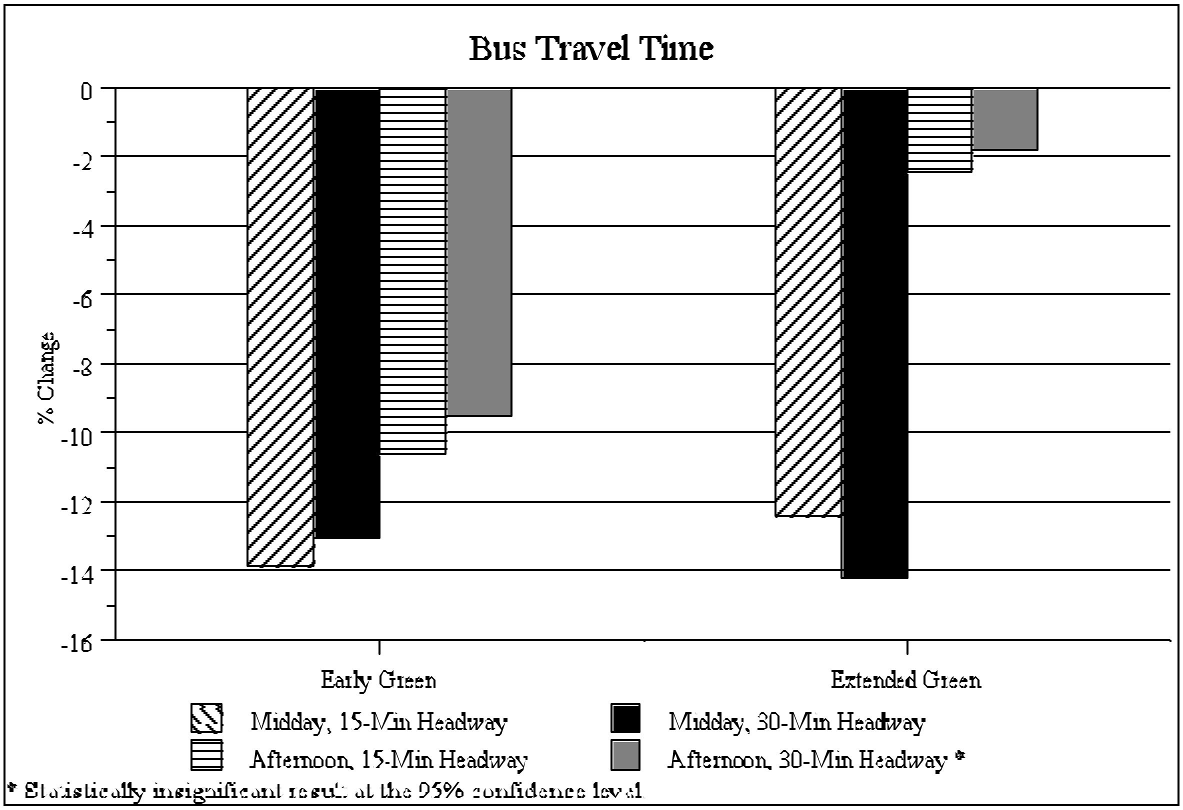

Figure 5.6. Bus Travel Time.

The low percentage reduction in bus travel time using green extension in the afternoon periods can be attributed to two factors: traveling too slow to reach the next intersection extended green call period and receiving an extended green on a left-turn movement, resulting in an early arrival to a red indication. Another explanation for the poor performance is the time available to receive an extended green priority strategy. The low numbers of actual arrivals benefitting from the extended green did not compensate for the negative observations mentioned previously.

Another consideration which has been addressed throughout this study is the interaction of buses from various routes in the case study network. Typical applications of TSP would be along arterial or collector corridors with few or no transit routes bisecting the corridor. Thus, the values estimated for the case study network are conservative.

Bus Delay

Bus total delay is calculated in the same manner discussed for side-street and network person-delay, i.e., when traveling below the desired speed. Figure 5.7 illustrates the changes in bus delay for various TSP strategies relative to the base case. As expected, the values indicate similar patterns to changes in bus travel times. The savings in bus total delay are greater than 26 percent for both TSP strategies in midday period, and greater than 16 percent for the early green afternoon periods.

Another measure of the impact of TSP strategies is the bus stopped delay. This MOE was measured whenever the bus speed was equal to zero. As Figure 5.8 illustrates, the stopped delay is reduced by as much as 38 percent, with early green providing at least a 25 percent decrease at all periods and headways. The extended green strategy also provides the same benefits during the midday periods, however, the afternoon periods experience a delay reduction near 5 percent. Figures 5.7 and 5.8 illustrate the impacts associated with increased headways (decrease benefits), and the impacts associated with the different TSP strategies (early green performing better than extended green).

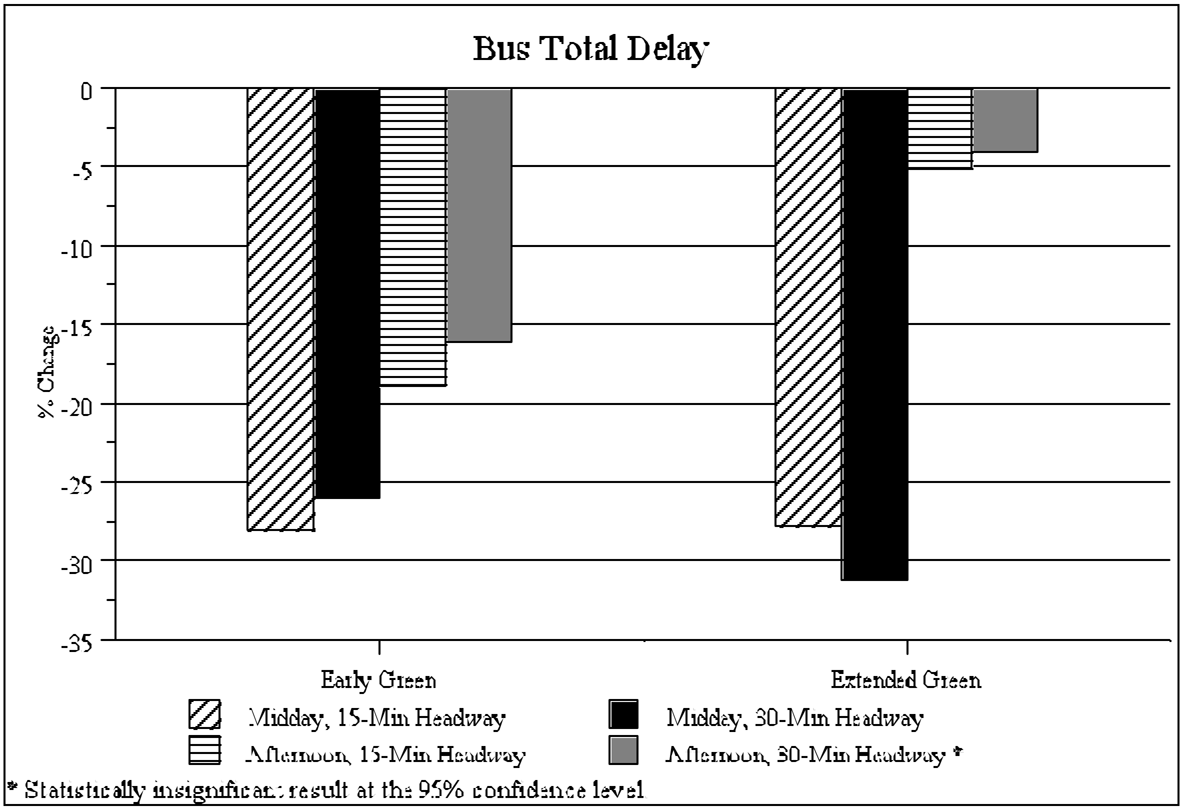

Figure 5.7. Bus Total Delay.

In this chapter, the results of the case study were presented in detail. The next chapter will attempt to dissect the information, summarize the results from the case study, provide recommendations, and conclude with limitations and need for further study.

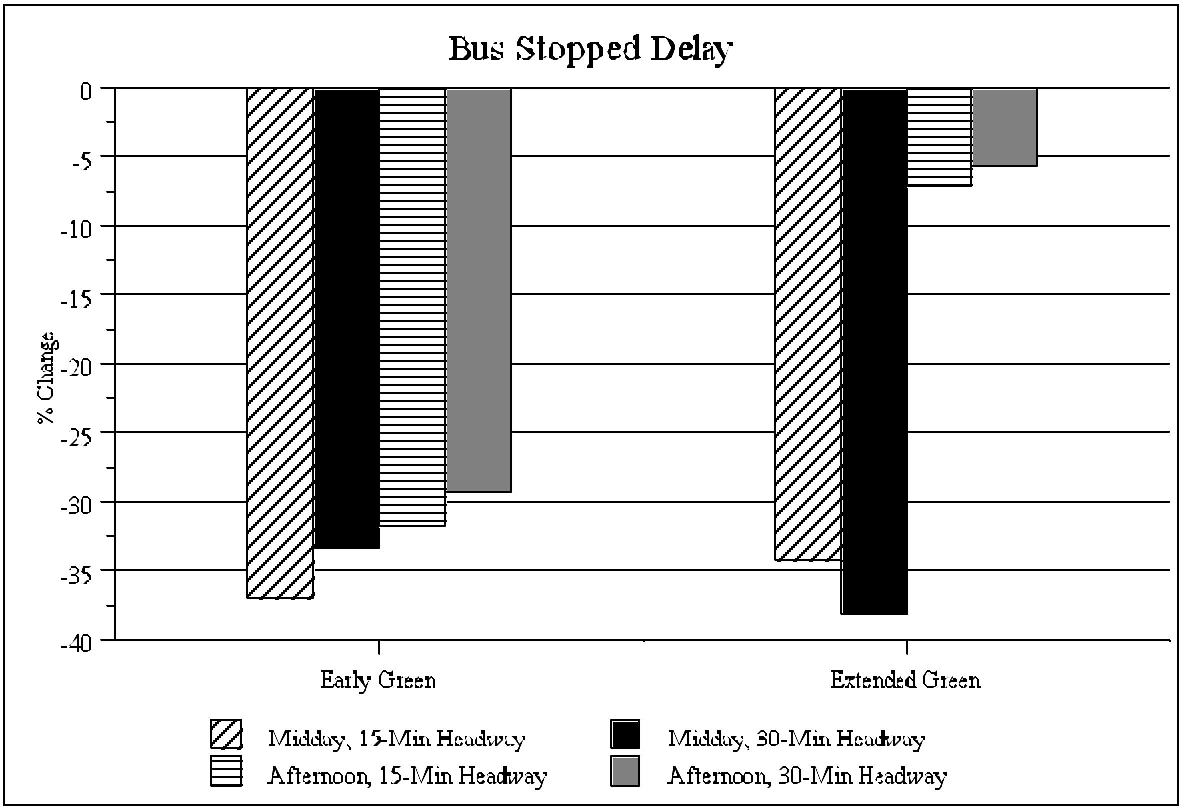

Figure 5.8. Bus Stopped Delay.

CHAPTER VI. CONCLUSIONS

This chapter will summarize the findings from the case study, provide insight into the impacts associated with two transit signal priority strategies, discuss the significance of these results, and provide recommendations for the potential application of this technology to small-medium size cities. The two TSP strategies investigated were an early green strategy and an extended green strategy. The case study used for this evaluation is located in the vicinity of the transit center in the downtown area of Fargo, ND. The GTC is a transfer point for a local transit agency servicing the cities of Fargo, ND, and Moorhead, MN, with 12 routes. Bus ridership levels are low to moderate with buses operating at 30-minute headways for most routes.

The traffic simulation model, VISSIM, was used to develop and evaluate the TSP strategies for the case study network. This model provided an effective method of evaluating the impacts and collecting the appropriate measures of effectiveness (MOE). The TSP strategies were evaluated for two periods, midday and afternoon peak, and for two headway values, fifteen and thirty minutes. The MOEs chosen for comparison were side-street approach person-delay, network person-delay, bus travel time, and bus delay time.

Summary of Findings

Overall, when considering bus delay and bus travel times, the early green TSP strategy performed better than the extended green TSP strategy. This performance could be explained due to the method in which the logic could react to a transit vehicle actuation and the probability of a transit vehicle arriving in an acceptable time frame. The early green strategy could respond to an actuation during approximately 40 percent of a cycle length, compared to the extended green strategy, which could respond to an actuation during only 10 percent of a cycle length. Overall, the early green strategy resulted in more statistically significant results and greater reductions in bus travel times and bus delay.

The TSP strategies also performed better during the midday period when compared to the afternoon period. Side-street approach delay was considerably higher in the afternoon period, with person-delay increasing as high as 14 percent. In comparison, midday periods experienced side-street person-delay reductions as high as 17 percent.

The 15-minute headways often resulted in similar findings for all MOE, usually within ±5 percent. There was no significant difference between the two TSP strategies. The only exception was noted for the afternoon period, where the network vehicle delay increased approximately seven percent. When comparing the person-delay, however, the difference dropped to within two percent. Some studies indicate that TSP should not be implemented for headways greater than 5-6 minutes. These studies may overlook problems associated with small to medium sized transit agencies.

The interactions between the buses in the case study network may have undermined the performance of the TSP strategies. While the findings are generally promising, minor increases in bus delay were observed in a number of simulation runs. These increased delay measurements can be associated with a bus receiving a TSP strategy on the opposing movement. This interaction will be addressed in the limitation and need for further research. The next section will discuss the findings from this study in more detail.

Impacts of Transit Signal Priority Systems

This section will discuss the impacts realized from TSP strategy implementation. The side-street approach delay and the network delay represent the negative impacts caused by TSP strategies. Bus travel time and bus delay savings represent the benefits.

Side-street person-delay was measured for each approach which was not the main coordinated movement. This measurement should represent the greatest negative impacts of TSP even though some approaches included bus route movements. Two main observations were made from the simulation analysis: midday periods experienced a reduction in side-street delay, and afternoon periods realize an increase in side-street delay. The side-street person-delay change for midday periods ranged from -7.6 percent for early green to -8.7 percent for extended green with 30-minute bus headways. At 15-minute bus headways, however, the changes increased to -16.9 percent for early green and -14.8 percent for extended green. When comparing the afternoon periods, the same trend is realized where increased headways improve side-street delay. This trend can be attributed to the side-street transit movements providing greater person-delay benefits than the increase in side-street person-delay caused by main-street transit movements. The afternoon side-street person-delay percentage changes were 12.9 percent for early green and 14.1 percent for extended green strategies with 30-minute headways. Similarly, for 15-minute headways, the afternoon peak side-street person-delay percentage changes were 10.7 percent for early green and 11.1 percent for extended green strategies.

Network person-delay was also investigated to examine the impacts associated with multiple transit routes. While the routes were simulated on 15- and 30-minute headways, they are actually clustered groups of arrivals occurring at 15- and 30-minute intervals. The results indicate that the extended green strategy impacts network delay less than the early green strategy during the afternoon period. This performance is attributed to the lower number bus priority calls experienced through the extended green strategy, as illustrated by the lower performance of the bus travel times (statistically insignificant for afternoon, 30-minute headways). The largest network person-delay experienced, 22.6 percent, occurred during the afternoon period with the early green strategy. The midday period network approach person-delay percentage changes were -3.1 percent for early green and -4.6 percent for extended green with 30-minute headways. For 15-minute headways, the changes were -8.5 percent for early green and -8.3 percent for extended green.

The final comparison is made between the bus travel times, which reflect bus delay reductions. The travel time savings ranged from 12.4 percent to 14.2 percent for all midday period scenarios. The afternoon period early green scenarios resulted in a travel time savings of 10.6 percent and 9.5 percent for 15-minute and 30-minute headways, respectively. Similarly, the afternoon period extended green strategy resulted in a 2.4 percent reduction (statistically insignificant change for the 15-minute headway). Refer to the case study results on page 56 for further information on the exact values obtained. Again, these numbers are a conservative representation of the TSP strategy impacts. The actual conditions for a single route corridor (or a model representing no side-street transit interactions) should result in greater travel time savings and fewer side-street impacts, given the same operational characteristics as this case study network.

Significance of Results

When reviewing the findings and results, it is evident that there are fewer benefits and potentially greater negative impacts when implementing TSP during a peak period with long cycle lengths for low bus ridership or less dense bus corridors. These results would suggest implementing a TSP strategy for only non-peak, shorter cycle lengths. The question is, however, do we accept an increase in delay on the system in return for facilitating bus operations? The afternoon peak traffic period is also when buses experience the highest number of missed connections. The trade-offs between the benefits and cost need to be addressed in the proper contexts and in consideration of the local priorities.

Mitigation of traffic demand may also be a larger concern for growing cities or areas where population densities are becoming greater. This effort requires great foresight and planning by communities. One aspect of mitigation is to provide competing alternative modes of transportation. Implementation of TSP for bus transit service may be one of the first components for traffic demand management.

Recommendations

The results from this study suggest that the early green strategy performs better than the extended green strategy, which was expected. Bus travel times and bus delay were reduced for both TSP strategies without substantial impacts to non-transit traffic. However, an evaluation project of these strategies applied to a couple of routes will provide real-world data which can be used for system-wide implementation decisions.

Limitations of Study

There are two interrelated and important limitations to a study of this type: data availability and the shortcomings of using traffic simulation models. Simulation models are becoming effective tools used by traffic engineers, yet there are some limitations to their use. VISSIM is a very powerful simulation model which allows the user to perform analysis of very complicated networks. The limitations result in the ability to correctly calibrate the model to local conditions, such as driver behavior. While the model allows the user to alter vehicle and driver parameters, these modifications are only possible with detailed traffic studies for the case study location.

There are some aspects of the model development which do not represent real-world conditions. The case study model did not provide a good representation of platoon arrival for NP Ave and Main Street due to the partial network used. While the simulation model uses a Poisson distribution to simulate traffic grouping, additional intersections should have been included in the model to provide a better representation of platoon arrivals.

Finally, although the TSP strategies simulated in this case study can be realistically implemented, they require special external logic control. This requirement is a concern for small-medium size cities which may not have the adequate resources to develop and implement these types of systems. Further, the first-come, first-served strategy with no compensation (increased green time to non-priority phase after passage of bus) provides a sub-optimal logic. The next section will make some suggestions to address these limitations in future studies.

Need for Further Study

There are several issues which need further investigation, specifically TSP logic development, evaluation of vendor standard applications, and cost analysis of TSP systems. Enhancements to the case study TSP strategies may include compensation methods and a methodology developed for handling multiple transit actuations from conflicting approaches. In addition, the integration of early green and extended green into one logic package would provide a better representation of the impacts of a typical system which incorporates both strategies.

Advancements in the area of hardware-in-the-loop simulation will allow for expanded research of vendor standard applications, such as low-priority preemption. As these systems mature through NEMA specifications or other governing bodies, research needs to continue to provide knowledge of the impacts and best practices, or encourage the industry in TSP development.

Finally, while this study investigated the impacts of an area with multiple transit routes, evaluation of a single route corridor would provide further understanding of the impacts associated with the entire transit route. Analysis of the traffic users' opportunity costs, hardware requirements, installation, and maintenance costs would give further insight into factors involved with TSP systems.

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