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Safety and Mobility Improvement at Highway-rail Grade Crossings Using Real-Time Optimized Preemption of Traffic Signal Strategies

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16. Abstract

This research project embarked on a crucial endeavor to enhance safety and efficiency at highway-rail grade crossings (HRGCs) through the innovative development and application of real-time optimized traffic signal preemption strategies. Recognizing the significant risks associated with HRGCs, especially in urban areas where such crossings are in close proximity to signalized intersections, this study aimed to address the complexities of traffic flow and preemptive signal operations to improve both safety and mobility. The project progressed through the completion of four major tasks: 1) Review and Identification of Limitations: Conducting a holistic review of existing preemption operations, national guidelines, and current engineering practices, the study began with studying in current HRGC preemption strategies. 2) Effectiveness Verification: Through the development of microsimulation models and sensitivity analysis, the project rigorously tested the efficacy of various preemption plans across different HRGC scenarios. 3) Standard Optimization Process: Aiming to maximize safety and operational efficiency, a standard optimization process for designing preemption strategies was developed. 4) Guideline Development: A significant outcome of the project was the development of a guideline that provides a standardized process for evaluating the effectiveness of signal control at HRGCs and adjacent arterials. This research represents a significant step forward in traffic safety and efficiency management at HRGCs, providing a model for similar traffic situations in other regions and laying the groundwork for future technological advancements in the field. The developed guideline serves to offer technical support in terms of application conditions, plan formation, and system operations, aiming to facilitate implementation while enhancing coordination between railway and highway agencies.

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List of Abbreviations

BNSF Railway Company (BNSF)

Federal Railroad Administration (FRA)

Highway-Rail Grade Crossing (HRGC)

Highway-Highway Signalized Intersection (HHSI)

Manual on Uniform Traffic Control Devices (MUTCD)

Mid-America Transportation Center (MATC)

National Cooperative Highway Research Program (NCHRP)

Nebraska Transportation Center (NTC)

Positive Train Control (PTC)

United States Department of Transportation (US DOT)

Union Pacific Railroad Company (UP)

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Abstract

This research project embarked on a crucial endeavor to enhance safety and efficiency at highway-rail grade crossings (HRGCs) through the innovative development and application of real-time optimized traffic signal preemption strategies. Recognizing the significant risks associated with HRGCs, especially in urban areas where such crossings are in close proximity to signalized intersections, this study aimed to address the complexities of traffic flow and preemptive signal operations to improve both safety and mobility. The project progressed through the completion of four major tasks:

1. Review and Identification of Limitations: Conducting a holistic review of existing preemption operations, national guidelines, and current engineering practices, the study began with studying in current HRGC preemption strategies.
2. Effectiveness Verification: Through the development of microsimulation models and sensitivity analysis, the project rigorously tested the efficacy of various preemption plans across different HRGC scenarios.
3. Standard Optimization Process: Aiming to maximize safety and operational efficiency, a standard optimization process for designing preemption strategies was developed.
4. Guideline Development: A significant outcome of the project was the development of a guideline that provides a standardized process for evaluating the effectiveness of signal control at HRGCs and adjacent arterials.

The project's methodological approach included field investigations, microsimulation modeling, and statistical optimization, ensuring a robust and comprehensive analysis. Key results demonstrated the profound impact of optimized preemption strategies on reducing vehicle

queues at HRGCs, thereby lowering the risk of accidents. Additionally, these strategies showcased improvements in traffic efficiency at adjacent intersections.

However, the research also illuminated the complexities of implementing these strategies in real-world settings. Effective implementation required multidisciplinary collaboration and continuous adaptation of strategies to changing traffic patterns and train schedules.

The project not only advanced knowledge in traffic engineering but also provided practical guidelines for transportation engineers and policymakers. While the study was geographically confined to specific HRGC corridors in Nebraska, its findings hold broad relevance and applicability. Future research directions include expanding the study's geographic scope, integrating advanced predictive algorithms for train arrivals and departures, and exploring the incorporation of AI, connected vehicle technology, and IoT applications in HRGC preemption strategies.

This research represents a significant step forward in traffic safety and efficiency management at HRGCs, providing a model for similar traffic situations in other regions and laying the groundwork for future technological advancements in the field. The developed guideline serves to offer technical support in terms of application conditions, plan formation, and system operations, aiming to facilitate implementation while enhancing coordination between railway and highway agencies.

Keywords: Highway-Rail Grade Crossing, Signal Control, Preemption, Safety Action Plan

Chapter 1 Introduction

The queue of roadway vehicles blocking the crossing area in urban highway-rail grade crossings (HRGCs) can be hazardous when a highway-highway signalized intersection (HHSI) is in close proximity. Traffic signal preemption operation strategies are widely used at intersections near HRGCs to prevent accidents by clearing vehicles off the tracks before a train arrives at a crossing.

As can be seen in Figure 1.1, when an HHSI is close to the HRGC, the queue space in between is short, which could cause queued vehicles to block the HRGC or HHSI and puts them in danger of being hit by a train. This infrastructure requires a properly designed traffic signal preemption system with a special mode that gives the right-of-way to trains as they approach to keep the queue from spilling back into the HRGC.

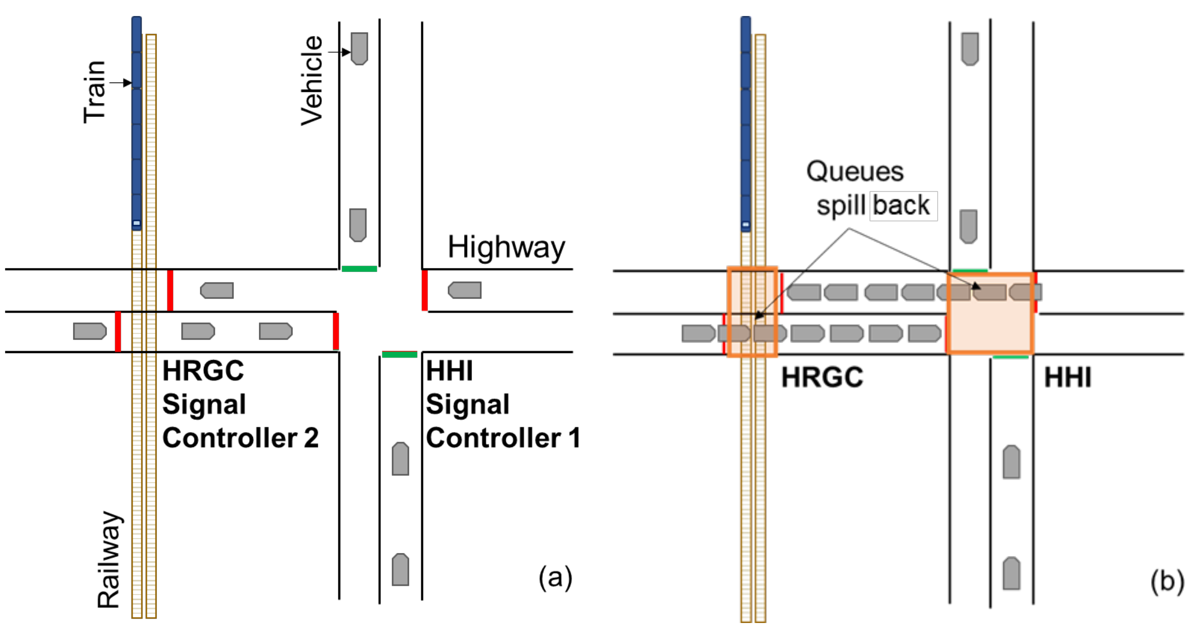


Figure 1.1 Concepts of HRGC preemption and problems without preemption

Traffic signal preemption operation for HRGCs is a complex process governed by the cooperation of both HHSI traffic signal operations and HRGC warning systems. These systems include flashing light signals and automatic gates (if applied) and various types of train detection devices. When the HHSI traffic signal controller unit is interconnected with the HRGC warning system, a comprehensive understanding of the design and operational parameters is required to ensure the effective functioning of the preemption system.

This project studies the optimization potential of preemption strategies to maximize the separation of traffic hazards between HRGCs and intersections in adjacent arterials. To this end, three main objectives are pursued.

First, the project will start by reviewing and identifying key limitations and conflicts in the current preemption operations. A holistic review of national guidelines, manuals, and current engineering practices will be investigated.

Second, the project will verify the effectiveness of signal preemptions and the interconnections between HRGCs on a railway corridor and the nearby intersections on an arterial. This task will be implemented through developing microsimulation models and conducting sensitivity analyses. Various preemption plans that account for different HRGC scenarios will be examined.

Third, the project will develop a standard optimization process for designing preemption plans with the goal of maximizing safety at HRGCs and nearby intersections, and to enhance the efficiency of the arterial intersections. As a result, a generic guideline will eventually be provided.

The benefits of this project are twofold. First, it will provide a standardized process of evaluating the effectiveness of signal controls at HRGCs and the adjacent arterials as a whole and confirm the cost-benefit threshold that warrants the application of preemption strategies. Second, the resulting guideline is expected to systematically provide technical support on the preemption control strategies in terms of application conditions, plan formation, and system operations, etc. The guideline is also expected to bridge gaps in understanding concepts, facilitating implementation, and improving coordination between railway and highway agencies.

Problem Statement

In 2015, as part of the Fixing America's Surface Transportation (FAST) Act, Congress directed the Federal Railroad Administration (FRA) to issue regulations that develop state specific HRGC action plans. The action plan is to (1) identify HRGCs that are high risk or have experienced recent and/or multiple accidents and incidents; (2) determine specific strategies for improving crossings safety; and (3) designate a state official responsible for plan administration. In December 2020, the FRA issued a final rule requiring each state to develop an HRGC action plan to fulfill the FAST Act mandate.

Region VII states: Nebraska, Missouri, Kansas, and Iowa, as well as other states across the country, are actively developing or updating their own HRGC action plans. Although a preemption strategy was not identified as a priority by the railroads (Iowa DOT, 2012), many states (e.g., California, Texas, Ohio) found it necessary to adapt preemption strategies in their safety action plan based on their engineering practices (USDOT, 2023)

Many State DOT's current practices for preemption strategies, including those in Region VII, is to follow the MUTCD guideline that when HRGCs are within 200 feet of a signalized intersection, a preemption signal operation should be applied (MUTCD, 2009). However, engineering practices indicate that in many cases this distance is not sufficient to warrant the installation of preemption signals (Engelbrecht et al., 2005). There are many other factors that should be taken into consideration, for example, queue length has become a critical factor when deciding whether preemption is needed (USDOT, 2002).

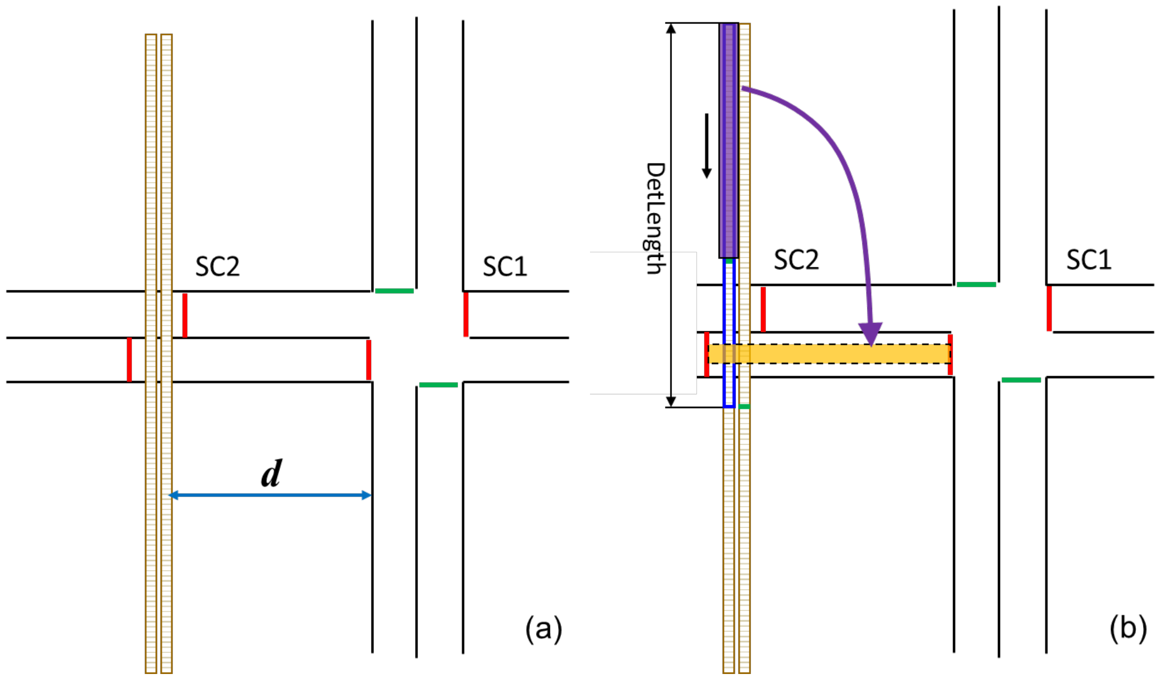


Figure 1.2 Factors to be considered during preemption

Maximizing the benefits of preemption and interconnection between railway and highway signal controls in improving HRGC safety requires systematic design, communication, and optimization. This involves the integration and coordination of the train warning, turning movements, pedestrian clearance, etc., and consideration of traffic volume, approach speed, number of approach lanes, train length, and train speed, etc. parameters (Lin et al., 2014). In addition, the randomness of some parameters (e.g., train arrival time) makes the optimization of preemption plans more necessary (Chen and Rilett, 2015).

The design of properly coordinated preemption systems requires close cooperation between local highway agencies and railway companies (Haas, 2010). Unfortunately, the critical concepts, terms, and nuances of signal preemption and interconnection between HRGC control devices and the nearby signalized intersections are not well understood by many engineers.

Therefore, research questions, for example "Does preemption optimization have engineering significance for improving the safety and mobility of HRGCs and the parallel highways?", need to be studied to understand the potential benefits of using the preemption signal control. There are several problem-oriented research needs to be addressed; specifically needs to:

(1) understand the current HRGC preemption strategies in Region VII, which helps to identify key limitations and conflicts in current preemption operations;

(2) develop a real-time simulation optimization procedure, which helps to determine the applicable conditions, preemption plans, and parameters that best suit the local practice; and

(3) develop a general preemption strategy for HRGCs and adjacent intersections, which helps implement preemption signal controls.

1.1 Research Methods

Research will be conducted through field investigation, microsimulation modeling, and statistical optimization. Specifically, the three methods are:

Field investigation of existing signal preemption operations at HRGCs will be performed to understand the current practices and limitations.

Simulation modeling of the traffic signals at HRGCs and intersections will be performed to examine the effectiveness of the preemption plans.

Statistical optimization of determining the preemption plan will be performed to generate the best solution in an automatic process.

It should be noted that the microsimulation model will be used to test various special train-actuated events. Special events may include the transport of hazardous materials or when there is a positive train control (PTC) request in which the HRGC preemption signal control must prioritize certain vessels in the intersections.

1.2 Task Overview

1.2.1 Task 1. Literature Search

To ensure no research was overlooked or duplicated, the project team reviewed published literature including guidelines and manuals (MUTCD, 2009; USDOT, 2002; Urbanik and Tanaka, 2017) to note the state-of-the-art and the state-of-the-practice signal preemptions involving HRGC control strategies. Special attention was given to engineering practices of preemption signal control types.

1.2.2 Task 2. Investigation of the existing HRGC preemption control plans

Preempted HRGCs in Lincoln, Nebraska were used as testbeds in the field investigation task. The existing signal preemption operations at the adjacent intersections and the interconnection with HRGCs were studied to understand the current practices in Region VII. This task also identified key limitations and infrastructure insufficiencies that might hinder the implementation of the preemption control strategy.

1.2.3 Task 3. Development and calibration of VISSIM simulation models

This task was accomplished through four subtasks (a – d) as described below.

a). Selection of study corridors: Two HRGC corridors in Lincoln, Nebraska were selected as the study testbeds. They were the HRGC corridor along Cornhusker Highway 6 (US-6) and the HRGC corridor along Nebraska Highway 2 (NE-2), including both a preempted intersection and non-preempted intersections in the study areas.

b). Data collection: Most of the data was obtained from the City of Lincoln, including traffic flows (e.g., turning movements, train volumes), signal control plans for the HRGCs and all the adjacent intersections along the arterial, and preemption settings (e.g., preemption type, circuit location). Road profiles and geometry data were extracted from Google Maps. On-site data collection efforts were necessary due to outdated or insufficient data (e.g., queue length).

c). Develop simulation models: Several simulation models will be developed in VISSIM to account for various scenarios including HRGC control strategies (e.g., normal vs preempted), preemption types (e.g., simultaneous vs advanced), and other factors (e.g., queue lengths, approaching speeds). In the simulation models, the preemption plans embedded in the signal controllers will be coded in Vehicle Actuated Programming (VAP) using VISSIM's Visvap module.

d). Calibration and validation: The simulation models will be calibrated to the two study corridors respectively. Field data (e.g., queue length) at selected intersections along the parallel highway will be used as the measure of performance to the calibration.

1.2.4 Task 4. Sensitivity analysis of impact factors to the HRGC preemption

The performance of the preemption plan is sensitive to site features and preemption parameters [6]. Therefore, a sensitivity analysis was performed using the established simulation models with or without preemption signals at HRGC corridors. The goal was to explore factors, such as traffic volume, train blockage duration, and train speed, that affect the HRGC performance given different preemption plans.

1.2.5 Task 5. Real-time optimization process in determining parameters

A simulation-based, real-time optimization procedure was instated to automatically optimize preemption parameters (e.g., phase sequence, clearance green, transfer time, and offset time) given the randomness of train speed, train length, and departure time. This procedure was implemented using advanced optimization methods, e.g. genetic algorithms (Kim, et a., 2013), which are coded and automated through MATLAB and VISSIM interfaces. The result will be an optimal preemption phase sequence with critical parameters.

1.2.6 Task 6. Development of Generic Guideline of Preemption Application

Based on the integration of the results from previous tasks, a general guideline that follows MUTCD was developed. It systematically provided technical support for state and local authorities on determining an optimized preemption strategy. The guideline included at the following contents: (1) definitions of technical terms to facilitate communication and understanding between highway and railway agencies; (2) adoption of existing preemption control devices by the Region VII states; (3) selection and optimization process of the preemption plan; and (4) evaluation of preemption strategy to identify the needs of installing auxiliary traffic control devices.

1.2.7 Task 7. Final Report and Presentation

The project results are included in this final report and PowerPoint presentation. The key sections of the report include evidence confirming the effectiveness of the preemption in reducing HRGC accidents, and technical guidance on preemption signal applications given specific HRGC and adjacent arterial conditions.

1.3 Expected Results

This research was expected to gain insights that will improve the safety and efficiency of signal control operations at HRGCs and adjacent intersections. Four main results were expected:

Identify conditions and criteria to help engineers in deciding whether a preemption signal control should be installed, what type of preemption plan provides the highest benefits, and what will hinder the operation of the HRGC preemption.

Find evidence of the effectiveness of the HRGC preemption control strategies in enhancing safety and efficiency. Identify complementary systems (e.g., pre-signals, and coordination) to maximize effectiveness.

Develop a simulation-based optimization process to choose the best solution of the real-time preemption plan from various what-if scenarios with different factor combinations.

Develop comprehensive guidance strategies for determining the application of the preemption signal control when safety is required, and conditions warrant. These strategies should maximize the use of other supporting measures as part of the preemption plan (e.g., pre-signal, advance flasher, queue cutter).

1.4 Technology Transfer Implementation

The direct output of this research will be a guideline that helps decision-makers determine optimized conditions and strategies for installing preemption signals. The guideline does not serve as policies, regulations, or standards. It was anticipated the results provide evidence to back suitable or appropriate preemption control at HRGC locations to reduce the impact of train-vehicle and vehicle-vehicle crashes. In addition, the results also help formulate focus-oriented traffic-control strategies to complement the regional or state HRGC safety action plans. The guideline is generic and comprehensive so it can be easily learned and implemented by other states in Region VII as well as the U.S.

Chapter 2 Literature Review

Standard preemption is the prevalent method employed at HRGCs within the United States. Its objective is to clear vehicles that have queued from a highway-highway intersection to a HGRC, thereby preventing congestion and potential hazards when a train is approaching (Chen et al., 2022). The technology underpinning this system relies on first-generation detection mechanisms (Venglar et al., 2000). These include (1) conventional track circuit systems that detect the presence of a train using the interruption of electrical circuits; (2) motion sensor systems that activate when they detect the movement of a train; (3) constant warning time systems, which provide a fixed interval before the arrival of a train; and (4) induction loop systems, which detect changes in magnetic fields caused by large metallic objects such as trains.

While effective in many scenarios, the standard preemption strategy comes with its limitations (Roberts and Brown-Esplain, 2005; Lin et al., 2014). The main issue is that it keeps the crossing warning time at a minimum and does not account for uncertainties of train schedules and speeds, which can fluctuate due to numerous factors like weather conditions, operational delays, and mechanical issues. As a result, the warning times may often be insufficient, leading to abrupt traffic stops and pedestrian phases at signalized intersections. This sudden termination can create unsafe situations, forcing vehicles and pedestrians to clear the tracks quickly, sometimes under dangerous conditions (Chen, 2015).

It is also challenging to adapt the inflexibility of the minimum warning time to real-time conditions. For example, if a train is delayed or arrives earlier than expected, the standard preemption system may not adjust its operations, accordingly, leading to either unnecessarily prolonged traffic halts or dangerously brief crossing clearances. This inflexibility highlights a critical need for the integration of more adaptive traffic management systems at railway crossings. Such systems would benefit from advancements in detection technology and real-time data processing, allowing for dynamic adjustment of crossing times in response to actual train arrival times and current traffic conditions on the roads.

A typical preemption sequence consists of three necessary components: (1) a clearance phase, used to remove queued roadway vehicles from the crossing; (2) a holding phase, used to restrict roadway vehicles at intersections from entering the crossing; and (3) a transitioning phase, used to smoothly transition from normal mode to preemptive mode, or vice versa, in signal control operation.

To optimize the preemption signal control operation, variables that make up the preemption plan, as well as the entire signal control plan, need to be taken into consideration. These variables include cycle length, maximum green time, and offset time for a normal signal timing, and the advance warning time, maximum clearance time, dwell time, etc., for preemption signal timing.

A detailed study on the optimization of the above-mentioned parameters has been completed by Chen and Rilett (Chen and Rilett, 2015). In other studies, a transition preemption strategy was studied with the focus of the transitioning phase, and optimized in previous studies [Chen and Rilett, 2015; Cho and Rilett, 2007] aiming to reduce pedestrian conflicts while reducing control delay at the traffic signals near an HRGC.

On the corridor scale, the benefit of signal preemption optimization is significant in improving both safety and efficiency. For example, Chen and Rilett used a genetic algorithm for optimizing signal timings while considering the constraints of the signal controller and preemption logic. This optimization is supported by a simulation module that includes roadway/railway networks and train arrival predictions. This integrated approach allows for the real-time generation and evaluation of preemption plans, enhancing both the safety of pedestrians and vehicular efficiency in corridors with multiple highway-rail grade crossings (Chen and Rilett, 2018).

In their latest study, the research team proposed an improved Transition Preemption Strategy model designed specifically for areas with multiple HRGCs and dual train tracks (Chen et al., 2022). They found that the standard preemption method, used to clear vehicles from tracks when a train is approaching, does not adequately address pedestrian safety or traffic delays. This strategy uses advanced detection and signal control techniques to provide longer warning times and adapt traffic signals in real-time based on the specific conditions of the crossing. The strategy was tested in a simulated urban environment in Lincoln, Nebraska, with results indicating significant improvements in reducing pedestrian phase cutoffs and vehicle delays compared to the existing standard preemption method. The studies recommended further refining preemption models with real-world data and possibly extending the simulation capabilities to include larger network and varied traffic scenarios to validate and scale the optimization strategies. At the same time, however, simulation models that need to generate preemption plans using real-time data have not yet been established.

Table 2.1 provides an overview of prior research dedicated to the preemption of Traffic Signal Strategies, with particular emphasis on HRGCs and emergency vehicle scenarios. Additionally, relevant signal preemption studies from alternative transportation infrastructures are included for comparative insights. After the table, comprehensive discussions on these studies are provided, elucidating the background, data collection methodologies, and analytical approaches utilized.

Table 2.1 Key Highlights from Previous Studies on Signal Preemption

Reference	Data	Methods	Highlights
Zhong and Chen, 2022	Simulation experiments conducted in SUMO, an urban traffic simulator.	On-demand signal timing, novel signal preemption, and recovery cycle strategy	The proposed On-Demand Synchronization (ODS) method optimized travel time by up to 62.9%, 50.9, and 11.6% improvements compared to different methods examined.
Chen et al., 2022	Data on traffic volumes, speed limits, and signal timing settings provided by the Public Works Department of Lincoln.	Calibrated VISSIM simulation model to evaluate the proposed TPS_DT algorithm	The TPS_DT algorithm significantly reduces pedestrian phase truncations and vehicle delays at HRGCs; a 92% average reduction in pedestrian phase truncations compared to the baseline SP method.
Chen and Rilett, 2020	Data collected from a 2.4 km by 3.2 km urban road network in Lincoln	Optimization Module Utilized that used a Genetic Algorithm (GA) to optimize signal timing plans, and VISSIM micro-simulation model to simulate the roadway/railway network	The TPS_DT strategy significantly reduces pedestrian phase cutoffs, enhancing safety at HRGCs; the optimized signal timing plans reduce intersection and corridor vehicle delays. Specifically, there was a 15.4% reduction in average delay at the target intersections and an 11.8% reduction in average corridor delay across six scenarios.
Chentoufi and Ellaia, 2018	Data taken from Inductive Loop Detectors, installed between 150m and 200m from intersections to detect tram arrival times; GPS technology and camera sensor data also utilized	Use of Transit Signal Priority techniques, combined with real-time data and adaptive signal control; Utilized Passing Vehicle Search Algorithm and traffic simulation module	The simulation results demonstrated improved timing plans, reduced delays for trams and emergency vehicles, and an overall enhancement in traffic flow efficiency at the intersections.
Mu et al., 2018	Data collection involves parameters like vehicle queues at intersections, traffic flow rates, arrival and	A multi objective programming model was used to determine the earliest and latest possible green light start times at each intersection, ensuring	Simulation results demonstrate the efficacy of the proposed method. Pareto optimal sets show trade-offs between reducing EV residence time and increasing general vehicle passage. The method effectively handles

Reference	Data	Methods	Highlights
	departure rates, and EV detection times.	EV transit without speed reduction or stops.	varying traffic volumes, ensuring faster EV transit even during peak periods.
Urbanik and Tanaka, 2017	Data from case studies, focused on Portland, Oregon, and the states of Ohio and California to illustrate advanced practices and highlight key issues and lessons learned.	Systematic Review and Survey; Detailed surveys were distributed to 40 U.S. Departments of Transportation and four Canadian provinces to gather data on current practices on traffic signal preemption	A majority (55%) of surveyed agencies use a simple two-wire preempt at their highway-rail grade crossings, with 58% of these using normally closed circuits; highway agencies coordinate inspections with railway agencies, despite encouragement from the FRA; The state of practice often does not reflect the advanced capabilities available, indicating a gap between potential and actual practices.
Lin et al., 2014	Traffic related data on traffic flow patterns, signal timings, intersection layouts, and other relevant parameters. collected on road network in Broward County	Generic plan development for coordinated pre-preemption implementation via the *ATMS.now* platform, triggered by train detection at control section entry points; VISSIM-based traffic simulation models	Upstream preemption signals were suggested to trigger pre-preemptions at downstream intersections, potentially eliminating the need for train information retrieval or new detectors; prediction of Estimated Time of Arrival was crucial, influenced by train speed and upstream preemption location.
Cho et al., 2011	Traffic volumes were gathered using video cameras. Data collected on cycle lengths, coordination schemes, and preemption warning times	VISSIM simulation modeling was utilized to assess the ITPS algorithm's performance under normal operating conditions	ITPS algorithm effectively enhances safety and reduces delays at signalized intersections near HRGCs; ITPS significantly reduced pedestrian phase truncations, enhancing safety. Moreover, it reduced delays by approximately 5-6% compared to other methods
We et al., 2010	Data collected on traffic control, volume, and intersection geometry in collaboration with North County Transit District,	Developed and tested optimization models in a simulation environment. Additionally, a pseudo-real-time ego-motion estimation method utilizing video camera	The extended traffic signal optimization model focused on coordinating signals around grade crossings, considering factors such as train preemption and traffic flow characteristics. The model minimized intersection delay while ensuring coordination is not

Reference	Data	Methods	Highlights
	Caltrans District 11, San Diego County, and various cities including Oceanside, Vista, San Marcos, and Escondido	input was developed to detect potential near-accident scenarios involving vehicles crossing in front of trains	disrupted by SPRINTER preemption
Cho and Rilett, 2007	Data collected at signalized intersection in College Station, Texas, situated approximately 12m from a Union Pacific railway line	Developing the ITPS algorithm, considering variability in train arrival times and providing more time to blocked phases during preemption	The ITPS algorithm effectively mitigated pedestrian clearance truncations, with zero truncations observed for APWT values of 100, 110, and 120s, compared to SP and TPS algorithms. The delay with ITPS (APWT 120s) was 5.4% lower than SP and TPS algorithms, indicating improved efficiency and safety
Mirchandani and Lucas, 2004	Data is collected from various sources including detectors, automatic vehicle locators, transponders, etc.	Categorized Arrivals-based Phase Re-optimization at Intersections that employs a dynamic programming-based approach, decomposing the traffic control problem into interconnected subproblems.	Simulation-based analyses demonstrate the effectiveness of CAPRI in minimizing delays and improving traffic flow compared to traditional systems; The system's adaptability to real-time traffic conditions is highlighted, showing promising results in reducing congestion and improving transit operations.

A recent study by Zhong and Chen (2022) focused on developing an intelligent traffic signal control strategy to prioritize emergency vehicles (EVs) and reduce their travel time in urban environments. The proposed approach included three key components: on-demand signal timing, a novel signal preemption strategy, and a recovery cycle strategy. On-demand signal timing adjusted traffic signals based on the Emergency Response Level (ERL), Congestion Level of the Road Section (CLRS), and Time Urgency Level (TUL) to reduce road saturation, allowing ordinary vehicles (OVs) to give way to EVs. The signal preemption strategy combined nonintrusive methods (adjusting signal cycle length and green splits) with intrusive methods (setting signals to green when an EV was detected) to ensure EVs could pass through intersections without stopping. The recovery cycle strategy used linear programming to reprogram signal cycles and restore normal traffic flow quickly after an EV had passed.

Data for this study were collected through simulation experiments conducted using the SUMO (Simulation of Urban MObility) traffic simulator, with a road network modeled after the area near the Shanghai fire station in Shanghai, China. The simulations included various intersections and T-intersections to test the method's effectiveness. The results showed that the proposed strategy significantly reduced EV travel times and minimized the overall impact on the road network. Compared to traditional methods, the strategy optimized EV travel times by up to 62.85% over fixed-time control methods, 50.83% over flexible signal preemption methods, and 11.62% over intrusive signal preemption methods. These improvements demonstrated the potential of the proposed strategy to enhance emergency response efficiency in congested urban settings.

In a recent study of Chen et al. (2022), they addressed the safety and efficiency issues associated with the standard preemption (SP) method used at intersections near HRGCs. The SP method prioritized vehicle clearance from railroad tracks but did not adequately consider pedestrian safety or overall system efficiency. To tackle these problems, they introduced a novel transition preemption strategy (TPS) named TPS_DT. This strategy aimed to improve safety and efficiency at HRGCs, particularly in corridors with multiple HRGCs and dual tracks. Using a calibrated VISSIM simulation model of an urban highway corridor in Lincoln, Nebraska, the study evaluated the TPS_DT algorithm by measuring pedestrian phase cutoffs, intersection vehicle delays, and corridor vehicle delays. Data for the study was collected from various sources, including traffic volumes and signal timings from Lincoln's Public Works Department, empirical train data, and Google Maps imagery. The results indicated that the TPS_DT algorithm significantly reduced pedestrian phase truncations and vehicle delays compared to the baseline SP method, with an average reduction in pedestrian phase truncations by 92%. The algorithm's effectiveness persisted even under scenarios with train arrival prediction errors, although improved prediction accuracy could enhance performance further. Despite the promising simulation outcomes, the research recommended field studies to validate the findings across different traffic demand levels and train schedules. The study also acknowledged potential political challenges in utilizing train arrival information from Positive Train Control (PTC) systems, despite their technical feasibility and expected accuracy benefits.

In another similar study by Chen and Rilett (2020), safety and traffic signal efficiency protocols at HRGCs and their nearby intersections were developed. The authors developed a simulation-based optimization methodology to enhance traffic signal timing on arterial corridors with multiple intersections near HRGCs. This included introducing a new transition preemption strategy for dual tracks (TPS_DT) and integrating a train arrival prediction model. The optimization utilized a Genetic Algorithm (GA) to refine signal timing plans, while the VISSIM micro-simulation model evaluated the traffic performance. Key objectives included improving pedestrian safety and reducing vehicle delays at intersections and along the corridor. Data was collected from a 2.4 km by 3.2 km urban road network in Lincoln, Nebraska, encompassing several intersections and HRGCs. The optimized signal timing plans were validated through multiple simulation runs, showing a significant reduction in pedestrian phase cutoffs and vehicle delays. Specifically, there was a 15.4% reduction in average delay at target intersections and an 11.8% reduction in average corridor delay. The methodology demonstrated considerable improvements in safety and efficiency and could be adapted for other locations facing similar challenges. The authors suggested that future studies should incorporate varying train speeds, traffic demands, and train volumes to enhance the model further.

Signal preemption was also studied by Chentoufi and Ellaia (2018). The study aimed to develop an adaptive traffic control system for coordinated tram intersections that balanced the priority needs of trams and emergency vehicles (EVs). Using Transit Signal Priority techniques (TSPT), the system employed a Passing Vehicle Search (PVS) algorithm for optimization, a database for managing real-time sensor data, and a traffic simulation module to evaluate the best timing plans. Key technologies included inductive loop detectors for trams, GPS for tracking EVs, and camera sensors for general vehicle detection. Data collection involved installing various sensors on traffic axes and intersections to capture real-time traffic information. The system was tested in Rabat, Morocco, and demonstrated improved traffic flow and reduced delays for trams and emergency vehicles. The simulation results showed that the proposed system effectively reduced delays and enhanced traffic efficiency at intersections. Future research was recommended to explore the system's application in scenarios with multiple emergency vehicles and to consider pedestrian priorities.

Mu et al. (2018) focused on improving the efficiency of emergency vehicle (EV) transit during emergencies by addressing delays at intersections. They mentioned in their research that traditional methods encountered challenges such as traffic congestion and the absence of dedicated emergency lanes, hindering swift EV movement. To tackle this, the study proposed a dynamic signal preemption method based on the route, aiming to optimize green light timings at intersections. By determining the earliest and latest feasible green light start times at each intersection along the evacuation route, the method ensured uninterrupted EV transit while minimizing delays. Using a multi-objective programming model, the research considered factors like EV detection times, intersection phase durations, and traffic flow rates to optimize green light timings. The model's objective was to reduce EV residence time at intersections while maximizing the passage of general vehicles, thus enhancing overall system efficiency.

The Particle Swarm Optimization (PSO) algorithm was employed to solve the model, ensuring effective optimization and validation through simulations. Simulation results demonstrated the effectiveness of the proposed method in reducing EV delay and improving system efficiency under various traffic conditions. Pareto optimal sets showed trade-offs between reducing EV residence time and increasing general vehicle passage. The method's adaptability to varying traffic volumes, including peak periods, indicated its potential to significantly enhance EV transit during emergencies while minimizing disruption to general traffic flow.

Urbanik and Tanaka (2017) did an extensive review on traffic signal preemption at intersections near HRGCs. They documented that while advanced capabilities existed, most agencies in the US and Canada, relied on outdated two-wire preempt systems, with 55% of the surveyed agencies using these basic systems, and 58% using normally closed circuits. This antiquated technology limited the information conveyed to traffic signal controllers. Detailed case examples from Portland, Oregon, Ohio, and California showcased advanced practices and lessons learned, underscoring the need for updated guidelines to optimize traffic signal operations at HRGCs for improved safety and mobility. Moreover, there was a notable lack of coordination between highway and railway agencies for joint inspections, despite federal recommendations, resulting in potential safety and operational inefficiencies. They identified several opportunities for improvement, such as addressing operational limitations, developing clear definitions, and encouraging the use of multiple signals and preempts. Enhanced coordination between agencies, comprehensive training for employees and contractors, and regular inspections with performance measures were also recommended.

Preemption during peak hours has been investigated in detail by Lin et al. (2014). The research addressed safety and mobility issues at HRGCs and adjacent arterials, particularly in urban areas like Broward County, Florida. The authors discussed that traditional solutions like preemption operations have had limitations in effectively mitigating these challenges, prompting the exploration of advanced traffic signal system software, notably the *ATMS.now* platform, as a potential avenue for improvement. To achieve its goals, the research developed and evaluated pre-preemption strategies triggered by train detection, utilizing VISSIM-based traffic simulation models. These models accurately replicated real-world traffic scenarios in Broward County, integrating data on traffic volumes, train operations, and pre-preemption designs.

The study tested two primary pre-preemption strategies: coordinated pre-preemption and Improved Transitional Preemption Strategy (ITPS)-based pre-preemption. Results from the simulations demonstrated the efficacy of the coordinated strategy in reducing traffic delay, average stops, and queue length along arterials near railroad crossings, suggesting its potential for enhancing safety and mobility in similar urban settings. Furthermore, the research highlighted the importance of accuracy when predicting trains' Estimated Time of Arrival (ETA) and the role of upstream preemption signals in triggering pre-preemptions at downstream intersections. The study's findings underscored the viability of utilizing advanced traffic signal system software like *ATMS.now* to address safety and mobility concerns at highway-railroad at-grade crossings, offering insights for transportation planners and policymakers in urban areas facing similar challenges.

Cho et al. (2011) also investigated the effectiveness of the Improved Transition Preemption Strategy (ITPS) in enhancing safety and efficiency at signalized intersections adjacent to HRGCs. The author discussed that traditionally, preemption methods have prioritized clearing the crossing for vehicles, often neglecting pedestrian safety and minimizing vehicle delay. However, the ITPS algorithm, developed to address these shortcomings, showed promising results in mitigating pedestrian phase truncations, thus improving safety standards. By implementing ITPS, pedestrian-related risks were significantly reduced, contributing to a safer environment for both pedestrians and drivers. Furthermore, the research revealed notable improvements in intersection efficiency with the adoption of the ITPS algorithm. Compared to standard preemption methods and the Transition Preemption Strategy (TPS), ITPS demonstrated a reduction in delays of approximately 5-6%. This reduction in delay translates to smoother traffic flow and improved overall intersection performance.

Notably, these enhancements were particularly significant under scenarios with high pedestrian volumes, where the ITPS algorithm outperformed traditional methods, emphasizing its efficacy in real-world conditions. Based on the findings, the study recommends the widespread adoption of the ITPS system at signalized intersections near HRGCs. The author highlighted the ability to both enhance safety through reduced pedestrian phase truncations and improve efficiency by minimizing delays. The ITPS algorithm presented a comprehensive solution to the challenges faced by conventional preemption strategies. Implementing ITPS, especially with an advance preemption warning time of at least 90 seconds, emerged as a viable approach to addressing pedestrian safety concerns and optimizing intersection operations for smoother traffic flow.

We et al. (2010) highlighted traffic congestion and safety issues resulting from frequent signal preemptions at HRGCs along the SPRINTER corridor. Collaborating with various agencies and jurisdictions since 2007, the study collected extensive data on traffic control, volume, and intersection geometry in cities such as Oceanside, Vista, San Marcos, Escondido, and San Diego County. This data formed the basis for developing and testing optimization models aimed at mitigating conflicts between the new SPRINTER light rail transit system and highways intersecting the rail line. One key aspect of the study involved extending the original traffic signal optimization model to handle multiple signals around grade crossings, emphasizing coordination to minimize traffic delays and enhance safety.

A significant component of the research involved the development of a pseudo-real-time ego-motion estimation method, utilizing video camera input to detect potential near-accident scenarios involving vehicles crossing in front of trains. This method aimed to enhance safety by identifying critical situations promptly, thereby enabling appropriate interventions. Additionally, the study outlined an extended traffic signal optimization model that considered factors such as train preemption and traffic flow characteristics. The model's objective was to design optimal signal timing plans that minimized intersection delay while ensuring coordination remained intact even during SPRINTER preemption events. Despite the progress made, the study acknowledged certain limitations, such as the assumption of uniform arrival flow rates, which may not have held true for coordinated corridors in general.

To address this, the research suggested further refinement of the model using updated traffic volume data. Implementation of the extended optimization model required state-of-the-art optimization software and validation through simulation evaluation models like PARAMICS and VISSIM. Moreover, calibration with reliable information, such as traffic volume data, was recommended to enhance the reliability of the optimized signal timing plans for field testing. Overall, the research contributed valuable insights into optimizing traffic signal control for rail-highway grade crossings, aiming to alleviate congestion and enhance safety along the SPRINTER corridor and similar transit systems.

In an earlier study by Cho and Rilett (2007), the limitations of existing preemption methods for traffic signals near HRGCs were identified. The study primarily focused on clearing vehicles from crossings, often neglecting pedestrian safety and efficiency concerns. The state-of-the-art transition preemption strategy (TPS) attempted to address these issues but faced challenges due to uncertainties in predicting train arrivals. Recognizing the need for enhanced strategies, the authors embarked on developing an Improved Transition Preemption Strategy (ITPS) specifically tailored to improve intersection performance while maintaining or enhancing safety levels. The methodology involved the development of the ITPS algorithm, which incorporated considerations for variability in train arrival times and allocated more time to blocked phases during preemption.

To evaluate the effectiveness of the ITPS algorithm, the authors employed a microsimulation model using VISSIM. This model facilitated the assessment of three preemption algorithms: Standard Preemption (SP), TPS, and ITPS. Safety metrics, such as the number and duration of truncated pedestrian clearance phases, along with efficiency measures, including average control delay, were utilized to gauge the performance of each algorithm. The results demonstrated the efficacy of the ITPS algorithm in mitigating pedestrian clearance truncations and improving intersection efficiency. Notably, zero truncations were observed for ITPS with advanced preemption warning time (APWT) values of 100, 110, and 120s, compared to SP and TPS algorithms. Furthermore, the delay with ITPS (APWT 120s) was 5.4% lower than that of SP and TPS algorithms, indicating significant improvements in both safety and efficiency. These findings underscored the importance of considering pedestrian safety alongside efficiency concerns in the development of traffic signal preemption strategies for IHRGCs.

Mirchandani and Lucas (2010) introduced a strategy called Categorized Arrivals-based Phase Re-optimization at Intersections (CAPRI), aiming to enhance traffic flow through real-time adaptive signal control. CAPRI integrated transit signal priority and rail/emergency preemption within a dynamic programming-based system. By utilizing sensor data for traffic flow predictions and hierarchical optimization, CAPRI sought to minimize delays and improve overall traffic performance. The methodology behind CAPRI involves decomposing the traffic control problem into interconnected subproblems and predicting traffic flows for various vehicle types. Optimization modules were utilized to solve hierarchical subproblems, with a focus on minimizing delays and optimizing traffic flow. Through simulation-based analyses, CAPRI demonstrated its effectiveness in reducing congestion and improving transit operations compared to traditional traffic control systems. Data collection for CAPRI involved gathering information from detectors, automatic vehicle locators, transponders, and other sources. Testing and implementation of the system were conducted in Tempe, Tucson, Seattle, Santa Clara, and Oakville. CAPRI's adaptability to real-time traffic conditions, coupled with its ability to integrate transit signal priority and emergency preemption, presented a promising solution to address traffic congestion and enhance overall traffic management strategies.

Chapter 3 Traffic Signal Preemption

This chapter specifies the need of traffic signal preemption, explains how to transition into or out of traffic signal preemption, and gives other supplementary guidelines required in the manual on uniform traffic control devices (MUTCD).

3.1 Preemption Criteria

The current practice in traffic control signal preemption follows the guidance and standards in the 9th MUTCD (2009). According to the guidelines, a signalized intersection traffic control signal should be preempted by the approach of a train when it is located within 200 feet of a HRGC. This distance is measured from the edge of the roadway to the nearest edge of the track. During the signal preemption phase, all existing turning movements toward the HRGC should be prohibited.

Made evident from the guidance provided, a set distance (i.e., 200 feet) is utilized to ascertain whether a nearby signalized intersection warrants preemptive measures. In practical scenarios, numerous instances arise where preemptive signals are necessary despite not meeting the specified distance criterion. For instance, those signalized intersections experiencing high traffic volumes may witness queue lengths exceeding 200 feet, potentially obstructing the HRGC and remaining susceptible to potential train crashes.

The MUTCD 2009 also provided additional clarification that queue detection should be considered for traffic signals located farther than 200 feet from the crossing. Regardless of the actual distance between the railroad crossing and a traffic signal, preemption should be considered whenever there is a likelihood that queuing will impact either the railroad crossing or the highway intersection. Factors that could affect queuing include traffic volumes, vehicle mix, train frequency, presence of driveways or unsignalized intersections, and traffic backed up from a nearby downstream intersection.

In the newly published 11th MUTCD (2024), traffic signal preemption is described more clearly. If preemption is provided, the normal sequence of highway traffic signal indications shall be preempted upon the approach of a train to obtain a track clearance interval while providing an opportunity for motor vehicles at the grade crossing to clear the minimum track clearance distance prior to the arrival of rail traffic. Several conditions warrant traffic signal preemption, and the requirements are listed below.

a. If a grade crossing is equipped with flashing-light signals and is located 200 feet or less from an intersection or midblock location controlled by a traffic control signal, the intersection should be provided with rail preemption unless otherwise determined by the traffic engineers.
b. Coordination with the flashing-light signals, such as using queue detection and queue cutter signals, blank-out signs, or other alternatives, should be considered where a traffic control signal is located more than 200 feet from the grade crossing. Factors to be considered should include traffic volumes, highway vehicle mix, highway vehicle and train approach speeds, frequency of trains, presence of midblock driveways or unsignalized intersections, and the potential for vehicular queues resulting from an adjacent downstream grade crossing or highway traffic signal to extend into the minimum track clearance distance.
c. The highway agency or authority with jurisdiction and the regulatory agency with statutory authority, if applicable, should jointly determine the preemption operation and the timing of highway traffic signals interconnected with grade crossings adjacent to signalized locations.

d. If a highway traffic signal is installed 200 feet or less from a passive grade crossing, unless otherwise determined by the traffic engineers, an active grade crossing warning system should be installed at the grade crossing to provide a means to preempt the highway traffic signal in order to clear vehicles from the minimum track clearance distance upon approach of rail traffic.
e. If a highway traffic signal is interconnected with flashing-light signals, the flashing-light signals should be provided with automatic gates to prevent additional vehicles from being drawn into the minimum track clearance distance during the track clearance interval prior to the arrival of rail traffic unless traffic engineers determine otherwise.
f. Where flashing-light signals are in place at a grade crossing, any highway traffic signal face installed within 50 feet of any rail shall be preempted upon the approach of rail traffic. Specifically, the operation of any flashing yellow lights installed within 50 feet of any rail should be considered to determine whether the operation of the traffic lights should be terminated during the approach and passage of rail traffic in order to avoid the display of signal indications that conflict with the flashing-light signals.

3.2 Preemption Types

There are different types of preemption to address various traffic and safety needs, as well as to accommodate different infrastructure and operational considerations. Some types of preemption that have been used are simultaneous preemption and advance preemption, as described below.

Simultaneous preemption is the notification of approaching rail traffic that is forwarded to the highway traffic signal controller unit or assembly and grade crossing warning system at the same time, as can be seen in Figure 3.1. This type of preemption ensures that all affected intersections transition to a preemption mode simultaneously, allowing for coordinated traffic flow adjustments to accommodate the train's passage.

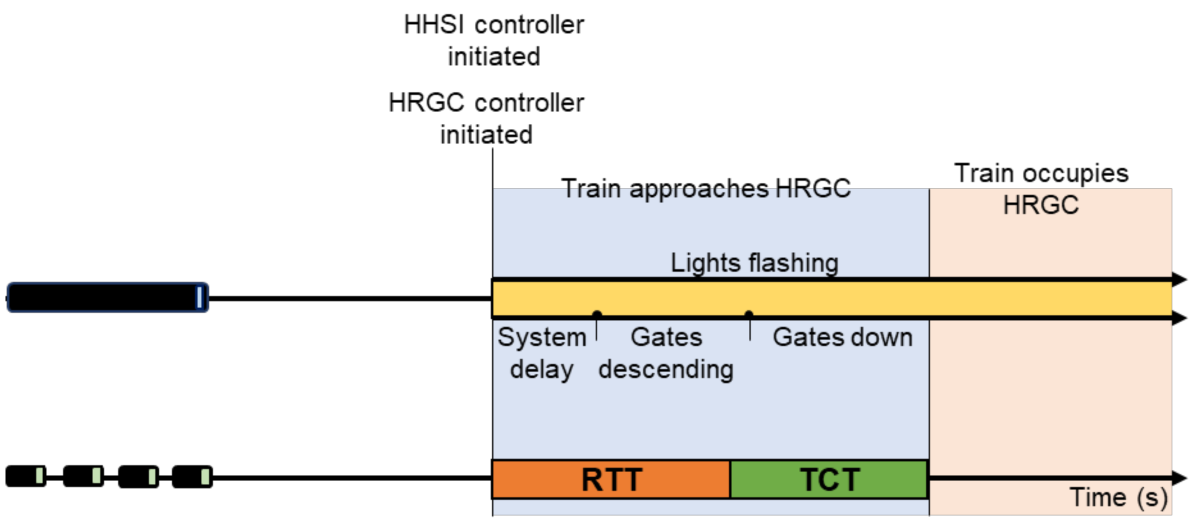


Figure 3.1 Simultaneous preemption signal timing

Advance preemption (Urbanik, et al., 2015) is the notification of approaching rail traffic that is forwarded to the highway traffic signal controller unit or assembly by the railroad equipment in advance of the activation of the grade crossing warning system, as can be seen in Figure 3.2. This type of preemption aims to minimize traffic delays and congestion by providing sufficient time for vehicles to clear the HRGC before the train arrives. More importantly, advance preemption allows extra time for right-of-way transfer from any signal phase to the track clearance phase. Advance preemption often relies on predictive algorithms to anticipate the train's arrival and initiate preemptive measures accordingly.

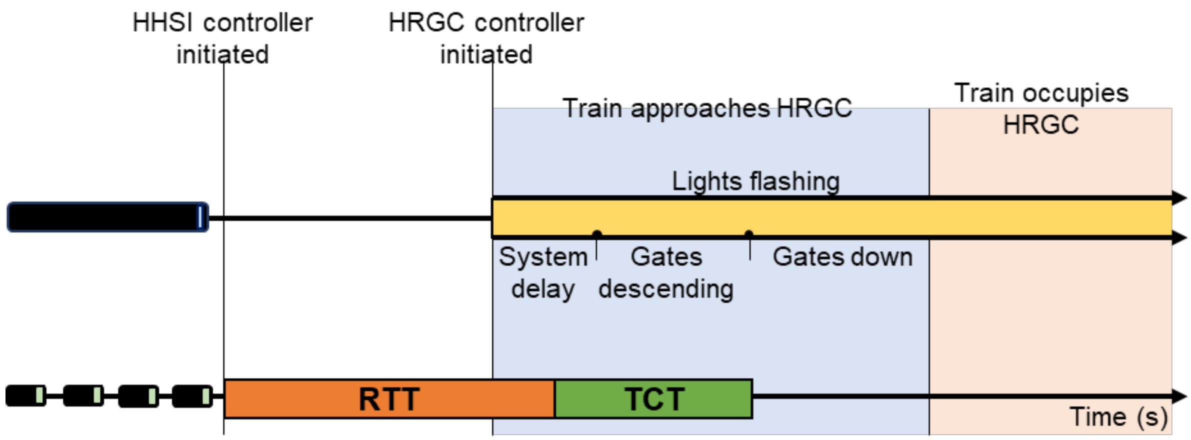


Figure 3.2 Advance preemption signal timing

Simultaneous preemption and advance preemption plans are the most common types of preemption systems utilized at HRGCs. Other types, for example smart preemption, involve multiple railway detector checks and communication with the highway controller. This advanced system is feasible in more state-of-the-art setups and requires collaboration between the highway and railway agencies to establish a mutually agreeable solution (Urbanik and Tanaka, 2017; Venglar, et al., 2000).

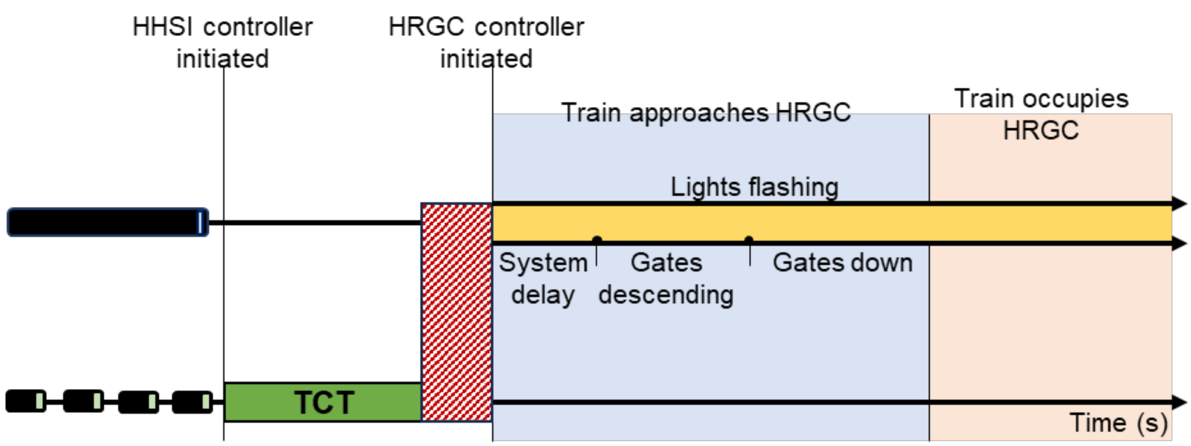


Figure 3.3 Preempt trap (marked in red area)

3.3 Preemption Time Sequence

The maximum preemption time is the maximum amount of time needed following initiation of the preemption sequence for the highway traffic signals to complete the timing of the right-of-way transfer time, queue clearance time, and separation time. The separation time is the component of maximum preemption time during which the minimum track clearance distance is clear of vehicular traffic prior to the arrival of rail traffic.

The right-of-way transfer time is the amount of time needed prior to display of the track clearance interval. This includes any time needed by the railroad, light rail transit, or highway traffic signal control equipment to react to a preemption call, and any traffic control signal green, pedestrian walk and clearance if used, yellow change, and red clearance intervals for conflicting traffic.

3.3.1 Minimum warning time

Minimum warning time is the least amount of time that warning devices operate prior to the arrival of a train at a HRGC, including a minimum time and a clearance time, expressed in Equation 3.1.

$$WT = MWT + CT \qquad \text{Equation 3.1}$$

2009 MUTCD recommended 20 seconds as the minimum warning time before the arrival of a train at the HRGC, and this criterion remains the same in the 2024 MUTCD. Clearance time depends on the track clearance distance.

When automatic gates are present and green signal indications are displayed at the downstream traffic control signal during the track clearance interval, the preemption sequence shall be designed such that the green signal indications are not terminated until the automatic gate(s) that controls access over the grade crossing toward the downstream intersection is fully lowered (MUTCD, 2024).

Advance preemption time is measured as the time difference between the maximum preemption time and the activation of the HRGC warning control. This time period allows the traffic signal controller at HHSI to begin the preemption phase before the HRGC warning control devices are activated (Ogden and Cooper, 2019). The warning time required in an advance preemption plan can be calculated through the time required to transit from the normal signal phase to the preemption phase, clear the vehicles in the clearance lane CLT, and other system delays or buffer time *X*. The calculation can be expressed as Equation 3.2.

$$wt_{req} = APT + (Y + R) + CLT + X \qquad \text{Equation 3.2}$$

3.3.2 Warning time and train detector location

Traffic signal preemption is designed according to the warning time. In simultaneous preemption, a minimum of 20 seconds is required. This warning time should include the transition time, clearance time, and other system delay time. If the warning time requires longer than 20 seconds, then additional warning time should be provided. The advance preemption can be used to provide extra warning time. In such cases, the train warning time would be expressed as Equation 3.3.

$$WT = max(20, wt_{req}) \quad \text{Equation 3.3}$$

Assuming train speed is not changing when approaching the HRGC, the train detector location can be determined using Equation 3.4.

$$d = S_0 * WT \quad \text{Equation 3.4}$$

Where d represents the distance between the train detector location and the HRGC. S_0 represents the initial speed of the train recorded by the detector at the first detection point. It is presumed that the train continued at this speed subsequently.

3.4 Movement Prohibited during Preemption

MUTCD 2024 clearly defined movements prohibited during preemption operation. At an HHSI located within 100 feet of an HRGC and the intersection traffic control signals are preempted by the approach of rail traffic, all existing permissive-only turning movements toward the grade crossing should be prohibited, steady red arrow signal indications should be shown to all existing protected/permissive and protected-only turning movements toward the grade crossing, and red signal indications should be shown to the straight-through movement toward the grade crossing during the signal preemption sequences (MUTCD, 2024).

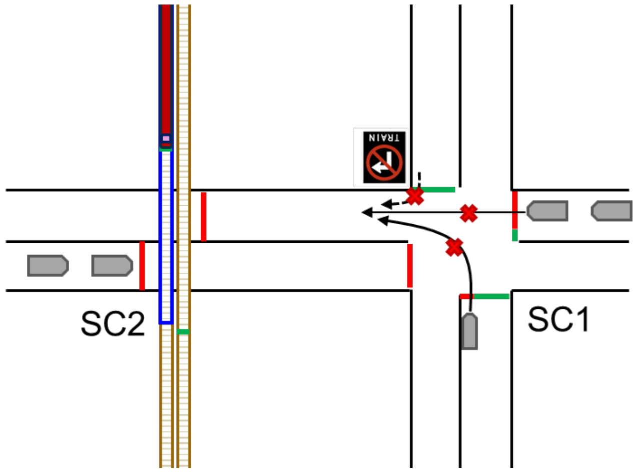


Figure 3.4 Movements Prohibited During Preemption

The prohibition of a permissive-only turning movement toward the grade crossing during preemption should be accomplished through the installation of a blank-out turn prohibition sign. Moreover, if the clear storage distance is more than 100 feet, it is optional that all movements toward the track may be prohibited at a signalized intersection preempted by the approach of rail traffic.

Chapter 4 Simulation Model Development

This chapter will delve into the intricate process of developing a simulation model tailored for traffic preemption control in the studied corridors. The overall process outlines the approach for signal control timing taken in this project, divided into four steps: (1) constructing the road network, (2) implementing fixed-time control, (3) establishing actuated control, and (4) integrating preemption strategies. This is the key to the simulation model for signal preemption involving HRGCs. Traffic volumes and other configurations are also important to input in simulations. Each component is crucial in accurately replicating the dynamics of HHSIs and HRGCs within the simulation environment.

The simulation model is developed in VISSIM, a versatile traffic simulation software, for both vehicular and train traffic at and near the HRGC corridors selected for this project. The comprehensive approach proposed in this research ensures a realistic and effective representation of traffic flow and control mechanisms, setting the stage for subsequent analyses and findings.

4.1 Overall Procedure

In this project, the traffic signal preemption plan is designed to include four critical states. Throughout the simulation process, each step will check whether the conditions are changed as a function of the detected location of a train when it approaches the HRGC. As can be seen in Figure 4.1, these four states are: S1: normal operation, S2: start preemption, S3: preemption hold, and S4: end preemption. These four states are outlined below.

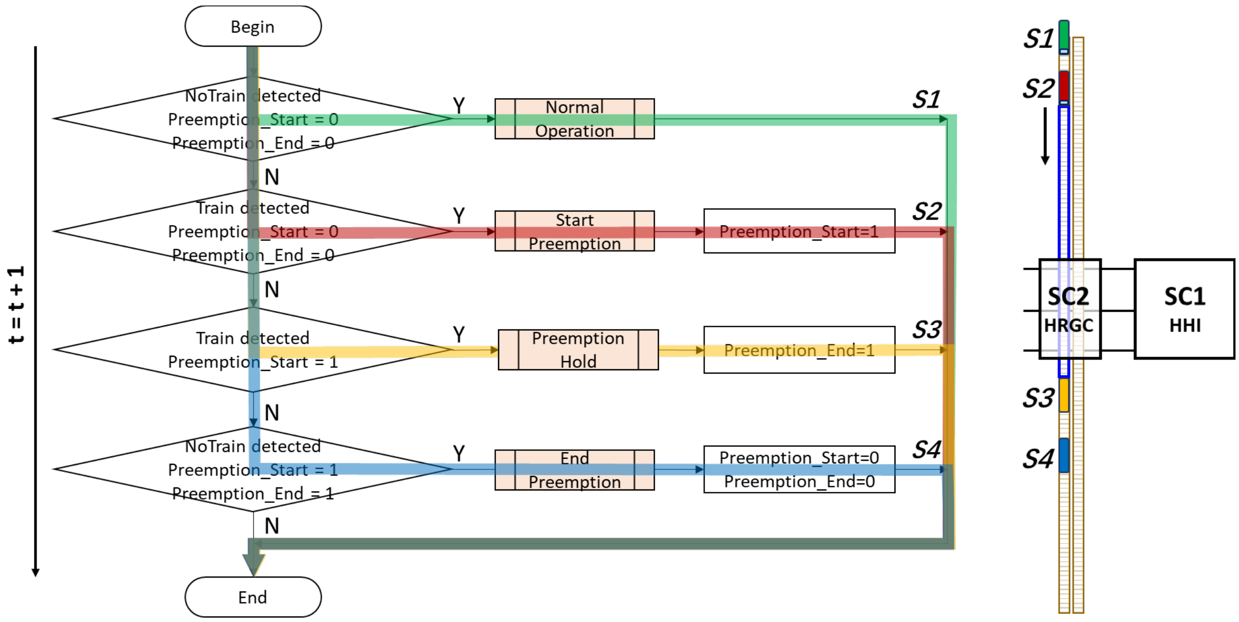


Figure 4.1 Preemption logic flowchart

- **S1 - Normal Operation**: At this state, the traffic signal functions under regular operating conditions, unaffected by the proximity of any trains.
- **S2 - Start Preemption**: When a train is detected approaching the HRGC, the system initiates the preemption process, signaling the onset of preemption procedures.
- **S3 - Preemption Hold**: During this state, the preemption signal plan remains active, and only traffic in certain non-conflicting directions, such as movement parallel to the train track, is given the green light.
- **S4 - End Preemption**: Once the train has cleared the HRGC and the track is deemed safe for vehicular traffic, the preemption status concludes, and normal signal operations resume.

Within the framework of the traffic preemption signal plan's four states, six steps are intricately tied to the train's location (T1 – T6) as identified by the detection algorithm. Figure

4.2 offers an alternative perspective on the preemption states, providing a detailed description of their dynamics.

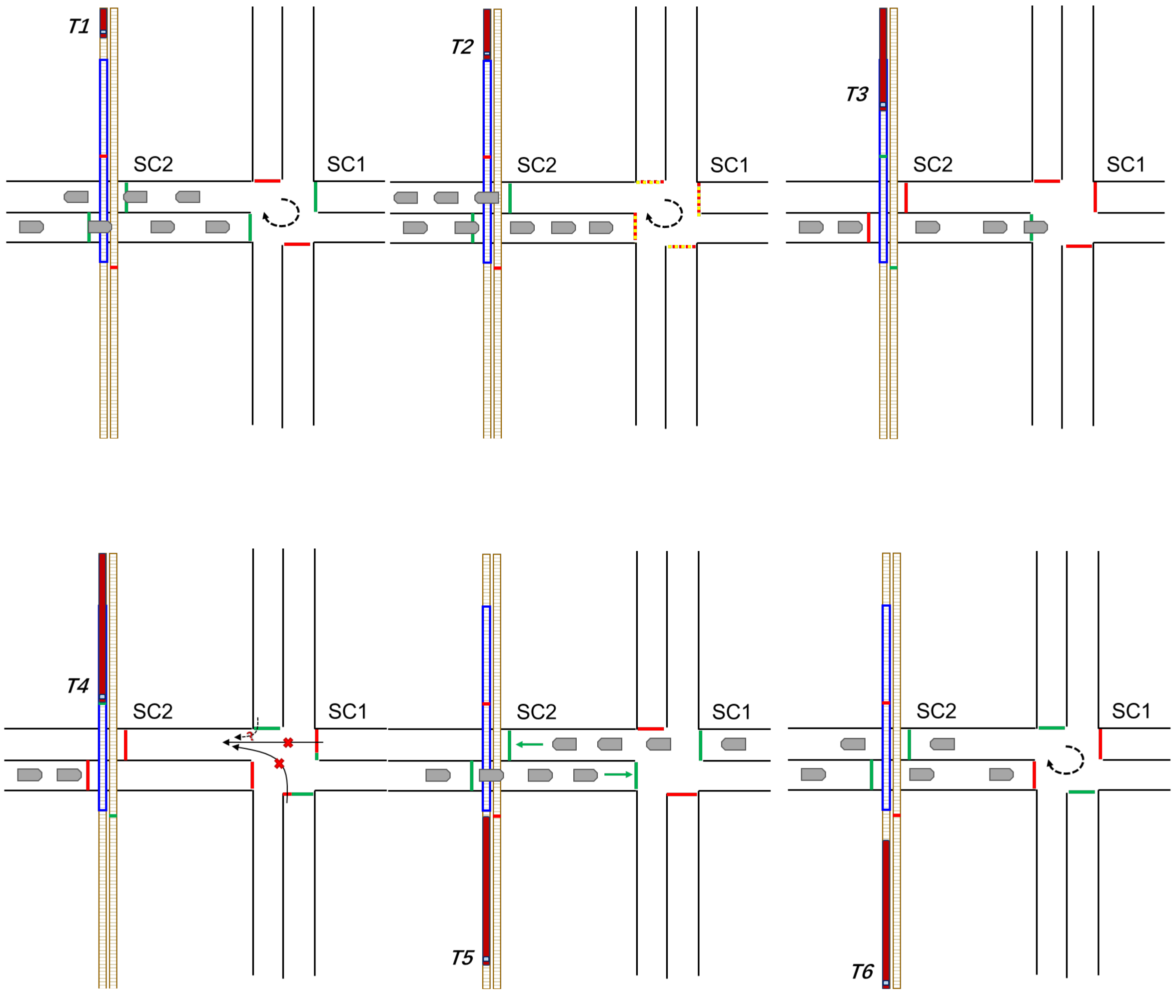


Figure 4.2 Critical timestamps of the relationship between train locations and the signal controls at HRGC and HHSI

T1 marks the phase where the approaching train has yet to reach the detector, with traffic signals operating in standard mode. The detector is activated by the train locomotive for the first time when transitioning to T2, prompting an immediate initiation of the preemption signal plan. Any ongoing signal sequence from the prior moment is promptly terminated through a signal transition, typically displaying yellow and all-red signals. At T3, the preemption plan commences as the train continues to engage the detector but has not yet reached the HRGC. During this phase, a clearance interval is executed within the preemption plan. This interval facilitates the clearance of any vehicles remaining between the HRGC and the HHSI. Moving to T4, the preemption plan stabilizes as the train arrives at the crossing. During this period, all the turning movements toward the HRGC are prohibited, indicated by red arrow signals. T5 occurs when the end of the train clears the detector, signaling the conclusion of the preemption signal plan. Subsequently, another clearance signal phase is enacted to prioritize delayed traffic directions. Finally, at T6, the traffic signal plan seamlessly transitions back to standard mode, returning to normal operation.

In the simulation implementation, the development of a simulation model for the preemption control went through four general steps, as described below.

4.1.1 Step 1: Road network

The initial development of the simulation model involves developing a basic model of a generic HHSI and the nearby HRGC. Specifically, this simulation model starts with building the road network for the study corridors, including lane geometry and configuration, initial speed distribution, traffic demand, traffic signal control, and so forth. Traffic flow data including the number of vehicles for each turning movement (i.e., vehicle routes) at the HHSI and the train volumes on both tracks that pass through the HRGC will be input in the simulation. An example of the simulation model for the HHSI and HRGC pair is illustrated in Figure 4.3.

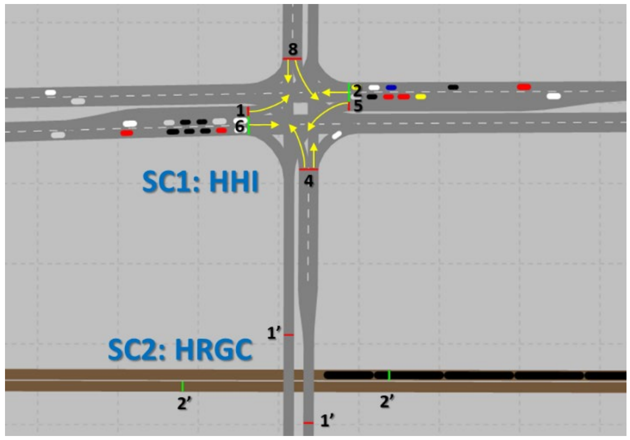


Figure 4.3 Road network and signal timing in the simulation model

4.1.2 Step 2: Signal control setup

Traffic signal controllers at the HHSI and HRGC are critical components in the successful development of the preemption plan. This step includes determining phases, sequencing, and timing of the signal heads for multiple road users, i.e., vehicles, pedestrians/bicycles, left turners, and train preemptions. Different combinations of these phases would lead to different signal preemption strategies and should be set up in the simulation environment in accordance with the signal timing plan using the field data.

4.1.3 Step 3: Actuated control (VAP control)

The preemption logic is coded using the Visvap application. Visvap is a graphical editor that retrieves information (e.g., instantaneous vehicular speed) from the virtual loop detectors in the VISSIM model as the simulation model is running. It then uses the information to ascertain current conditions (e.g., average traffic speed), which is used to identify the train location and the arrival time that is sent to the vehicle actuated programming (VAP) controller at the HHSI. There are three critical components to the VAP control logic, as introduced in detail below.

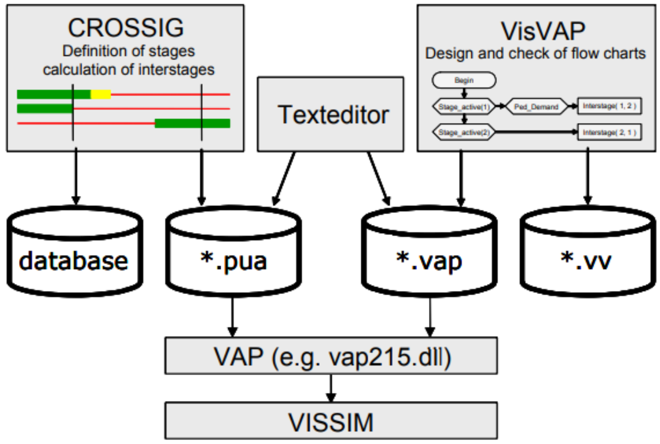


Figure 4.4 VAP control structure

4.1.3.1 Detector setup and configuration

The detectors are set at the HHSI in semi-activation mode, meaning the major arterial (i.e., NE-2) through traffic is always in the green phase until left-turns on NE-2 or the minor road (i.e., the street intersects with NE-2) have a call for right-of-way. Under this logic, loop detectors at the HHSI are set up on the corresponding phases. Another set of loop detectors is put along the tracks to determine when the train is approaching and when it is occupying an HRGC. The location and length of the train detectors are determined as a function of the train speed, predefined warning time and buffer time, and the HRGC geometry (e.g., distance to the HHSI).

4.1.3.2 Traffic state check

The current traffic conditions (e.g., train operation) are checked at each time step to determine whether the traffic signal operation needs to be changed. This adjustment is mainly triggered by the arrival of a train and the activation of detectors, which serve as key factors in determining the transition to different signal plans.

4.1.3.3 Intergreen determination

The intergreen interval is the transitional period between the end of the green phase for one movement and the start of the green phase for another movement. This interval usually includes the yellow light and may include an all-red phase. This intergreen timing will be configured in a PUA file and connected to VISSIM together with the VAP file.

4.1.4 Step 4: Preemption Implementation

Based on the preparation of the previous steps, this step implements the preemption strategies in the simulation model. The key is to connect and coordinate the signal controller at the HHSI (i.e., SC1) and the signal controller at the HRGC (i.e., SC2). During this step, the warning time is determined as a sum of minimum warning time, system response time, and buffer time.

The MUTCD recommends the minimum warning time is 20 seconds before the train approaches and occupies the HRGC. In this way, it can back-calculate the location of the train detector. For example, if a train approaches with an average speed of 50 mph, the minimum distance of installing the train detector from the HRGC would be 50*1.47*20 = 1470 ft (indicated as “X” in Figure 4.5). This distance should be much longer than the length of the lane between the HHSI and the HRGC, i.e., the clearance distance. This way, the last queued vehicle that occupied the HRGC (and already crossed the stop line) will have enough time to clear the short lane before the traffic signal on this clearance phase turns red at the HHSI.

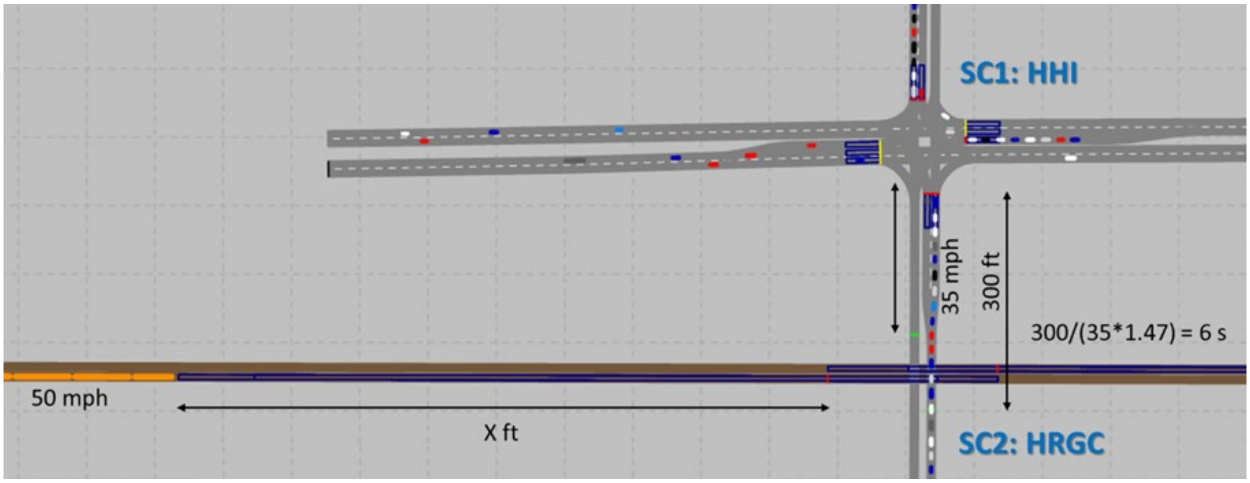


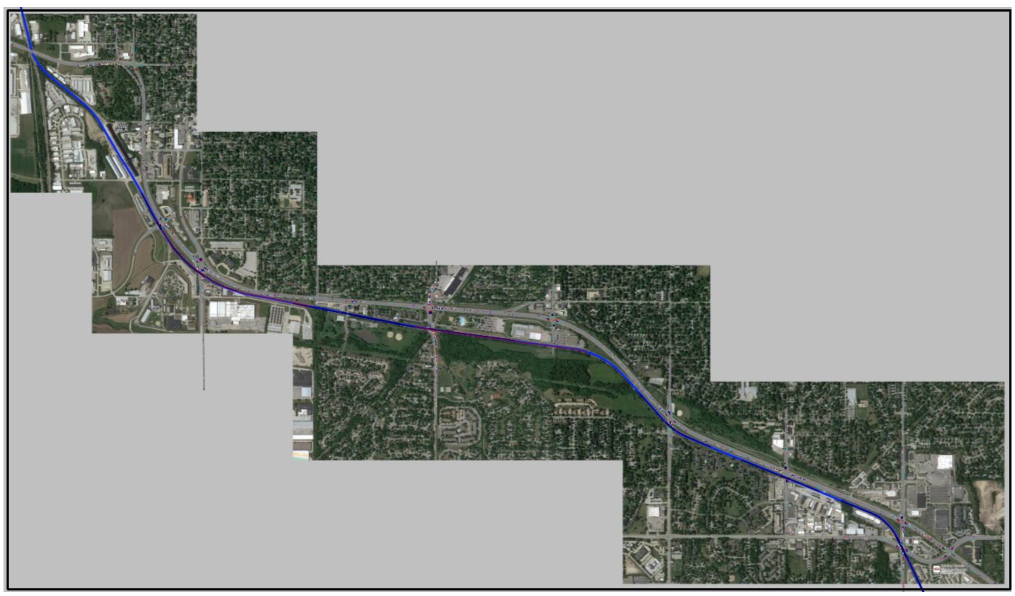
Figure 4.5 Example of the warning time calculation in the simulation model

It is important to highlight that the detector configuration described above represents simultaneous preemption signal control, where both the HHSI and HRGC signals are activated simultaneously upon the detector's identification of a train. For the purpose of simulating advanced preemption, it is necessary to employ two distinct sets of detectors. These detectors are tasked with specifically informing the HHSI and HRGC signals. Detailed information on this approach will be presented in the subsequent sections, focusing on the actual simulation development for the study sites.

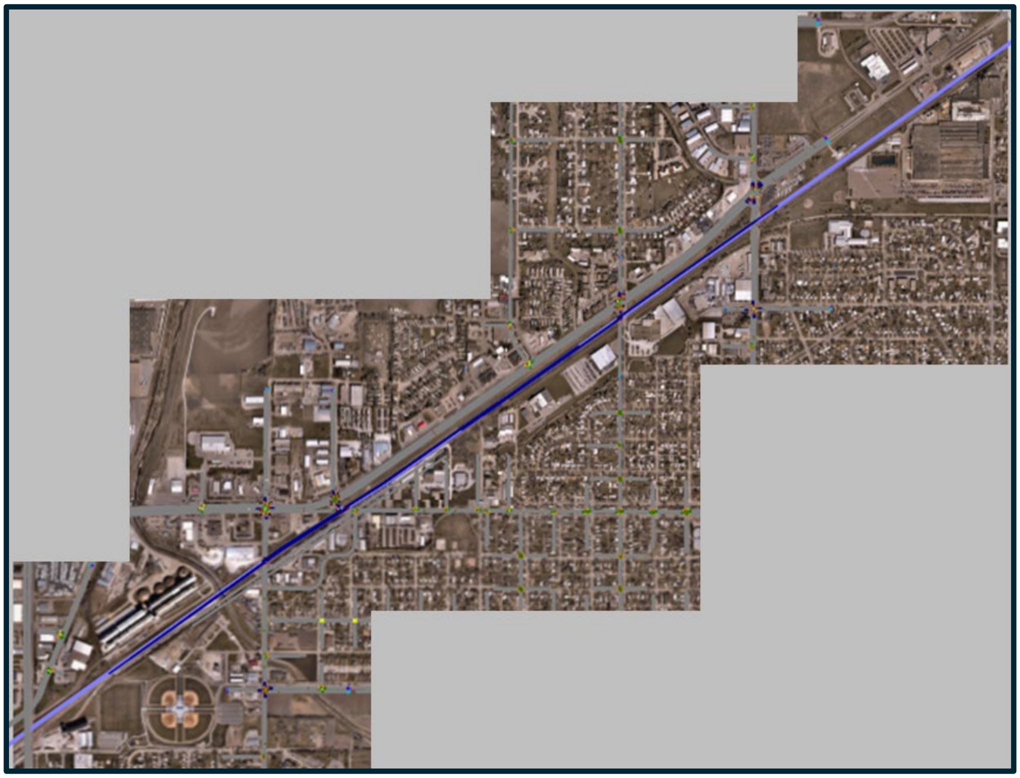
These four steps will be carried out using actual data in the field along the study corridors. It may also be adjusted to accommodate specific intersection conditions, which will be discussed in the later sections. The framework of the overall approach used in this project ensures a highly detailed and reliable simulation model, facilitating the development of HHSI/HRGC preemption control plans and assessment of their performance in the next chapters.

4.2 Study Corridors

Two HRGC corridors were selected for this project, i.e., Nebraska Highway 2 (NE-2) and Cornhusker Highway 6 (US-6). Along the NE-2 corridor, there are 11 signalized intersections in the 4-mile-long study section, while the US-6 corridor has 4 signalized intersections in the 1-mile-long study section. In this sample, 6 intersections on NE-2 and 2 on US-6 have preemption features in coordination with nearby HGCs, making them the focus of our study.



(a) NE-2 corridor



(b) US-6 corridor

Figure 4.6 Study corridors in this project

Another distinction between the two chosen corridors is that while the NE-2 corridor features only a single track, the US-6 corridor is equipped with two tracks, allowing trains to arrive at the crossing from both directions simultaneously. Regarding train volume, US-6 encounters a significantly higher number of trains, approximately 30-50 daily, in contrast to NE-2, which only sees about 1-2 trains per day.

In the following sections, NE-2 & 14th HHSI and the nearby HRGC are used as an example to describe the simulation model parameters. The settings for other HHSIs and HRGCs along the study corridors are similar, with their traffic condition information provided in the appendix.

4.3 Traffic Volumes

Table 4.1 provides the traffic volumes for each movement at the study intersections along Nebraska Highway 2 and Cornhusker Highway 6. The traffic counts were conducted by the City of Lincoln from 2021-2022.

Table 4.2 Traffic volumes at the study intersections (Unit: vehicles per hour)

Intersection	NBL	NBR	NBT	EBL	EBR	EBT	WBL	WBR	WBT	SBL	SBR	SBT
Pioneers Blvd & NE highway 2	167	6	1390	160	275	3	17	17	2	3	78	1431
14th & NE highway 2	482	188	416	14	637	986	141	179	1192	248	32	491
Southwood Dr & NE highway 2	79	76			123	1376	98		1444			
27th & NE highway 2	248	297	248	77	253	1053	238	253	1184	297	74	751
40th & NE highway 2	224	96	443	26	249	1093	129	84	964	114	534	27
48th & NE highway 2	128	150	339	86	137	1090	86	107	992	142	61	411
56th & NE highway 2	162	54	698	200	175	988	21	197	854	194	178	748
33rd & Cornhusker highway 6	296	95	29	38	280	1240	116	35	1156	63	52	64
35th & Cornhusker highway 6	327	9	8	29	619	839	23	19	867	24	34	23
44th & Cornhusker highway 6	29	9	21	65	45	851	21	27	796	45	44	20

Since both Nebraska Highway 2 and Cornhusker Highway 6 are major arterials on the east-west corridor, the traffic volumes are predominantly eastbound and westbound through traffic (except the Pioneers Blvd and Nebraska Highway 6 intersection, where the corridor's direction changes to N-S). The select intersections in Table 4.1 also represent a wide range of the traffic volume scenarios in the north and south directions that intersect with the two corridors.

4.4 Signal Control Configuration

The research team coded the signal control configuration in the Visvap program. The field data regarding the signal sequence and timing is obtained from the City of Lincoln in a Synchro file document updated in 2022. At the NE-2 and 14th St. HHSI, the traffic signal plan includes 8 phases (pedestrian phases are not studied in this project). Other key information is provided below.

4.4.1 Signal timing at the HHSI near the HRGC

Table 4.2 listed the signal timing information at the HHSI regarding the phases, minimum green time, maximum green time, yellow and all-red time for each of the 8 phases, respectively. Note that phases 4 and 8 represent the NE-2 corridor in the east-west direction, which is the major road. Phases 2 and 6 align with 14th Street, a minor road running in the south-north direction. The major road (NE-2) in phases 4 and 8 are the max recall phases, indicating the longest duration set of signal group for the NE-2 corridor through movement before it must change to allow traffic flow in other directions.

Table 4.3 Signal timing information for HHSI

Phase	1	2	3	4	5	6	7	8
Direction	N-L	S-T	E-L	W-T	S-L	N-T	W-L	E-T
Min Green	5	10	5	10	5	10	5	10
Vehicle Exit	1.5	2	1.5	2	1.5	2	1.5	2
Max1	30	30	15	50	20	30	25	50
Max2	30	40	20	60	30	40	25	60
Yellow	3	3.6	3	4.3	3	3.6	3	4.3
Red Clear	1	3	1	3	1	3	3	3
Max Recall				X				X

For the traffic signal preemption phase, Table 4.3 listed the information at the NE-2 and 14th St. HHSI. Phases 1 and 6 in the northbound direction (N-L and N-T) serve as the track clear phases.

Table 4.4 Signal timing information for HHSI preemption

Phase								
Direction	N-L	S-T	E-L	W-T	S-L	N-T	W-L	E-T
Track Clear Vehicle	X					X		
Cycling Veh			X	X	X			X
Exit Phase	X					X		
	Min Green			Red			Yellow	
Track Clearance Times	29			5			10	
Entrance Times	5			5			10	

4.4.2 Visvap coding for the HHSI

Table 4.4 lists the parameter settings for the HHSI in Visvap regarding detector lengths in both directions. This length of 1082 ft, which is calculated using Equation 3.4. Table 4.5lists predefined array settings for the signal preemption algorithm. Table 4.6 lists expressions and Table 4.7 lists subroutines that have been called during the program.

Table 4.5 Parameters of HHSI

PARAMETERS	Description	Value
DetLength1	Detector length 1	1082 ft
DetLength2	Detector length 2	1082 ft
MinWarnTime	Minimum warning time	20 sec
PreemptMin	Minimum preemption time	5 sec
TrackClrTime	Track clearance time	7 sec

Table 4.6 Arrays of HHSI

ARRAYS	Dim	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	Comment
tamber	8	3	4	3	4	3	4	3	4	Yellow time
RedClear	8	1	3	1	3	1	3	1	3	All-red time
MinGreen	8	5	10	5	10	5	10	5	10	Minimum green time
MaxGreen	8	15	50	30	30	25	50	20	30	Maximum green time
Recall	8	0	1	0	0	0	1	0	0	Recall phase (2, 6) regardless of whether vehicles are detected
Passage	8	1.5	2	1.5	2	1.5	2	1.5	2	Passage time to extend the green
DwellRecall	8	0	1	0	0	0	1	0	0	Dwell recall phase
split	8	19	57	34	37	31	57	24	37	Split time (max green, yellow, and all-red)

Table 4.7 Expressions of HHSI

EXPRESSIONS	Contents	Comment
TrainDemand	presence(50) or occupancy(50) or presence(51) or occupancy(51)	Detection of an approaching train from EB (50) or WB (51)
TrainArrival	presence(211) or occupancy (211) or presence (611) or occupancy (611)	Detection of an arriving train from EB (211) or WB (611)
call1	presence(1) or occupancy (1) or recall[1]	If EBL detects a waiting car, call phase 1
call2	Recall[2] or DwellRecall[2]	Keep phase 2 if not reach maximum or no other call
call3	presence(3) or occupancy (3) or recall[3]	If SBL detects a waiting car, call phase 3
call4	presence(4) or occupancy (4) or recall[4]	If NBT detects a waiting car, call phase 4
call5	presence(5) or occupancy (5) or recall[5]	If WBL detects a waiting car, call phase 5
call6	Recall[6] or DwellRecall[6]	Keep phase 6 if not reach maximum or no other call
call7	presence(7) or occupancy(7) or recall[7]	If NBL detects a waiting car, call phase 7
call8	presence(8) or occupancy(8) or recall[8]	If SBT detects a waiting car, call phase 8
gapout1	headway(1)>passage[1]	
gapout3	headway(3)>passage[3]	
gapout4	headway(4)>passage[4]	

EXPRESSIONS	Contents	Comment
gapout5	headway(5)>passage[5]	
gapout7	headway(7)>passage[7]	
gapout8	headway(8)>passage[8]	
minover1	t_green(1)>=mingreen[1]	
minover3	t_green(3)>=mingreen[3]	
minover4	t_green(4)>=mingreen[4]	
minover5	t_green(5)>=mingreen[5]	
minover7	t_green(7)>=mingreen[7]	
minover8	t_green(8)>=mingreen[8]	
maxout1	t_green(1)>=maxgreen[1]	
maxout2	t_green(2)>=maxgreen[2]	
maxout3	t_green(3)>=maxgreen[3]	
maxout4	t_green(4)>=maxgreen[4]	
maxout5	t_green(5)>=maxgreen[5]	
maxout6	t_green(6)>=maxgreen[6]	
maxout7	t_green(7)>=maxgreen[7]	
maxout8	t_green(8)>=maxgreen[8]	
gapout15	gapout1 and gapout5	
gapout37	gapout3 and gapout7	
gapout48	gapout4 and gapout8	
minover15	minover1 and minover5	
minover37	minover3 and minover7	
minover48	minover4 and minover8	
maxout15	maxout1 and maxout5	
maxout26	maxout2 and maxout6	
maxout37	maxout3 and maxout7	
maxout48	maxout4 and maxout8	
call26	call2 or call6	
call15	call1 or call5	
call48	call4 or call8	
call37	call3 or call7	
TrainspeedEB	velocity(50)	
Trainspeed WB	velocity(51)	
AdvancePreemptEB	(DetLength1/TrainspeedEB)-(MinWarnTime+1)	
AdvancePreemptWB	(DetLength2/TrainspeedWB)-(MinWarnTime+1)	

Table 4.8 Subroutines of HHSI

SUBROUTINES	Filename	Comment
Start_preemption_14th	.\Start_preemption_14th.vv	
End_preemption_14th	.\End_preemption_14th.vv	
Normal_operation_14th	.\Normal_operation_14th.vv	
Hold_preemption_14th	.\Hold_preemption_14th.vv	

The logic flowchart for the main program and the subroutine procedures and functions are shown in Figure 4.7.

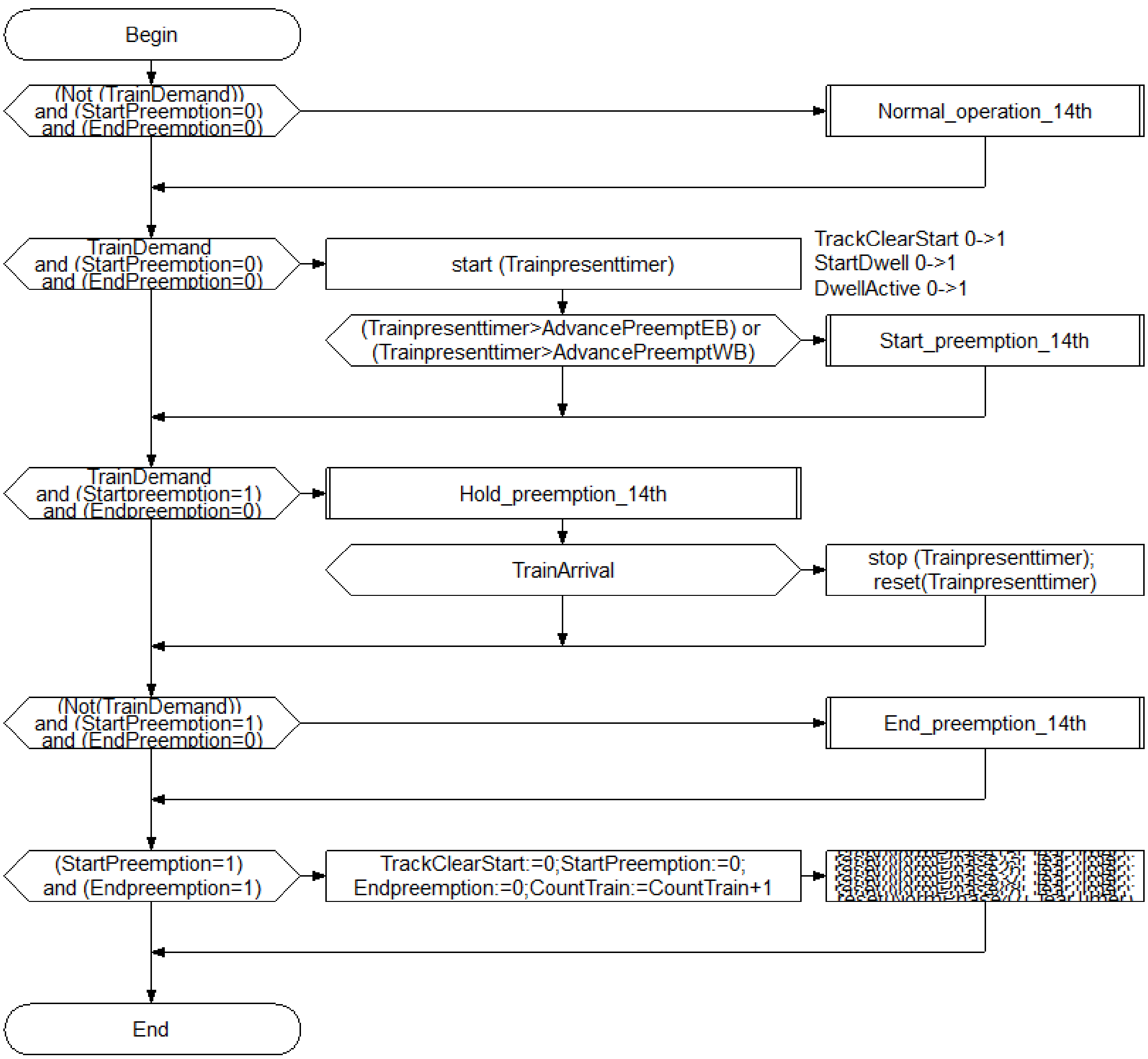


Figure 4.7 Flowchart of the preemption signal control from Visvap

4.4.3 Visvap coding for HRGC

HRGC signal control is coded in Visvap to simulate the active gate and flashing light control when a train arrives. The overall Visvap flowchart is shown in Figure 4.8 There are two critical calculations in the HRGC Visvap coding, as shown in Table 4.8. One is to calculate the time to arrive at the crossing from the moment when the train triggered the train detectors on the railway. As can be seen in Table 4.9, the train detectors, train signal heads for trains, and gate signal heads for vehicles in both WB and EB. The other is to control the HRGC signal in deciding when to switch in coordinating with the HHSI signal (Table 4.10).

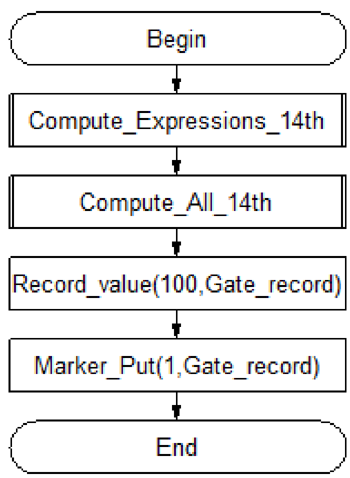


Figure 4.8 HRGC VisVAP

Table 4.9 Two critical calculations for the HRGC Visvap program

SUBROUTINES	Filename	Comment
Compute_Expressions_14th	Compute_Expressions_14th.vv	
Compute_All_14th	Compute_All_14th.vv	

Table 4.10 Visvap parameters for HRGC

PARAMETERS	Gen	Comment
TrainDetectorIn1	60	long detector extending from point of RR2 start through the intersection (length = 1024 ft, 20 s)
TrainDetectorIn2	61	long detector extending from point of RR2 start through the intersection (length = 1024 ft, 20 s)
GateSignalHead1	202	signal head number placed on road, represents the gates, EB
GateSignalHead2	206	signal head number placed on road, represents the gates, WB
TrainSignalHead1	204	signal head number placed on tracks
TrainSignalHead2	208	signal head number placed on tracks
BellRingTime	6	starts at detection, precedes gate down - 4 seconds in OR
GateMoveTime	6	time for gates to come down - 6 seconds in OR
TrainClearTime	0	The Sum of BellRingTime + GateMoveTime + TrainClearTime >= 20 seconds (MUTCD)
TrainSignalEarlyGreen1	0	EB early green time in the advanced preemption
TrainSignalEarlyGreen2	0	WB early green time in the advanced preemption
INITIAL	1	Initial signal phase (always give to highway)
CHECKIN	2	Check if there is no train occupying the detector
TIMEOUT	3	Timeout for checking
YELLOW	4	Yellow time
RDCLEAR	5	Red clear time

Table 4.11 HRGC signal timing

ARRAYS	Dim1	[1]	[2]	[3]	[4]	Comment
TA	4	0	0	0	0	Amber time
RC	4	0	0	0	0	Red Clearance time

Chapter 5 Sensitivity Analysis

Sensitivity analysis is an essential component aimed at understanding how various factors impact the performance of the preemption plan at HRGCs. To execute this task, the research team will utilize the established simulation models developed in Chapter 4, which incorporate different preemption scenarios and site characteristics. This includes systematically varying factors such as traffic volume, train length (crossing blockage duration), and train speed. Ten test sites (i.e., HRGC and HHSI pairs) along the two study corridors (i.e., NE-2 and US-6) are selected for the sensitivity analysis.

By conducting a thorough sensitivity analysis, the performance of the design and implementation of optimized preemption strategies will be measured under varying operating conditions. This analysis will inform the guideline development of the preemption strategies in the next chapter (Chapter 6) aimed to improve safety and mobility at HRGCs.

5.1 Selected Sites

In total, seven test sites from NE-2 and three test sites from US-6 were selected for sensitivity analysis. The geometry of the HHSI and HRGC for each test site is shown in Figure 5.1. By order they are: (a) Pioneers Blvd & NE-2 (b) 14th & NE-2 (c) Southwood Dr & NE-2 (d) 27th & NE-2 (e) 40th & NE-2 (f) 48th & NE-2 (g) 56th & NE-2 (h) 33rd & US-6 (i) 35th & US-6 (j) 44th & US-6. The distances between the HRGC and the HHSI, measured between the edge of the nearest track and the nearest lane, range from 41 ft (i.e., (f) 48th & NE-2) to 487 ft (i.e., (g) 56th & NE-2).

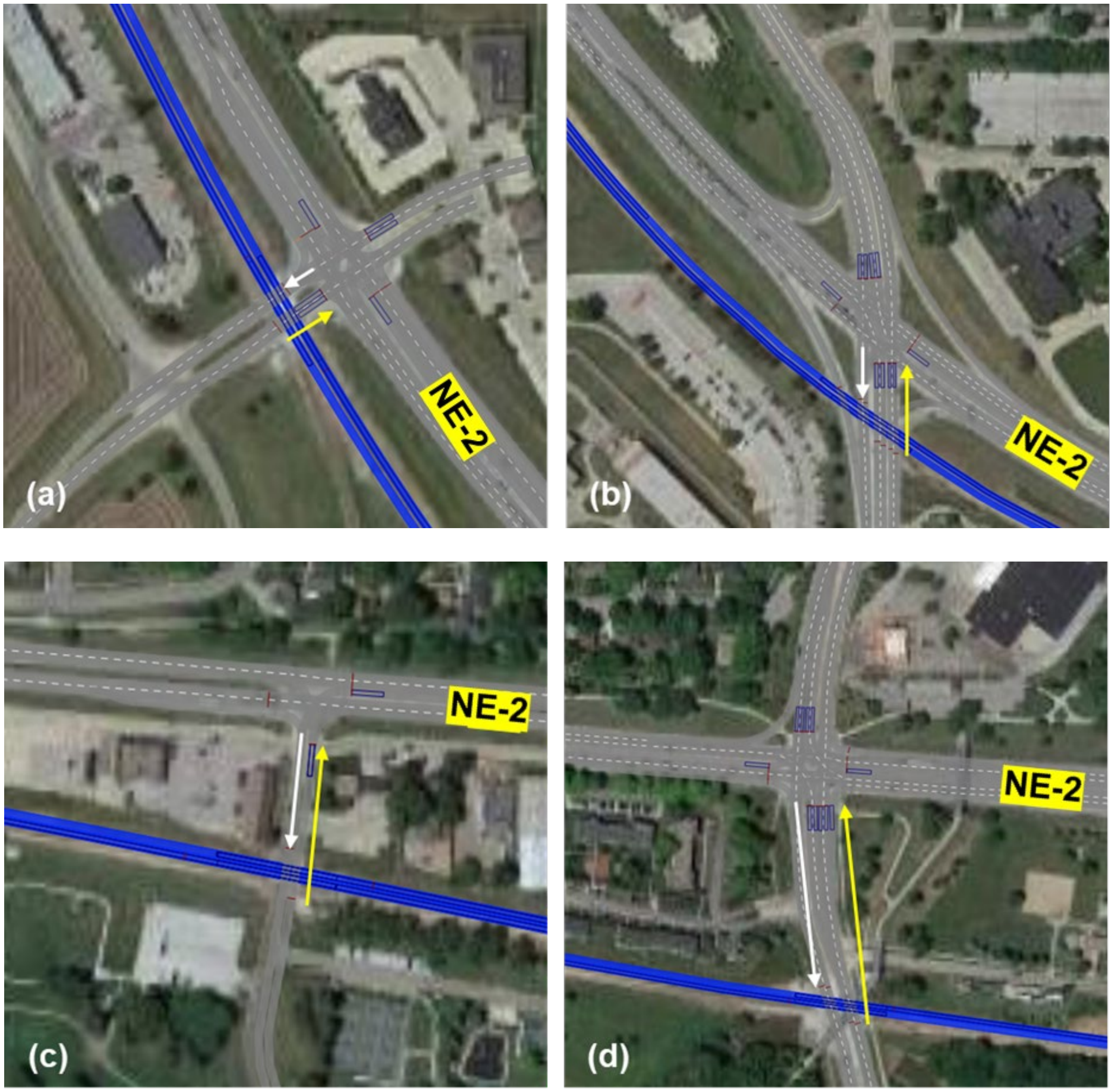


Figure 5.1 Test sites along the Nebraska highway 2 corridor (a-g) and Cornhusker highway 6 corridor (h-j)

Figure 5.1 cont. Test sites along the Nebraska highway 2 corridor (a-g) and Cornhusker highway 6 corridor (h-j)

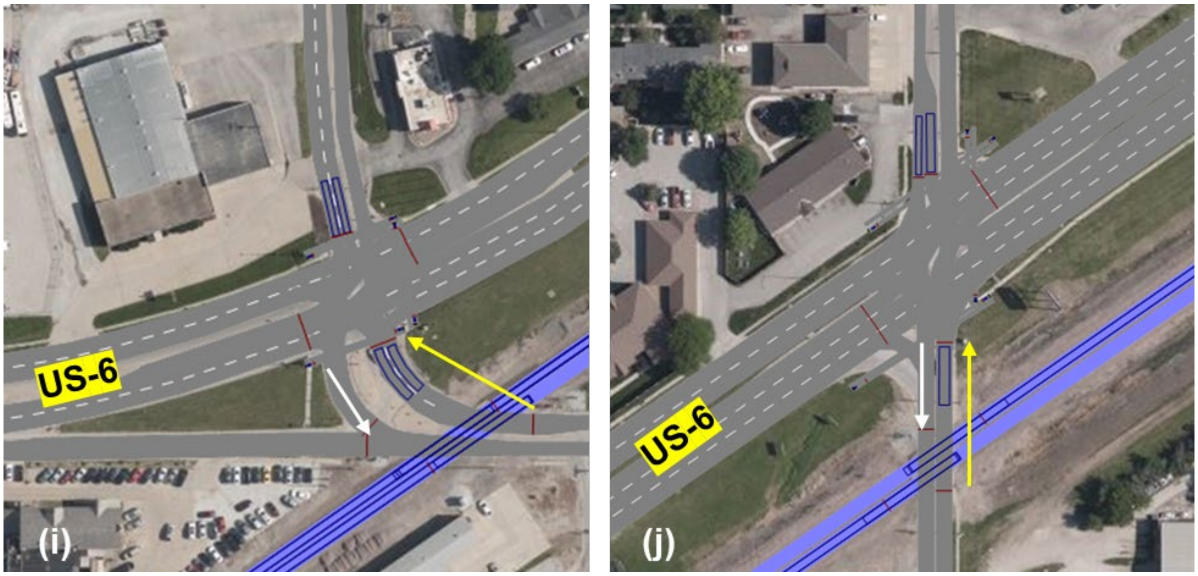


Figure 5.1 cont. Test sites along the Nebraska highway 2 corridor (a-g) and Cornhusker highway 6 corridor (h-j)

In Figure 5.1, there are two distances marked at each HRGC and HHSI pair. They measure the clearance distance (yellow arrow) and the storage distance (white arrow). To define these two distances, we used two concepts from the HRGC handbook (Ogden and Cooper, 2019), which defined the minimum track clearance distance and clear storage distance, as shown in Figure 5.2. according to the HRGC handbook, the upstream point of the minimum track clearance distance is the portion of the automatic gate arm that is farthest from the nearest rail. The downstream point of the minimum track clearance distance is either six feet beyond the track(s) or six feet beyond the edge of the downstream highway-highway intersection, whichever is closer. This distance is measured along the center or edge of the highway and perpendicular to the farthest rail.

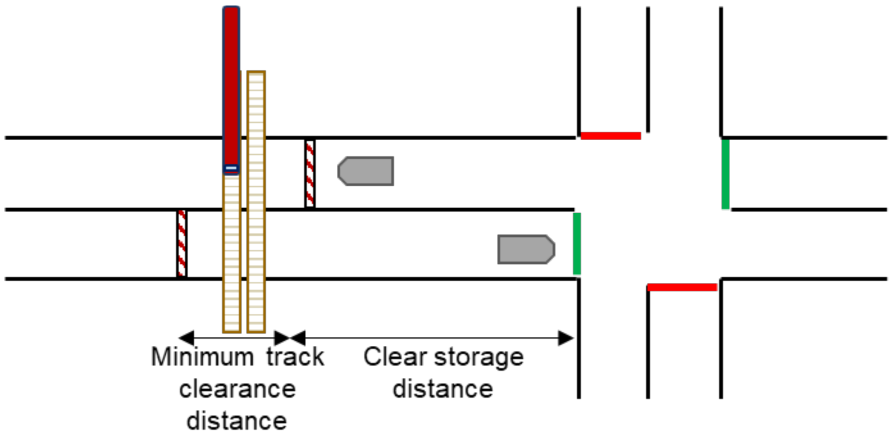


Figure 5.2 Definition of clearance distances in the HRGC handbook

To facilitate the study and to be consistent, the clearance distance in this project (yellow arrow in Figure 5.1) refers to the sum of the minimum track clearance distance and the clear storage distance defined in the HRGC handbook, and the storage distance in this project (white arrow in Figure 5.1) refers to the clear storage distance defined in the HRGC handbook. These two distances are measured at each test site and are summarized in Table 5.1.

Table 5.12 Summary of the road geometric parameters

Corridor	Crossing street	No of storage lanes	Storage distance (ft)	No of clearance lanes	Clearance distance (ft)
NE-2	Pioneers	1	24	2	91
NE-2	14th	2	81	4	166
NE-2	Southwood	1	209	1	261
NE-2	27th	2	408	4	457
NE-2	40th	2	60	4	161
NE-2	48th	2	26	3	78
NE-2	56th	2	453	2	589
US-6	33rd	1	528	2	583
US-6	35th	1	78	2	194
US-6	44th	1	57	1	126

5.2 Performance Measure

Queue lengths at the clearance lane (defined in the previous section), as shown in Figure 5.2, are expected to experience regular accumulation and dissipation cycles when no train is approaching. When there is a train that preempts the traffic signal, the queue at the clearance lane is expected to be cleared before the train occupies the HRGC. On the other hand, queue lengths at rail tracks in the same direction (e.g., northbound in this example), as shown in Figure 5.2, would be zero if no queued vehicles accumulated from the clearance lane. When a train occupies the HRGC, queues in front of the rail track would grow extremely long.

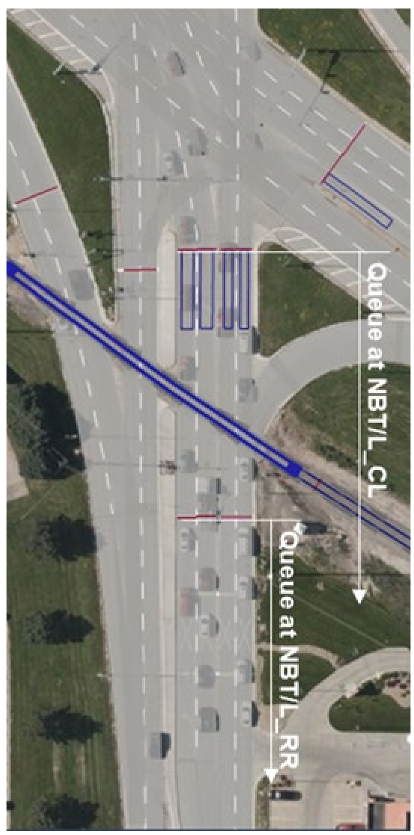


Figure 5.3 Queue length measurement at clearance lane (CL) and rail track (RR) in NB

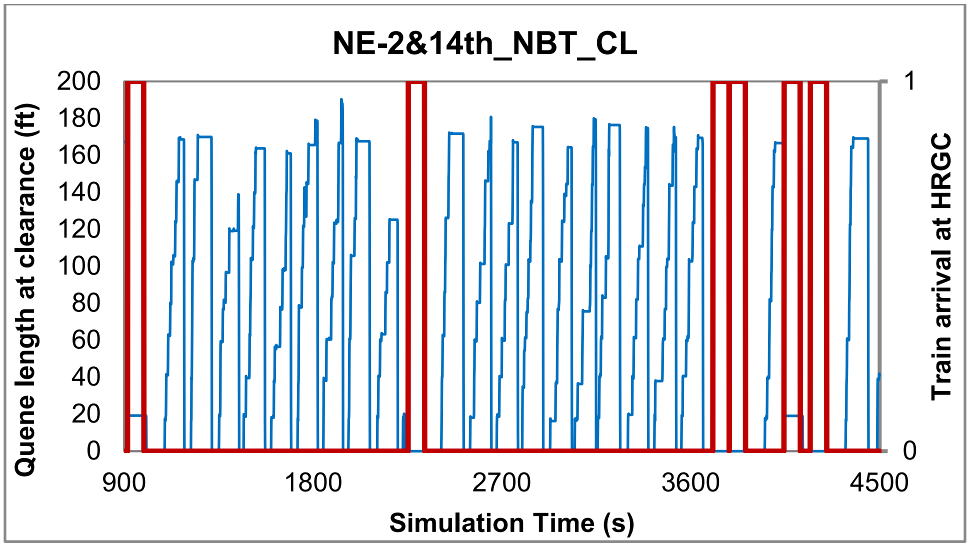
In VISSIM, the results are measured at a one-second interval in the simulation output. Note the first 15 minutes (i.e., 900 seconds) of the simulation are used as “warm-up” time in which the simulation model is run, and no data is collected. The data collection is recorded from 900 to 4500 seconds (one hour) when the system is steady (e.g., all road segments are covered with traffic, traffic signals have operated on a normal basis). Queue detectors, (i.e., Queue Counter) are put at all HHSI and HRGC stop lines where signal controllers are installed. Table 5.2 provides a summary of the queue statistics at a one-hour average at N-2 & 14^{th} St. Results for other sites are provided in the appendix.

Table 5.13 Queue measurement at each stop line in the simulation (1-hour average)

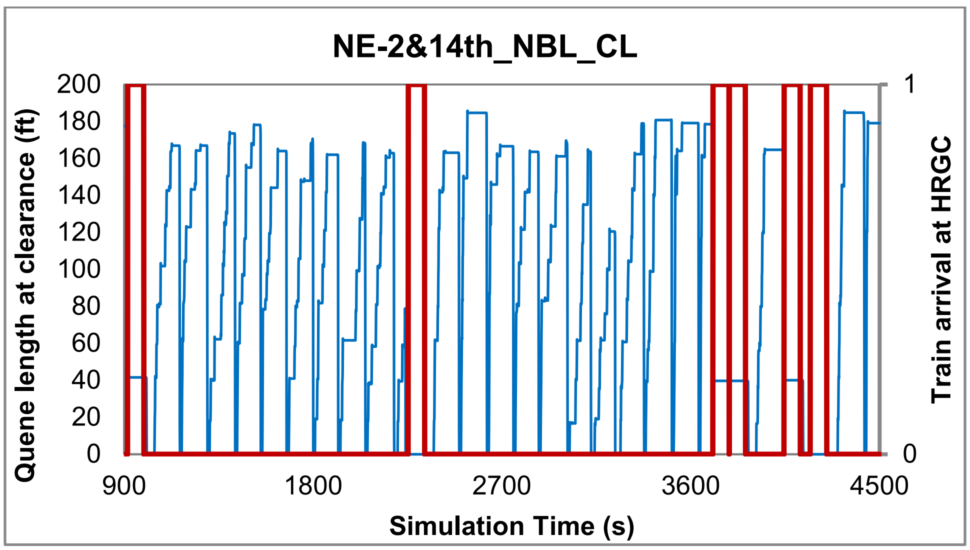
Counter No	Queue Counter Name	QLen	QLenMax	QStops
1	NBT_CL	190	193	2
2	NBL_CL	185	189	3
3	NBT_RR	1058	1064	5
4	NBL_RR	921	924	5
5	SBT_RR	0	0	0
6	SBT	741	745	3
7	SBL	553	557	3
8	EBT	179	182	2
9	EBL	85	87	1
10	EBR	250	253	2
11	WBT	205	208	3
12	WBL	523	526	2

Three queue performance measures: Queue length (QLen), maximum queue length (QLenMax), and the number of queue stops (QStops), are output from the simulation model. In each time step, the current queue length is measured upstream by the queue counter and the arithmetic mean (average), i.e., QLen, and the maximum, i.e., QLenMax, are thus calculated per time interval. A queue stop is where one vehicle that is directly upstream or within the queue length falls below the speed of the Begin attribute defined for the queue condition. In the simulation model, the speed threshold is set as 3.1 mph (VISSIM default value) to define a stop vehicle.

Figure 5.3 (a) and (b) show the change in clearance lane queue lengths over the simulation time. The blue line represents the queue length from the stop line. The red line represents the train arrival at the HRGC, measured by a data collection point detector that records train arrival and occupancy at the crossing.



(a) Northbound through traffic in the clearance lane

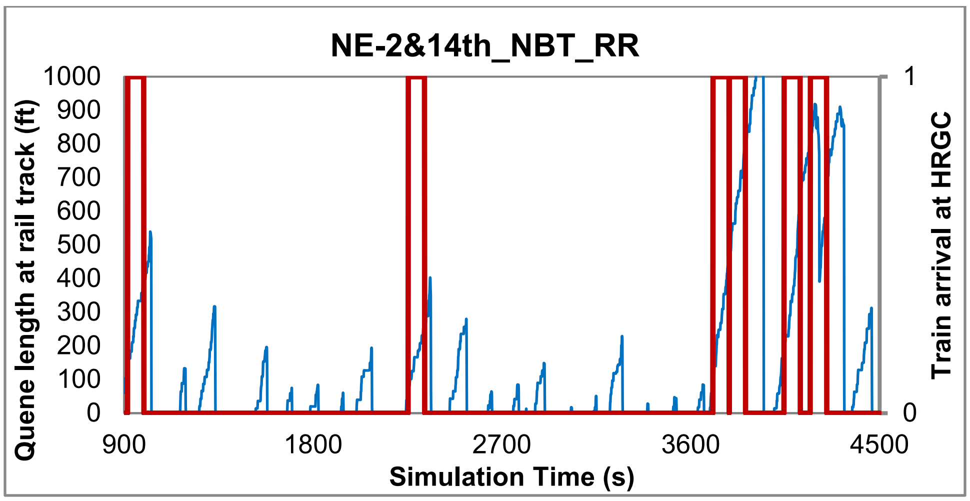


(b) Northbound left-turn traffic in the clearance lane

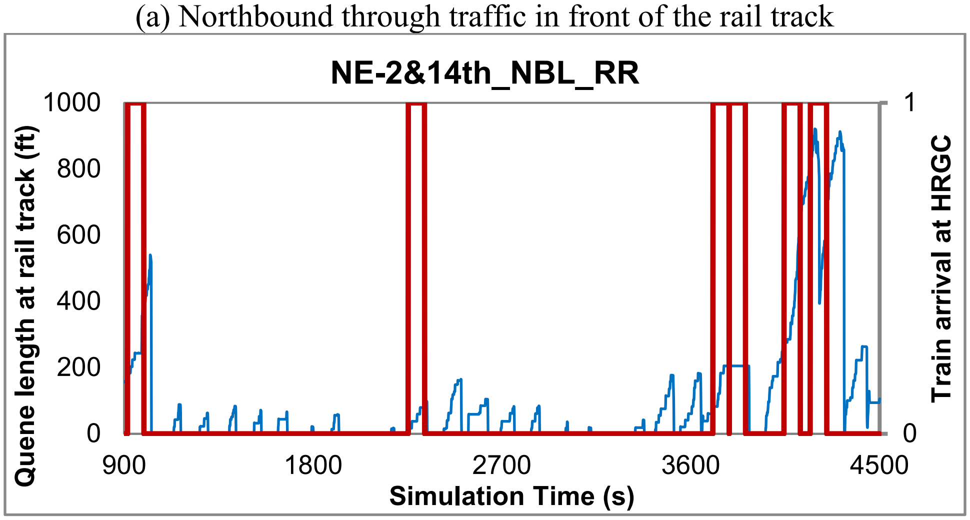
Figure 5.4 Queue length change in the clearance lane over simulation time given a train is present or not (blue line is the queue length, red line is the train arrival)

As expected, there is no maximum or minimum queue in the clearance lane during the train arrival at the HRGC (blue line does not overlap with red line), indicating a positive result for the preemption plan at HHSIs. The queue length metric serves as a critical performance measure of safety at HRGCs in relation to the signal preemption strategy. Longer queues that extend onto the HRGC are considered high-risk scenarios due to their increased likelihood of encroaching into the train's path, potentially leading to collisions.

As a comparison, Figure 5.4 (a) and (b) show the queue length change over the simulation time in front of the rail track. The blue line represents the queue length, and the red line represents the train arrival at the HRGC. As can be seen, the queue length accumulates during the train arrival (blue line overlaps the red line). During other periods, queue lengths are intermittent, depending on whether vehicles are queuing from the upstream clearance lane.



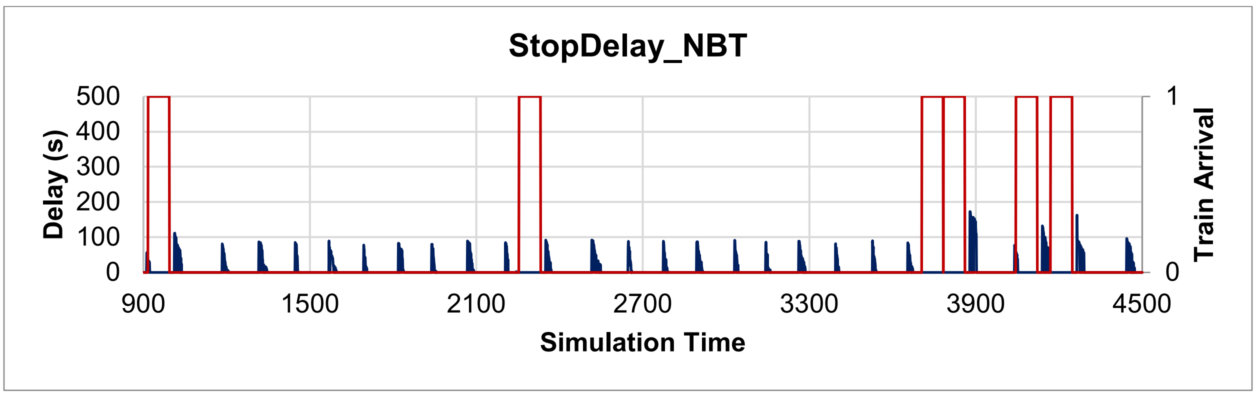
(a) Northbound through traffic in front of the rail track

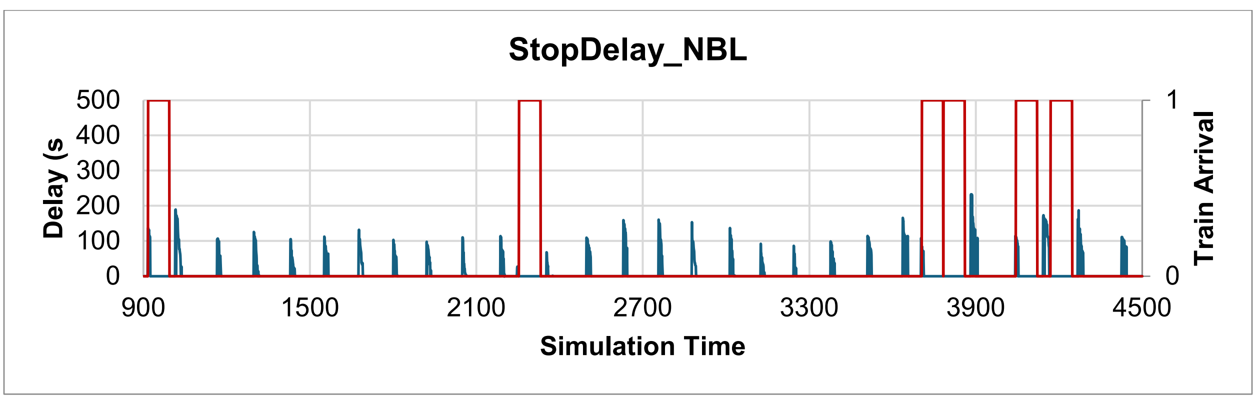


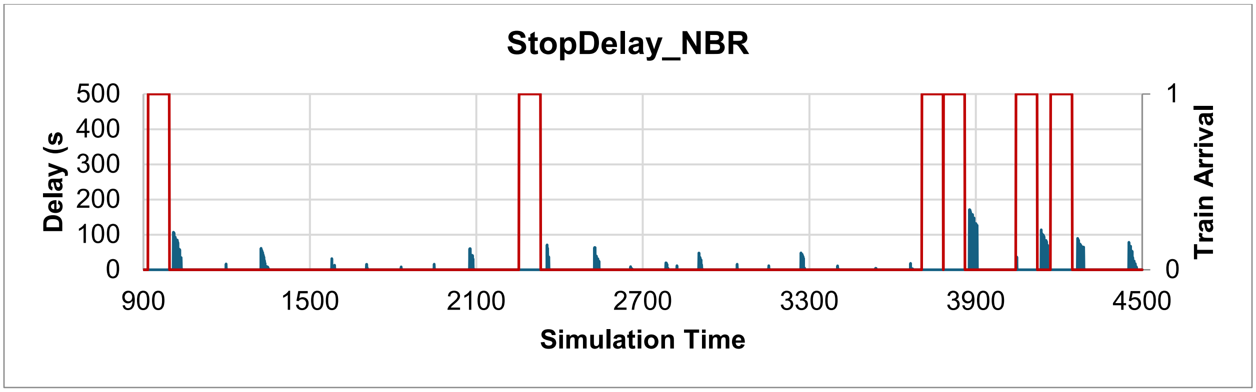
(b) Northbound left-turn traffic in front of the rail track

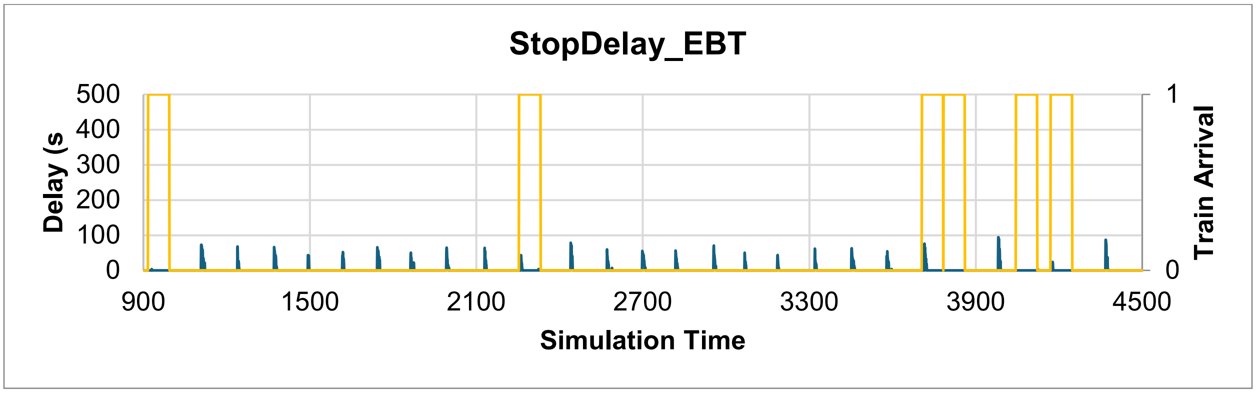
Figure 5.5 Queue length change at the rail track over simulation time given a train is present or not (blue line is the queue length, red line is the train arrival)

We also examined the stop delay at each traffic movement, which measures the average stopped delay per vehicle in seconds, as can be seen in Figure 5.5. The dark blue lines represent the vehicle stop delay (seconds) measured at each simulation. The red or yellow bars indicate the trains' arrival at the HRGC (1 = ye, 0 = no). According to the data, there were six train arrival events in the one-hour study period. The red bar representing the traffic movement is directly impacted by the train arrival (e.g., NBT, NBL, NBR, SBT, SBL, EBR, WBL), while the yellow bar represents the traffic movement may be not impacted by the train arrival (e.g., SBR, WBL, EBL, WBR, EBL).






StopDelay_NBR
Delay (s
500
400
300
200
100
0
900
1500
2100
2700
3300
3900
4500
Simulation Time
1
0
Train Arrival


StopDelay_EBT
Delay (s
500
400
300
200
100
0
900
1500
2100
2700
3300
3900
4500
Simulation Time
1
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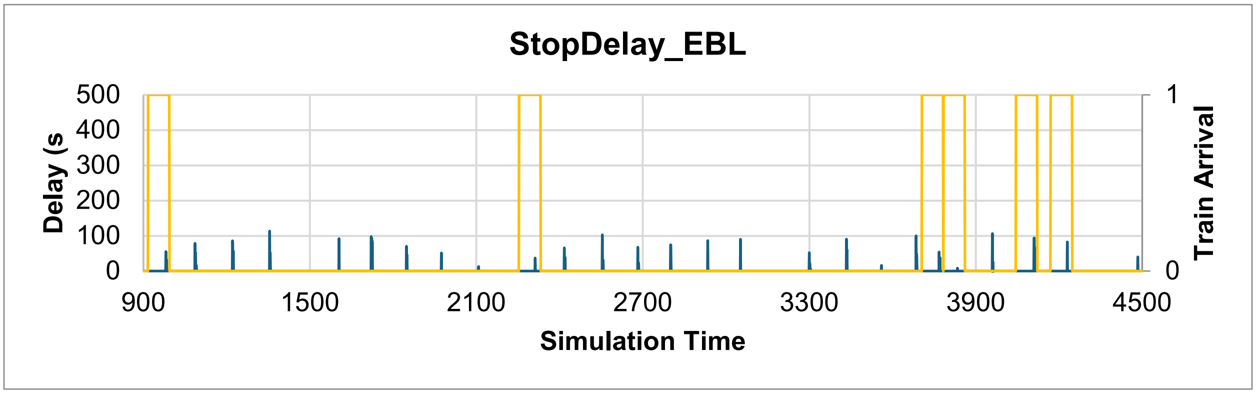
Train Arrival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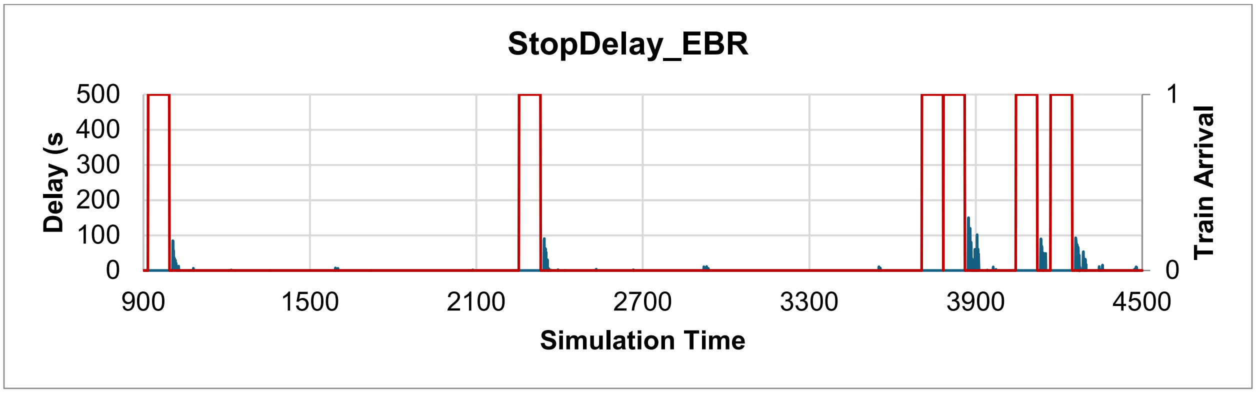
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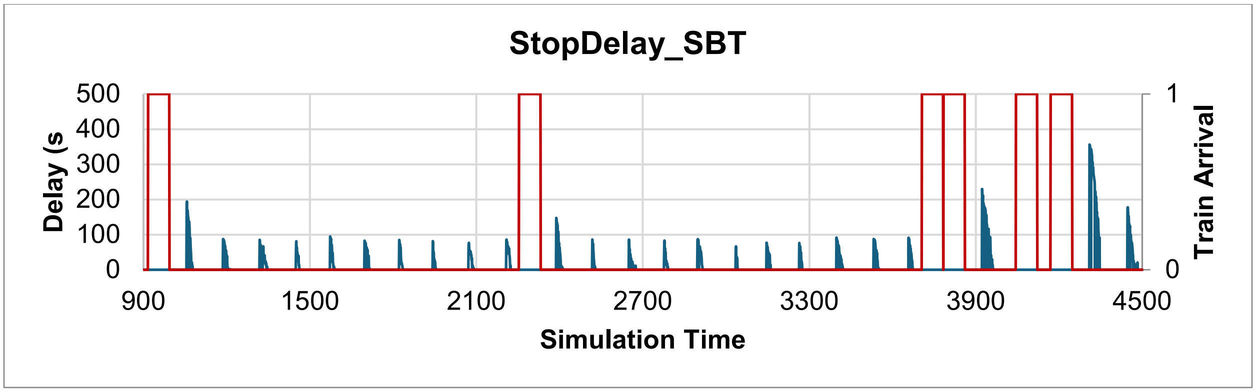
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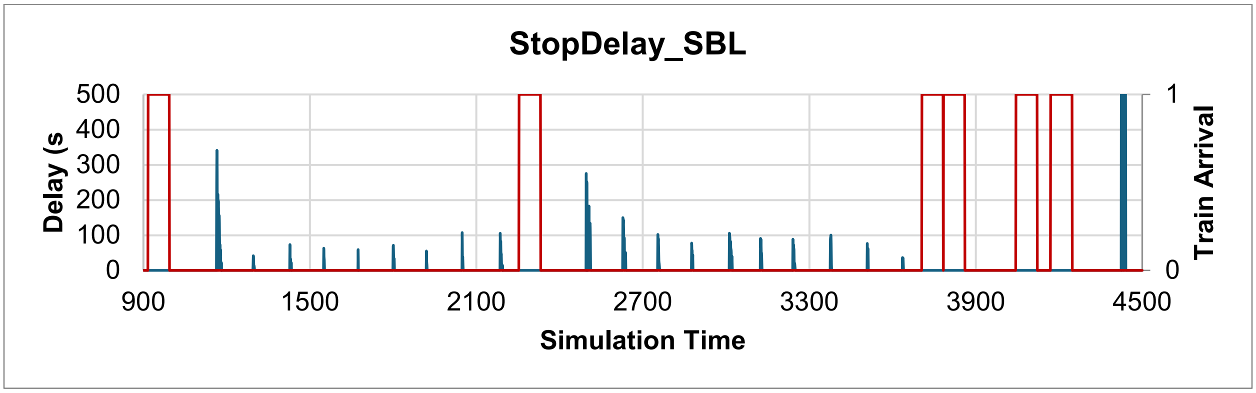
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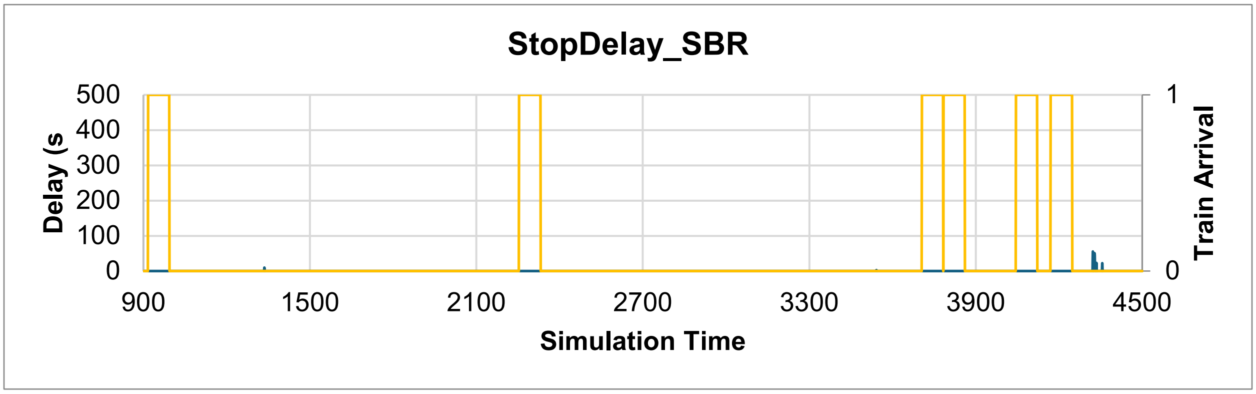
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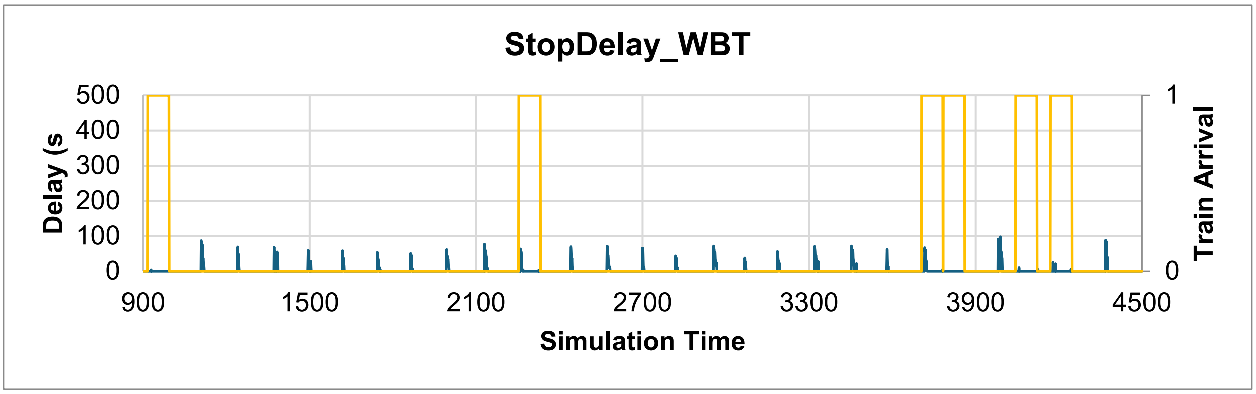
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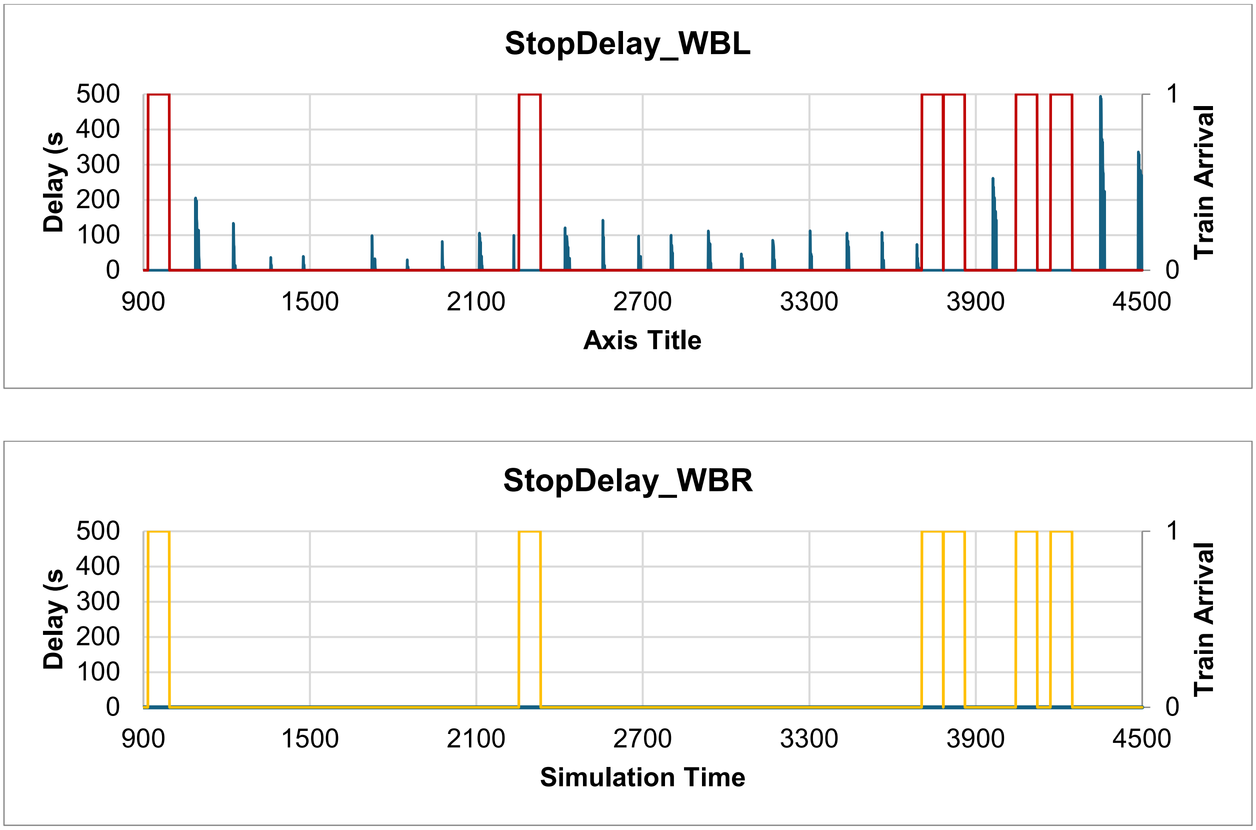

Figure 5.6 Stop delay measured at each traffic movement at the HHSI

In Figure 5.6, the stop delay metric reveals consistent outcomes concerning the effect of train arrivals on conflicting traffic movements. For instance, traffic movements that appear to be unaffected by the arrival of the train, as indicated by the yellow bars, exhibit either minimal average vehicle stop delays or display a random delay pattern that does not correlate with train arrival times. Conversely, traffic movements directly influenced by the train's arrival (highlighted by red bars) experienced markedly increased vehicle stop delays following the train's departure. This observation aligns with expectations, considering that the train's presence at the HRGC causes significant vehicle accumulation in queues, awaiting the opportunity to proceed through the crossing once the train has passed. This vehicle stop delay metric is a critical performance measure of mobility for the traffic flow at the HHSI.

Chapter 6 Guideline for HRGC Preemption

This project aimed to develop a standard optimization process for designing preemption plans, with the goal of maximizing safety at HRGCs and nearby intersections and enhancing the efficiency of arterial intersections. This led to the creation of a generic guideline, expected to provide a standardized process for evaluating the effectiveness of signal control at HRGCs and adjacent arterials as a whole. Although we briefly touched upon the MUTCD guidelines in an earlier section, it is important to discuss in greater detail the key sections of the MUTCD that address signal preemption guidelines for rail crossings. Therefore, detailed MUTCD preemption guidelines are provided before presenting the generic guidelines based on our research.

6.1 MUTCD Detailed Preemption Guidelines

The Manual on Uniform Traffic Control Devices (MUTCD) outlines detailed guidelines for the preemption of traffic signals at HRGCs to ensure safety and efficiency in traffic flow when a train approaches. These standards are complemented by additional publications such as the "2018 AREMA Communications & Signals Manual" and the "2021 edition of Preemption of Traffic Signals Near Railroad Crossings" by the Institute of Transportation Engineers (ITE). The MUTCD specifies that normal traffic control priorities, as described in the "Uniform Vehicle Code," should govern vehicle movement unless local agencies assign higher priority to Light Rail Transit (LRT) systems. This can involve creating separate signal phases for LRT, restricting vehicle movements, or preempting highway traffic signals for LRT movements. It is important to mention that most signal preemption-related guidelines in MUTCD are presented for LRT-based crossings, but they are very relevant to HRGCs, which is why they are also included in this section.

Section 8B.08 of MUTCD provides details on Turn Restrictions During Preemption. According to the guidelines, at signalized intersections within 200 feet of a highway-rail grade crossing, turning movements toward the crossing should be prohibited during preemption sequences. This can be achieved using blank-out or changeable message signs, such as the R3-1a and R3-2a signs, which display their message only when activated. These signs are particularly useful on roads paralleling LRT alignments to prevent turns across tracks. Alternatively, exclusive signal phases ensuring that all movements crossing the tracks receive a steady red indication may be used in conjunction with "No Turn on Red" signs.

Section 8C.09 of the MUTCD provides details on Traffic Control Signals at or Near Highway-Rail Grade Crossings. It elaborates that for crossings within 200 feet of an intersection or midblock location with traffic signals, preemption should be provided as recommended in Section 4D.27. The preemption operation and signal timing must be determined jointly by the highway agency and the regulatory authority. Additionally, these traffic signals should have a backup power supply to ensure continuous operation during preemption. The guidelines also elaborate that the preemption feature should avoid highway vehicle entrapment on the grade crossing by interrupting the normal signal sequence upon a train's approach. This system requires a closed-circuit or supervised communication circuit to activate the traffic signal preemptor. The preemption condition remains active as long as the warning system is operational, extending until crossing gates start to rise. For crossings within 50 feet (or 75 feet for highways frequently used by multi-unit vehicles) of a traffic signal-controlled intersection, pre-signals should be considered to control approaching traffic. These pre-signals must show a steady red during the track clearance portion of the preemption sequence. Furthermore, Section 4D.27 further details the preemption requirements, and intersections with emergency-vehicle preemption capabilities should coordinate these with rail traffic operations. Prohibiting turning movements during preemption, as outlined in Section 8B.08, and managing signal phasing and timing, as described in MUTCD Part 4, are essential components of the overall traffic control strategy at HRGCs.

6.2 Preemption signal optimization strategy

The optimization of preemption signal strategies at HRGCs in this project centers around two primary objectives: minimizing queue length at the clearance lane and minimizing the overall delay at intersections. The expressions can be seen in Equation 1 and Equation 2. These objectives are crucial for ensuring both the safety and efficiency of traffic flow in HRGC contexts.

$$\min Q = \frac{1}{i}\sum_{t} q_i \qquad \text{Equation 1}$$

$$\min D = \sum_t \sum_{i=1}^{12} d_i * F_i \qquad \text{Equation 2}$$

Where Q is the average queue length and q_i is the queue length at the clearance lane for traffic movement i; D is the total vehicle stop delay at the HHSI, d_i is the delay per vehicle for each traffic movement i, and F_i is the traffic volume for each traffic movement i.

Queue length minimization is critical for safety at HRGCs. Longer queues that extend onto the tracks can lead to dangerous scenarios, especially when a train is approaching. The optimization model aims to minimize the total queue length (minQ) at the clearance lane, which is a critical area where vehicles might get trapped on the tracks. This is formulated as an objective function in the optimization model (Equation 1), where Q represents the average queue length. The model takes into consideration various factors like vehicle arrival rates, traffic signal timings, and train schedules to ensure that queues do not extend onto the tracks.

The second key objective is to minimize the total delay experienced by vehicles at intersections near HRGCs (minD). This involves optimizing signal timings to ensure smooth traffic flow, reducing the waiting time for vehicles at intersections. The objective function for this aspect is formulated as shown in Equation 2. This approach balances the need to prevent queuing on tracks with the broader goal of maintaining efficient traffic flow at intersections.

The implementation of these optimization strategies involves complex modeling and simulation work. Using VISSIM, the real-world traffic conditions are replicated in the simulation model, incorporating various traffic volumes, train frequencies, and signal timings. The model is calibrated against field data to ensure its accuracy. The optimization algorithms then use this model to test different signal timing scenarios, evaluating them based on the defined objective functions of queue length and overall delay.

6.3 Preemption general guidelines

We provide the guidelines for implementing preemption strategies at HRGCs, which are designed to provide actionable and specific conditions under which various preemption plans should be activated. The overall goal of the guidelines is to provide a more detailed and condition-specific approach to implementing preemption plans at HRGCs, ensuring safety and efficiency in traffic flow. The emphasis is on practical and measurable criteria for determining the appropriate type and duration of preemption through considering queue length in the clearance lane and overall intersection delay to determine the nature and duration of preemption at the HHSI.

- Queue Length: Preemption should be activated when the queue length exceeds a certain percentage of the clearance lane length. For instance, if the queue length is more than 75% of the clearance lane, advanced preemption should be initiated to clear the queued vehicles and prevent spillback onto the tracks. The threshold percentage can be adjusted based on the specific characteristics of the HRGC and surrounding road network.

- Intersection Delay: Overall intersection delay is another crucial metric. If the average delay per vehicle exceeds a certain threshold (e.g., 60 seconds), this indicates congestion that could lead to hazardous situations at the HRGC. In such cases, simultaneous preemption may be necessary to immediately halt intersection traffic and prioritize clearing the HRGC area.

We have also provided a guideline for the selection of the signal preemption plan type, i.e., whether using simultaneous preemption or advanced preemption. In cases where immediate action is required (such as when queue spillback is imminent), simultaneous preemption is used. This plan involves instantly changing traffic signals to clear the HRGC as soon as a train is detected. The duration of simultaneous preemption should be sufficient to ensure complete clearance of vehicles from the HRGC, considering the current queue length and traffic conditions. On the other hand, the advance preemption involves activating signal preemption a specified time before the arrival of a train. The duration of advance preemption depends on factors such as train speed, expected queue length, and the time required to safely clear vehicles from the clearance lane. For instance, if the average train speed is high and the anticipated queue length is long, a longer advance preemption time may be required.

It should be noted that flexibility in preemption plan activation is crucial, considering the variability in traffic patterns and train schedules. The thresholds and durations mentioned should be adjustable based on ongoing assessments of traffic and train movement data. This in turn emphasizes the need for continuous monitoring and adaptation of preemption strategies to ensure their effectiveness in changing traffic patterns and train schedules, and advocates for a dynamic approach to traffic management, moving away from traditional static models to more adaptive and responsive systems.

Chapter 7 Concluding Remarks

7.1 Conclusion and Discussion

This research project aimed to enhance safety and mobility at HRGCs through the development and application of optimized real-time traffic signal preemption strategies. The project addressed the complexity of traffic flow at intersections near HRGCs and sought effective solutions to mitigate the risks associated with these crossings.

The study commenced with a comprehensive review of existing preemption strategies, identifying key limitations and conflicts in current operations. Effectiveness of signal preemption was verified through the development of microsimulation models and a sensitivity analysis, examining various preemption plans under different HRGC scenarios. A standard optimization process was developed, aiming to maximize safety at HRGCs and efficiency at adjacent intersections. This led to the creation of generic guidelines for preemption strategy implementation. The research successfully integrated field investigations, simulation modeling, and statistical optimization to develop a nuanced understanding of HRGC preemption. Key outcomes include improved traffic safety and mobility, reduced risks of accidents, and enhanced coordination between railway and highway agencies. The findings offer significant insights into the optimization of traffic signal operations in the proximity of HRGCs.

The research presents several critical insights into the operational dynamics of highway-rail grade crossings HRGCs and the impact of optimized preemption on safety and mobility. The use of real-time data and simulation models in developing preemption strategies represents a significant leap forward in traffic engineering for HRGCs. These models not only facilitate the understanding of traffic flow dynamics but also allow for the testing of various scenarios, providing a more comprehensive view of the potential impacts of different preemption strategies.

One of the key findings is the effectiveness of these strategies in reducing the queuing of vehicles at HRGCs. This reduction is crucial, as it directly impacts the risk of accidents at these intersections. The models developed in this research provide a framework for predicting and managing traffic flow, offering a proactive approach to HRGC safety.

The study also highlights the complexity of implementing such strategies in real-world settings. The coordination between railway warning systems, traffic signal operations, and train detection devices presents a significant challenge, underscoring the need for a multidisciplinary approach to traffic management at HRGCs. The successful implementation of these strategies requires close collaboration between various stakeholders, including transportation engineers, railway companies, and policy makers.

Another notable aspect of the research is the emphasis on the need for continuous monitoring and adaptation of preemption strategies. As traffic patterns and train schedules change, so must the preemption strategies to ensure their continued effectiveness. This dynamic approach to traffic management represents a shift from traditional, static models of traffic control, towards more adaptive and responsive systems.

In conclusion, the research provides valuable insights into the development and implementation of optimized preemption strategies at HRGCs. While significant progress has been made, the complexity of these systems and the need for ongoing adaptation and collaboration highlight the challenges that remain in ensuring the safety and efficiency of these critical intersections.

7.2 Contributions, limitations, and future work

This research significantly advances the knowledge in the field of traffic engineering, particularly in the context of HRGCs. The study introduces a novel approach to real-time traffic signal preemption, blending microsimulation modeling with statistical optimization. This methodology offers a more dynamic and responsive system compared to traditional preemption strategies, accommodating the variability in traffic and train schedules.

The practical implications of this research are profound. The developed guidelines for optimized preemption strategy provide a valuable resource for transportation engineers and policymakers. These guidelines are poised to influence future designs and implementations of HRGC safety measures, not only enhancing traffic flow and safety at these crossings but also serving as a model for similar traffic situations in other regions.

This research has its limitations. The most notable limitation is the scope of the study, which was confined to specific HRGC corridors in Nebraska. This geographical limitation may affect the generalizability of the findings to other regions with different traffic patterns and HRGC configurations. Additionally, the simulation models, although robust, are based on certain assumptions and predefined parameters. The real-world variability in train schedules, traffic volumes, and driver behavior may not be fully captured in the simulation environment. These limitations highlight the need for cautious interpretation of the study's findings and their application.

Future research should focus on expanding the geographical scope of the study to include a diverse range of HRGCs in different regions. This would enhance the generalizability of the findings and provide a more comprehensive understanding of HRGC preemption strategies. Another avenue for future research is the exploration of advanced predictive algorithms for train arrivals and departures. This would further optimize the traffic signal preemption strategies, making them more dynamic and responsive to real-time conditions. The field of traffic engineering and HRGC safety is rapidly evolving with advancements in technology. Future work could explore the integration of artificial intelligence, connected vehicle technology, and Internet of Things (IoT) applications in HRGC preemption strategies. Such advancements have the potential to significantly enhance the safety and efficiency of HRGCs by providing more accurate and timely data for traffic signal control.

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