EVALUATING THE EFFECTS OF RAIL PREEMPTION STRATEGIES ON HIGHWAY SAFETY AND OPERATIONS

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Evaluating the Effects of Rail Preemption Strategies on Highway Safety and Operations

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ABSTRACT

Bratlien, Andrew Lee, M.S., Department of Civil Engineering, College of Engineering and Architecture, North Dakota State University, May 2011. Evaluating the Effects of Rail Preemption Strategies on Highway Safety and Operations. Major Professor: Dr. Amiy Varma.

Previous research related to signal preemption near highway-rail grade crossings has emphasized safety considerations, which are paramount due to the severity of potential train-vehicle collisions. The purpose of this research was to quantify the safety and efficiency implications of several common preemption strategies using the conditions in a small urban context. The research evaluates several important characteristics of rail preemption, including track clearance time, advance preempt time, and dwell cycle strategy, particularly with regard to surface street operational efficiency, that current traffic engineering practice do not adequately address. The context and preemption strategies were modeled using simulation software VISSIM. The results identified two separate and potentially serious safety issues related to the interaction of advance preempt time, track clearance time, and existence of four-quadrant gates at railroad crossing. In addition, the research also highlighted the negative effect of excessive track clearance time and dwell cycle on adjacent surface street operations.

ACKNOWLEDGMENTS

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Finally, thanks to my wonderful fiancé Tiara, the love of my life, for her patience and support during trying times – through long hours of model calibration and all-night writing sessions. I look forward to beginning the next chapter of life with my best friend and partner.

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CHAPTER 1. INTRODUCTION

1.1. Background

Highway-rail grade crossings create a special type of highway intersection in which at least two very different modes of transportation must share right-of-way. The contrasting physical and operational characteristics of vehicles and trains create a high risk of serious injury or death resulting from any collision. This inherent safety risk is compounded when signalized highway intersections exist in close proximity to crossings, a situation shown in Figure 1.1. Normal vehicle queues can create potentially dangerous situations during train events, when queued vehicles can become trapped on the tracks. This risk creates a need for preemption of normal traffic signal operations during train crossings.

Traffic signal preemption is defined by the National Electrical Manufacturers Assocation (NEMA) (2003) as the interruption of normal signal operation to provide modified timings under special circumstances. The primary goal of rail preemption is to improve safety by clearing vehicle queues from the crossing in the event of an approaching train (Venglar, et al., 2000). Effective rail preemption should also seek to facilitate the continued operational efficiency of affected surface streets before, during, and immediately after a train event.

Historical crash data evidences the safety challenges of highway-rail grade crossings. Throughout much of the 20th Century, crossing accidents grew with the expansion of highway and rail traffic (FRA 2010b). The Institute of Transportation Engineers (ITE) took the first significant step toward establishing industry-wide preemption standards with 1979's *Preemption of Traffic Signals At or Near Railroad*

Grade Crossings with Active Warning Devices: A Recommended Practice. Around the same time, crossing accidents began to decline.

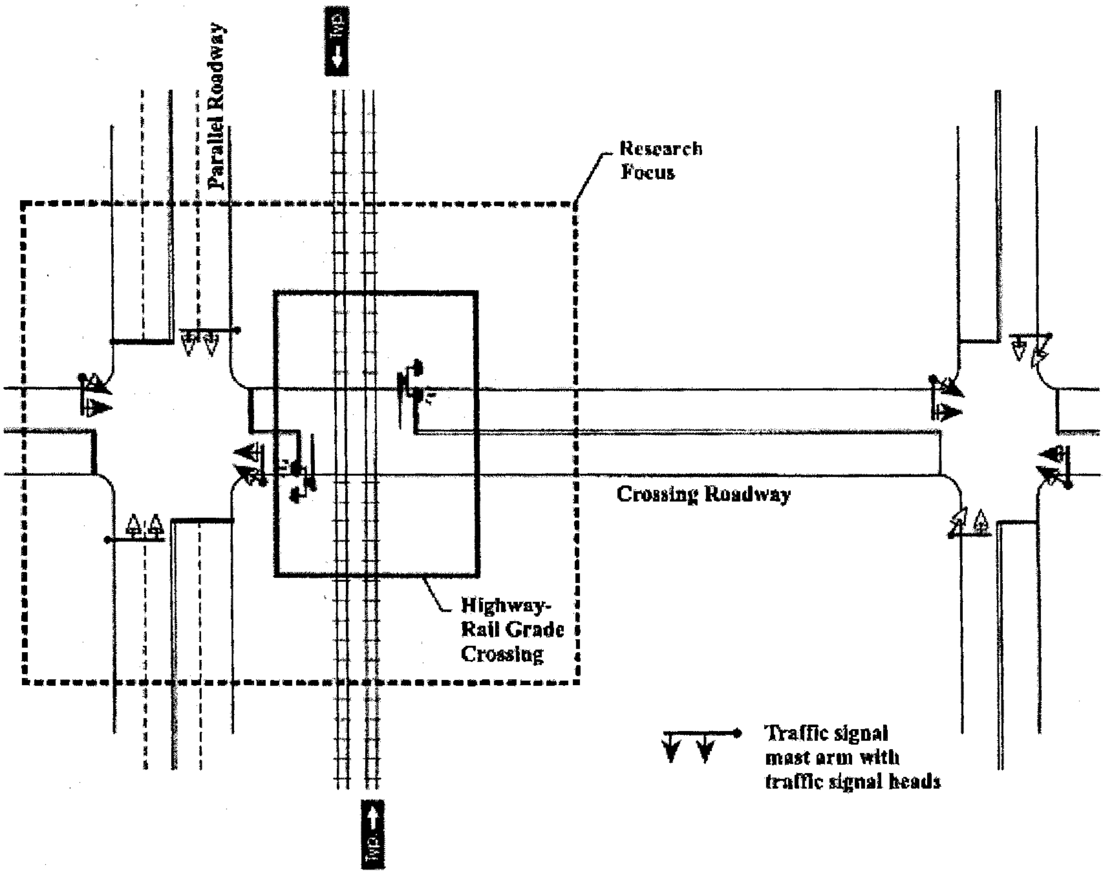


Figure 1.1. Highway-rail grade crossing with nearby signalized intersection.
Source: (Korve 1999)

In October 1995, a commuter train in Fox River Grove, Illinois struck a school bus that was stopped on a crossing while waiting at a red signal. Seven school children died and 24 others were injured in the accident (NTSB 1996). The tragedy prompted a reevaluation of crossing safety at the federal and state levels, leading to major updates in preemption guidelines and a further decline in crossing accidents.

Although highway-rail crossing safety has improved considerably, with train-vehicle collisions falling 85 percent from 1978 to 2009 (FRA 2010), there remains room for improvement. Hundreds of motorists and pedestrians are still killed each year in crossing accidents. Many of these accidents occur near signalized intersections (Engelbrecht et al. 2005).

1.2. Problem Statement

This research will address the lack of information regarding the effectiveness of current railroad preemption practice on highway safety and efficiency. The primary goal of rail preemption is to improve safety by clearing vehicle queues from the crossing in the event of an approaching train (Venglar 2000). Effective preemption should strike a balance between crossing safety and intersection operations, but current literature only addresses the safety issue. This study will also address the lack of industry-wide guidelines on the determination of the track clearance and dwell phase stages of preemption.

Preemption is a complex process involving a large number of geometric and control variables (ITE 2003). To gain an understanding of the uncertainties and operational challenges relevant to rail preemption, field observation is essential. Queue length and delay data can be collected to evaluate the severity of the disruption to traffic movement due to preemption. Field data, however, is limited to the observation of existing conditions. The complexity of preemption and the various factors influencing safety and operations under a broad range of conditions can be effectively studied through the use of simulation. A properly constructed simulation model can accurately represent the interaction between train and vehicle movements. The examination of simulation results may provide insight not only into which factors can influence traffic operations, but also the degree of influence of those factors. These examinations can, in turn, help achieve a better balance between ensuring safety and improving traffic operations by promoting better control strategies near highway-rail grade crossings. This research will be the first to apply a microsimulation model to compare the effects of preemption strategies on safety and operations.

1.3. Research Objectives

This research will use microscopic simulation to examine the effect of various rail preemption strategies on the safety and efficiency of surface street traffic. The preemption strategies will be evaluated based upon: (1) ability to consistently clear vehicle queues from crossings before the arrival of a train, and (2) alleviation of delay to surface street traffic. The primary objectives of this study are:

1. Review the current state of practice in rail preemption.
2. Evaluate current methodologies for determination of track clearance green time in a small urban area context.
3. Develop, calibrate, validate, and apply a simulation model to understand the implications of various configurations of advance preemption time, track clearance interval, and dwell cycle.
4. Document conclusions and lessons learned from the model's application.

1.4. Scope

This research focused on two intersections in a small urban central business district (CBD), each within 200 feet of highway-rail grade crossings. Each crossing was controlled by active warning systems with four-quadrant gate arms, and utilized advance signal preemption. The intersections used fixed time, coordinated timing plans. The analysis was conducted for evening peak hour conditions.

1.5. Thesis Organization

Chapter 1 is an introduction and includes background information, purpose, research objectives, and scope of the study. Chapter 2 is a literature review, discussing the history, terminology and characteristics of highway-rail crossing warning systems and signal preemption, describing the state of practice in rail preemption, and examining several proposed methodologies for the determination of track clearance green phase of preemption. It also provides a brief introduction to microscopic simulation. Chapter 3 includes a description of the case study location, and the results of the track clearance time methodologies. Chapter 4 details the development of the simulation model, from experimental design through calibration and validation, and includes a description of analysis scenarios and methods of analysis. Chapter 5 presents and discusses simulation results, and chapter 6 presents the study's conclusions and recommendations.

CHAPTER 2. LITERATURE REVIEW

This chapter reviews current literature regarding traffic operations near highway-rail grade crossings. It introduces the need for preemption, describes basic grade crossing and preemption terminology, and discusses the state of research and current practice.

2.1. Highway-Rail Grade Crossing Accidents

Crossing safety was forced to the forefront of the public consciousness when, on October 25, 1995 in Fox River Grove, Illinois, a morning commuter train collided with a bus full of schoolchildren. The bus's driver stopped at a red signal indication and unaware that the rear of the vehicle was positioned on the track. See Figure 2.1. The resulting collision killed 7 children and injured 24 others (NTSB 1996).

Figure 2.1. Fox River Grove crash scene.
Source: (NTSB 1996)

In the aftermath of the Fox River Grove accident, the US Department of Transportation formed a Grade Crossing Safety Task Force which identified major problems in rail preemption practice, including an absence of specific guidelines on when and how to implement preemption (Korve 1999). In response to the Task Force's findings, various state and federal agencies updated and expanded their preemption guidelines.

Highway-rail grade crossing accidents have been in decline since reaching a peak of 13,557 in 1978 (FRA 2010b). The number of incidents per year has decreased in 26 out of 31 years since then. Crashes have become more dangerous, however, with an increasing proportion of crashes resulting in fatalities. Vehicle-train collisions at crossings with active warning equipment have remained fairly constant (Engelbrecht et al. 2005). Figure 2.2 presents an overview of crossing incidents, injuries and fatalities in the most recent six years for which data is available.

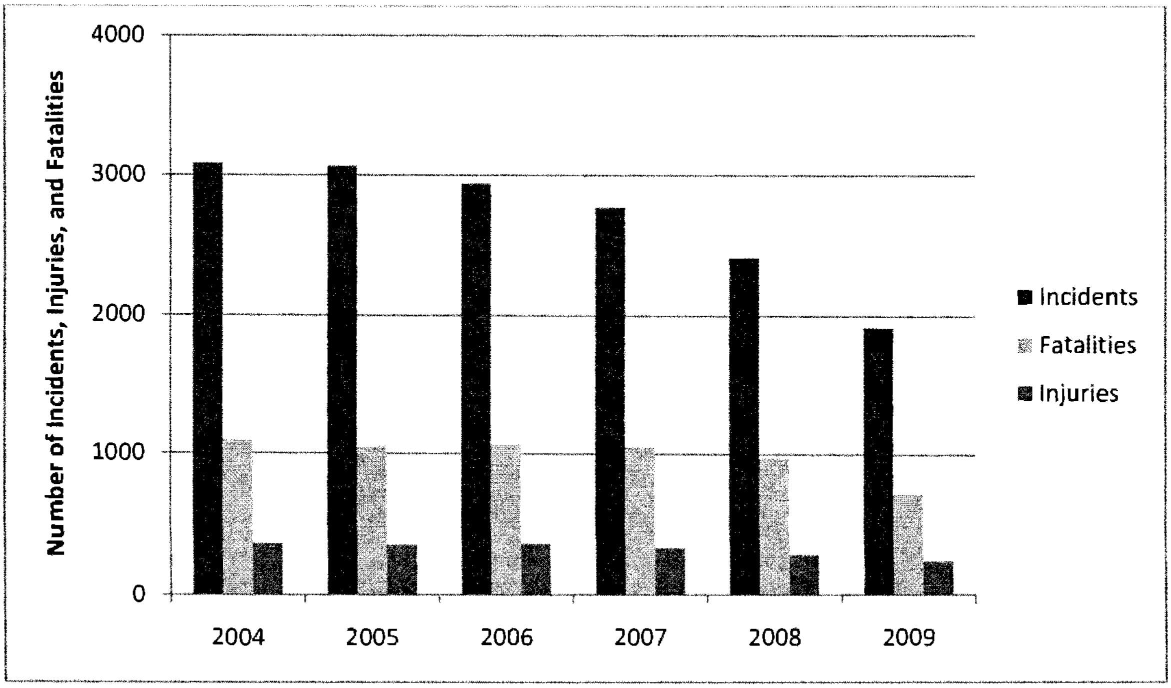


Figure 2.2. US grade crossing crash data.
Source: (FRA 2010b)

2.2. Highway-Rail Grade Crossing Warning Systems

Grade crossings create a unique type of intersection, in which two modes of transportation with very different physical and operational characteristics must share right-of-way. In contrast with a four-way stop-controlled intersection, in which right-of-way is assigned alternately to opposing traffic movements, the road user at railroad crossings must always yield right-of-way to the train (Korve 1999). Highway-rail crossing operation is, in that respect, similar to that of a two-way stop-controlled intersection. However, while automobiles on an uncontrolled approach of a two-way stop intersection may have the opportunity to slow down or swerve to avoid a crossing collision, trains do not. The physical characteristics of a moving train that make it very difficult to stop also make it likely that any vehicle-train collision will have severe consequences. This unique conflict makes it critical for motorists to be made aware of active railroad crossings and the need to yield right-of-way to approaching trains. This is achieved through the use of crossing warning devices, which can be classified into two types: 1) passive warning devices, and 2) active warning devices (FHWA 2007).

2.2.1. Types of Warning Systems

Passive warning systems incorporate devices which remain in their "active" state regardless of train presence, serving as a warning that a train may, at any time, be approaching the crossing. Such devices can include pavement markings, lighting, crossbucks, and other warning signs. Passive warning systems often utilize more than one of these devices (e.g. crossbucks with pavement markings) to alert drivers to a crossing.

Active warning systems remain at rest in their inactive state until they detect an approaching train. These systems may incorporate flashing signals, bells, and crossing gates, and may also incorporate passive warning devices which prohibit certain actions, such as stopping on the tracks, and encourage the exercise of due caution regardless of train presence. Traffic signal preemption requires the presence of an active warning system (Venglar 2000).

2.2.2. Train Detection and Warning Time

Train detection at active warning controlled crossings can utilize a variety of technologies. Track circuitry, the most commonly used detection method (Korve 1999), uses the rails as conductors to establish an electrical circuit on a length of track. When an approaching train enters the detector, the locomotive's axles short the track circuit, sending a call to the crossing warning equipment. The required track detection circuit length is determined by the maximum train speed and the minimum required warning time (Venglar 2000). The minimum warning time is designed to allow safe clearance of the track dynamic envelope prior to a train event, and has been established by the American Railway Engineering and Maintenance-of-Way Association (2000), Federal Highway Administration (2003), and Federal Railroad Administration (2003) as 20 seconds.

Traditional track circuits can lead to a great deal of variability in crossing warning time due to train acceleration and deceleration (Korve 1999). A train moving slower than the detection circuit's design speed will extend the effective warning time during which warning equipment is active before train arrival. This added warning time will impart delay to highway users and, if perceived as excessive or unnecessary, may cause frustrated motorists to maneuver around crossing gates. More sophisticated constant warning time

(CWT) systems are designed to reduce warning time variability by calculating train speed when it crosses the detection circuit. The calculated speed is used to estimate the train's arrival at the crossing, reducing warning time error. Even using CWT systems, however, warning time will vary due to acceleration or deceleration of a train after the train speed has been calculated (Korve 1999). If, for example, a train accelerates toward the crossing after its speed has been measured by a CWT system, it will arrive at the crossing before the minimum warning time has been provided (Venglar 2000).

2.2.3. Interconnection to Traffic Signals

When an active warning controlled crossing is located near a signalized intersection, crossing warning devices must be interconnected with the traffic signal controller via an underground circuit, allowing the two systems to function as one. Upon receiving a train call, the signal controller enters preemption operation to clear vehicles from the tracks while the track warning equipment prevents additional vehicles from moving toward the intersection.

The *Manual on Uniform Traffic Control Devices* (MUTCD) (FHWA 2007) recommends interconnection at signalized intersections within 200 feet of active warning controlled rail crossings. This guideline was established in the 1961 MUTCD, but it is unclear how the 200-foot distance was derived (Marshall and Berg 1997). ITE (2003) cautions against a fixed distance guideline, recommending that the need for preemption be determined by the 95th percentile queue length as determined through a detailed queuing analysis. A 1999 NEMA survey of transportation agencies echoed this recommendation.

2.3. Traffic Signal Preemption

Traffic signal preemption is defined by NEMA (2003) as the interruption of normal signal operation to provide modified timings under special circumstances. Rail preemption is designed to improve safety at grade crossings by clearing vehicles from the crossing before the arrival of a train (Korve 1999). This goal requires the execution of several events involving the crossing warning system and the traffic signal controller. The exact sequence and timing of these events is dependent on numerous variables at both ends, making preemption a highly complex process. This section will introduce the basics of rail preemption by describing the necessary stages and types of preemption.

2.3.1. Preemption Sequence

Safety and efficiency during preemption depends on the sequence and timing of five specific stages. Each stage is critical to the safe clearance of the crossing approach and the efficient movement of other approaches before, during, and after a train crossing. The required signal phases are described in NCHRP Report 271 (Korve 1999):

1.) Entry into preemption,

2.) Termination of the interval in operation (transfer of right-of-way),

3.) Clear track intervals (including clear track green),

4.) Preemption dwell intervals, and

5.) Return to normal operations.

The sequence begins when a call from a track detector to an interconnected signal controller activates the controller's preemption mode. Signal phases which oppose the crossing movements are terminated after the completion of their minimum green and standard clearance intervals. Preservation of minimum green time during the transfer of right-of-way prevents the driver confusion that could result from early green termination. ITE's Recommended Practice (2003) allows any pedestrian phases which would delay the transfer of right-of-way to be truncated or omitted. The right-of-way transfer time can vary depending on the time in signal cycle at which a call is placed.

Once right-of-way has been transferred to the track crossing approach, the track clearance interval begins. This phase facilitates the clearance of crossing approach queues before the arrival of a train, and uses a fixed interval. An adequate track clearance interval is critical to ensuring crossing safety, while an excessively long interval can leave unused green time and impart additional delay to opposing approaches.

Upon completion of the track clearance interval, the signal controller enters the preempt dwell phase, which serves movements that were interrupted by track clearance. These movements are typically served for the duration of the train event (FHWA 2007). If signal control technology allows, the preempt dwell stage can also cycle through phases which do not directly oppose the crossing (Korve 1999).

Once the train leaves the crossing, the signal controller begins its return to normal operation. ITE (2003) recommends returning service to the track crossing movements, which often experience the worst delay due to preemption. If an opposing approach has developed vehicle queues that disrupt an adjacent intersection, it may be preferable to first return a green interval to that phase. Recovery strategies should be designed to meet each crossing's unique characteristics (Marshall and Berg 1997).

2.3.2 Preemption Types

Signal response to rail preemption calls can be classified as one of two types: simultaneous or advance. Simultaneous preemption occurs when a preemption call is sent to the crossing's active warning system and the traffic signal controller at the same time. This causes the crossing warning equipment to activate at the same time the signal enters preemption. Simultaneous preemption can be provided where the railroad's warning time, typically the federally-mandated 20 second minimum, provides adequate time for the traffic signal to clear the track before a train's arrival (Korve 1999). Figure 2.3 presents an example timeline of rail equipment and traffic signal operation during simultaneous preemption.

If the required maximum, or "worst case," preempt time is greater than the warning time provided by the railroad, advance preemption should be provided (Korve 1999). During advance preemption, the traffic signal controller receives a preempt call some time before the activation of the crossing warning equipment. This allows the controller additional time to execute the transfer of right-of-way and track clearance interval. The advance preemption time is defined by Kenon (2004) as the difference between the time the signal controller and the railroad warning equipment each receive a train notification. A typical advance preemption timeline is illustrated in Figure 2.4. It should be noted that "preemption time" from Figure 2.4 is referred to in this study as "advance preemption time."

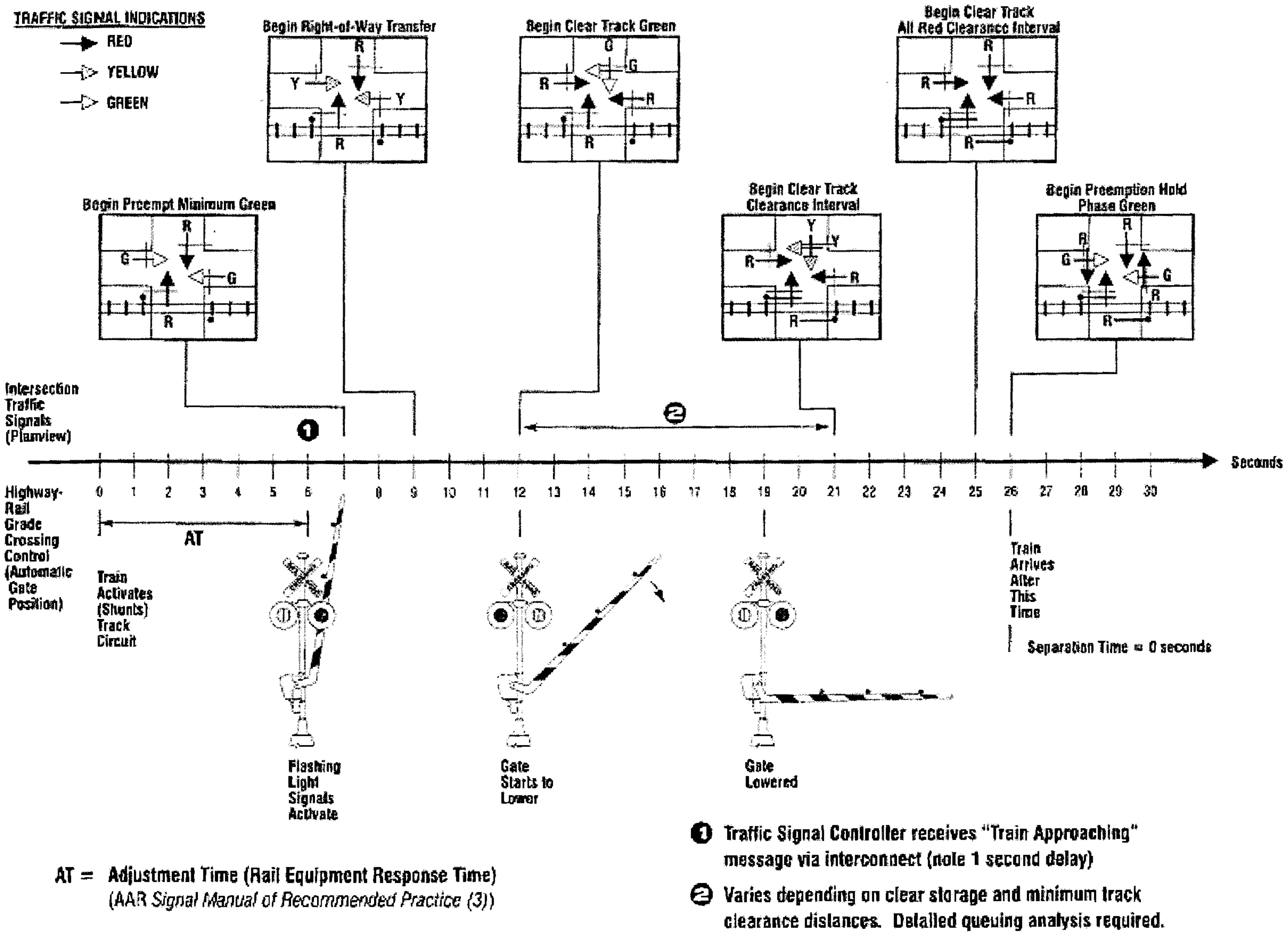


Figure 2.3. Sample simultaneous preemption timeline.
Source: (Korve 1999)

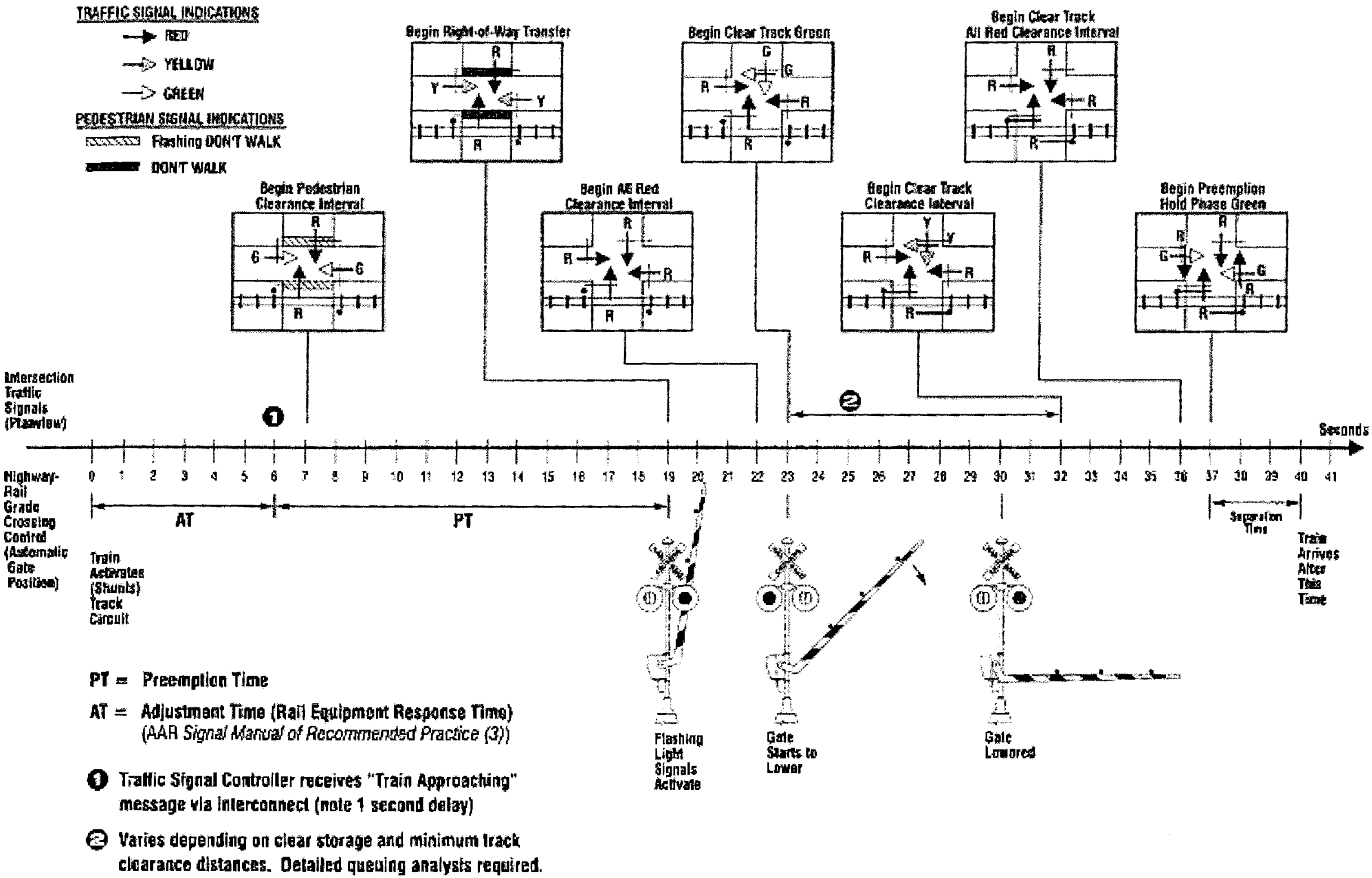


Figure 2.4. Sample advance preemption timeline.
Source: (Korve 1999)

2.4. Advance Preempt Trap

Variations in advance preemption time (APT) and right-of-way transfer time can lead to a situation known as the advance preempt trap (Engelbrecht et al. 2005). This occurs when crossing gates and flashers activate after the end of the track clearance interval, allowing vehicles to proceed to the intersection and potentially stop on the tracks. Upon activation of crossing warning equipment, the clearance phase has already been used, leaving vehicles have no opportunity to escape. This creates the effective equivalent of no preemption for track crossing movements. The advance preempt trap has two causes: high APT – which can result from train deceleration – and low right-of-way transfer time – which can occur if the traffic signal is already in the track crossing phase when preemption is activated (i.e. zero right-of-way transfer time). Figure 2.5 illustrates the problem.

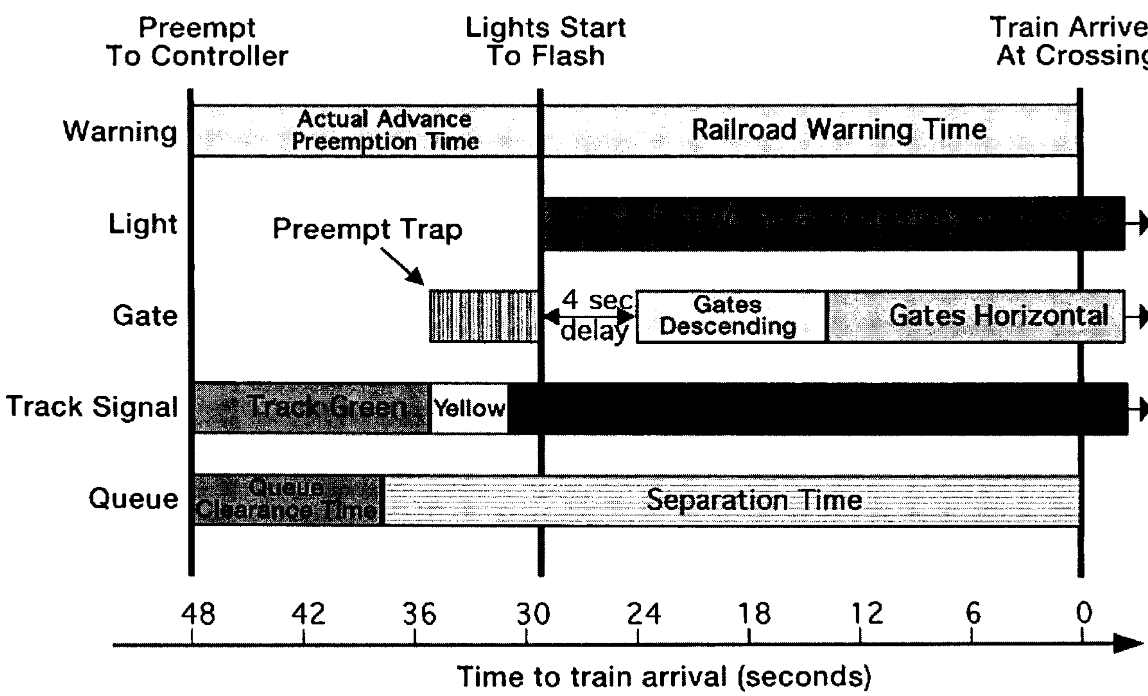


Figure 2.5. Advance preempt trap.
Source: (Engelbrecht et al. 2005)

Several solutions have been proposed to remedy the advance preempt trap. The most basic method (Engelbrecht et al. 2002) involves a simple extension of track clearance green to match the longest observed or expected advance preemption time. This would reduce the probability of a trap, but could result in very long clearance intervals, imparting unacceptable delay to the intersection's other movements. An actuated track clearance interval with a "gate-down" confirmation at the tracks, proposed by Yohe and Urbanik (2007) would eliminate the problem, but current signal controller technology does not support dynamic track clearance green time. Changes to controller specifications would be required. Another proposed solution by Engelbrecht (2002) would use a "not-to-exceed" timer in the track circuitry to limit maximum APT. This would address the railroad side of the advance preempt trap problem but it would not address the variability in right-of-way transfer time. Another option is the use of two preempts during rail events. The first, a low priority preempt, would dwell in the track-crossing phase after transfer of right-of-way. A higher priority preempt would be activated when gates begin closing, essentially acting as a simultaneous preempt. This would effectively extend the track clearance interval, but would also require advances in signal controller technology.

2.5. Track Clearance Time

The track clearance interval is critical to preventing vehicle-train collisions. If the track clearance interval is too short, the crossing may not be cleared before a train's arrival. If the interval is too long, however, opposing movements will experience unnecessary delay. Excessive delay can, in turn, lead to unsafe driver behavior (Engelbrecht et al. 2005). Until recently, despite the importance of track clearance green, there existed little information guiding the determination of track clearance green (Long 2002).

2.5.1. Greenshields Method

Many state transportation agencies (Venglar 2000) have traditionally used a modified version of Greenshields' discharge headway model (McShane and Roess 1990) to determine queue clearance time. The model is simple in its application but makes several assumptions which may not be appropriate for all contexts. It is designed to clear the entire crossing approach, which may lead to overly conservative track clearance intervals for long storage distances. The Greenshields minimum track clearance green time can be defined as the sum of the time required for the vehicle ahead of the critical vehicle to move (t_1), and the time required for the critical vehicle to move to a position clear of the tracks (t_2) (Mn/DOT, crossing inspection form, 2002). The first subinterval can be expressed as:

$$t_1 = 3.7 + 2.1n \tag{2.1}$$

where n is the number of vehicles queued ahead of the vehicle that is to be cleared from the tracks. The values 3.7 and 2.1 are used for startup delay and saturation headway, respectively (McShane and Roess 1990).

The time necessary for a stopped vehicle to move clear of the tracks once the vehicles ahead of it have begun to move (t_2) can be defined as:

$$t_2 = [2\ (L + D)\ /\ a]^{1/2} \tag{2.2}$$

where: L = length of design vehicle (ft),

D = minimum track clearance distance (ft),

a = design vehicle acceleration rate (ft/sec^2).

The track clearance interval as defined by the sum of these subintervals assumes the critical vehicle will move clear of the crossing at the moment a train arrives. Because of the likely severity of any train-vehicle collision and the extreme discomfort that a driver may experience if trapped on the tracks until the moment before a train arrives, a safety buffer or "separation time" of 4 to 8 seconds is often provided (Engelbrecht et al. 2005).

2.5.2. Marshall and Berg Method

In a 1997 study published in the ITE Journal, Marshall and Berg presented a method for determining track clearance time based on shockwave theory and Highway Capacity Manual saturation flow calculations. Clearance time in the Marshall and Berg method is defined as the time needed for a queued vehicle on the tracks to move to a safe position away from the tracks, and, similar to the Greenshields-based model, can be defined as the sum of two subintervals: the time required for the vehicle ahead to begin to move out of the way (t_1), and the time required for the vehicle in question to move to a safe position (t_2). The first subinterval can be expressed as:

$$t_1 = (L * k_j) / (2.94s) \tag{2.3}$$

where: L= critical length of queue, measured from the intersection stop bar to the point where a vehicle needing to be cleared may be stopped (ft),

k_j = jam density (vpm),

s= saturation flow rate (vph).

The second subinterval, time required for a stopped vehicle to move clear of the crossing (t_2), considers design vehicle length and acceleration and crossing geometry. It can be expressed as:

$$t_2 = [2\,(L + 2D + W) / a]^{1/2} \tag{2.4}$$

where: L = length of design vehicle (ft),

D = clearance distance on either side of tracks (ft),

W = distance between the outermost rails (ft).

a = design vehicle acceleration rate (ft/sec^2). Recommended values are shown in Table 2.1.

Table 2.1. Suggested design vehicle acceleration rates.

Design Vehicle	**Acceleration Rate (ft/sec^2)**
Passenger car (P)	4.4
Single-unit truck (SU)	2.5
Multi-unit truck (MU)	1.6

Source: (Marshall and Berg 1997)

2.5.3. Long Method

In 2003, Long proposed a 12-step method to clear the n^{th} queued vehicle from a railroad crossing. Long's method requires relatively simple input, using roadway geometry and design vehicle characteristics, with adjustments for special circumstances. Track clearance time is defined as the time necessary for a queued vehicle to (1) begin moving after a traffic signal turns green and (2) once moving, to find a position clear of the tracks. The exact methodology is contained in Appendix A. Due to the difficulty and inefficiency of designing for a "worst case" queue clearance scenario, the method was calibrated to achieve a 99.9% confidence interval.

2.5.4. Engelbrecht Method

The most recent method for determination of track clearance time was established in a 2005 study by Engelbrecht. Engelbrecht's method provides guidelines for vehicle and pedestrian green time truncation and track clearance green time, and has been adopted by the Texas and Minnesota departments of transportation (Mn/DOT 2006).

This method was the first to identify and address the problem of the advance preempt trap, by defining track clearance time as the greater of two intervals: (1) time required to prevent the track clearance phase from terminating before crossing gate closure, and (2) time required to clear the desired portion of the clear storage distance (CSD). To avoid unnecessarily long track clearance intervals, the entire CSD need not be cleared when it exceeds 150 feet. This methodology is contained in Appendix B.

2.6. Summary

This study's literature review highlighted the safety implications and complexity of railroad preemption. While guidelines for preemption have improved since the Fox River Grove incident in 1995, the issues of advance preempt trap and determination of track clearance time are not adequately addressed in current practice. Previous studies have discussed the safety implications of track clearance and advance preemption, but none have evaluated the tradeoff between crossing safety and intersection efficiency. Nor has any research conducted a direct comparison of preemption strategies. This study will address these issues.

CHAPTER 3. CASE STUDY DESCRIPTION

3.1. Rationale for Selecting Study Sites

The study focused on two intersections along Fargo, North Dakota's downtown Main Avenue corridor. The Fargo-Moorhead metropolitan area includes 17 rail crossing-interconnected signal controllers, eight of which are located in the metro's downtown train horn quiet zone. The intersections of 4th Street and 6th Street along Main Avenue are the only two preempt-equipped intersections which are coordinated and use advance preemption. The case study location will provide unique insight into the impact of preemption in an urban context.

3.2. Study Site Geometry and Signal Control

Main Avenue is an east-west principal arterial spanning the Fargo-Moorhead metro. Its downtown corridor runs parallel to the KO subdivision, which serves the BNSF Railway Company, and includes eight preemption-equipped intersections. The study area includes the intersections of Main Avenue with 4th Street and 6th Street, both in Fargo. Figure 3.1 displays the study site locations.

3.2.1. Main Avenue and 4th Street

Fourth Street is a north-south four-lane minor arterial. Its intersection with the east-west Main Avenue is 104 clear feet south of the KO subdivision. At the intersection, 4th Street includes two through lanes in each direction. The southbound approach has one southbound left turn lane while the northbound includes both left and right turn lanes. Main Avenue carries two through lanes and a left turn lane in each direction.

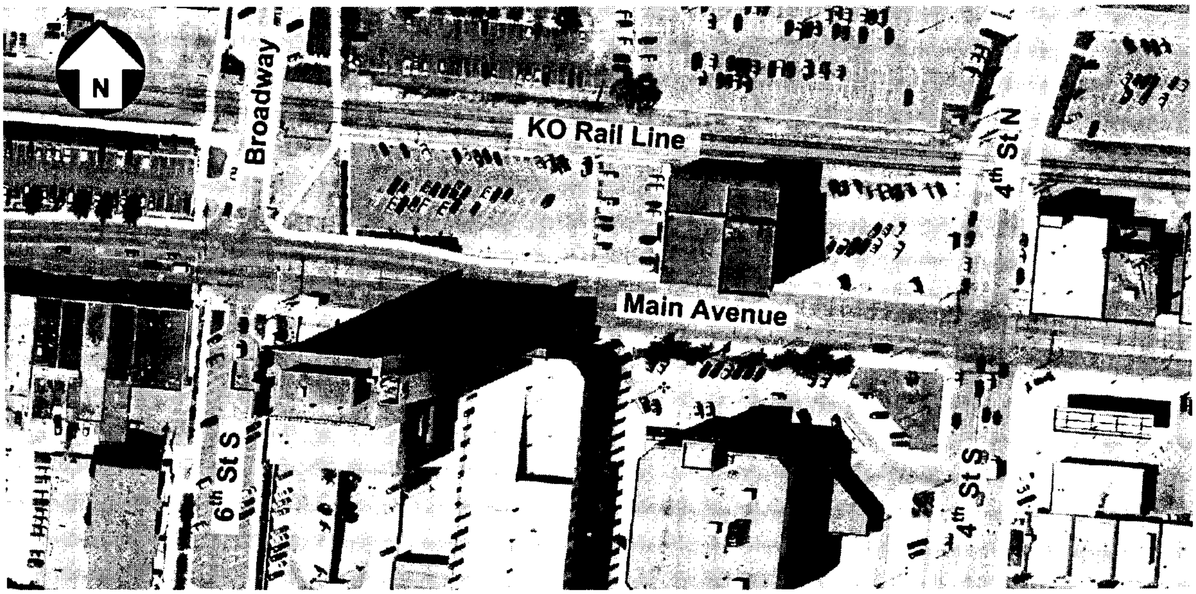


Figure 3.1. Case study location.

Signal operation at Main Avenue and 4th St is pretimed, with cycle 90 seconds, and coordinated with the adjacent 6th Street intersection. During evening peak hour, the signal uses a three-phase cycle, with a protected left turn on the eastbound approach. "No right turn on red" signs are in place on the southbound and westbound approaches. The signal controller's preemption dwell sequence allows eastbound and westbound non-crossing movements to alternate with northbound/southbound through and northbound protected left turn phases. It is unusual during preemption to serve a movement that directly opposes a nearby crossing (e.g. northbound through), but 4th Street's north approach does include a driveway which would otherwise be isolated during a train event. Figure 3.2 illustrates the intersection's lane groupings and signal phasing.

3.2.2. Main Avenue and 6th Street

Sixth Street is a north-south two-lane minor arterial serving Fargo's downtown shopping and business district. Its north approach to Main Avenue includes a southbound exclusive right turn lane, and both approaches carry a single through lane. Main Avenue at 6th Street is a four-lane principal arterial serving 16,200 vehicles per day, with a left turn lane in each direction. The intersection is located two blocks west of Main Ave and 4th Street. Clear storage distance from the southbound stop line to the KO crossing is 96 feet. It should be noted that, north of Main Avenue, Sixth Street is known by the City of Fargo as Broadway. This study will refer to the entire link as 6th Street.

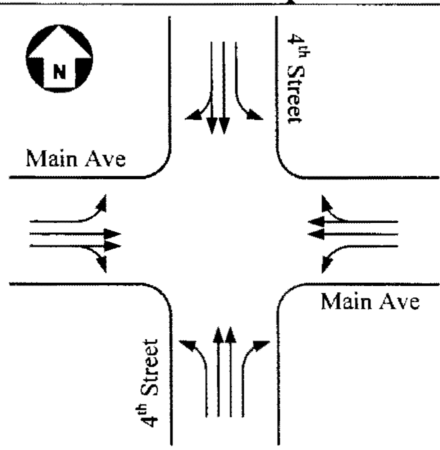
Lane Groups	Signal Phases
	Basic Timing: 1.) EB + EBL 2.) EB + WB 3.) NB + SB Preemption Dwell: 1.) EB + WB 2.) NBL + SBL 3.) NB + SB

Figure 3.2. Lane groups and signal phases at Main Avenue and 4th Street.

The intersection's signal controller is pretimed and coordinated with 4th Street. During evening peak hour, it uses a three-phase timing plan similar to the adjacent intersection, providing a protected left turn for eastbound movements. During crossing events, the signal controller dwells on eastbound/westbound through movements. Figure 3.3 shows lane groupings and signal phasing at Main Avenue and 6th Street.

3.3. Railroad Operations and Warning Equipment

The Fargo-Moorhead area initially grew as a rail hub and much of its early development was built around its rail activity (City of Moorhead 2010). As a result, the downtown metro is intersected by two active railroads, the KO and Prosper subdivisions, which have a major impact on local street traffic.

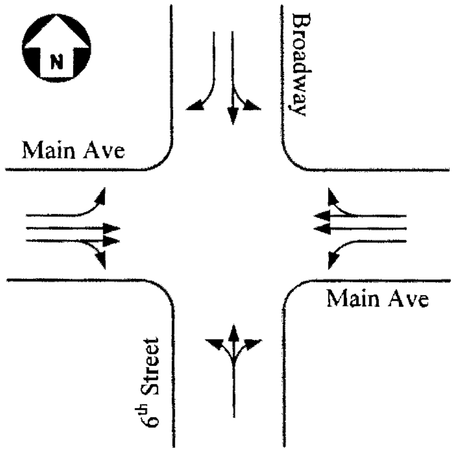
Lane Groups	Signal Phases
	Basic Timing: 1.) EB + EBL 2.) EB + WB 3.) NB + SB Preemption Dwell: EB + WB

Figure 3.3. Lane groups and signal phases at Main Avenue and 6th Street/Broadway.

A railroad quiet zone, as defined by the Federal Railroad Administration (FRA 2010a), is "a section of a rail line…that contains one or more consecutive public highway-rail grade crossings at which locomotive horns are not routinely sounded because acceptable safety improvements have been installed." In 2003, the FRA approved quiet zones encompassing 20 crossings in the Fargo-Moorhead area, including the two study crossings included in this research (see also Shorten 2005).

Numerous safety measures were implemented as a result of the quiet zone designation, including four-quadrant gates. Four-quadrant gates block highway approaches and departures on both sides of the railroad crossing, preventing motorists from bypassing lowered gate arms (Korve 1999). Each crossing also uses warning bells and flashing beacons to warn drivers of approaching trains, and pavement markings to delineate the crossing. Advance preemption is provided at both study crossings.

The KO subdivision runs just north of and parallel to Main Avenue. It serves 67 trains per day at a speed limit of 35 mph (USDOT, crossing inventory report, 2009), with 45 percent of the movements occurring between 10:00 pm and 7:00 am (Shorten 2005).

3.4. Track Clearance Intervals

The track clearance time calculation methods described in chapter 2 were applied to both intersections and compared to current conditions. Results are shown in Table 3.1, with existing values used by the City of Fargo in bold. Current track clearance intervals at both intersections were obtained from the City of Fargo and were 22 seconds each, matching the CSD clearance interval from the Engelbrecht methodology. Engelbrecht's preempt trap prevention interval was much longer, at 47 and 49 seconds for 4th Street and 6th Street, respectively. The Marshall and Berg procedure required more complex data which was not available, and the method was not applied. The Greenshields and Long methods yielded midrange clearance intervals of 30 and 31 seconds, respectively, for both intersections.

Table 3.1. Track clearance green time results.

Intersection	**Track Clearance Time**			
	Greenshields	Long	Engelbrecht	
			To avoid preempt trap	To clear CSD
Main Ave & 4th St	30	31	47	**22**
Main Ave & 6th St	30	31	49	**22**

Note: values used by City of Fargo in bold

3.5. Summary

This chapter described geometric, control, and crossing warning features of the two study intersections in the Fargo, North Dakota central business district. The intersections of Main Avenue with 4th Street and 6th Street were selected for their ability to represent several features of interest in rail preemption, including advance preemption, dwell cycle, and coordinated operation, in an area with high train and street traffic demand. A comparison of several track clearance interval methodologies revealed both intersections to be using Engelbrecht's CSD clearance interval. Three other methods resulted in longer track clearance intervals, the most conservative of which was Engelbrecht's worst-case "advance preempt trap" prevention interval.

CHAPTER 4. MODEL DEVELOPMENT METHODOLOGY

Microsimulation is a very time- and labor-intensive analysis tool, requiring a great deal of input data and calibration to yield meaningful results. This chapter will detail the study's methodology for model development, describing the selected simulation software, data collection, model construction, calibration and validation. The methodological framework, shown in Figure 4.1, was adapted from a recommended practice in FHWA's *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Software* (2004).

4.1. Microscopic Simulation

An analysis of railroad preemption strategies requires a model which can reflect the complexity of preemption. The microscopic simulation software VISSIM, developed by PTV, was selected for this research because of its ability to model driver behavior and advanced signal control strategies under various levels of train and highway traffic, and its position as one of the most widely used microscopic simulation programs (Ahmed 2005). This research used version 5.30.

4.1.1. Network Structure

VISSIM networks are built on a link-connector structure. Network geometry typically begins by importing and scaling an image of the study area, then tracing the appropriate thoroughfares with links and connectors. Several network attributes, including number of lanes, lane width, and driver behavior type, are embedded in the links. Once the network geometry has been constructed, other necessary network attributes – speed decisions, vehicle inputs, stop lines, vehicle detectors, and conflict areas – are added. Other parameters, including vehicle weight, power, and desired speed, are defined by vehicle type and assigned to individual vehicles entering the network based on a distribution.

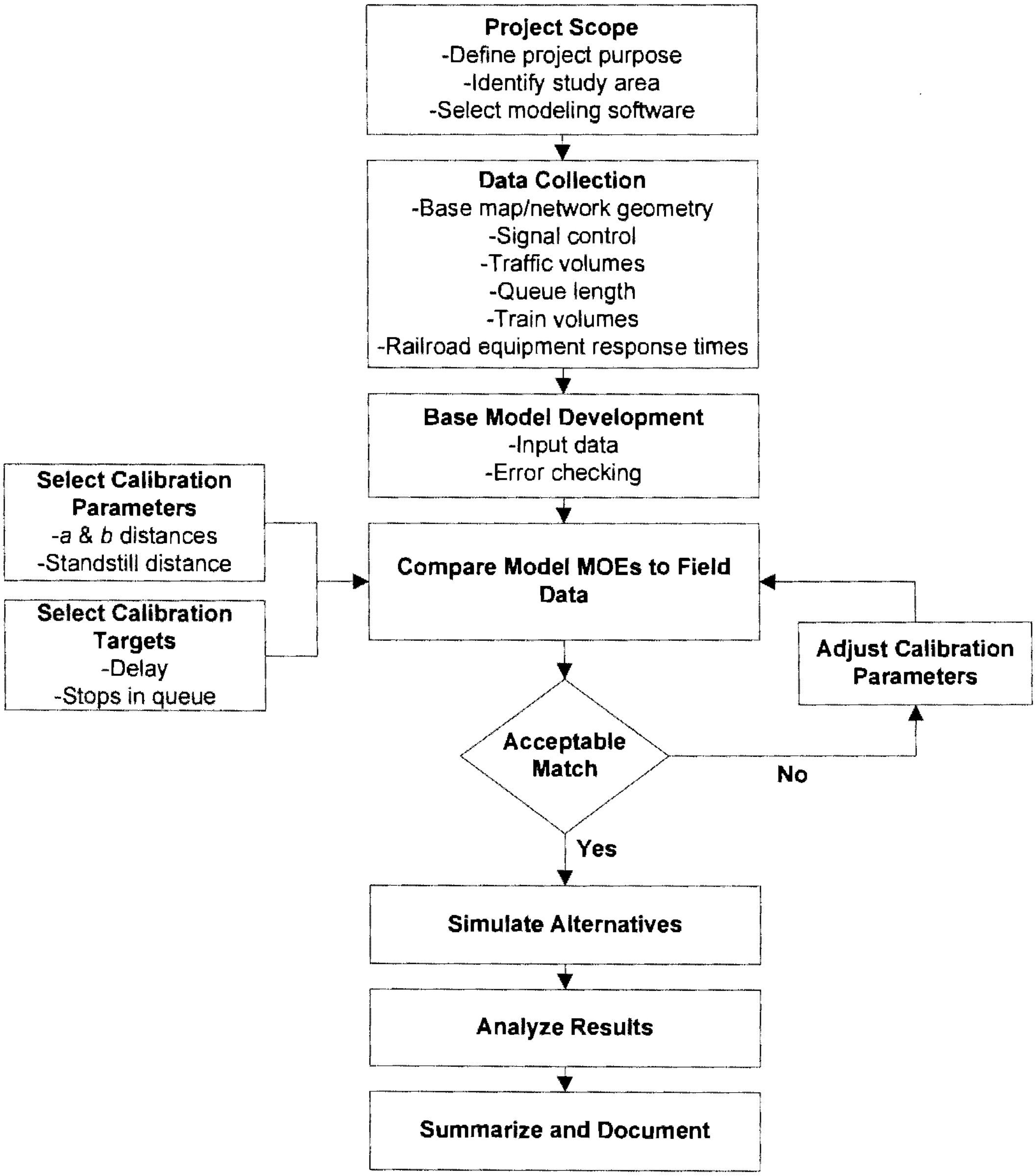


Figure 4.1. Methodological framework.

4.1.2. Traffic Input and Movement

Vehicle volumes are entered at the start of links, usually on the edges of a network. Traffic compositions are defined by a distribution at each input point. Route choices are modeled with one of two methods: (1) static routing decisions at each decision point, or (2) dynamic assignment through an origin-destination matrix. This study used static routing decisions based on intersection turning movement counts.

4.1.3. Signal Control

In the past, simulation of preemption and other advanced signal controller functions required the use of hardware signal controllers interfaced through the simulation software, a configuration known as hardware-in-loop simulation (HILS). HILS allows the signal controller to respond in simulation exactly as it would in practice, but suffers from its inability to simulate faster than real-time. This can be time-prohibitive in studies which require dozens or hundreds of simulation runs. Recent improvements in signal control emulation, however, have reduced the need for HILS by allowing software signal controllers to model the response time and advanced capabilities of their hardware counterparts (Stevanovic et al. 2009). This study used VISSIM's signal controller emulator, which includes advanced rail preemption capabilities and 0.1-second resolution.

4.1.4. Driver Behavior

Microscopic simulation is based on the movements of individual vehicles through a network. In order to reflect the complexity of individual driver-vehicle behavior, microsimulation typically involves a large number of input parameters. In VISSIM, these driver behavior parameters are divided into four categories: car following, lane changing, lateral, and signal control.

Car following logic can be defined by two models, both based on the research of Wiedemann – Wiedemann 74 for urban surface street traffic and Wiedemann 99 for freeways. The Wiedemann 74 model uses the following equation to compute the distance *d* between two vehicles:

$$d = ax + bx \tag{4.1}$$

where *ax* is the average standstill distance, an input parameter defined as the average desired distance between stopped vehicles, with a fixed variation of $\pm$ 1m. The desired safety distance *bx* is defined as:

$$bx = (bx_{add} + bx_{mult} * z) * \sqrt{v} \tag{4.2}$$

where bx_{add} represents additive part of desired safety distance, an input parameter, bx_{mult} is multiplicative part of desired safety distance, an input parameter, *z* is a value of range [0,1] which is normally distributed about 0.5 with standard deviation of 0.15 (m), and *v* is vehicle speed (m/s).

It should be noted that car following logic has a significant impact on saturation flow rate, which is not explicitly defined in VISSIM (Ahmed 2005).

Lane changing behavior is defined by the preferred and maximum deceleration rates of merging and trailing vehicles, as well as headway between vehicles. Lateral driver behavior parameters dictate the lateral movement of vehicles within their lane and the overtaking of other vehicles within the same lane. These parameters include desired position at free flow, recognition of vehicles in adjacent lanes, and consideration of approaching turns, among others. Finally, signal control parameters determine a driver's response to a yellow signal, based on local driving patterns (Baker 2008).

4.1.5. Evaluation

The random nature of driver behavior is reflected in VISSIM through the assignment of a random seed to each simulation run. As such, model results can vary from one run to the next. To address this variability and establish convergence of results, several simulation runs are usually required. VISSIM's multi-run feature makes this possible by automatically conducting a user-defined number of runs. Simulation output can include numerous methods of evaluation (MOEs), including volume, speed, queue length, and travel time, based on study requirements.

4.2. Data Collection

Base case data was collected at Main Ave & 6th St on Wednesday April 21, 2010 and at Main Ave & 4th St on Wednesday, April 28, 2010, both from 4:00 to 6:00 pm. Observations included traffic volumes in 15-minute intervals, train crossing times, and signal phase change times. Speed limits were noted, and overall traffic composition was taken from a 2009 USDOT crossing inspection form.

Calibration data was collected at Main Ave & 6th Street on Monday, December 6, 2010, from 4:00 to 6:00 pm. It included queue length and delay in 15-second intervals, volume in 5-minute intervals, and train crossing and warning equipment activation times. A validation data set was collected at Main Avenue and 4th Street on Tuesday, December 7, 2010 from 4:00 to 6:00 pm.

Additional train and preemption data was also collected at both study crossings. Warning equipment response times, train arrivals and departures, and signal phase changes were observed during 20 train crossing events during the 4:00 to 6:00 pm period. Track clearance intervals and dwell phases matched information obtained from the City of Fargo. Maximum advance preemption time was 35 seconds, minimum was 10 seconds, and the average for all 20 events was 16 seconds at 6th Street and 23 seconds at 4th Street. Crossing geometry – length of dynamic envelope, distance between outer rails, clear storage distance and crossing width – was measured to 1-foot accuracy using a rolling wheel.

4.3. Network Construction

Network geometry was based on a 2005 aerial photograph, which includes no significant differences from 2010 geometry. The study intersections are bordered on the north by NP Avenue, on the east by 2nd Street, on the south by 1st Avenue South, and on the west by 8th Street. Figure 4.2 illustrates the simulation network, with study intersections highlighted.

After tracing the necessary links and connectors over the imported background image, other network elements – vehicle entry points, routing decisions, speed changes, conflict areas, signal heads, and vehicle detectors – were defined. Train and traffic volumes were defined at the edges of the network and turning movement counts were specified in routing decisions at each intersection based on field data. Travel time sections, data collection points, and queue counters were defined on the appropriate approaches. Crossing gate arms were modeled using signal heads and were interconnected to nearby signals using VISSIM's VAP (Vehicle Actuated Programming) signal control module.

Signal preemption was modeled using the RBC signal controller. The unusual preemption sequence at Main Avenue & 4th Street – which includes modified splits and a left-turn phase which is not served during normal operation – was not supported by the

RBC. Instead, the signal phases included in normal operation were allowed to cycle during dwell, after completion of the track clearance interval.

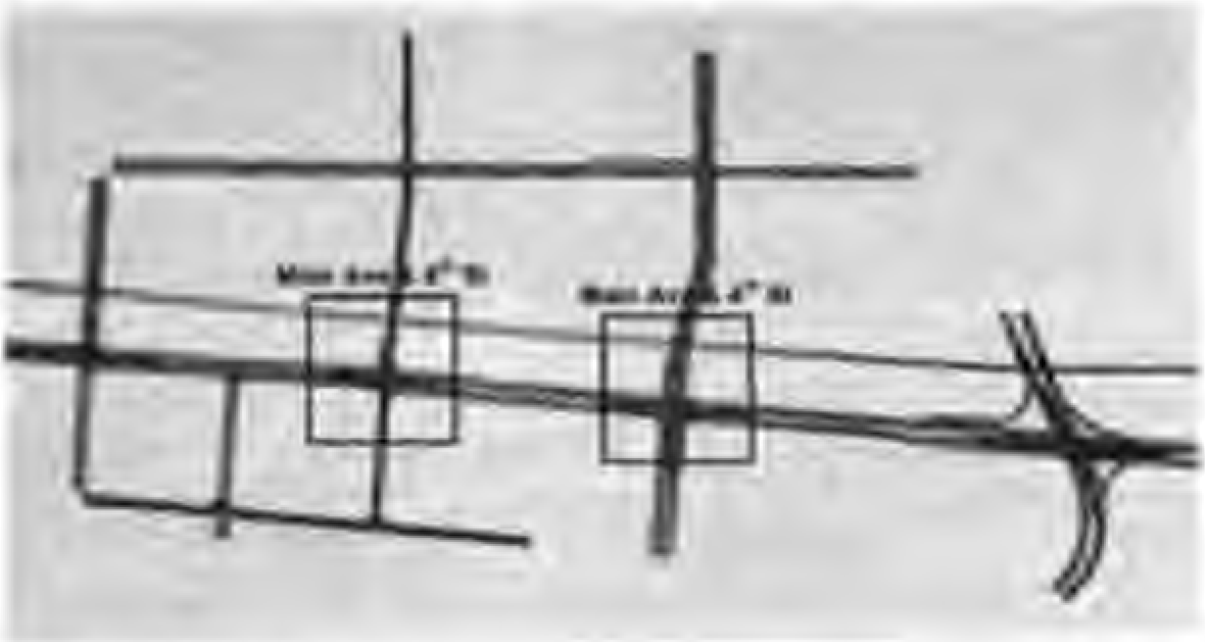


Figure 4.2. VISSIM network.

Base case, calibration, and validation train lengths were derived using observed crossing occupancy time and a 35 mph speed limit obtained from the railroad. Train composition (locomotive and car length) was based on BNSF specifications (BNSF 2010). Advance preemption time was fixed at each crossing, based on observed values. Warning time was similarly fixed, using observations and train speed to define crossing detectors of appropriate length.

4.4. Calibration

Since no single simulation model can be expected to accurately reproduce all possible traffic conditions (Dowling et al. 2004), calibration is a critical step in the model development process. Simulation model calibration is defined by the FHWA (Dowling et al. 2004) as "the adjustment of model parameters to improve the model's ability to reproduce local driver behavior and traffic performance characteristics." It is an iterative process by which model parameters are adjusted and results are compared against field data until results fall within determined target ranges (Ahmed 2005). This study used a five-step calibration approach adapted from Park and Schneeberger (2003):

(1) Selection of measures of effectiveness (MOE),

(2) Determination of calibration targets,

(3) Field data collection,

(4) Selection of calibration parameters,

(5) Iterative adjustment of parameters until calibration targets are met.

Eastbound delay and southbound stops at Main Avenue and 6th Street were selected as calibration MOEs for their respective relevance to efficiency and safety, and the ease with which they can be collected in the field. Calibration targets were based on a paired differences t test of field observations and simulation results over a one-hour period.

Network calibration in VISSIM can be a daunting task, as model performance can be impacted to varying degrees by hundreds of parameters (Dowling et al. 2004). To make the process manageable, a limited number of adjustable parameters were identified before running the simulation. Fixed values were assigned to as many inputs as could be observed or reasonably assumed. These included volume, route choice, traffic composition, lane change distance, and desired speed and acceleration. Three critical driver behavior parameters, additive and multiplicative parts of safety distance and average standstill distance, were identified for their role in determining network performance. These parameters have been shown to have the greatest impact on capacity in Weidemann 74-based models (PTV AG 2010).

Due to the stochastic nature of VISSIM, individual simulation runs will produce variability in results (Tian 2002). This variability was overcome by conducting multiple runs of each scenario. After 10 initial runs, the equation below (Baker 2008) was applied to determine whether additional runs would be needed to achieve convergence of results. Results indicated that four additional runs, for a total of 14, were necessary.

$$n = \left(\frac{z_{\alpha/2}\sigma}{E\mu}\right)^2 \tag{4.3}$$

where

n	= required number of simulation runs,
σ	= sample standard deviation (based on initial 10 runs),
$z_{\alpha/2}$	= threshold value for a 100(1-α) confidence interval (for a 95% confidence interval, $z_{\alpha/2}$ = 1.96),
E	= allowed error range, taken as 10% for a 95% confidence interval,
μ	= sample mean (based on initial 10 runs).

Calibration targets were achieved after two calibration iterations of 14 runs each. Two additional iterations were tested in an effort to improve the match between simulated and field values, but iteration 2 ultimately provided the best match while passing a visual inspection of the model. Table 4.1 outlines each iteration's calibration parameters.

A paired difference t-test of simulated and observed eastbound delay yielded a P value of 0.222 for iteration 2, indicating a lack of evidence to suggest a statistical difference in field and simulated means. Simulated hourly delay was 1.0 second greater than observed delay. The same test, when performed on southbound stops, resulted in a P value of 0.0698. This exceeded the minimum P value of 0.05 required to suggest a difference between simulation and field conditions at the 95% confidence level. Results are displayed in Table 4.2.

Table 4.1. Calibration parameters.

Car Following Parameter	Iteration 1	**Iteration 2**	Iteration 3	Iteration 4
Avg standstill distance (ft)	6.56	**6.56**	4.5	4.5
Additive part of safety distance	2	**0.1**	0.1	0.1
Multiplicative part of safety distance	3	**1.1**	1.1	0.5

Table 4.2. Calibration results.

	EB Delay			SB Stops		
Time	Observed	Simulated	Difference	Observed	Simulated	Difference
17:00	3.2	8.5	-5.3	24	8	16
17:05	7.3	6.0	1.4	26	12	14
17:10	5.5	7.2	-1.8	16	10	6
17:15	4.6	9.9	-5.3	20	14	6
17:20	8.4	5.9	2.5	15	16	-1
17:25	4.1	7.0	-2.9	12	8	4
17:30	7.5	6.7	0.8	8	8	0
17:35	5.9	5.3	0.6	7	15	-8
17:40	3.6	6.7	-3.1	11	6	5
17:45	7.5	6.0	1.5	9	7	2
17:50	6.0	4.9	1.1	8	8	0
17:55	6.0	7.7	-1.7	5	3	2
Average	5.8	6.8	-1.0	13.4	9.6	3.8
Std.Dev	1.7	1.4	2.7	6.9	4.0	6.6
P value	**0.222**			**0.0698**		

4.5. Validation

Model validation is a means of verifying the accuracy of a simulation model by applying a calibrated model to a different data set. Validation MOEs included eastbound delay and southbound stops in addition to turning movement volume. A paired differences t-test of the validation model against field data passed a 95 percent confidence level match for delay and stops. P values for eastbound delay and southbound stops were 0.5484 and 0.9909, respectively, both far greater than the 0.05 required to establish a significant difference between population means at the 95 percent confidence level. Approach volumes matched within two percent of field conditions. A visual inspection of the running model confirmed vehicles were behaving realistically. Results are shown in Table 4.3.

Table 4.3. Validation results.

	EB Delay			SB Stops		
Time	Observed	Simulated	Difference	Observed	Simulated	Difference
17:00	12.9	10.5	2.5	17	18	-1
17:05	11.9	11.3	0.6	23	22	1
17:10	22.9	18.4	4.5	44	30	14
17:15	11.8	11.4	0.4	25	33	-8
17:20	12.2	11.4	0.8	13	20	-7
17:25	16.2	14.0	2.2	24	19	5
17:30	8.3	9.8	-1.5	19	18	1
17:35	23.6	11.7	11.9	9	17	-8
17:40	7.5	17.9	-10.4	24	17	7
17:45	13.1	10.1	3.0	19	22	-3
17:50	13.8	12.9	1.0	11	8	3
17:55	11.3	15.1	-3.8	11	15	-4
Average	13.8	12.9	0.9	13.4	19.9	0.0
Std.Dev	5.0	2.9	5.2	9.5	6.5	6.6
P value	0.5484			0.9909		

4.6. Analysis Scenarios

This study's analysis scenarios were designed to measure the effect of variations in advance preemption time, track clearance, and dwell cycle. The base case scenario used existing volumes, crossing equipment response times, and signal plans. Advance preemption was 16 seconds at 6th Street and 23 seconds at 4th Street, dwell cycle was implemented at 4th Street, and track clearance green was 22 seconds at both intersections. Table 4.4 illustrates the control settings of each analysis scenario.

Variations in advance preemption time are an unavoidable consequence of track detection technology, resulting from train acceleration and deceleration after detection. While these variations are beyond the control of the traffic engineer, it is important to understand the impact they may have on traffic operations and safety. Scenarios 2-4 were designed to measure the consequences of these variations. Scenario 2 used simultaneous preemption, with an advance preemption time of zero at both crossings. Scenarios 3 and 4 used modified advance preempt times of 10 seconds and 35 seconds, respectively, based on minimum and maximum field observed APT. The 35-second preemption time could lead to the worst-case preempt trap of 13 seconds shown in Figure 4.3.

Table 4.4. Analysis scenarios.

Scenario	Advance preempt time		Track clearance green		Dwell cycle	
	4th & Main	6th & Main	4th & Main	6th & Main	4th & Main	6th & Main
1 (base)	23	16	22	22	Yes	No
2	0	0	22	22	Yes	No
3	10	10	22	22	Yes	No
4	35	35	22	22	Yes	No
5	23	16	18	18	Yes	No
6	23	16	30	30	Yes	No
7	23	16	22	22	Yes	Yes
8	23	16	22	22	No	No

The next two alternatives focused on track clearance intervals. Scenario 5 used 18 seconds, the minimum time required by the Engelbrecht method to clear only the track dynamic envelope at both intersections. Scenario 6 used the more conservative Greenshields method, with a track clearance green time of 30 seconds at both intersections.

Scenarios 7 and 8 tested the impact of a signal cycle during the preempt dwell stage, similar to the current strategy at Main Ave & 4th Street. Cycling during preempt dwell is a strategy of reducing delay to approaches which oppose the crossing and would not otherwise be served during dwell, in this case the north and south approaches. Scenario 7 implemented a 90-second dwell cycle serving all four approaches at each intersection. The dwell hold eastbound/westbound strategy currently used at 6th Street was applied to both intersections in the final scenario.

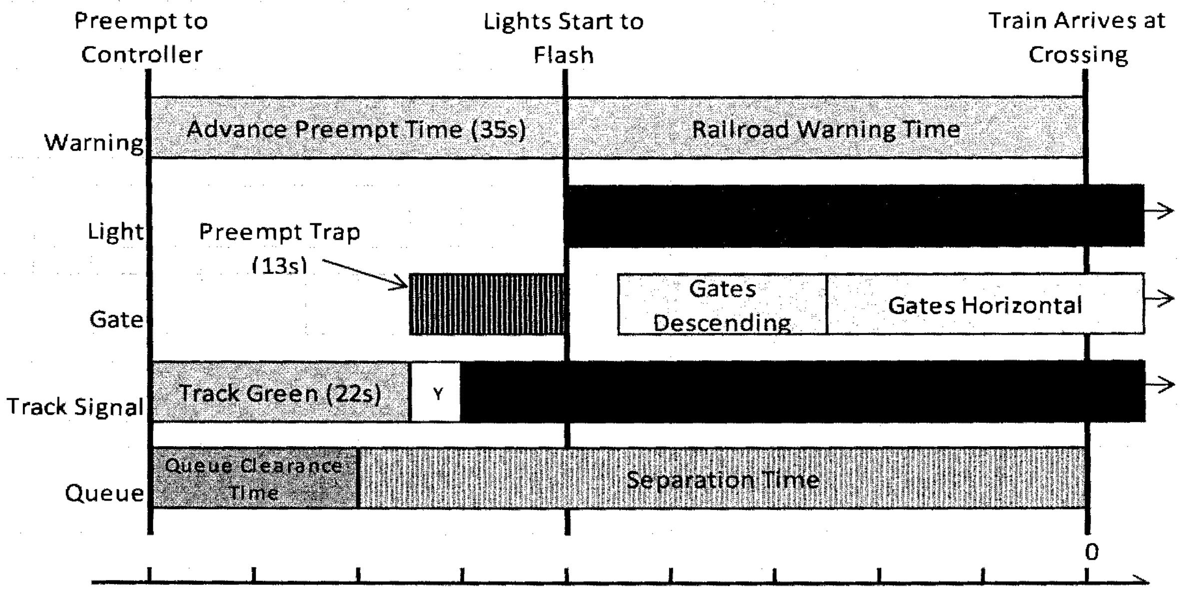


Figure 4.3. Advance preempt trap for 35-second APT.

4.7. Analysis of Model Results

Efficiency was measured in terms of delay using a 20-second data collection interval and averaged over 15 simulation runs. The 20-second data collection bin was determined to best reflect the quickly-changing nature of rail preemption events. Delay was measured using VISSIM's travel time section feature, which defines the parameter as the difference in actual travel time and ideal travel time between two points in the network.

Delay is recorded only after a vehicle has crossed the endpoint of the travel time section. Endpoints were placed after the stop bars on the lanes of interest; as such, delay incurred from a preemption event is recorded one to two intervals after the event.

Delay was tabulated and delineated into four stages: normal, track clearance, preempt dwell, and recovery. "Normal" delay was calculated during the 5 minutes immediately preceding preemption. Delay due to track clearance interval applies to preempted movements (eastbound and westbound), and appears immediately following the termination of the track clearance phase, when eastbound vehicles are allowed to proceed through the intersection.

Safety was measured as the percentage of train crossing events, out of 50 simulation runs with one event each, in which a crossing conflict occurred. Crossing conflicts were defined by a data collection point placed at the crossing exit gate. Any train event in which the data collector recorded vehicle queues on the track after full gate descent was recorded as a crossing event. Crossing events are, therefore, situations which have the potential for a train-vehicle collision. An example is shown in Figure 4.4.

4.8. Summary

This chapter summarized this study's VISSIM model development process, including model selection, data collection, network construction, calibration and validation, analysis scenarios, and analysis MOEs. The model required a significant amount of data collection to accurately reflect the complex interaction between train and traffic movements during preemption. Data collected for this study included vehicle volume, delay and stops; train event times and frequency; signal timing plans during normal operation and preemption; and network geometry. Calibration involved the modification of selected simulation parameters until simulation results matched field observations at Main Ave & 6th St for delay and stops. Validation applied the same simulation model to a different set of data at Main Ave & 4th Street. Once the accuracy of the model was established, eight analysis scenarios were designed to test the impact of several signal preemption strategies and rail equipment response times on two selected MOEs: delay and crossing accidents.

Figure 4.4. Crossing conflict in VISSIM.

CHAPTER 5. RESULTS AND DISCUSSION

This chapter summarizes and discusses the results of the eight analysis scenarios. Results are divided into three sections, each focusing on one of the three test variables – advance preemption time, track clearance interval, or dwell cycle.

5.1. Existing Conditions

The analysis period represented evening peak hour conditions with one train event. Results are shown in terms of total delay, per vehicle delay, and percentage of train events which caused crossing conflicts.

Simulated train event times are shown in Table 5.1. Each scenario used the same simulated train, which was designed based on field data described in chapter 3. Events of interest – start of preemption, end of track clearance green, and end of preempt – are shown at their corresponding times by reference lines on Figures 5.1 and 5.2.

Table 5.1. Simulation train times.

Simulation Train Times	6th Street	4th Street
Transfer of ROW	5:32:04 PM	5:32:16 PM
Begin track clearance	5:32:10 PM	5:32:20 PM
Gates begin closing	5:32:20 PM	5:32:39 PM
End track clearance	5:32:32 PM	5:32:44 PM
Train arrives at crossing	5:32:47 PM	5:33:01 PM
Train departs crossing	5:34:46 PM	5:35:00 PM
Gates open	5:35:01 PM	5:35:15 PM

At 4^{th} Street, Main Avenue eastbound delay reached 34 seconds per vehicle immediately after the track clearance interval. The signal cycle during dwell resulted in a cyclic delay pattern for the eastbound approach, reaching 24.7 seconds per vehicle during eastbound green (when stopped vehicles are allowed to complete their travel time section).

See Table 5.2. Operations on the west approach of the intersection saw no lasting negative impact from preemption, with delay returning to normal one cycle after train departure. Fourth Street's southbound approach experienced no delay during preempt because all southbound vehicles had been cleared by the combination of track clearance phase and advance preemption time. A recovery delay of 71 seconds was recorded after train departure, once vehicles that had been stuck at the crossing were allowed to complete the travel time section. Delay returned to normal levels after two signal cycles.

Eastbound delay at 6th Street reaches 22 seconds at the termination of the track clearance phase before settling at 2 seconds throughout preempt dwell. This can be credited to the signal controller's eastbound/westbound dwell hold.

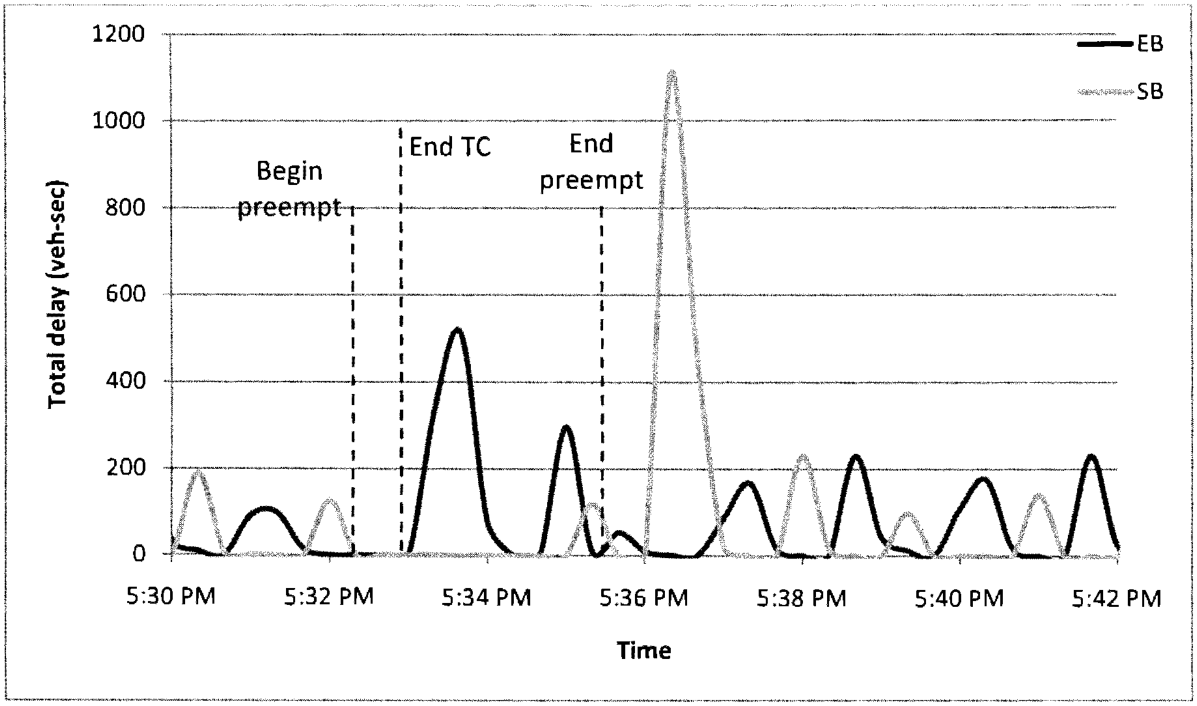


Figure 5.1. Total delay, base case, 4th St & Main Ave.

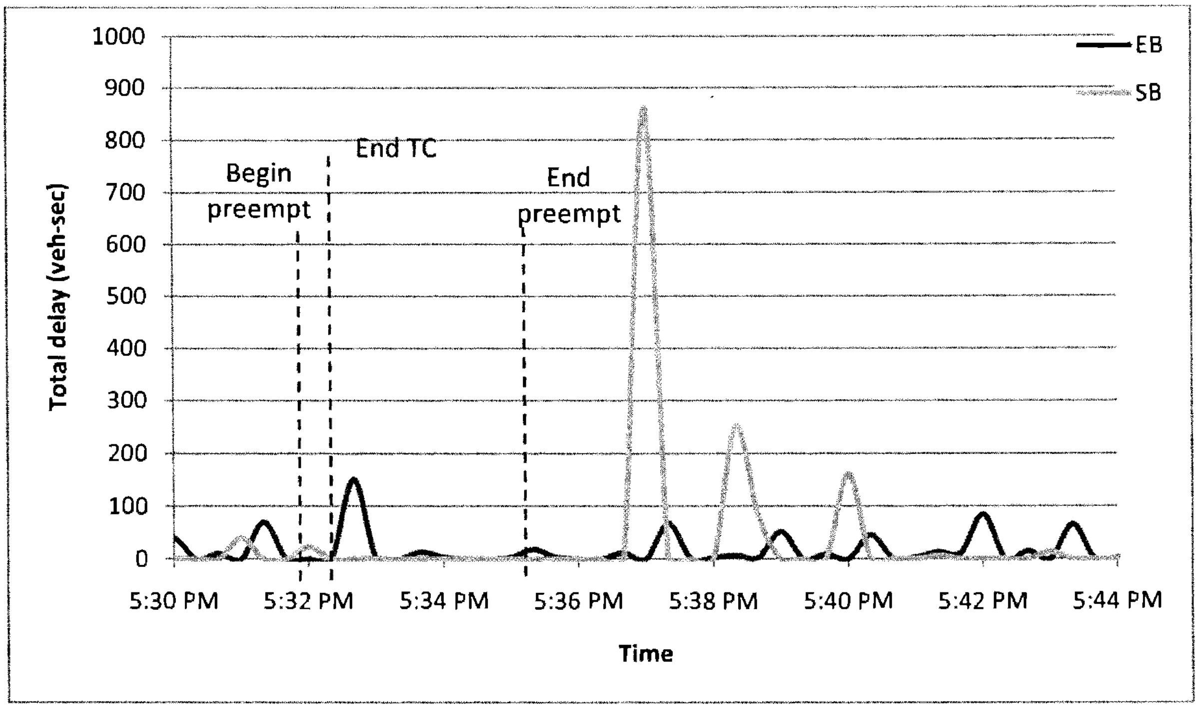


Figure 5.2. Total delay, base case, 6th St & Main Ave.

The intersection's southbound approach, similar to 4th Street, is successfully cleared by the track clearance interval and advance preemption. The first southbound vehicles served after train departure experience 162.5 seconds of delay. Recovery to normal (7.6 sec/veh) takes approximately four signal cycles.

Table 5.2. Per-vehicle delay, base case.

Delay (sec/veh)	Normal	Track Clearance	Dwell	Recovery
EB @ 4th St	13.4	34.0	24.7	11.2
SB @ 4th St	18.2	0.0	0.0	71.0
EB @ 6th St	7.6	22.0	2.0	2.1
SB @ 6th St	22.0	0.0	0.0	162.5

Simulation results indicated no safety concerns at either crossing (see Table 5.3), with no conflicts in 50 simulated train events.

Table 5.3. Crossing conflicts, base case.

Crossing Conflicts (%), base case	
4th Street	0
6th Street	0

5.2. Advance Preempt Time

Three alternative advance preempt times were tested in addition to the base case. They included the minimum and maximum APTs observed in the field, 10 and 35 seconds respectively, and a hypothetical simultaneous preempt scenario with zero advance preempt time. Variation in advance preempt time had no significant effect on eastbound delay at Main Avenue and 6th Street, as shown in Figure 5.3 and Table 5.4..

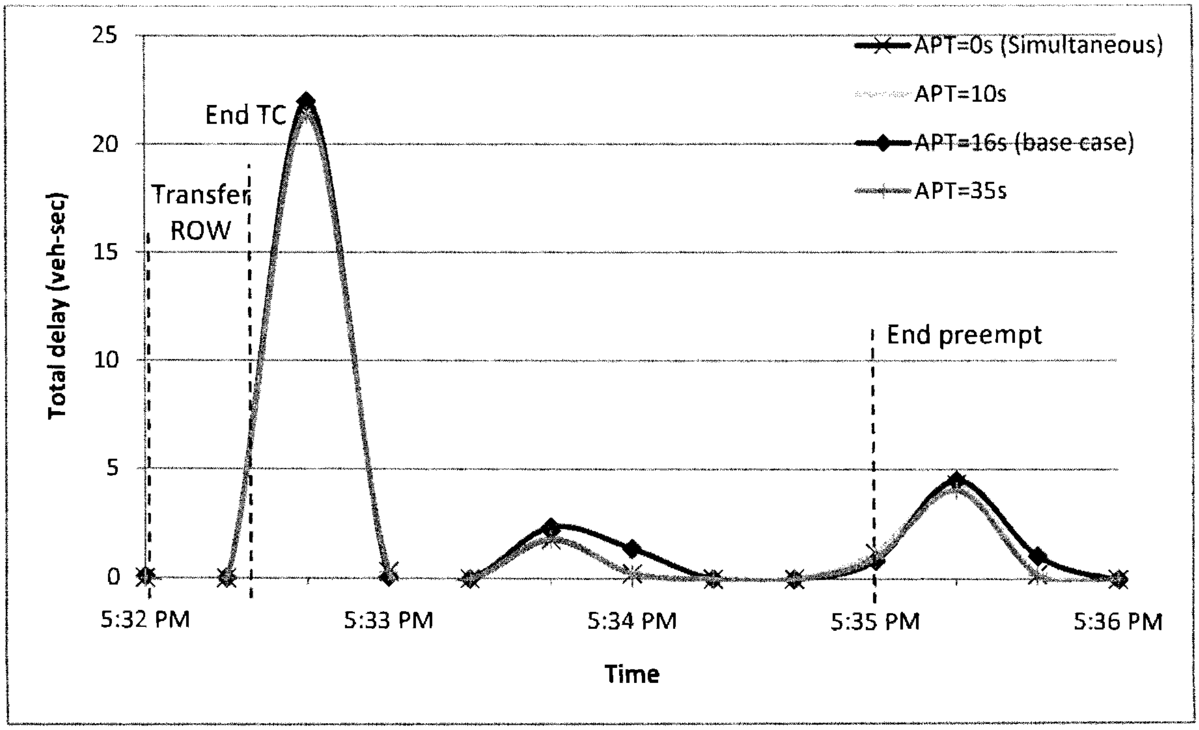


Figure 5.3. Total delay, APT, EB Main Ave at 6th St.

Southbound delay (see Figure 5.4 and Table 5.5) was similarly unaffected by variations in APT. Track clearance and dwell state delay were both zero, while recovery delay ranged from 162.5 sec/veh using a 10-second APT to 174.7 sec/veh under simultaneous preemption.

Table 5.4. Per-vehicle delay, APT, EB Main Ave at 6^{th} St.

Delay (sec/veh), EB at 6th St	Normal	Track Clearance	Dwell	Recovery
APT=0s (Simultaneous preempt)	8.1	21.3	1.4	2.0
APT=10s	8.1	21.3	1.4	1.9
APT=16s (Base case)	7.6	22.0	2.0	2.1
APT=35s	8.1	21.3	1.4	1.7

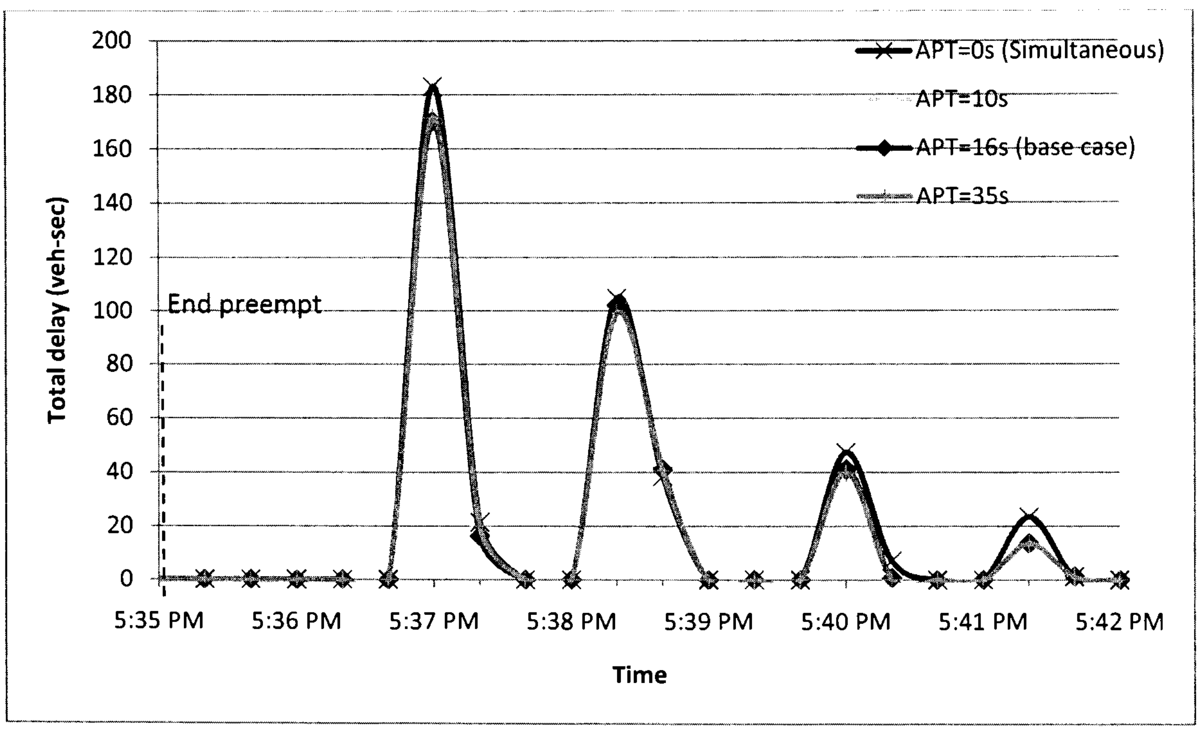


Figure 5.4. Total delay, APT, SB Main Ave at 6^{th} St.

Advance preemption time had a significant impact on crossing safety, particularly at the 6^{th} Street crossing. Simultaneous preemption resulted in trapped vehicles in 10 percent of crossing events. This accident rate was reduced to 2 percent with an advance preemption time of 10 seconds, and was eliminated entirely under base case conditions. The accident rate (see Table 5.6) increased to 58 percent with a 35-second APT.

Table 5.5. Per-vehicle delay, APT, SB Main Ave at 6th St.

Delay (sec/veh), SB @ 6th St	Normal	Track Clearance	Dwell	Recovery
APT=0s (Simultaneous preempt)	22.0	0.0	0.0	174.7
APT=10s	22.0	0.0	0.0	162.5
APT=16s (Base case)	22.0	0.0	0.0	162.5
APT=35s	22.0	0.0	0.0	164.0

Visual inspection of the crossing conflicts indicated two distinct problems occurring as a result of reduced APT and extended APT, respectively. A long APT of 35 seconds resulted in an advance preempt trap situation as discussed in chapters 2 and 4. Track clearance time terminated before crossing gates had activated, allowing vehicles to queue on the tracks with no opportunity to clear once gates began closing.

Crossing conflicts during shortened advance preempt times were the result of a separate phenomenon unique to the four-quadrant gate configuration. Shorter APT intervals of 0 and 10 seconds did not allow adequate time for the track clearance phase to clear track queues before the exit gate closed, trapping queued vehicles in the crossing.

Eastbound delay at 4th St (see Figure 5.4 and Table 5.7) was not impacted by APT variations. Track clearance, dwell, and recovery delay varied by no more than 5.4 sec/veh.

Table 5.6. 6th St crossing conflicts, APT.

Crossing Conflicts (%), 6th Street	
APT=0s (Simultaneous preempt)	10
APT=10s	2
APT=16s (Base case)	0
APT=35s	58

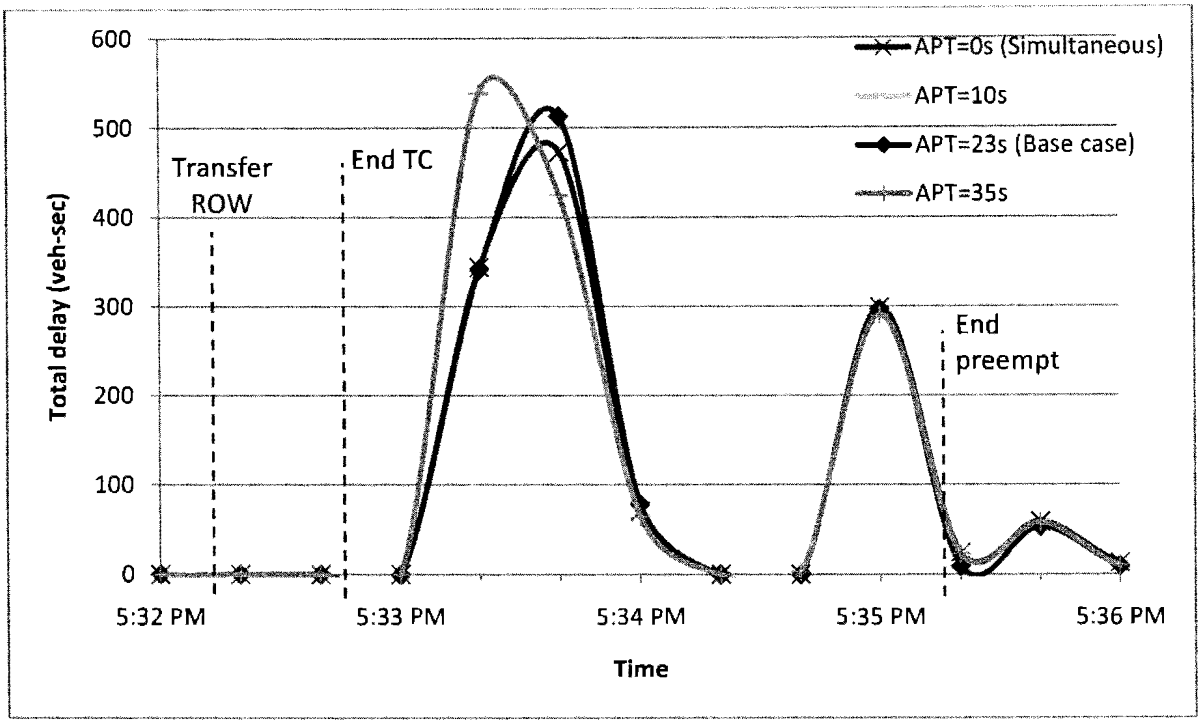


Figure 5.5. Total delay, APT, EB Main Ave at 4th St.

Table 5.7. Per-vehicle delay, APT, EB Main Ave at 4th St.

Delay (sec/veh), EB at 4th St	Normal	Track Clearance	Dwell	Recovery
APT=0s (Simultaneous preempt)	12.7	33.5	25.3	9.7
APT=10s	12.7	38.9	23.1	9.9
APT=23s (Base case)	13.4	34.0	24.7	11.2
APT=35s	12.7	38.9	22.9	9.9

Southbound movements at 4th St did experience a notable reduction in delay with increasing advance preemption time, as shown in Figure 5.6 and Table 5.8. The largest tested APT, 35 seconds, resulted in a 19.8% reduction in recovery delay from simultaneous preemption at the southbound approach, from 85.7 sec/veh to 68.7 sec/veh.

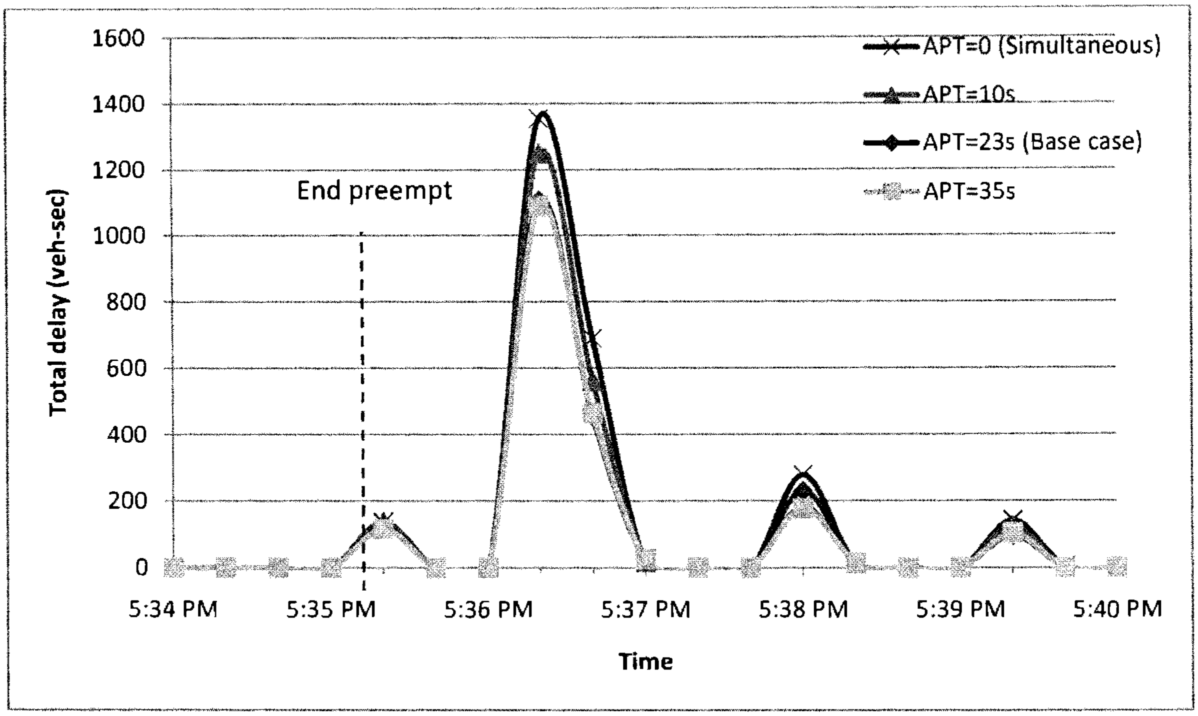


Figure 5.6. Total delay, APT, SB Main Ave at 4th St.

Table 5.8. Per-vehicle delay, APT, SB Main Ave at 4th St.

Delay (sec/veh), SB at 4th St	Normal	Track Clearance	Dwell	Recovery
APT=0s (Simultaneous preempt)	18.5	0.0	0.0	85.7
APT=10s	18.5	0.0	0.0	79.8
APT=23s (Base case)	18.2	0.0	0.0	71.0
APT=35s	18.5	0.0	0.0	68.7

The crossing at 4th Street experienced a 2 percent crossing conflict rate using a 10-second advance preemption time, but was conflict-free in every other scenario. See Table 5.9.

Table 5.9. 4th St crossing conflicts, APT.

Crossing Conflicts (%), 4th Street	
APT=0s (Simultaneous preempt)	0
APT=10s	2
APT=23s (Base case)	0
APT=35s	0

5.3. Track Clearance Interval

Two alternative track clearance intervals were evaluated against the base case. The minimum 18-second clearance was the minimum calculated using the Engelbrecht method to clear only the track dynamic envelope and not the entire clear storage distance, as specified by the methodology. The more conservative 30 second track clearance interval calculated using the Greenshields method was also tested.

Eastbound delay (see Figure 5.7 and Table 5.10) was impacted by changes in track clearance, with a 6 sec/veh increase at 6^{th} Street between the minimum and base case track clearance interval. Similarly, the 30-second clearance interval of the Greenshields method resulted in a 9.8 sec/veh increase in track clearance delay over the base case.

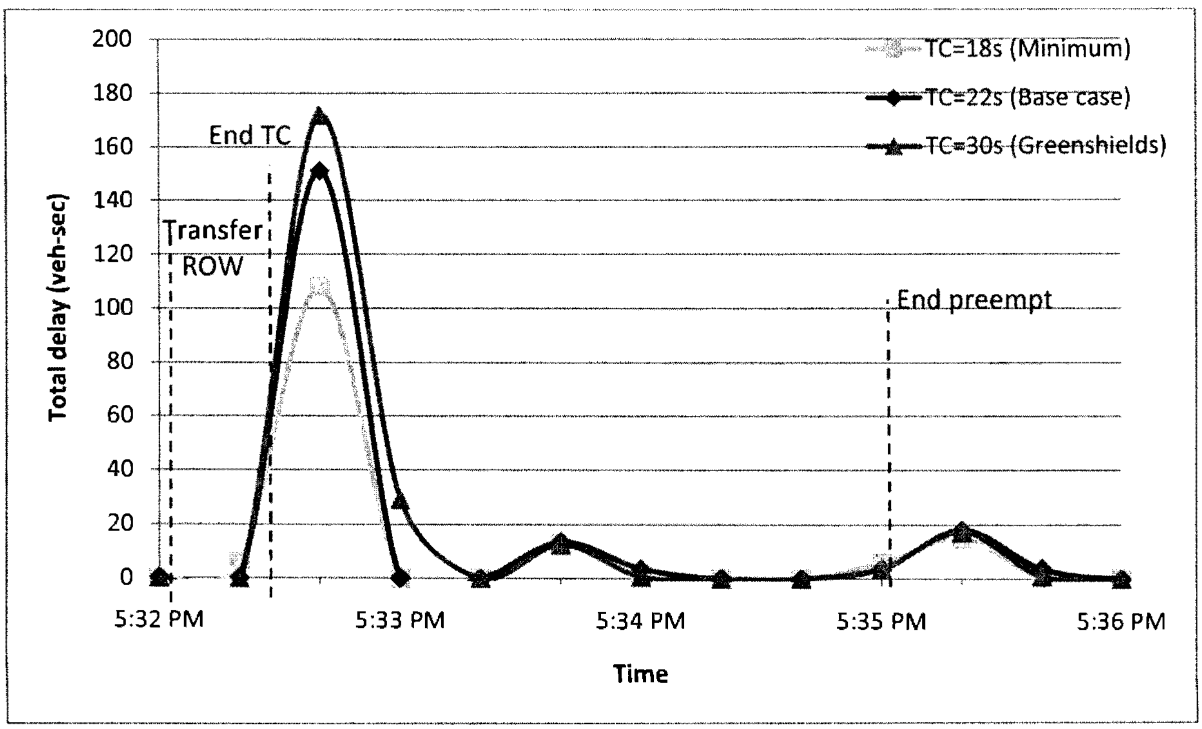


Figure 5.7. Total delay, TC interval, EB Main Ave at 6^{th} St.

Table 5.10. Per-vehicle delay, TC interval, EB Main Ave at 6th St.

Delay (sec/veh), EB at 6th St	Normal	Track Clearance	Dwell	Recovery
TC=18s (Minimum)	8.1	16.0	1.5	1.9
TC=22s (Base case/Engelbrecht)	7.6	22.0	2.0	2.1
TC=30s (Greenshields)	8.1	31.8	1.5	2.0

Southbound delay at 6th Street (see Figure 5.8 and Table 5.11) was unaffected by variations in clearance time, indicating complete clearance of the clear storage distance using even the minimum track clearance time.

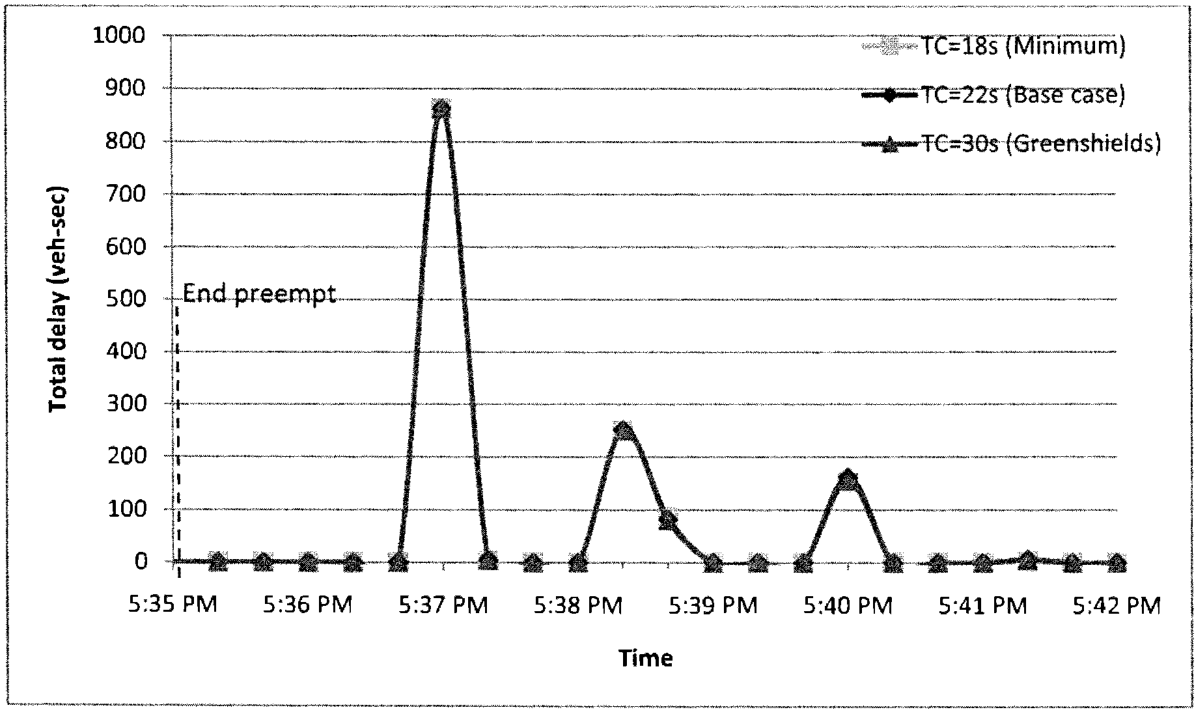


Figure 5.8. Total delay, TC interval, SB Main Ave at 6th St.

Table 5.11. Per-vehicle delay, TC interval, SB Main Ave at 6th St.

Delay (sec/veh), SB at 6th St	Normal	Track Clearance	Dwell	Recovery
TC=18s (Minimum)	22.0	0.0	0.0	162.5
TC=22s (Base case/Engelbrecht)	22.0	0.0	0.0	162.5
TC=30s (Greenshields)	22.0	0.0	0.0	162.5

Safety implications are shown in Table 5.12. A shortened track clearance interval of 18 seconds had no measured negative impact on safety at 6th Street. None of the scenarios caused crossing conflicts.

Table 5.12. 6th St crossing conflicts, TC interval.

Crossing Conflicts (%), 6th Street	
TC=18s (Minimum)	0
TC=22s (Base case/Engelbrecht)	0
TC=30s (Greenshields)	0

Fourth Street eastbound track clearance delay was only slightly affected by changes in track clearance time, ranging from 33.7 seconds using the minimum clearance time to 34.8 seconds under the Greenshields method. See Figure 5.9 and Table 5.13. Delay during the dwell cycle was also slightly impacted, increasing from 18.8 to 26.2 sec/veh.

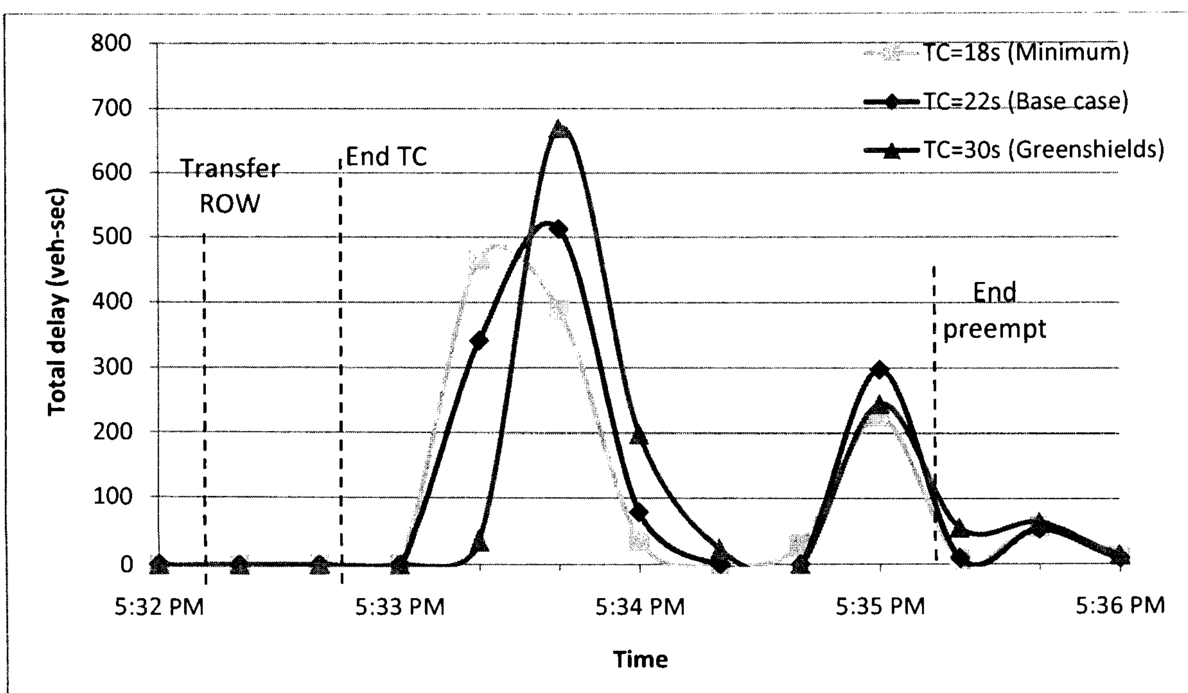


Figure 5.9. Total delay, TC interval, EB Main Ave at 4th St.

Table 5.13. Per-vehicle delay, TC interval, EB Main Ave at 4th St.

Delay (sec/veh), EB at 4th St	Normal	Track Clearance	Dwell	Recovery
TC=18s (Minimum)	12.7	33.7	18.8	10.0
TC=22s (Base case/Engelbrecht)	13.4	34.0	24.7	11.2
TC=30s (Greenshields)	12.7	34.8	26.2	10.3

Southbound delay at 4th Street (see Figure 5.10 and Table 5.14), similar to 6th Street, was unaffected by variations in clearance time, indicating complete clearance of the clear storage distance using even the minimum track clearance time.

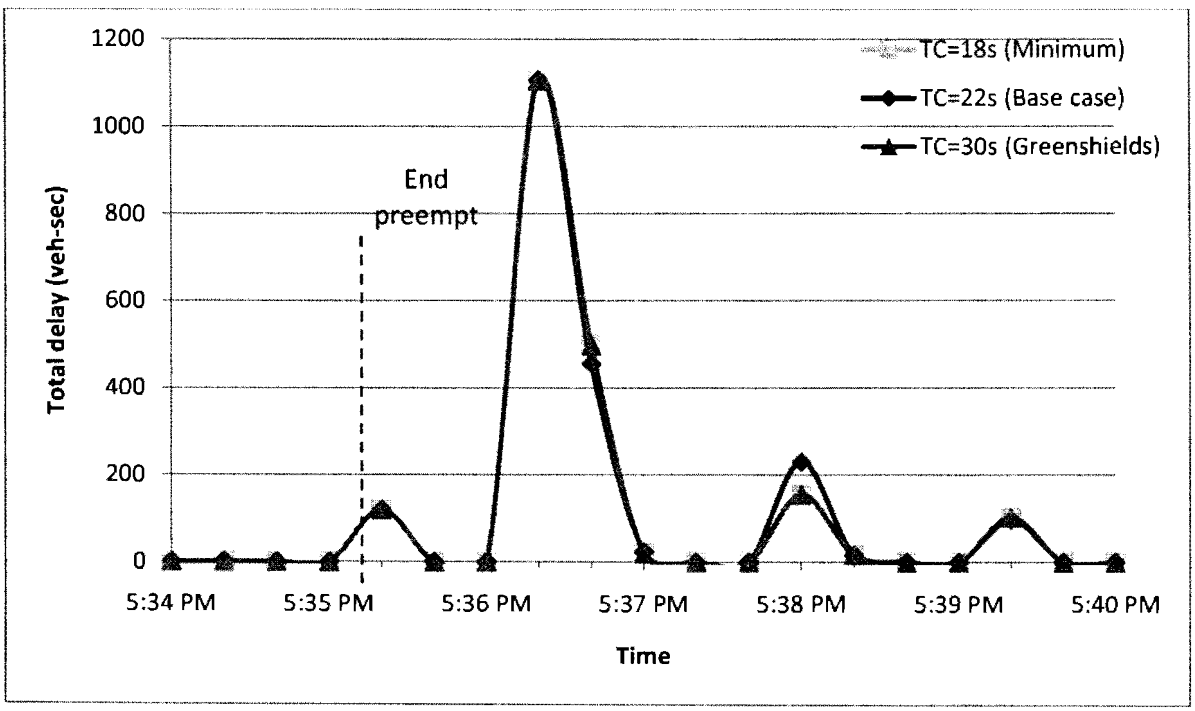


Figure 5.10. Total delay, TC interval, SB Main Ave at 4th St.

Table 5.14. Per-vehicle delay, TC interval, SB Main Ave at 4th St.

Delay (sec/veh), SB at 4th St	Normal	Track Clearance	Dwell	Recovery
TC=18s (Minimum)	18.5	0.0	0.0	70.6
TC=22s (Base case/Engelbrecht)	18.2	0.0	0.0	71.0
TC=30s (Greenshields)	18.5	0.0	0.0	70.6

A shortened 18-second track clearance interval had no measured negative impact on safety at 4th Street. None of the scenarios caused crossing conflicts. See Table 5.15.

Table 5.15. 4th St crossing conflicts, TC interval.

Crossing Conflicts (%), 4th Street	
TC=18s (Minimum)	0
TC=22s (Base case/Engelbrecht)	0
TC=30s (Greenshields)	0

5.4. Dwell Cycle

Base case control included dwell cycle at 4th Street and dwell hold at 6th Street. Dwell cycle scenarios applied each strategy to both intersections. Therefore, while control strategy at 4th Street did not change from the base case to the dwell cycle scenario, results were expected to be different due to the dwell cycle at 6th Street.

Preempt dwell cycle is designed to serve movements that would otherwise be neglected for the duration of a preempt event (i.e. northbound left-turn and southbound through and left turns in this case study). By "borrowing" green time from track-parallel approaches during the dwell stage, preempt dwell cycling is designed to strike a balance between alleviating delay on track-conflicting approaches (i.e. north and south) and imparting undue delay to the opposite (east and west) approaches.

Northbound left-turn delay was not measured due to low volumes observed at both intersections during the study hour.

As expected, eastbound efficiency at both intersections was impacted by the allocation of green time to other approaches during dwell (see Figure 5.11 and Table 5.16). Main Ave and 6th Street experienced 5.5 sec/veh peak during dwell cycle, compared to a 1.6 sec/veh peak during dwell hold. Recovery delay was unaffected.

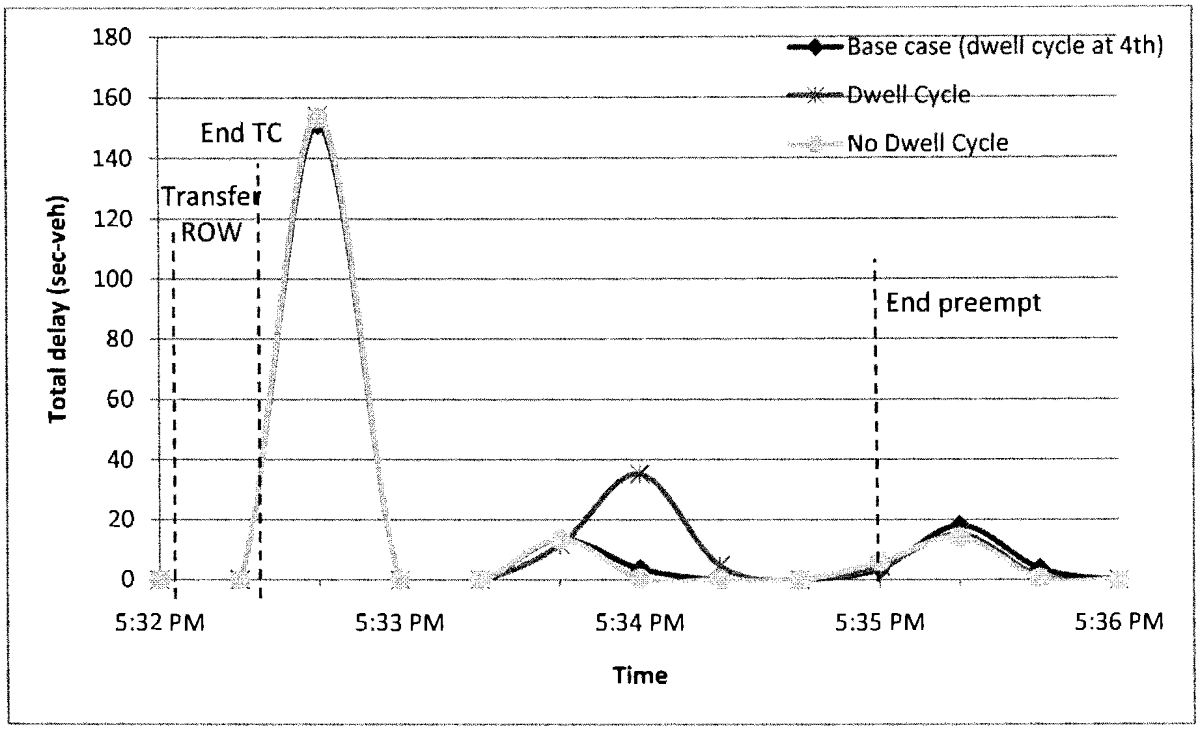


Figure 5.11. Total delay, dwell cycle, EB Main Ave at 6th St.

Table 5.16. Per-vehicle delay, dwell cycle, EB Main Ave at 6th St.

Delay (sec/veh), EB at 6th St	Normal	Track Clearance	Dwell	Recovery
Base case (dwell cycle at 4th St)	7.6	22.0	2.0	2.1
Dwell cycle (both intersections)	8.1	21.3	5.5	1.8
Dwell hold (both intersections)	8.1	21.3	1.6	1.8

Southbound movements at 6th Street experienced no delay benefit from dwell cycle, suggesting the clear storage area (between crossing exit gate and stop bar) was adequately cleared prior to the dwell stage and no vehicles were served by dwell cycle. See Figure 5.12 and Table 5.17. Delay was consistently zero during dwell. Crossing safety at 6th Street (see Table 5.18) was not impacted by the implementation of dwell cycle.

Fourth Street's eastbound approach (shown in Figure 5.13 and Table 5.19) was significantly impacted, with 34.0 sec/veh delay in the interval immediately following track clearance in the base case (using dwell cycle at 4th St only), 26.4 sec/veh using dwell cycle at both intersections (the increase due to platoon arrival from 6th Street), and 3.9 seconds using dwell hold at both intersections. Implementing a dwell hold eliminated the delay peak during dwell, reducing delay from 24.7 sec/veh in the base case to 0.2 sec/veh. Recovery delay was slightly affected.

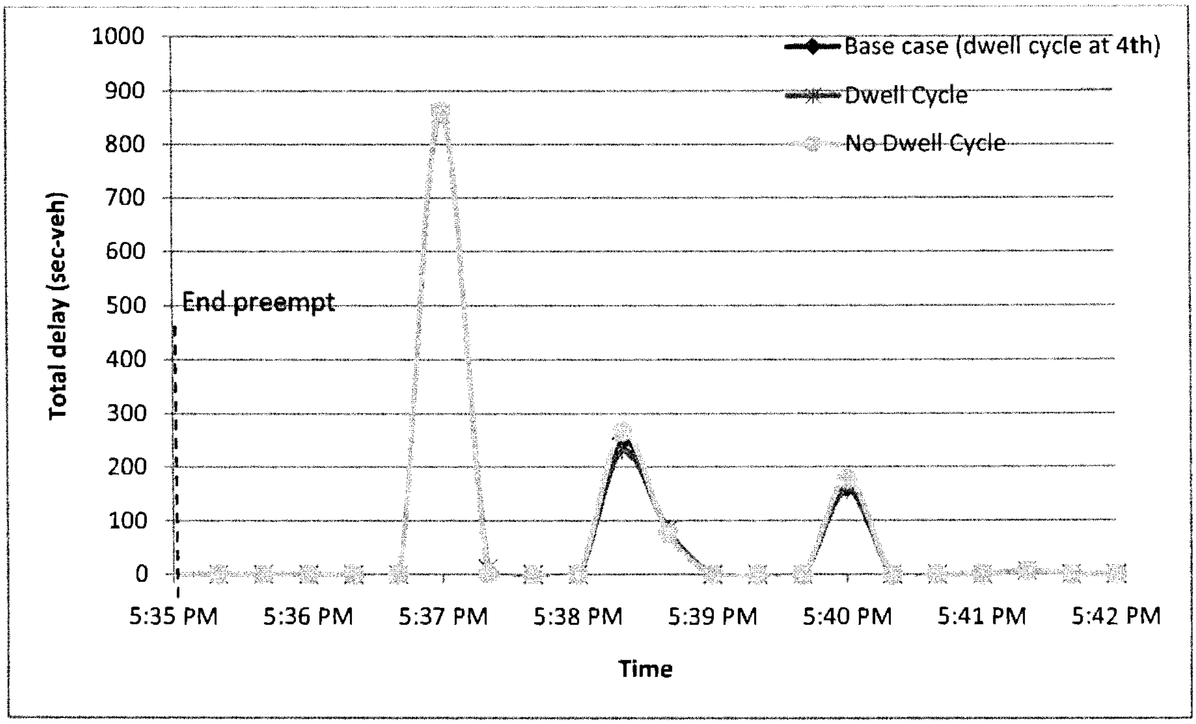


Figure 5.12. Total delay, dwell cycle, SB Main Ave at 6th St.

Table 5.17. Per-vehicle delay, dwell cycle, SB Main Ave at 6th St.

Delay (sec/veh), SB at 6th St	Normal	Track Clearance	Dwell	Recovery
Base case (dwell cycle at 4th St)	22.0	0.0	0.0	162.5
Dwell cycle (both intersections)	22.0	0.0	0.0	158.9
Dwell hold (both intersections)	22.0	0.0	0.0	166.1

Southbound movements at 4th Street experienced no benefit from dwell cycle, suggesting the clear storage area (between crossing exit gate and stop bar) was adequately cleared prior to the dwell stage and no vehicles were served by dwell cycle. See Figure 5.14 and Table 5.20. Delay was consistently zero during dwell. Table 5.21 shows no crossing conflicts resulting from variations in dwell strategy at 4th St.

Table 5.18. 6th St crossing conflicts, dwell cycle.

Crossing Conflicts (%), 6th Street	
Base case (dwell cycle at 4th St)	0
Dwell cycle (both intersections)	0
Dwell hold (both intersections)	0

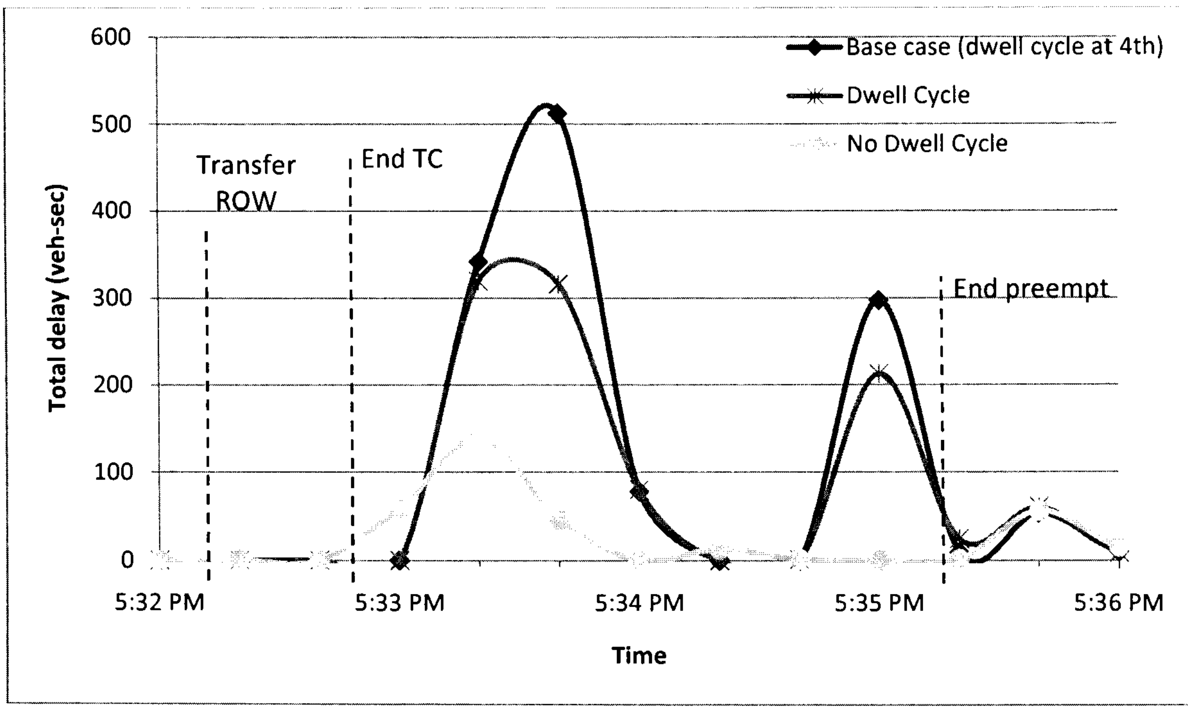


Figure 5.13. Total delay, dwell cycle, EB Main Ave at 4th St.

Table 5.19. Per-vehicle delay, dwell cycle, EB Main Ave at 4th St.

Delay (sec/veh), EB at 4th St	Normal	Track Clearance	Dwell	Recovery
Base case (dwell cycle at 4th St)	13.4	34.0	24.7	11.2
Dwell cycle (both intersections)	12.7	26.4	17.6	10.4
Dwell hold (both intersections)	12.7	3.9	0.2	9.9

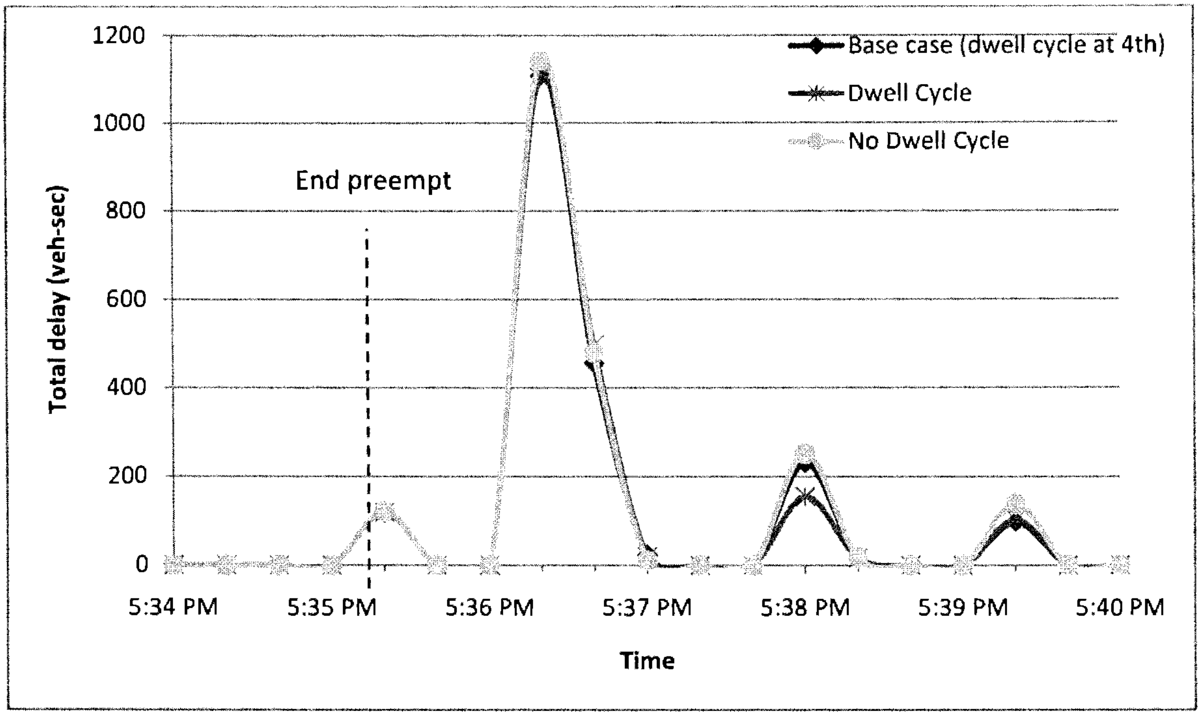


Figure 5.14. Total delay, dwell cycle, SB Main Ave at 4th St.

Table 5.20. Per-vehicle delay, dwell cycle, SB Main Ave at 4th St.

Delay (sec/veh), SB at 4th St	Normal	Track Clearance	Dwell	Recovery
Base case (dwell cycle at 4th St)	18.2	0.0	0.0	71.0
Dwell cycle (both intersections)	18.5	0.0	0.0	70.6
Dwell hold (both intersections)	18.5	0.0	0.0	73.5

Table 5.21. 4th St crossing conflicts, dwell cycle.

Crossing Conflicts (%), 4th Street	
Base case (dwell cycle at 4th St)	0
Dwell cycle (both intersections)	0
Dwell hold (both intersections)	0

5.5. Summary

This chapter presented model results with respect to efficiency and safety at both study intersections. Advance preemption time was the only test variable which had a measurable negative impact on safety at either intersection. An excessively long APT of 35 seconds caused the advance preempt trap discussed in chapter 2, with a 58 percent accident rate. Truncated APTs of 0 and 10 seconds caused 10 and 2 percent accident rates, respectively, as a result of a different phenomenon, known in this study as the four-quadrant gate trap. Shortened APT forced queued vehicles to become trapped between the descending crossing gates before the signal controller's track clearance phase had cleared the queue. This problem is unique to the four-quadrant gate configuration present at both study crossings. Larger advance preemption times led to a slight reduction in southbound delay due to vehicles which would otherwise be stopped at the crossing gates being allowed to continue through the intersection during the track clearance interval.

Crossing safety in this study was not impacted by the shortening of the track clearance interval. The minimum time required to clear the track dynamic envelope using the Engelbrecht method resulted in zero crossing conflicts. Delay increased slightly with track clearance time on both eastbound approaches, with a 9.8 sec/veh delay difference between 30-second and 18-second track clearance intervals at 6th Street, and a more modest 1.1 sec/veh increase on eastbound Main Avenue at 4th Street.

Dwell cycle had a negative impact on delay to track-parallel movements at both intersections, causing delay peaks of 5.5 sec/veh and 24.7 sec/veh (base case) at 4th Street. Delay at 4th Street was improved when Main Ave and 6th Street also utilized a dwell cycle. Southbound delay saw no significant improvement due to dwell cycle, and northbound left turn volumes were too low to have a significant impact on intersection operations. Safety was not affected by dwell cycle.

CHAPTER 6. CONCLUSIONS & RECOMMENDATIONS

This chapter describes the conclusions to be drawn for each test variable, lessons learned from data collection and model development, and general conclusions for railroad preemption in a small urban area context. It also presents suggestions for further research and recommendations for implementation of this study's findings.

6.1. Conclusions

6.1.1. Advance Preempt Time

Variations in advance preempt time pose a potentially severe crossing safety hazard. The results illustrated the potential danger of the advance preempt trap, with an advance preemption time of 35 seconds producing 58 conflicts for every 100 crossings at one of the study crossings.

Shortened advance preemption times or the use of simultaneous preemption at crossings with four-quadrant gate configurations can cause a separate safety hazard – an exit gate trap. This situation occurred when a crossing's exit gates closed before the backward recovery shockwave from the track clearance phase had reached the crossing, trapping queued vehicles between gate arms. The exit gate trap caused a small number of crossing conflicts compared to the advance preempt trap, but the potential severity of any train-vehicle collisions requires great care be taken to avoid any incidents.

The small differences in delay imparted by varying APT is rendered moot by the important safety issues presented in the advance preempt trap and four-quadrant gate trap. An understanding of the two separate gate trap phenomenon is critical to signal preemption design. Although some variability in advance preemption time is an inevitable product of current track detection technology, the signal control practitioner can mitigate the potential safety issues by implementing longer preempt times to avoid the advance preempt trap and requesting advance preemption from the railroad if a four-quadrant gate configuration exists. Recommendations for implementation will be discussed further in section 6.2.

6.1.2. Dwell Cycle

Implementation of a signal cycle during the dwell stage of preemption is designed to alleviate delay to movements that do not directly oppose the rail crossing, but which would not otherwise be served during preempt dwell. In this study, these include northbound left and southbound movements. This strategy can have a positive effect on intersection operations if high demand exists on unserved movements, particularly if queues would extend back into adjacent intersections during long train events. In this case study, however, peak hour volumes on the northbound and southbound approaches were not high enough to justify the use of a preempt dwell cycle. By reallocating green time from the major east and west approaches, the strategy led to significant delays during preempt dwell. The use of a standard eastbound/westbound dwell hold during preempt eliminated delay peaks and allowed through movements on Main Avenue to continue unimpeded through the network during preemption. Dwell cycle would be recommended only if northbound left turn demand is high or if high-demand driveways existed between the southbound stop bar and the grade crossing.

6.1.3. Track Clearance Interval

Numerous methods have been suggested for the determination of track clearance interval. Each method is based on different assumptions for vehicle performance, driver attentiveness, queuing behavior, and design vehicle characteristics, and lead to different track clearance intervals for the same setting.

Ease of applicability, though not a primary concern, should not be neglected when comparing track clearance determination methods. The Engelbrecht and Greenshields methods benefitted by requiring relatively little data and following a simple procedure. The data requirements of the Marshall and Berg method make it difficult to apply without some time and resource investment.

This study found that the Engelbrecht method achieved crossing safety with the least negative impact on intersection operations. The 22 seconds required at both study intersections to clear the entire clear storage distance (CSD) was adequate in preventing crossing conflicts. A shortened track clearance interval of 18 seconds, designed using the Engelbrecht method to clear only the track dynamic envelope, also provided adequate safety at the study crossings while causing a slight improvement in eastbound delay. The more conservative 30-second clearance interval derived using the Greenshields method resulted in longer delay on both eastbound approaches.

It can be concluded that the shortest track clearance time which adequately clears the crossing should be implemented. Overly conservative clearance intervals lead to wasted green time, causing unnecessary delay and the potential for driver frustration on opposing movements. This study recommends the use of the Engelbrecht method for its ability to clear the crossing approach without unduly impacting intersection operations.

6.1.4. Data Collection

The simulation of an urban arterial with train preemption events requires a great deal of data. Care must be taken to collect accurate measurements of crossing events (activation of warning equipment, start of gate closure, train arrival, train departure, and gate opening), preemption events (track clearance interval, dwell phase strategy, recovery phases), and highway vehicle data (volume and delay). Each of these observations must be observed simultaneously, requiring significant manpower. Synchronization of watches between data collection personnel is critical, as rail preemption involves a very complex and time-sensitive interaction between systems. Collection of calibration and validation data requires the utmost precision, as small errors in data collection can lead to a great deal of difficulty in model calibration and validation.

The one-hour analysis period used for this study required several two-hour data collection efforts in order to capture the necessary scenario. Data collection should include one contiguous hour with at least 15 minutes of normal peak hour operation before preemption, preemption by a unit-length train, and at least 15 minutes of recovery operation after the end of preemption. Depending on train volumes, this can take several collection efforts. Five-minute data collection intervals were used to reflect the brief and changing nature of preemption, allowing a clearer picture of preemption operations than could be obtained using a 15-minute interval.

This study's calibration and validation methods of evaluation, stops and delay, were selected for their respective relevance to crossing safety and intersection efficiency. These MOEs were easily observable in the field and provided valuable insight into model performance. Reasonable results were achieved at 6th Street after two iterations of model parameter adjustment. The same model was applied at 4th Street using different vehicle and train volumes, and was found to hold true. This illustrated the value of proper model calibration and the need for thorough and accurate data collection.

6.1.5. Model Development

The simulation software VISSIM was selected for its ability to reflect the stochasticity of driver behavior and to model complex signal control and track warning equipment operation. Simulation allows the evaluation of various signal control strategies without changing real-world conditions, and is particularly well-suited for this study's network of signalized intersections in a small urban context, where interactions between intersections can have an effect on network performance.

VISSIM's RBC signal control emulator was well-suited for modeling the complexities of signal preemption, with support for user-defined track clearance interval, multiple preemption inputs, dwell phase strategies, and recovery strategies. The RBC's advanced capabilities allow a level of accuracy in simulation signal control which would have until recently required the use of hardware-in-loop simulation. Analysis scenarios were designed to isolate variables of interest – advance preemption time, track clearance interval, and dwell phase – without changing other model parameters. The selection of testing variables was based on those factors which are most relevant to preemption safety and efficiency

Model calibration was based on adjustments to the driver behavior parameters additive and multiplicative parts of safety distance and average standstill distance because these had been shown (Ahmed 2005) to have the most significant impact on link capacity in VISSIM. The calibration process should involve a limited number of variables, and each iteration should be limited to the adjustment of a single variable in order to isolate and understand its effect. Careful model calibration is particularly important for the simulation of rail preemption, where vehicle following and queuing behavior can have a dramatic impact on crossing safety.

6.2. Recommendations

6.2.1. Further Research

Simulation was an effective tool for the evaluation of complex signal preemption operations. Future research could investigate the feasibility of simulating variations in advance preemption time and warning time using accelerating and decelerating trains. It would also be useful to simulate and evaluate the effectiveness of an actuated track clearance phase with gate-down confirmation to prevent the advance preempt trap. A simulation model could also be used to investigate the potential for loop detectors to improve crossing safety by actuating the descent of exit gates. These experiments may require advances in signal control emulation.

6.2.2. Implementation

The four-quadrant gate trap can pose a serious problem during short advance preemption times and is not adequately addressed in current practice. NCHRP Synthesis 271 (Korve 1999) recommends loop detectors at the tracks to delay exit gate closure. This would solve the problem, but there is no evidence of its current use. An alternative solution would be to impose a longer delay between the descent of entry and exit gates. Without actuation, though, this method could allow drivers to navigate around the entry gates before exit gate descent, defeating the purpose of the four-quadrant gate configuration. This study recommends the implementation of loop detectors to prevent the four-quadrant gate trap.

The advance preempt trap presents another safety hazard which is not addressed in current practice. This study illustrated the potential for serious safety issues at the case study location using a 12-second preempt trap. A dynamic or actuated track clearance interval with a gate-down confirmation would guarantee sufficient track clearance without wasting green time when not needed. This would require changes to signal controller specifications, which do not currently support actuation of the track clearance phase. Both types of preempt trap could be addressed with loop detectors at the tracks to delay exit gate descent, and a dynamic track clearance interval with gate-down confirmation.

The determination of track clearance interval has been well documented, but there is currently no widespread acceptance of a single method to calculate this critical component of preemption. This study found that, in the case study location and barring advance preempt complications, the Engelbrecht method provides sufficient clearance time to ensure crossing safety without wasting green time and imparting unnecessary delay to other movements. This method is currently in use by at least two state departments of transportation (Engelbrecht 2005; Mn/DOT 2006) and this study recommends its widespread application. Other methods are either too conservative or too difficult to apply.

Due to the delay caused to track-parallel movements by cycling signal phases during preempt dwell, this study recommends the use of a dwell cycle only when high demand is expected on track-opposing movements.

Rail crossing accidents have declined over the past several years, but there remains room for improvements in safety guidelines and practice. Crossing safety is of the utmost importance at rail crossings, but previous research had not addressed the need to balance this concern with intersection operations, particularly in urban areas. Current preemption guidelines provide little or no specific recommendations on the determination of track clearance green or dwell phasing strategy; nor do they address the safety hazards posed by advance preemption and four-quadrant crossing gate systems. While no specific preemption strategy can be applied to every situation, the findings of this and other research studies can guide practitioners in the implementation of safe and effective railroad preemption.

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APPENDIX A. LONG CLEARANCE TIME PROCEDURE

(1) Determine whether the signalized intersection is within 200 ft of the railroad crossing, as specified in the 2001 MUTCD §8D.07, or whether expected maximum queues are likely to extend back as far as the track such that traffic signal preemption for queue clearance is needed.

(2) Identify the appropriate design vehicle in compliance with MUTCD §8A.01(4).

(3) Obtain the design length and acceleration category of the design vehicle by consulting Table 1.

(4) Determine the minimum track clearance distance in compliance with MUTCD §8A.01(8).

(5) Determine the clear storage distance in compliance with MUTCD §8A.01(3).

(6) Add the minimum track clearance distance and the clear storage distance to get the critical queue length.

(7) Enter Figure 2 with the critical queue length and get the expected progressive startup delay.

(8) Add any needed special adjustments for non-ideal factors such as conflicting left-turn stragglers that deter the startup of lead vehicles, intersection turning-vehicles inhibited by sharp corner radii or obtuse turning angles or pedestrians, drivers distracted by surrounding activities, inattentive drivers, interferences by vehicles either turning in or out of adjacent driveways, or other factors.

(9) Add the design vehicle length and the minimum track clearance distance to get the repositioning distance.

(10) Enter Figure 3 with the repositioning distance, the design vehicle type and acceleration category (and grade if the design vehicle is a combination truck) and get the expected maximum repositioning time.

(11) Add the expected maximum startup delay and expected maximum repositioning time to get the expected safe track-clearance time.

(12) Add the train-detection equipment-delay time, pedestrian minimum truncation time, yellow change interval time, train separation time and other necessary time adjustments to the expected safe track-clearance time to get the expected safe minimum-preemption time (beyond the scope of this paper.)

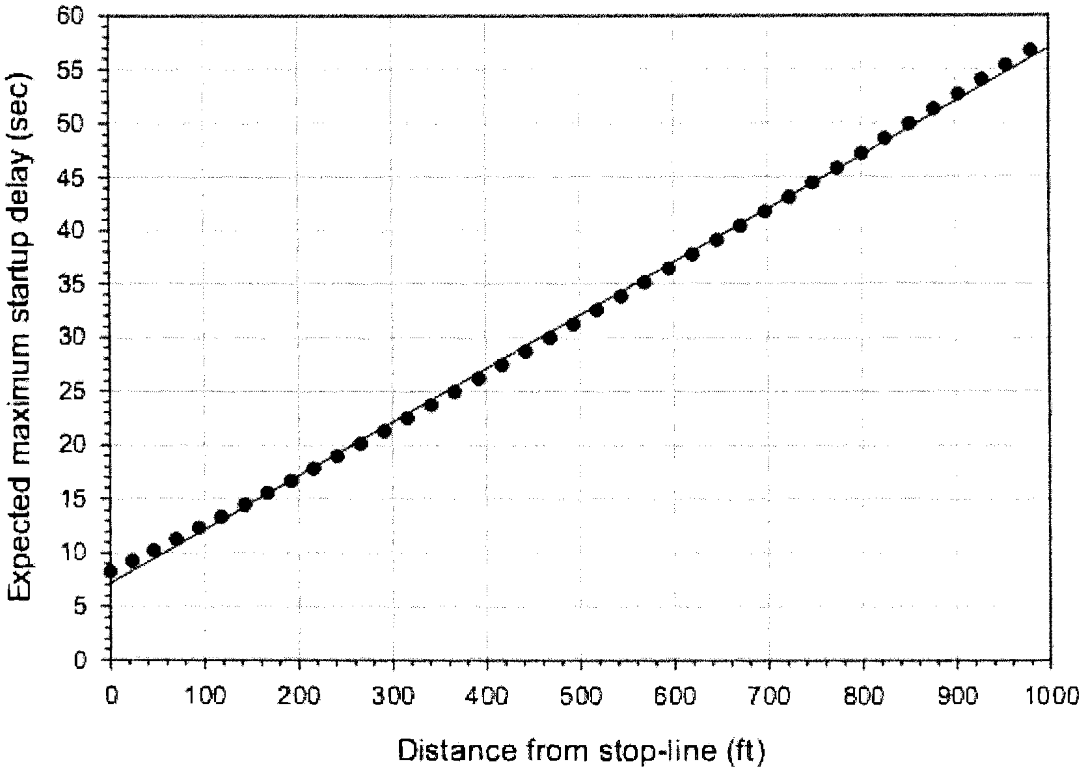


FIGURE 2 Expected maximum startup delay by distance from front of queue.

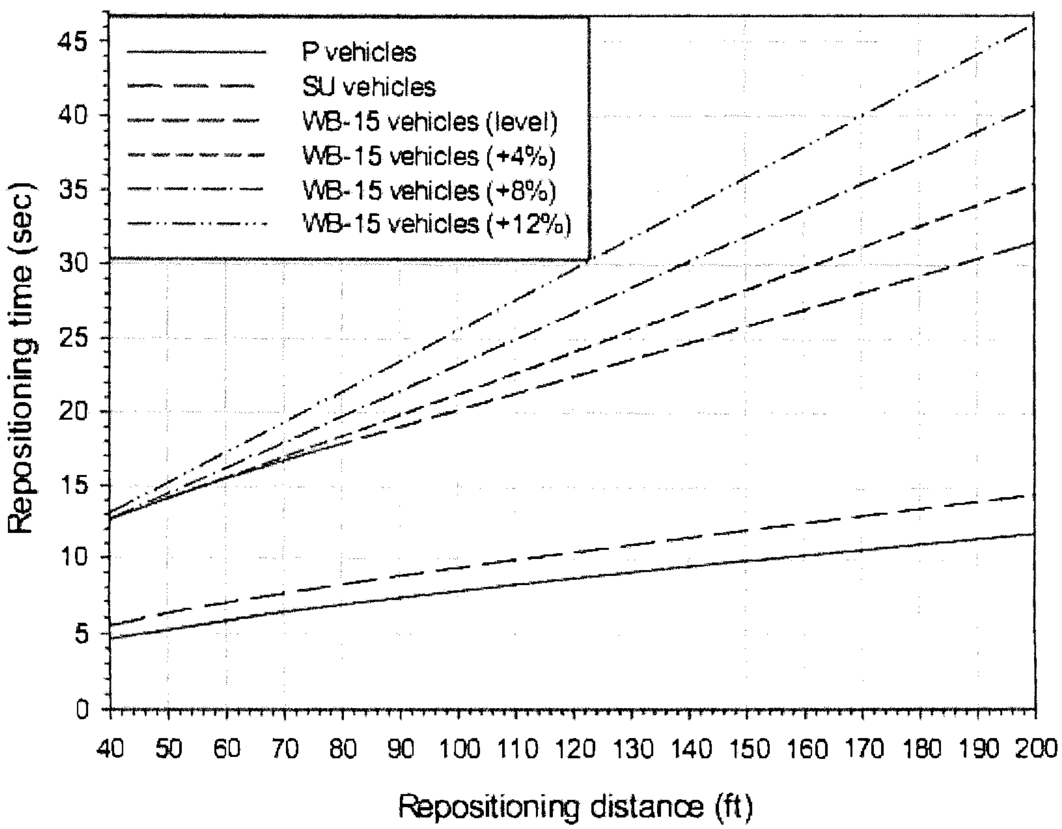


FIGURE 3 Repositioning time by vehicle type.

APPENDIX B. ENGELBRECHT CLEARANCE TIME PROCEDURE

Texas Department of Transportation

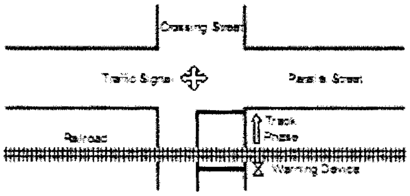
GUIDE FOR DETERMINING TIME REQUIREMENTS FOR TRAFFIC SIGNAL PREEMPTION AT HIGHWAY-RAIL GRADE CROSSINGS

City ____________________ Date ____________________

County ____________________ Completed by ____________________

District ____________________ District Approval ____________________

Show North Arrow



Parallel Street Name ____________________

Crossing Street Name ____________________

Railroad ____________________ Railroad Contact ____________________

Crossing DOT# ____________________ Phone ____________________

SECTION 1: RIGHT-OF-WAY TRANSFER TIME CALCULATION

Preempt verification and response time — **Remarks**

1. Preempt delay time (seconds) .... 1. [ ]
2. Controller response time to preempt (seconds) .... 2. [ ] — Controller type: ________
3. Preempt verification and response time (seconds): add lines 1 and 2 .... 3. [0.0]

Worst-case conflicting vehicle time — **Remarks**

4. Worst-case conflicting vehicle phase number .... 4. [ ]
5. Minimum green time during right-of-way transfer (seconds) .... 5. [ ]
6. Other green time during right-of-way transfer (seconds) .... 6. [ ]
7. Yellow change time (seconds) .... 7. [ ]
8. Red clearance time (seconds) .... 8. [ ]
9. Worst-case conflicting vehicle time (seconds): add lines 5 through 8 .... 9. [0.0]

Worst-case conflicting pedestrian time — **Remarks**

10. Worst-case conflicting pedestrian phase number .... 10. [ ]
11. Minimum walk time during right-of-way transfer (seconds) .... 11. [ ]
12. Pedestrian clearance time during right-of-way transfer (seconds) .... 12. [ ]
13. Vehicle yellow change time, if not included on line 12 (seconds) .... 13. [ ]
14. Vehicle red clearance time, if not included on line 12 (seconds) .... 14. [ ]
15. Worst-case conflicting pedestrian time (seconds): add lines 11 through 14 .... 15. [0.0]

Worst-case conflicting vehicle or pedestrian time

16. Worst-case conflicting vehicle or pedestrian time (seconds): maximum of lines 9 and 15 .... 16. [0.0]

17. **Right-of-way transfer time (seconds): add lines 3 and 16** .... 17. [0.0]

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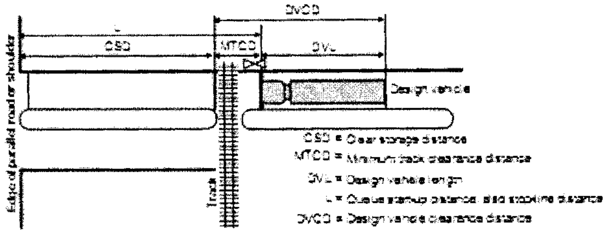
SECTION 2: QUEUE CLEARANCE TIME CALCULATION



			Remarks
18. Clear storage distance (CSD, feet)	**18.**		
19. Minimum track clearance distance (MTCD, feet)	**19.**		
20. Design vehicle length (DVL, feet)	**20.**		Design vehicle type:

			Remarks
21. Queue start-up distance, L (feet): add lines 18 and 19	**21.**	0	
22. Time required for design vehicle to start moving (seconds): calculate as 2+(L÷20)	**22.**	0.0	
23. Design vehicle clearance distance, DVCD (feet): add lines 19 and 20	**23.**	0	
24. Time for design vehicle to accelerate through the DVCD (seconds)	**24.**		Read from Figure 2 in instructions
25. Queue clearance time (seconds): add lines 22 and 24	**25.**	0.0	

SECTION 3: MAXIMUM PREEMPTION TIME CALCULATION

			Remarks
26. Right-of-way transfer time (seconds): line 17	**26.**	0.0	
27. Queue clearance time (seconds): line 25	**27.**	0.0	
28. Desired minimum separation time (seconds)	**28.**	4.0	
29. Maximum preemption time (seconds): add lines 26 through 28	**29.**	4.0	

SECTION 4: SUFFICIENT WARNING TIME CHECK

			Remarks
30. Required minimum time, MT (seconds): per regulations	**30.**	20.0	
31. Clearance time, CT (seconds): get from railroad	**31.**		
32. Minimum warning time, MWT (seconds): add lines 30 and 31	**32.**	20.0	Excludes buffer time (BT)
33. Advance preemption time, APT, if provided (seconds): get from railroad	**33.**		
34. Warning time provided by the railroad (seconds): add lines 32 and 33	**34.**	20.0	
35. Additional warning time required from railroad (seconds): subtract line 34 from line 29, round up to nearest full second, enter 0 if less than 0	**35.**	0	

If the additional warning time required (line 35) is greater than zero, additional warning time has to be requested from the railroad. Alternatively, the maximum preemption time (line 29) may be decreased after performing an engineering study to investigate the possibility of reducing the values on lines 1, 5, 6, 7, 8, 11, 12, 13 and 14.

Remarks: ______________________________

SECTION 5: TRACK CLEARANCE GREEN TIME CALCULATION (OPTIONAL)

Preempt Trap Check

36. Advance preemption time (APT) provided (seconds): .... **36.** [ ] Line 33 only valid if line 35 is zero.

37. Multiplier for maximum APT due to train handling .... **37.** [ ] See instructions for details

38. Maximum APT (seconds): multiply line 36 and 37 .... **38.** [0.0]

39. Minimum duration for the track clearance green interval (seconds) .... **39.** [15.0]

Remarks

For zero advance preemption time

40. Gates down after start of preemption (seconds): add lines 38 and 39 .... **40.** [15.0]

41. Preempt verification and response time (seconds): line 3 .... **41.** [0.0]

42. Best-case conflicting vehicle or pedestrian time (seconds): usually 0 ...... **42.** [ ]

Remarks

43. Minimum right-of-way transfer time (seconds): add lines 41 and 42 .... **43.** [0.0]

44. Minimum track clearance green time (seconds): subtract line 43 from line 40 .... **44.** [15.0]

Clearing of Clear Storage Distance

45. Time required for design vehicle to start moving (seconds), line 22 .... **45.** [0.0]

46. Design vehicle clearance distance (DVCD, feet), line 23 .... **46.** [0]

47. Portion of CSD to clear during track clearance phase (feet) .... **47.** [ ]

Remarks

CSD* in Figure 3 in Instructions.

48. Design vehicle relocation distance (DVRD, feet): add lines 46 and 47 ...... **48.** [0]

49. Time required for design vehicle to accelerate through DVRD (seconds) .... **49.** [ ] Read from Figure 2 in instructions.

50. Time to clear portion of clear storage distance (seconds): add lines 45 and 49 .... **50.** [0.0]

51. Track clearance green interval (seconds): maximum of lines 44 and 50, round up to nearest full second ..... 51. [15]

SECTION 6: VEHICLE-GATE INTERACTION CHECK (OPTIONAL)

52. Right-of-way transfer time (seconds): line 17 .... **52.** [0.0]

53. Time required for design vehicle to start moving (seconds), line 22 .... **53.** [0.0]

54. Time required for design vehicle to accelerate through DVL (on line 20, seconds) ..... **54.** [ ] Read from Table 3 in instructions

55. Time required for design vehicle to clear descending gate (seconds): add lines 52 though 54 .... **55.** [0.0]

Remarks

56. Duration of flashing lights before gate descent start (seconds): get from railroad .... **56.** [ ]

Remarks

57. Full gate descent time (seconds): get from railroad .... **57.** [ ]

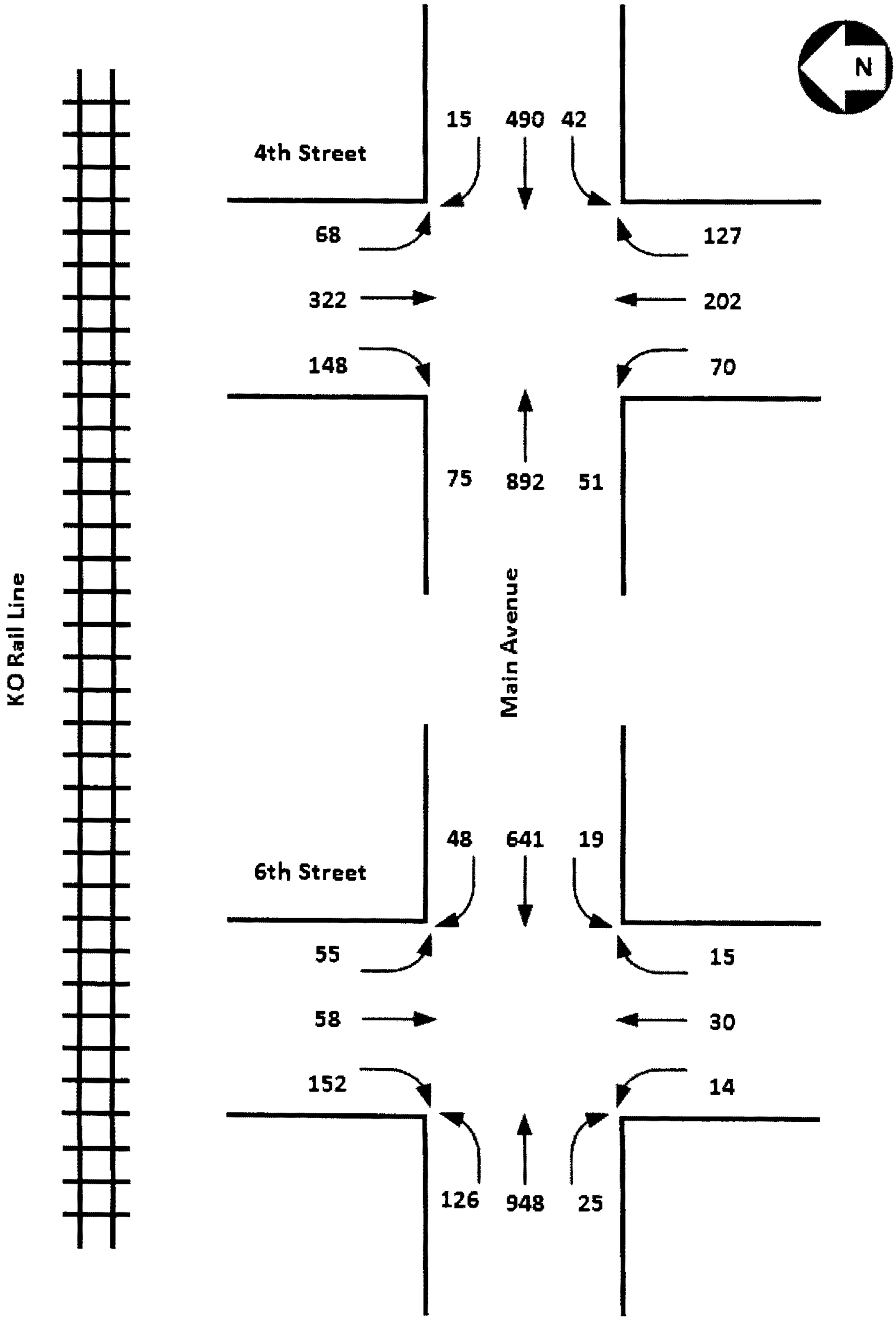
58. Proportion of non-interaction gate descent time .... **58.** [ ] Read from Figure 5 in instructions

59. Non-interaction gate descent time (seconds): multiply lines 57 and 58 .... **59.** [0.0]

60. Time available for design vehicle to clear descending gate (seconds): add lines 56 and 59 .... **60.** [0.0]

61. Advance preemption time (APT) required to avoid design vehicle-gate interaction (seconds): subtract line 60 from line 55, round up to nearest full second, enter 0 if less than 0 .... 61. [0]

APPENDIX C. ADDITIONAL DATA



File View Help Notes: Main Ave & 4th St Frequency 10

Basic

SG Number	1	2	3	4	5	6	7	8								
Min Green		12		12	1	12		12								
Max 1		45		35	9	32	15	35								
Yellow		3		3.2	3	3	3	3.2								
Red Clearance		2.5		2.2	1	2.4	2	2.2								
Walk		7		7		7		7								
Start Up	☐	☑	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Max Recall	☐	☑	☐	☑	☑	☑	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
Dual Entry	☐	☑	☐	☑	☐	☑	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐

Track Clearance 1

Preempt Number	1	2
Track Clearance 1	22	
TC1 Veh SGs	8	8
TC1 Ped SGs		
TC1 Ovl SGs		

Track Clearance 2

Preempt Number	1	2
Track Clearance 2	0	0
TC2 Veh SGs		
TC2 Ped SGs		
TC2 Ovl SGs		

Dwell

Preempt Number	1	2
Dwell Veh SGs	2,4,6,7,8	2,4,6,7
Dwell Ped SGs		
Dwell Ovl SGs		

Exit

Preempt Number	1	2
Exit Veh SGs	4,8	
Exit Ped SGs		

Ø2 50sec Ø4 40sec

Ø5 13sec Ø6 37sec Ø8 40sec

File View Help Notes: Main Ave & 6th St Frequency 10

Basic

SG Number	1	2	3	4	5	6	7	8								
Min Green		12		12	5	12		12								
Max 1		61		19	8	48		19								
Yellow		3.2		3	3	3.2		3								
Red Clearance		2		2.5	1	2.3		2.5								
Walk		7		5		7		5								
Start Up	☐	☑	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Max Recall	☐	☑	☐	☑	☑	☑	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐
Dual Entry	☐	☑	☐	☑	☐	☑	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐

Track Clearance 1

Preempt Number	1	2
Track Clearance 1	22	
TC1 Veh SGs	8	
TC1 Ped SGs		
TC1 Ovl SGs		

Track Clearance 2

Preempt Number	1	2
Track Clearance 2	0	0
TC2 Veh SGs		
TC2 Ped SGs		
TC2 Ovl SGs		

Dwell

Preempt Number	1	2
Dwell Veh SGs	2,6	2,6
Dwell Ped SGs		
Dwell Ovl SGs		

Exit

Preempt Number	1	2
Exit Veh SGs	4,8	
Exit Ped SGs		

Ø2 66sec Ø4 24sec

Ø5 12sec Ø6 54sec Ø8 24sec