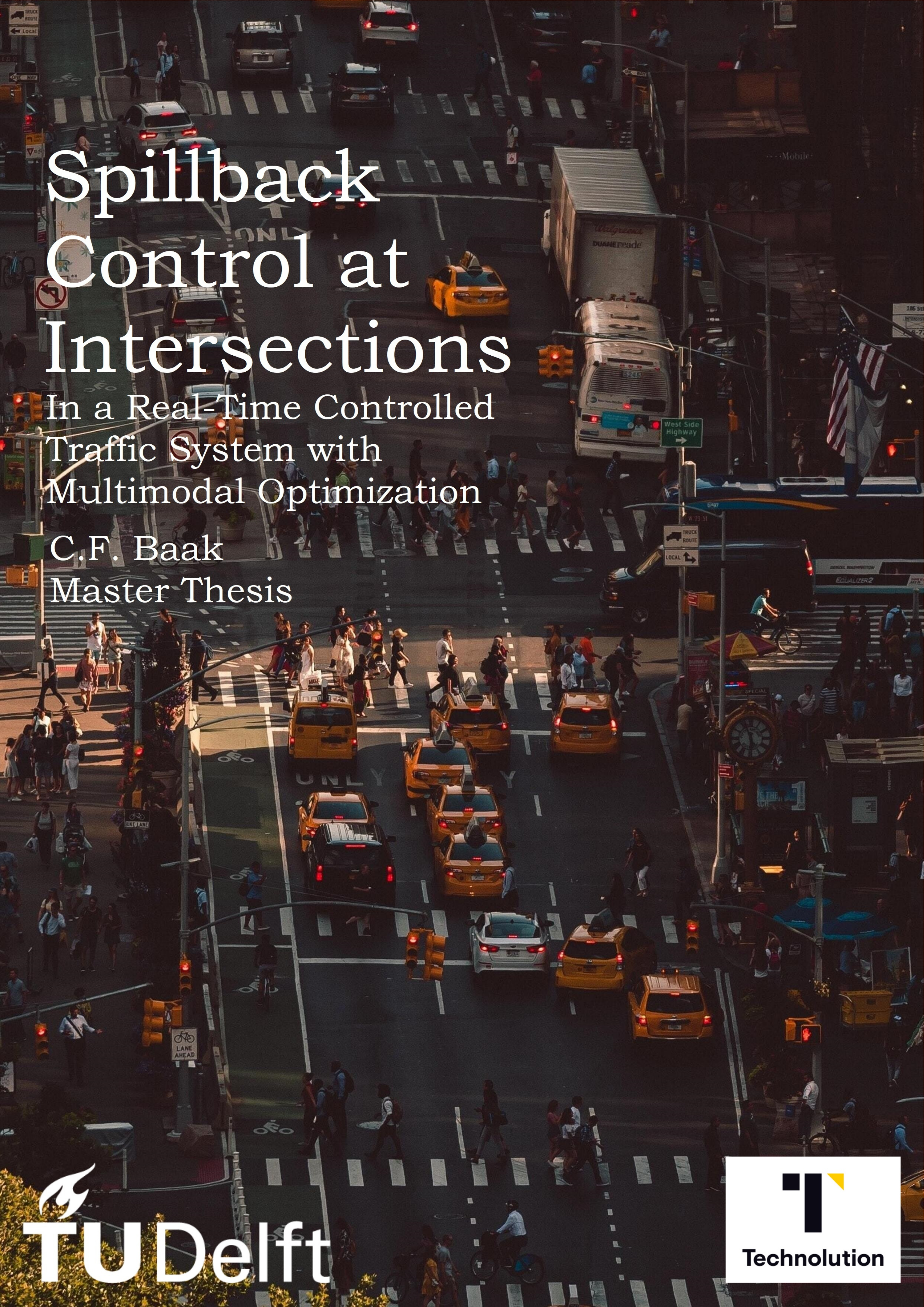

Spillback Control at Intersections

In a Real-Time Controlled Traffic System with Multimodal Optimization

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Master Thesis

TU Delft

Technolution

Controlling Spillback Effects In Multimodal Real-time Controlled Traffic Systems

by

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at the Delft University of Technology,

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This thesis is confidential and cannot be made public until 8-12-2022

Preface

When I started my Master's in Transport, Infrastructure, and Logistics, I started doing the specialization 'operations', which focuses on the operational management and control of traffic and the technologies and methodologies facilitating it. It confirmed my interest in operational management and control, and after following the courses, I felt interested in graduating in this domain. I have been working on this thesis for the past eight to nine months. I am happy that I chose this research direction and that I learned about the complexity of an actual transport model, in which I was given an opportunity to design an additional component for. I think I will never look the same again at spillback effects when I am experiencing them myself or when I see them unfolding.

I did this thesis at Technolution as part of an internship. At the company, I would like to thank my supervisors, Tom and Edwin, for their input, availability and help in familiarizing myself with MobiMaestro-Flow. I enjoyed my time a lot at Technolution. I would also like to thank my graduation committee, which helped improve my work with their feedback. A special thanks to my daily supervisor, Henk Taale, who gave me very helpful feedback during the process and also suggested doing weekly syncs together with Tom and Edwin. This has helped me to maintain focus and motivation, but it also was a nice break from working on the thesis.

Lastly, I would also like to thank my parents and Eva for their endless support during this whole process.

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Contents

List of Figures

Summary

Many configurations of traffic systems have been proposed, tested, and implemented to promote traffic flow and network performance in urban environments. When traffic demand is high and the intersection lacks throughput, traffic phenomena occur, such as oversaturation of a turning bay which leads to lane blockage. In addition, oversaturation of an intersection lane could lead to vehicles spilling over to an upstream intersection. These phenomena are called spillback effects and could lead to unsafe traffic situations. In some municipalities, traffic safety is assigned a high priority. In the United States, one-third of intersection fatalities still occur at signalized intersections, and existing real-time controlled traffic systems (RTCS) could contribute. By ensuring that emerging unsafe situations, such as spillback effects, are avoided or handled faster by providing additional priority in traffic light control. Priority in traffic light control is not new, as traffic light control with priority for transit already existed. Transit Signal Priority (TSP) has been used to improve the level of service of transit users and can be incorporated into the signal control. Existing signal plans are modified; however, the impact of multiple types of road users in urban areas increased the complexity of finding optimal signal control. Hence RTCS with multimodal optimization have been developed to optimize various road users in the same control objective. The control objective is either configured as the vehicle or personal delay. These multimodal RTCS have been tested in undersaturated conditions. However, they have yet to be refined to work in moderate or oversaturated conditions. Furthermore, research regarding multimodal RTCS that cope with oversaturated conditions (spillback effects) has been limited. Moreover, it is not clear what the consequences are of spillback control strategies in a multimodal RTCS. Although additional priority for spillback could be beneficial for avoiding or handling emerging unsafe situations. To fill in the knowledge gap a spillback component is designed and tested. More specifically, a spillback detection method and control strategy were designed to gain insight into the effects of applying spillback control strategies to traffic and network performance. This resulted in two main research questions: *How can an existing RTCS be extended with spillback detection and spillback control strategies in a multimodal context?*, and *What is the effect of controlling spillback in a multimodal RTCS at signalized intersections on the traffic and network performance?*
To answer the research questions, a literature review was conducted to identify suitable approaches to detect and control spillback in an existing RTCS with multimodal optimization. Furthermore, a simulation study is performed to gain insight into the effects. The identified spillback detection and control methods were implemented as an extension to a multimodal RTCS. The utilized multimodal RTCS was MobiMaestro-Flow (MM-Flow). MM-Flow continuously optimizes individual intersections by minimizing the waiting costs over an optimization horizon of 120 seconds and an update frequency of 1 to 5 seconds. The waiting costs consist of the multiplications of the waiting time per vehicle, the movement, and object priority. The utilized algorithm is referred to as the Traffic Flow Engine (TFE). The literature review showed that the spillback detection method depends on the utilized traffic sensors. When using a more conventional sensor, such as a loop detector, mainly two approaches were used—first, detecting spillback by using a link capacity in terms of the number of vehicles, and second, by defining a queue threshold in meters. The approach with the queue threshold requires a queue method. In contrast, when more sophisticated sensors are used, spillback can be measured directly from video detection. Regarding the spillback control strategies, also two types were widely used. The first one solves spillback by an objective criterion in the optimization algorithm, promoting the flow of the congested link or the overall intersection flow. The other approach is metering. Vehicle inflow is limited upstream, the outflow is promoted downstream, or both are applied at the congested intersection.

Regarding the design of the spillback component, it was chosen to detect spillback by a queue threshold. The reason for this is that with a queue threshold (and a queuing model) spillback can also be seen in weather conditions (e.g. mist). Additionally, the required sensors are cheaper in purchase costs and the generated shockwave profile can also be used for delay estimation. The threshold is either the length of the link or the length of a turning bay. Spillback is detected when the estimated maximum queue length (L^n_{max}) during a traffic light cycle n exceeds the queue threshold. In terms of the spillback control strategy, two spillback control strategies were designed as an extension to the TFE (Figure 1). The main difference between the two control strategies is that the first strategy alters the optimization outcome by enforcing green time for the congested direction. The second spillback control strategy penalizes the direction affected by spillback so that when spillback is detected, the direction receives higher priority in optimization. This leads to an earlier green and advantages for the congested link.

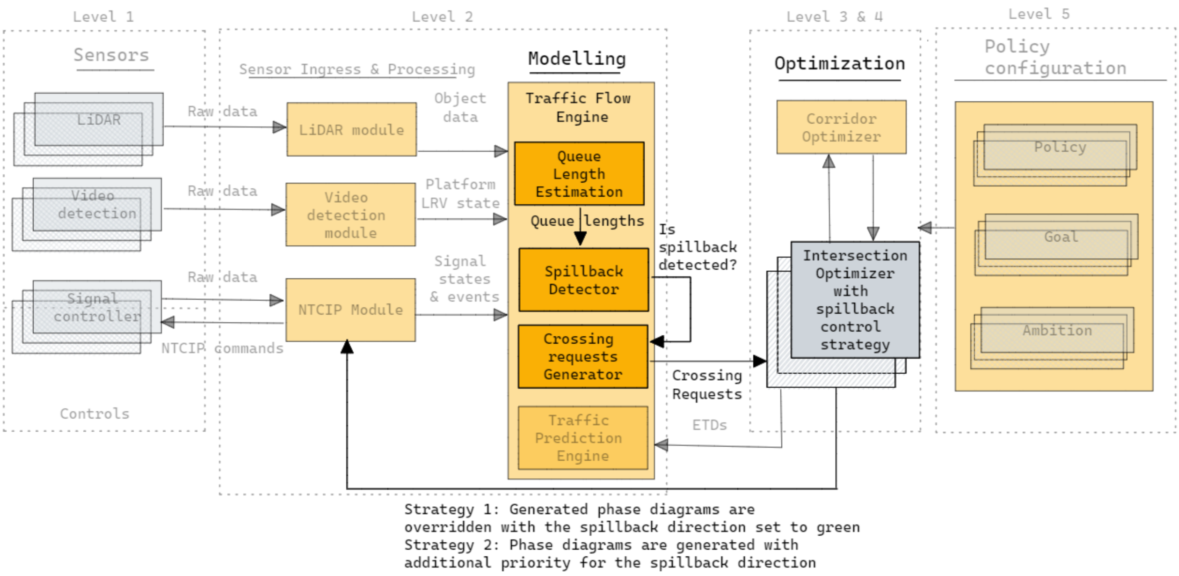


Figure 1: Implementation of control strategies in TFE structure

The effects of the spillback components were tested according to several experimental scenarios. The scenario were distinguished by the used simulation network model, the included modes, demand, and the spillback handling method. The experiments were performed at an isolated intersection and a corridor consisting of ten intersections comparable to a part of 3rd Street in San Francisco. For each experiment, data was collected for the spillback duration, the delays of six routes, and the network performance. The demand in the first quarter was halved, in the second and third quarter the demand factor was one, in the fourth quarter demand was halved again. In the experiments, the vehicles were prioritized as in Table 1

The outcomes of the experiments showed that, in general, the intersection performance decreases when a spillback control strategy is applied in traffic light control optimization. Regarding the height of the spillback penalty, only when the demand for disadvantaged directions is low enough that a higher spillback priority increases intersection performance. The provision of additional spillback priority causes unbalanced allocations of green time, meaning that in higher demands, the overall performance of an intersection is only increased without spillback control. In terms of spillback duration, a small spillback penalty leads to the best results when the demand is higher. A bus line, in combination with a low spillback penalty, improved spillback directions and decreased queue durations for the bus direction. With increased penalty factors, traffic control leans into an advantage for spillback directions causing higher delays for the bus and non-spillback directions. In a network, the intersection performance is most often increased at the ends of the corridor and the intersection downstream of the intersection affected by spillback. Regarding the network, the performance increased with a moderate vehicle flow and a minor spillback penalty. Furthermore, the network performance increased for all spillback control strategies during the peak period. Except when additional priority was provided for the arterial of the corridor.

Table 1: Vehicle priority configuration

Traffic object	Mode-priority
LRV	2000
Truck/bus	100
Pedestrian	10
Car	5

The experiments at the corridor showed that a spillback priority effectively decreases spillabck durations and works well in combination with higher prioritized public transit. When a bus was included in the traffic flow, lower delays and spillback durations were found for spillback directions. However, the effect was paired with higher delays for disadvantaged directions; when buses travel in the spillback direction, spillback priority leads to practically absolute priority.

In terms of the height of the spillback penalty, a too-high priority negatively impacts the intersection and network performance. However, in some cases, a (high) spillback priority is necessary to provide enough priority so that a growing unsafe situation is avoided. Therefore, it is crucial to determine the intended use and applicability when assigning spillback priority. When an unsafe situation emerges, a very high spillback priority can be feasible, for example, when preemption is needed for an emergency vehicle and vehicles are spilt over at an intersection.

The designed methods and performed experiments are paired with limitations. First, regarding the developed control method, the proposed method cleans up instead of avoiding the spillback effect. Additionally, the control method assigns additional priority when a queue length exceeds the lane capacity. Still, the delay road users experience is not considered in the allocation of green time. Furthermore, non-recurrent spillback is not identified by the proposed method. In terms of the researched effects in the simulation, the simulation environment does not fully replicate real-life behaviour. Furthermore, the performed experiments assumed an exact and correct queue length retrieved from the simulation, and sensor faults or misestimation of queue length are not considered. Regarding the corridor, the network performance could be overestimated as no spillbacks can occur from directions that leave the corridor. The pedestrians are included in the simulation without adequate behaviour; additionally, the behaviour of the drivers and the environment itself is limited. Therefore, the effects may be underestimated or overestimated compared to a real-life setup.

This research led to several recommendations for future research. First, in terms of spillback detection, it is advised to research further the identification of non-recurrent congestion and the corresponding effects occurring from that congestion, such as the change in link capacity and handling that congestion in terms of traffic signal control. Second, regarding the priority provided to a spillback direction, the advice is to research further how spillback should be prioritized in different types of traffic situations in a multimodal context. Additionally, more insight can be gained in combining different priorities, such as the configuration of the vehicle priority in combination with other spillback priorities. Regarding spillback control strategies, it is advised to look into the current design and vary the weights given to the spillback penalty depending on the traffic situation. Regarding alternative control strategies, it is recommended to research other control strategies and their effect on the traffic and network performance, such as approaches with an alternative objective function when spillback is detected or including downstream and upstream metering in the solve method. In terms of policy, it is recommended to gain insight into the effects of different combinations of priorities (vehicle, movement, and spillback) to fulfil different policy goals, and the effects of these policy goals on the traffic and network performance. Altogether, when the policy goal is to reduce traffic fatalities to zero as soon as possible, it should be no surprise that controlling an emerging unsafe situation, such as spillover at an upstream intersection, should be highly prioritized in traffic signal control.

1

Introduction

1.1. Research context

Many configurations of traffic systems have been proposed, tested, and implemented to promote traffic flow and network performance in urban environments. When traffic demand is high and the intersection has a lack of throughput, phenomena that are paired with oversaturated conditions occur. For example, oversaturation of a turning-bay which leads to lane blockage. In addition, oversaturation of an intersection lane, which could lead to vehicles spilling over to an upstream intersection. These phenomena are called spillback effects and could lead to unsafe traffic situations. For example, when green time is allocated to a direction, while conflicting traffic is not yet sufficiently cleared. In the United States, some municipalities assign traffic safety a really high priority, such as the San Francisco County Transportation Authority (2018) has the vision of reducing traffic fatalities to zero by 2024. As in the United States, one-third of intersection fatalities still occur at signalized intersections (Stewart, 2022), one way existing traffic systems could contribute to this goal is by ensuring unsafe situations that are paired with oversaturated conditions are avoided or handled faster by providing additional priority in the traffic light control.

1.1.1. Real-time traffic control systems and spillback

Many real-time control traffic systems configurations have been around for quite some time. Such as as the Sydney Coordinated Adaptive Traffic System (SCATS) and the Split Cycle and Offset Optimization Technique (SCOOT) which were designed in the 1970s (Sims & Dobinson, 1980; Bretherton, 1990). Or relatively newer RTCS such as UTOPIA/SPOT (Mauro & Di Taranto, 1990; Wahlstedt, 2013) or RHODES (Mirchandani & Head, 2001), which were designed in the early and late 1990s, respectively. Although varying in configuration and focus, RTCS have the same philosophy, namely switching traffic light signals or modifying a signal plan according to the optimization of a criterion for the next n seconds. The number of seconds depend on a configured time horizon, and every m seconds the horizon is renewed depending on the update frequency (Boillot et al., 1992). These RTCS have struggled to consider congested conditions due to uncertain traffic flows and cause wrong prediction, misestimation of the actual traffic state, or insufficient traffic control strategies (Boillot et al., 1992; H. Liu et al., 2009; Ramezani & Geroliminis, 2013). Over the years traffic control have been further developed, not only to control and optimize traffic in undersaturated conditions, but also for moderate and oversaturated traffic conditions (Wahlstedt, 2013) (such as SCOOT and RHODES (Zargari et al., 2016)).

Traffic phenomena that occur with oversaturated conditions are spillback effects. When using loop detectors, spillback is mainly detected using lane capacity in various ways. Approaches use link capacity in terms of link length and queue length, the maximum allowed queue length, and maximum allowed occupancy. Another approach is detection of vehicle speed of a downstream vehicle or vehicle occupancy combined with a probability that estimates spillover probability. In terms of solving spillback, signal control strategies are used in two ways. The first strategy is a form of metering by limiting the inflow with a reduction in green time for critical phases at upstream intersections, the green time extension for the congested link, or both. The second approach is with an objective function. It uses an optimization criterion that minimizes a variable to solve spillback queues, such as minimizing the queue length, maximizing the throughput or minimizing the delay. The objective function optimizes the criterion so that the green time for the critical link is set to green. On the other hand, traffic is not only prioritized for spillback control. With a traffic mix with multiple types of road users, public transit can also receive priority, and in urban areas also priority is provided for bicycles (Fietserbond, 2022).

1.1.2. Multimodal real-time control systems

In the development of RTCS, providing priority to transit was found to be effective. Transit Signal Priority (TSP) has been used to improve the level of service of transit users, with key performance indicators such as regularity and punctuality. TSP is incorporated into the signal control and modifies the normal signal operation process to accommodate transit vehicles (Baker et al., 2002). In combination with bus priority, SCOOT uses inductive loop detection and has proved effective and reliable (Hounsell & Shrestha, 2005). In addition, with improved sensors (e.g. roadside beacons for the bus), TSP was demonstrated as more effective. RTCS with TSP for other modes, such as LRVs, have also been developed. Here the LRV has the additional priority and traveltime for the vehicle is minimized, while the delays for passenger cars do not increase (A. Stevanovic, Kergaye, & Martin, 2009). An improvement in sensor quality, from magnetic loop detectors to data-driven sensors such as video detectors or laser sensors, feed the exact vehicle location, speed, and trajectory to the traffic system. In combination with the improvement in computing power, data-driven models have become a valuable addition to RTCS. However, the impact of multimodal users in urban areas increases the complexity of finding optimal signal control because the RTCS and TSP systems often have conflicting control objectives (He et al., 2014). Hence, RTCSs have been developed to optimize multiple road users into the control objective. The control objective is based on vehicle delay but could also be based on personal delay. The personal delay was found more successful in objective functions since it considers the passenger occupancy of a vehicle (Christofa, 2012; J. Stevanovic, 2011). For multimodal RTCS that optimize vehicle delay, user-specified priority lists are included to account for difference in occupancy (Yagar & Han, 1994; J. Stevanovic, 2011). For example, a light-rail vehicle (LRV) can be weighted 20 times more due to the number of passengers in the vehicle or the justification that the LRV has to adhere to the transit schedule.

1.2. Knowledge gaps

Many real-time controlled systems have been proposed, compared, and assessed in the literature. Control strategies have been developed to detect, avoid or manage spillback effects. Previous studies on unimodal RTCS have improved control strategies to also control vehicles in more moderate and congested conditions, along an arterial or in a network, in which detection and control strategies for queue spillback have been found. With the rise of multimodal optimization in RTCS as the control objective, reduced delay and improved flow are perceived benefits (Van Katwijk, 2008; He et al., 2014; Mein et al., 2022). These systems have been tested and operate in undersaturated conditions. However, they have yet to be refined to work in moderate or oversaturated conditions. Therefore, looking into the feasibility of spillback control strategies in a multimodal context (Noaeen et al., 2021) can be valuable. It was recommended to incorporate detection methods and control strategies for spillback, as these multimodal systems currently have researched benefits in undersaturated traffic conditions (Yagar & Han, 1994; Christofa et al., 2013; He et al., 2014; Christofa et al., 2016; Mein et al., 2022). To research these components, research questions are proposed.

1.2.1. Scientific relevance

There has been little research on spillback control strategies in real-time controlled systems with multimodal optimization. In unimodal RTCS Noaeen et al. (2021) developed a control strategy that avoids and handles spillback effects, suggesting that more research is needed to include more modes and test transit priority in traffic control that incorporates spillback modelling. In the context of multimodal RTCS, it is suggested that a more sophisticated queue estimation model is used (He et al., 2014), which is done by Christofa et al. (2016) with a queue model that applies SWT. However, using SWT to estimate delays, not queues, leads to no detection of spillback and the possibility to control the identified spillback. Therefore, it is useful to gain insight into the effect of spillback control strategies on the traffic performance and network performance in a RTCS with multimodal optimization.

1.2.2. Societal relevance

Research results lead to a more robust multimodal RTCS, which benefits the traffic participants in urban areas. First, in terms of throughput in which (transit) vehicles could achieve higher overall throughput leading to lower travel times for road users. Second, avoiding or handling unsafe situations that occur due to oversaturated traffic phenomena, as this leads to less conflicts between different road users. For example, when an intersection is not cleared when an approaching light-rail vehiclecrosses the street or when pedestrians cross the street when passenger cars are still halted at the crosswalk due to downstream congestion.

1.3. Research questions

The research focus is to gain insight into the effects of spillback control strategies in a real-time controlled system with multimodal optimization on traffic and network performance. A spillback detection method and control strategy must be designed to gather insight, furthermore, the detection method and control strategy must be implemented in the RTCS. Thereafter, the designed approach should be tested on a simulation network. The knowledge gaps and the research focus result in the following research questions (RQs):

1. *How can an existing RTCS be extended with spillback detection and spillback control strategies in a multimodal context?*
   - 1.1 How could spillback be detected?
   - 1.2 How could spillback be avoided or handled?
   - 1.3 What is the architecture of a multimodal RTCS?
   - 1.4 How can 1.1 and 1.2 be designed in a RTCS with multimodal optimization?
2. *What is the effect of controlling spillback in a multimodal RTCS at signalized intersections on the traffic and network performance?*
   - 2.1 What is the effect of spillback control strategies on the traffic and intersection performance of an isolated intersection with a car flow, and a mixed traffic flow?
   - 2.2 What is the effect of spillback control strategies on the traffic and network performance in a corridor with a mixed traffic flow?

1.4. Overview of methodology

To answer the research questions a literature review is conducted, an existing RTCS with multimodal optimization is extended with a spillback detection method and spillback control strategies, furthermore, a simulation study is performed. In Figure 1.1 an overview is given how these research steps have been performed and structured in the thesis. In the next subsections the research steps are described.

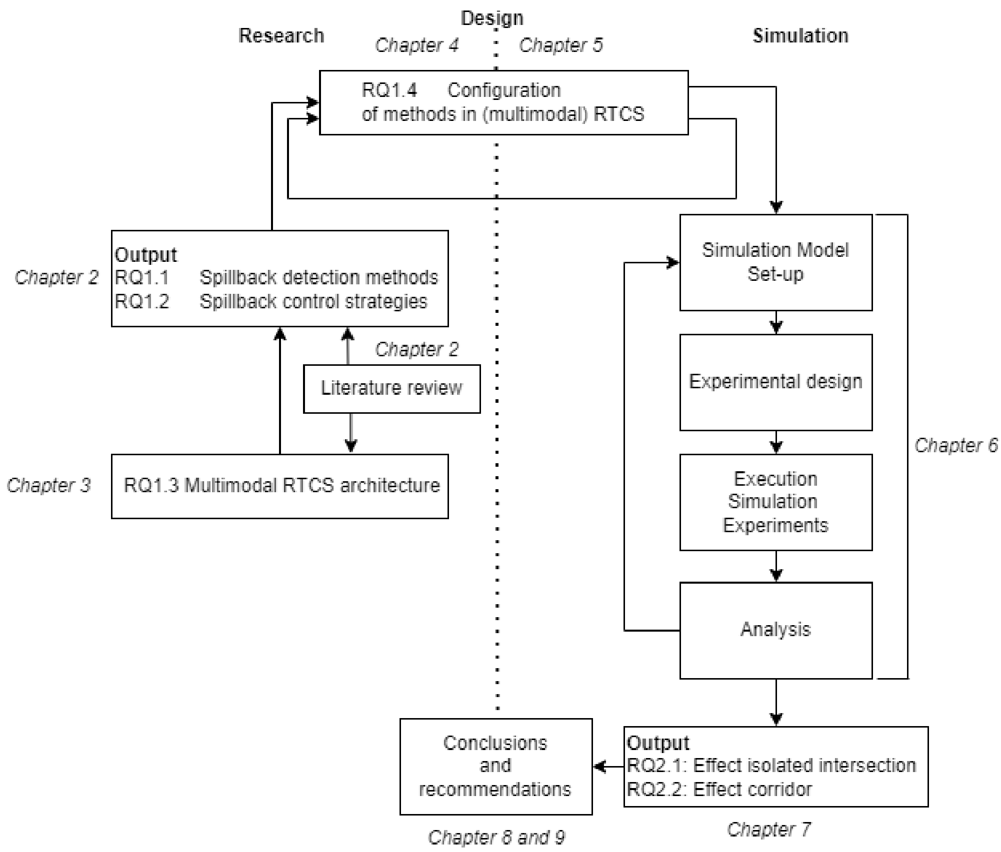


Figure 1.1: Overview research steps and methods

1.4.1. Literature review

To fill in the knowledge gap, a literature review was conducted to gain insight into spillback control strategies in RTCS and also to identify the architecture of the used RTCS with multimodal optimization. First, relevant keywords were constructed for the literature review surrounding traffic control in RTCS which incorporate spillback control at signalized intersections. The keywords led to papers that research spillback detection methods or spillback control strategies in real-time controlled traffic systems, the collection was extended by forward and backwards snowballing. An overview of the paper trail is shown in Table A.1. Second, the found articles were evaluated using the PROMPT (Presentation, Relevance, Objectivity, Method, Provenance, Timeliness) approach. As the papers were found using a peer-reviewed database and found papers were part of a scientific journal or conference proceedings, most papers were according to standards regarding the presentation and provenance (e.g. origin) of the paper. In terms of relevance, it was inspected whether the papers proposed applicable spillback detection methods and control strategies. This led to a first collection of relevant papers. The resulting collection was further analyzed in terms of objectivity, but no papers from the collection were dropped from this.

The literature review led to a collection of papers with approaches to detect and control spillback control strategies. This collection was used as input for the design of spillback component, in which there was evaluated whether the method was suitable as the extension of an existing RTCS with multimodal optimization.

1.4.2. Design of spillback component

The literature review generated a collection of approaches to detect and control spillback (RQ1.1 and RQ1.2). The identified architecture of the multimodal RTCS (RQ1.3) provided a framework to implement the methods in. The design of the spillback components consisted of two parts. First, the component design as an extension to the RTCS, second, the implementation of the spillback component to a test environment.

For the test environment, the traffic system was translated into a software-in-the-loop simulation (SILS). As the system controls traffic light, based on individual vehicle delay, the test framework uses a microsimulation. The test framework of MobiMaestro-Flow already existed in this framework and were extended by the spillback detection method and spillback control strategies, in which the spillback detection queue lengths were retrieved directly from the simulation, assuming perfect information about the queue length. In this environment experiments were performed and data was generated by the simulation environment SUMO.

1.4.3. Simulation

Data collection
Data for the analysis was generated by the simulation-software. More specific data, such as the vehicle speed and locations were generated by detectors placed in the simulation network. For example, to measure the duration of spillback, a detector was placed upstream of a turning bay to detect lane blockage.

Data from two simulation networks was used. The first network was an isolated intersection; the second simulation network was a corridor consisting of ten intersections. The collected data was filtered and processed to retrieve relevant variables. These relevant variables were used in the assessment to determine the effects of spillback control strategies. The key performance indicators (KPIs) for traffic performance were chosen as the delay, and the spillback duration. The spillback duration was chosen because it shows a direct effect of the spillback control strategy; furthermore, in directions where no spillback could occur, the duration resembles the queue duration. The delay is included to assess the impacts on the vehicle routes when a conflicting, or non-conflicting direction, receives additional spillback priority and therefore more green time. The delays is derived from travel time. For the network performance, it was chosen to include the network delay which is the sum of the individual intersection delays.

Analysis
For each scenario, the data consisted of the means and the standard deviation of every replication from the scenario. For the analysis ten replications of each scenario were compared. The traffic light control consisted of an adaptive traffic signal control that minimized the waiting time for all road users and was constrained by the ring-and-barrier structure. Experiments were carried out without the spillback control strategy (base case), and also with the incorporation of the spillback control strategy. The KPI means of these scenarios were compared. To test statistical significance, a Welch t-test was performed to test whether the means are significantly different with a two-tailed significance.

The methodology covers multiple chapters. The structure of the thesis is depicted in Figure 1.1.

1.5. Thesis outline

The thesis consists of eight chapters. After the introduction, the literature is reviewed in chapter 2, starting with state-of-the-art RTCS, followed by spillback detection methods, spillback control strategies, transit signal priority (TSP), and RTCS with multimodal optimization. After that, the utilized multimodal RTCS is described in chapter 4. The output of the literature review is used as input for the design of the spillback component, which is described in chapter 4. Furthermore, the implementation of the spillback component in the test framework is described in chapter 5. In this test framework multiple experiments are performed which follow the experimental design described in chapter 6. The results of the experiments are presented in chapter 7, followed by the discussion of the results. In chapter 8, the research questions are concluded and the limitations of the research are described. Lastly, the recommendations are done in terms of future research topics, policy, and model extensions.

2
Literature review

This chapter describes the results of the conducted literature review. The main goal of the literature review is to gain insight into spillback detection methods, and spillback control strategies as an extension to multimodal RTCS. First the research approach is described. After that, state-of-the-art RTCS are described after which spillback detections methods in RTCS are reviewed. As RTCS with multimodal optimization are part of systems that provide signal priority, an outline is given of the development in (transit) signal priority. Next, insight is provided on spillback control strategies in comparable real-time controlled traffic systems. The following sections describe the developments regarding transit signal priority in these systems, which lead to the sections surrounding real-time control with multimodal optimization, and the lack of spillback control in these systems. The found results lead to a conceptual framework depicted in Table 2.2 at the end of this chapter. Finally, the findings of the literature review are concluded.

Approach
First, Mein et al. (2022) and the references were analyzed to gain knowledge in the literature on RTCS with multimodal optimization and transit signal priority and identify the architecture of a multimodal RTCS. Subsequently, relevant keywords were constructed for the literature review about traffic control in RTCS, incorporating spillback control at signalized intersections. Keywords used for the literature review for spillback detection and control strategies are depicted in Table 2.1.

Table 2.1: Generated search queries for literature study

Spillback modelling keywords:	
spillback effects	
Spillback modelling	
spillback detection	
spillback handling	
Traffic control	
Traffic system	
Resulting query:	**hits**
1. spillback AND (effects OR modelling OR detection OR handling)	193
2. (spillback AND (effects OR modelling or detection OR handling)) AND traffic system	118
3. (spillback AND (effects OR modelling OR detection OR handling)) AND (real-time OR realtime OR real time)	76
4. (spillback AND (effects OR modelling OR detection OR handling)) AND traffic system AND (real-time OR realtime OR real time)	65
5. (spillback AND (effects OR modelling OR detection OR handling)) AND ((traffic AND system) AND (real-time OR realtime OR real time) AND control	**54**

Search strategy
The queries were entered in Scopus to find peer-reviewed literature surrounding spillback control strategies. First, ad-

ditional keywords were added to the query to narrow search results. This led to too few papers. Query 5, with 54 hits, was used as a starting point to review the literature.

The found articles were scanned and filtered, as explained in subsection 1.4.1. The results consisted spillback detection methods and control strategies, and insight into the architecture of a multimodal RTCS. These papers were analyzed and distinguished according to the following characteristics: included road users in the proposed model, vehicle priority, objective function used for traffic light signal control (if any), and used traffic sensors for traffic detection. Furthermore, the utilized queuing model (if any), the type of spillback detection, and the spillback control strategy. The consideration between the different methods aims to answer research questions 1.1 to 1.3. An overview of the paper trail can be found in Table A.1 in Appendix A, furthermore, the literature review led to a conceptual framework, which is fully depicted in Table A.2. In the next sections the literature is reviewed.

2.1. State-of-the-art RTCS

Real-time traffic control systems can be divided into two categories. The first category is making minor changes to a previously defined signal plan; the second is more dynamic by switching traffic lights to red or green at each timestep. Despite this categorization, the configuration and focus vary, such as minimum green times or red time clearance. A part of this state-of-the-art real-time controlled traffic systems share the same philosophy: switching traffic light signals or modifying a signal plan according to an optimization criterion for the next n seconds. The number of seconds depends on a configured time horizon, and the horizon renews every m seconds according to a specified update frequency (Boillot et al., 1992). For example, an optimization criterion is usually the total delay at the intersection of multiple intersections in the network during the time horizon, which is approached by the sum of the individual car delay lengths over each timestep on the controlled links. Additionally, other optimization criteria have been developed, such as the sum of vehicle stops, delay experienced per person (personal), maximum vehicle flow, or combinations of other indicators.

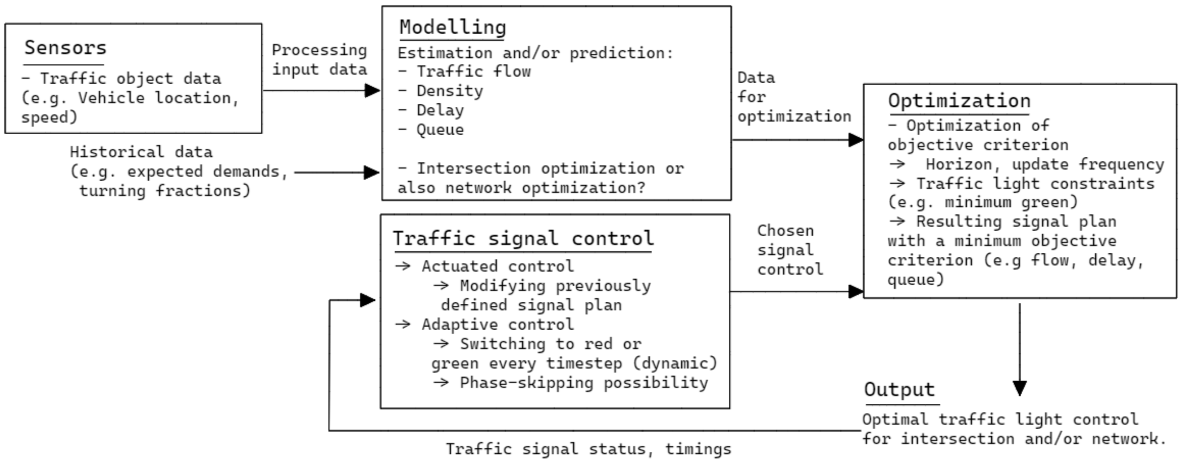


Figure 2.1: Conceptual framework of Real-time control traffic systems

A RTCS of the first category is SCOOT, a traffic signal control system developed in the 1970s that modifies existing traffic signal settings based on the sum of the stops and the saturation degree (Bretherton, 1990; Robertson & Bretherton, 1991). Like SCOOT, SCATS considers adjustments of various signal timing separately; however, SCATS adjusts signal timings based on changes in traffic flows from previous cycles. Collected sensor data measures the Degrees of Saturation (DS) and Link Flows (LF) to allocate green time per direction (Sims & Dobinson, 1980). The system then calculates the cycle length, phase splits, and offsets (Boillot et al., 1992; A. Stevanovic, Kergaye, & Martin, 2009). Some examples in the second category of RTCS, deciding whether to switch the traffic light or not, are The Optimize Policies for Adaptive Control (OPAC), developed by Gartner et al. (2001), and CRONOS developed by Boillot et al. (1992). Updates of OPAC realized enhancements with features such as full intersection simulation with individual and platoon vehicle identification, performance functions for total delay or stops of intersections, cycle length and offset optimization, mode coordination, and dynamic phasing. Furthermore, CRONOS controls zones of multiple intersections. In addition, it utilizes video sensors instead of conventional loop detectors for traffic flow measurements and handling oversaturation traffic phenomena (Boillot et al., 1992, 2006). The forecasting module in CRONOS predicts the future arrivals on each link, which uses the simulation module and calculates the optimization criterion for traffic signal states (e.g. a red or green light status). The following time step identifies traffic signal states to choose an optimal sequence. Furthermore, large-scale system control systems were developed to control multiple traffic participants, such as UTOPIA/SPOT (Mauro & Di Taranto, 1990). The main features of UTOPIA/SPOT are priority assignment to public transit and optimization of private vehicles in all traffic conditions. UTOPIA/SPOT uses local minimization of a cost function for each intersection using a SPOT unit to optimize signal timings. The SPOT units from the systems communicate the counted and predicted traffic flows and signal changes. After that, each controller determines the cycle coordination for each intersection. All in all, for each RTCS, traffic sensors need to supply the RTCS with sufficient information for optimal signal control.

2.1.1. Traffic sensors

RTCS collect infrastructure data and traffic object data, such as the status of a traffic light, or the location or speed of a vehicle. The type and amount of data collected for the RTCS depend on the used traffic sensors. For example, magnetic loop detectors as sensors upstream of an intersection can count vehicles, approximate vehicle speed, and the time gap between cars. However, more precise data, such as the vehicle gap and speed, are more sensitive to sensor faults, such as a wrongly parked car on the side of the road. Nevertheless, RHODES uses these upstream detectors to predict arrivals and includes these future arrivals in the queue length prediction to allow for a longer prediction horizon (Mirchandani & Head, 2001). But also, OPAC uses upstream-placed detectors to obtain arrival data for the head portion of the prediction (Gartner et al., 2001).

The loop detectors used by RTCS are interchangeable with traffic sensors, enabling RTCS to receive more accurate data. For example, traffic objects can be identified using LiDAR sensors (J. Wu et al., 2020) or cameras (Albiol et al., 2011), or travel times measured by cameras can be used for arrival predictions in queue length estimation (Ma et al., 2018). Furthermore, CRONOS uses machine vision to incorporate spatial information into estimating traffic densities, flows, and speed, such as the number of vehicles in the inner junction of an intersection (Boillot et al., 2006). Data-driven traffic models use data to promote a better traffic flow. However, when it is raining or misty, the reliability of these sensors reduces drastically; bad weather will also reduce the sensor range for a precise approximation. However, recent research showed a deep learning approach where a queue length is estimated using convolutional neural networks (Umair et al., 2021), making the estimation of traffic variables possible with a limited-quality video input.

Ultimately, data from the traffic sensors is collected and processed so that the data can be used for modelling, namely the estimation and prediction of traffic variables, such as the traffic flow or the vehicle density. .

2.1.2. Modelling

In the modelling part of a RTCS, specific variables are predicted or estimated, dependent on the configuration of the RTCS. For example, SCOOT calculates the occupancy and vehicle flows for the allocation of green time, SCATS uses the traffic flows from previous cycles, and OPAC uses performance function for total delay or vehicle stops of intersections. Furthermore, CRONOS also uses the delay as an optimization criterion, in which queues are stored as the number of vehicle on the link.

The queue, or the number of vehicles on the link, used for the delay calculation are often calculated based on an input-output method, as shown in Equation 2.1. The number of vehicles in the next time step $t+1$ is equal to the number of vehicles in the queue during time step t plus vehicles flowing in, the arrivals $A(t)$, minus vehicles flowing out, the departures $D(t)$. The vehicles in the queue can then be described using the number of vehicles, but can also be described in meters, using the vehicle length and the gap between two consecutive vehicles.

$$\text{Vehicles in queue}(t+1) = \text{Vehicles in queue}(t) + A(t+1) - D(t+1) \tag{2.1}$$

In the next subsections, traffic variables that are commonly estimated or predicted, such as the traffic flow, the delay, and the queue length.

Traffic flow and density

For the estimation of arrivals, the expected arrival time is predicted using upstream detectors, the time-instant is recorded, and the arrival time is estimated using the travel time of the vehicle i, which travels over the sensor during time step t, to the downstream intersection, as shown in Equation 2.2.

$$\text{Arrival time}(i,t) = \text{Arrival time detector}(i,t) + \text{distance of upstream-detector}/v_{freeflow} \tag{2.2}$$

The number of departures during a cycle depends on the allocated green time T_g^n to the vehicles in queue. The discharge of vehicles is dependent on the queue discharge rate of the vehicles. The queue discharge rate is dependent on the utilized queue method. For example, in Equation 2.3 the number of departures are calculated using a queue discharge rate that is equal to the saturation headway of the vehicles, furthermore, a start-up delay is included for the first vehicle ($i = 1$). The upper limit I is the number of vehicles that are able to depart during the allocated green time.

$$\text{Departures}(i, n) = (\text{start-up delay} + \sum_{i=2}^{I} \text{vehicle}(i) \cdot \text{Queue discharge rate}) \leq T_g^n \tag{2.3}$$

The expected arrivals and departures can also be used for the density calculation. For example, SCOOT uses the density and gives the factor a degree to determine the weight of the density compared to the available road capacity (Degrees of Saturation). In combination with the vehicle flows, this is used in the green time allocation.

Queues

The estimated number of departures, but also the vehicle delay computation is dependent on the utilized queue method. Two types of queuing models are widely used. On the one hand, queuing models that neglect the spatial characteristics of a queue (vertical queue). On the second hand, models that take spatial variables into account to estimate the head and tail of the queue (horizontal queue), as depicted in Figure 2.2.

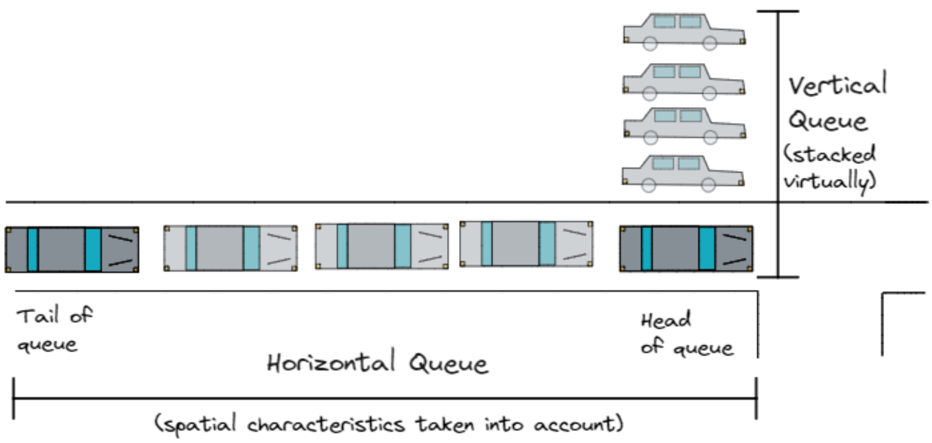
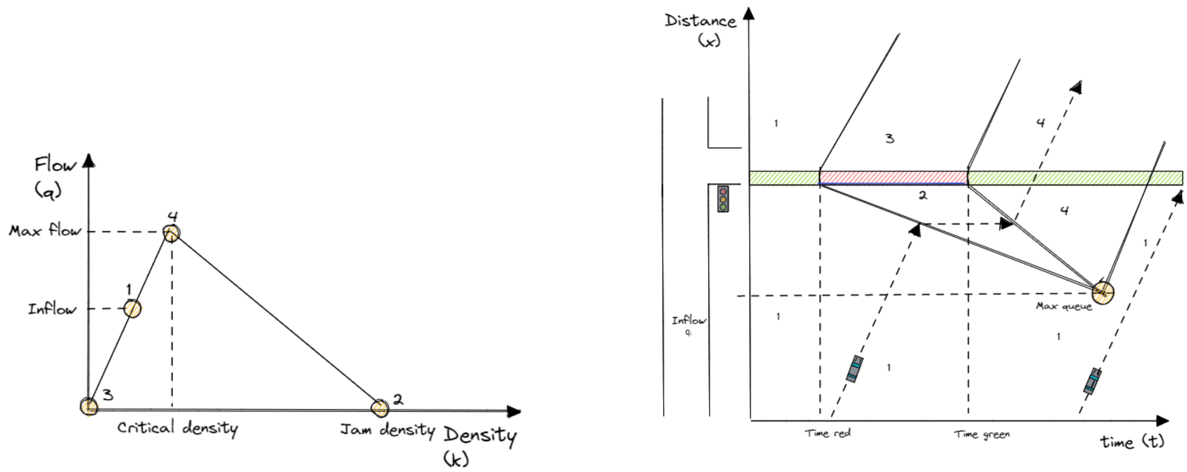


Figure 2.2: Horizontal Queue vs. Vertical queue

A vertical queuing model considers a standing queue where vehicles are stacked virtually, the cars are stacked at the bottleneck's place, in the case of an intersection, at the stopbar. Consequently, the queue length has no influence on approaching vehicles (Y. Liu et al., 2018). The queuing process consists of a deterministic queue profile: at the queue's release, the queue's bottom is released first, following a First in First Out method (FIFO). For the queue discharge, a queue discharge rate is set based on the vehicle headway, the acceleration rate, or a combination of both. For the first vehicle a (fixed) start-up delay is taken into account for the driver's responsiveness.

A HQM describes a queue with, for example, the cell transmission model, in which the road is divided in cells to describe kinematic wave equations (Daganzo, 1995). Another widely used approach is applying a shockwave queuing profile developed by Lighthill & Whitham (1955), which estimates the head and tail of the queues by describing time and space-dependent dynamics. When SWT is used as a queue method, a queue profile is constructed using the traffic flow, density, and speed. These three variables are referred to as traffic states, in which vehicles can transition between uncongested and congested states, according to a corresponding density, speed, and flow. In a fundamental diagram, points are used to describe traffic flow phenomena, such as the queue built up and the queue discharge process. The fundamental diagram (see Figure 2.3a) and shockwave profile (see Figure 2.3b), show the queue process, according to allocated green time, red time, the queue built up, and queue discharge. The numbers indicated in Figure 2.3a are corresponding to the indicated numbers in Figure 2.3b, and resemble a traffic state – for example, state 2, indicates a jam density with a vehicle flow of zero.



(a) Example of fundamental diagram (FD)

(b) Resulting shockwave profile, according to the FD and traffic light signals

Figure 2.3: A fundamental diagram and a queue profile, according to SWT

The VQM and HQM are different in operational mechanisms but are both vehicle-trajectory oriented and operable using fixed-location sensors. However, both have a lack of operability when sensors are faulty or insufficient information is available (Y. Liu et al., 2018). In that case, the benefit of choosing a VQM above an HQM is computational efficiency. On the other hand, an HQM has the benefit of describing spatial queue characteristics, with advantages such as implementing the queue length in the objective function, a check whether a queue length exceeds a lane threshold, and delays of long queues are less underestimated compared to VQMs.

Delay calculation

The delays computation depends on the queue method of RTCS. For delays, using a VQM, are often comparable, such as the approaches from Sharma et al. (2007); Boillot et al. (2006); He et al. (2014); A. Stevanovic et al. (2015); Bhouri et al. (2015), with a fixed queue discharge rate, based on the start-up delay and configured vehicle headways. This leads to the following equation, in which I is the total number of vehicles in the queue:

$$\text{Delay}(i) = \text{start-up delay} + \sum_{i=2}^{I} \text{vehicle}(i) \cdot \text{Queue discharge rate} \tag{2.4}$$

Another approach, which takes spatial characteristics into account, is by applying shock wave theory. The shockwave profiles, as in Figure 2.3b, can be used to estimate collective delays experienced by vehicles. The delay is calculated as the time vehicles wait for a red traffic light. Assuming that the cars arrive in platoons without dispersion, Christofa (2012) uses the arrival time of the first vehicle, the platoon size, and the residual queue of the upstream intersection of the previous traffic light cycle to estimate the collective delay, an example is depicted in Figure 2.4.

According to Figure 2.4, the individual vehicle delay d of vehicle i during cycle c can be estimated using the time t_i^c the vehicle i arrives at the intersection, during cycle c, and the time t_i^c the vehicle i is expected to leave the intersection at cycle $c+1$: t_i^{c+1}.

$$d(t)_i^c = t_i^{c+1} - t_i^c \tag{2.5}$$

The individual vehicle delays are then summed to calculate the collective vehicle delay during cycle c:

$$D(t)_i^c = \sum_{i=1}^{I} d(t)_i^c \tag{2.6}$$

In the modelling part of a RTCS, the estimated or predicted traffic flows, densities, queue length, or delays are calculated so that they can be utilized for the optimization of an objective function.

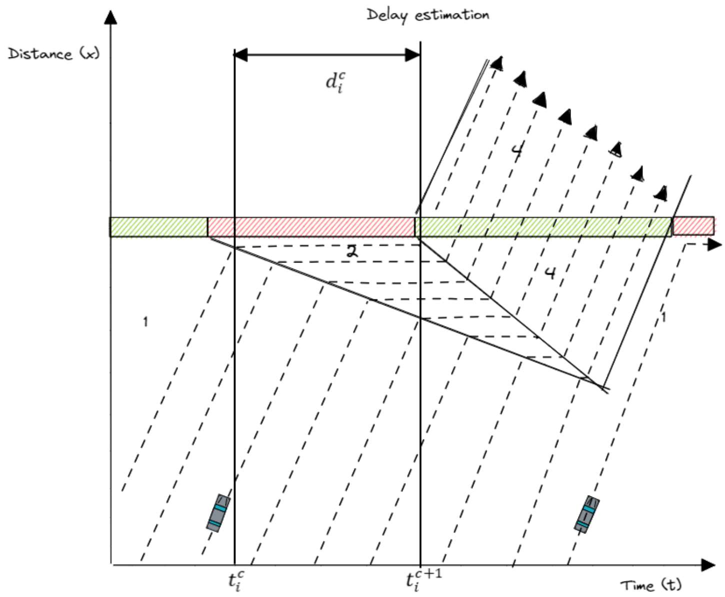


Figure 2.4: Delay computation in a shockwave profile

2.1.3. Optimization

The modelled traffic variables, such as the vehicle delay, is used in the optimization of the RTCS. The optimization is also dependent on the chosen signal control, in which existing traffic timings are adjusted with minor changes (e.g. SCOOT), or a signal plan can be adjusted dynamically by switching to red or green every time step (e.g. OPAC, CRONOS), with an adaptive approach that also considers phase skipping. The optimization consists of the minimization or the optimization of the objective criterion, which is found by different search algorithms.

In some cases an approach that searches brute force through the possible signal plans is used. For example, when the traffic network is small, or the signal plans are already predefined. But also search algorithms for local optima are used, to increase the update frequency or to expand the optimization horizon. A disadvantage is that the found signal plan may not the optimal signal plan, but the optimization time for a new traffic signal plan is minimized. For example, CRONOS, finds new traffic signal states for the next second, in less than a second (Boillot et al., 2006).

2.1.4. Spillback effects

When demand is high, traffic phenomena occur that come with oversaturated conditions. For example, when a queue grows, it spills over to the upstream intersection. Spillover could lead to blocking other passenger cars at the intersection and other travel modes, such as light-rail vehicles. Another effect is lane-blockage, for example, when an oversaturated turning bay blocks straight-through traffic. Furthermore, the straight-through lane could also be oversaturated, causing lane blockage to the turning-bay (Boillot et al., 1992; H. Liu et al., 2009; Ramezani & Geroliminis, 2013). With that in mind, more situations could occur due to spillback, such as blocking pedestrians when vehicles spill over to the upstream intersection. Examples of these spillback effects are depicted in Figure 2.5

Unsafe situations occur with spillback effects, such as when a passenger car spills over to an upstream intersection and blocks an incoming Light-Rail vehicle. Additionally, when cars are blocking other road users – for example when cars cannot travel further downstream as other vehicles spill back to the intersection. Consequently, these cars block other more vulnerable road users such as cyclists and pedestrians.

In RTCS traffic variables are taken into account that measure performance criterions of cars, but when RTCS can identify spillback situations, the system could provide additional priority to solve situations as in Figure 2.6, so that straight traffic have improved throughput. Therefore, unsafe situations that can occur with spillback, such as conflicts between different types of road users, are avoided. The following section describes spillback detection and solving methods of RTCS.

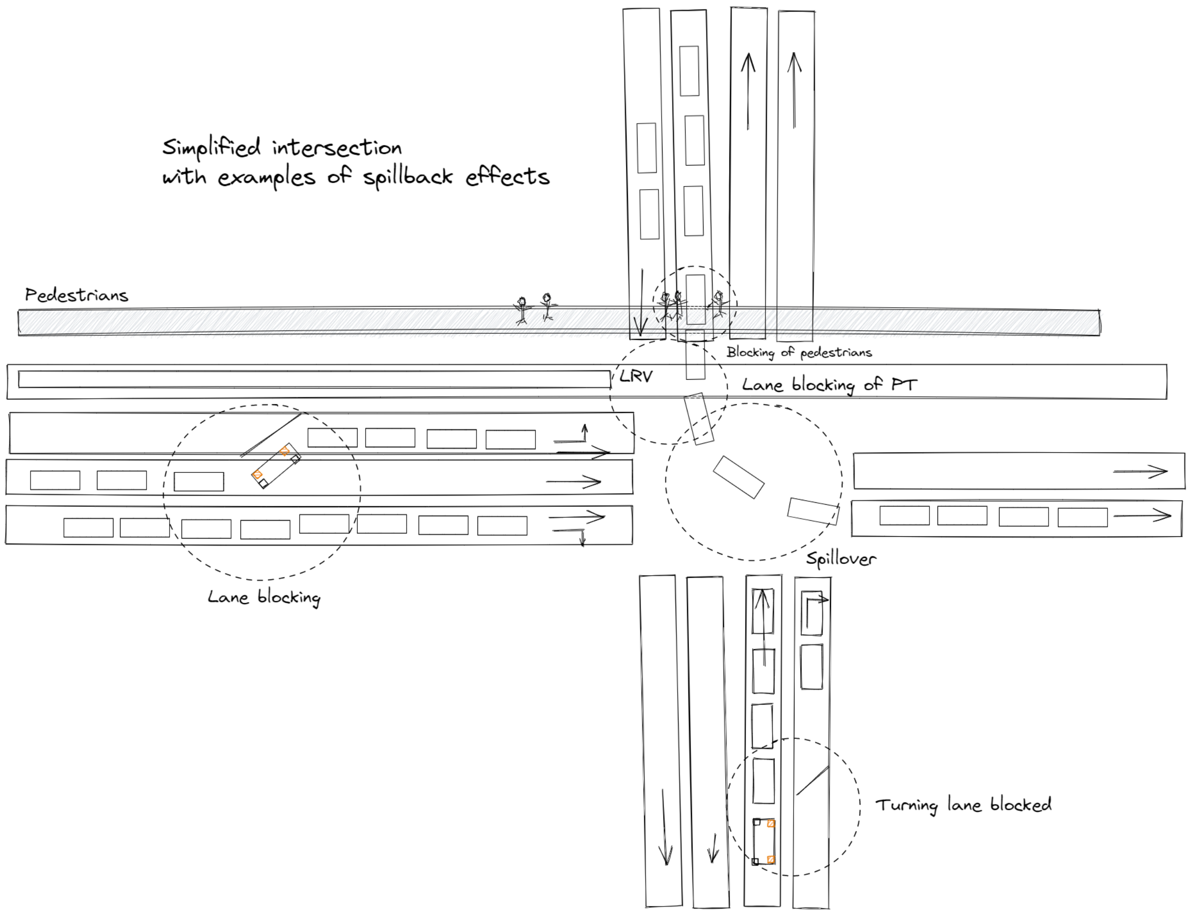


Figure 2.5: Examples of spillback effects at a signalized intersection

Figure 2.6: Spillback effects and conflicts with multiple road users on the Burgermeester Jamessingel

2.2. Spillback control in RTCS

Several approaches have been researched and developed to detect and handle spillback effects in RTCS. In these papers, several characteristics that vary in the detection and handling method of spillback effects have been identified. In terms of spillback detection and control strategies, the components included road users, vehicle priority, the utilized objective function (if any), the type of traffic signal control, used traffic sensors, and queue method (if any). In the next sections, these components are described, according to the found literature.

2.2.1. Spillback detection

The spillback detection method is dependent on the utilized traffic sensors and if a queue method is used. In literature, two types of spillback are defined in detection: lane blockage and vehicles that spill over to an upstream intersection. The lane blockage can be a straight-forward direction blocking a turning-bay, or the other way around. Spill over is often used in terms of overflowing to an upstream intersection.

The following approaches were used often. First off, spillback is detected using a link capacity by defining a capacity in terms of the number of vehicles that a turning bay could handle without blocking another direction or the capacity of a link without spilling over to an upstream intersection (Y. Zhang & Tong, 2008; Y. Liu & Chang, 2011; Han & Gayah, 2015; Ramezani et al., 2016). The traffic system obtains the number of vehicles by counting the departures at an upstream intersection or the passing vehicle at an advance detector. The second mainly used approach was comparable: a queue model estimates the queue length for the traffic light cycle. When the queue length exceeds the queue threshold, spillback is detected (Christofa et al., 2013; Wong & Lee, 2020; Mohajerpoor & Cai, 2020; Noaeen et al., 2021; H. Zhang et al., 2020). The queue threshold can be a turning-bay length or the link length of two consecutive intersections. Additionally, there are three other methods found. X. Wu et al. (2010) proposed an additional oversaturation index: the time a vehicle spends in a queue and the length of the queue determines whether spillback is sustained and should be dealt with. Or whether the spillback is acceptable as the vehicle moves further to the downstream intersection. Another approach that uses an upstream detector, is the method by Ren et al. (2017), spillback is detected by finding a low speed at this upstream detector, with effective result, however it is very sensitive to sensor faults. Another approach that does not require estimation, is when problem areas, such as the inner junction of an intersection, or turning bays, are tracked using data-driven traffic sensors, such as cameras or laser sensors (Boillot et al., 2006).

Traffic sensors

The used traffic sensors have an impact on the approach used for queue estimation and spillback detection methods. The more information an RTCS receives about the vehicle state, the more accurate the detection and handling of spillback is applied. For example, the systems from Y. Zhang & Tong (2008); Y. Liu & Chang (2011); Ramezani et al. (2016); Wong & Lee (2020); Mohajerpoor & Cai (2020) assume perfect information about the queue length, vehicle position, and lane-changing behaviour. However, outcomes could overestimate the effects measured by the spillback control and handling strategies as perfect information is available. Other developed systems use connected vehicles in a connected vehicle environment (Christofa et al., 2013; Ramezani & Geroliminis, 2015; Cao et al., 2019; H. Zhang et al., 2020), with advantages such as a more accurate and efficient traffic control, but also assumes accurate vehicle position, speed, turning behaviour, and vehicle gaps. As the approaches need connected vehicles, the approaches are less likely to be applied in the short term. Designs that have a calibrated traffic sensor, such as upstream loop detectors or stopbars, have the advantage that it is applicable in the short term in an urban environment. However, the approaches inliterature that only use detectors, also require a queue method to detect potential spillback.

Queue model

Queuing models were used to detect the maximum (and residual) queue length in real time to detect whether a queue threshold was exceeded. The most widely used queue model for spillback detection is the method that applies shock wave theory to estimate the maximum queue length (X. Wu et al., 2010; Christofa et al., 2013; Han & Gayah, 2015; Ramezani & Geroliminis, 2015; Noaeen et al., 2021; Mohajerpoor & Cai, 2020; H. Zhang et al., 2020; Ren et al., 2017). Other approaches measured the queue length directly from the simulation, such as Y. Zhang & Tong (2008); Y. Liu & Chang (2011); Chen & Chang (2014); Ramezani et al. (2016). But also traffic variables from connected vehicles were used, such as the approaches from Christofa et al. (2013); Ramezani & Geroliminis (2015); Cao et al. (2019). Another method by Wong & Lee (2020), was a cell transmission model (CTM) around the intersection to describe queue dynamics. The CTM made it possible to optimize traffic signals, including the red and green time duration, cycle time based, in which lane markings on the road are included as binary optimization variables. Also, a gap-based queuing model from Christofa et al. (2013) was researched, but proved to be less accurate than applying shockwave theory.

Traffic signal control

In the articles, regarding spillback control with RTCS mainly two types of traffic signal control were used. The first is fixed time control, in which the traffic lights follow a predefined signal plan. The other type is adaptive control, which controls the traffic lights according to an optimizing an objective criterion. For fixed time traffic signal, the spillback control strategy interferes with the signal plan, and for adaptive control, the spillback control strategy can alter the objective criterion – for example, the objective function is changed to minimizing the total time spent on an intersection. Or the control strategy interferes with the optimal signal control. These strategies are explained in the next section.

2.2.2. Spillback control strategies

In the literature, two types of spillback control strategies have been found. The first one solves spillback by an objective criterion. The other approach is metering upstream, downstream, or both at the congested intersection.

Objective function

In some of the researched articles, systems used an objective function to control the traffic. Approaches that utilize an objective function that detect spillback, uses additional delay, reduced link capacity for the congested intersection, and impacts on upstream intersections as new variables in the optimization. Y. Liu & Chang (2011) use the objective function that maximizes the flow using a genetic algorithm and checks every step if oversaturation is present until the stop criterion is met. When oversaturation is found, a fitness evaluation determines whether the solution is near the optimal solution. The research from Chen & Chang (2014) builds further and incorporates heavy mixed traffic flows in the optimization. Wong & Lee (2020) also maximizes the flow for every direction in which the optimization prevents overflow. Another approach is that less capacity is assigned in the optimization to the link affected by spillback (Han & Gayah, 2015). The last type of optimization calculates the saturated green time (when a queue is fully discharged during a cycle) for all movements (Noaeen et al., 2021). The optimization minimizes the saturated green time for each possible stage and selects the phase with the maximum outflow rate for the phase time. After that, stages are improved by finding the set of phases with more movements compared to the selected stage. After that, the phase with the maximum outflow rate and the total queue length among the selected phases is chosen. Lastly, extended green is facilitated to allow flow continuation if a movement has received green in the previous and current phases.

Metering

Metering is restricting or promoting a flow in a specific direction to reduce or promote the incoming or outgoing traffic. In terms of metering, metering upstream is used to solve spillback by limiting the inflow to the congested link (Christofa et al., 2013; Mohajerpoor & Cai, 2020). Upstream metering is combined with downstream metering to promote downstream intersection flow and restrict upstream intersection flow (Ramezani et al., 2016; Cao et al., 2019). Additionally, sidestreets can be added in upstream metering to limit the inflow even more (Ren et al., 2017).

Multiple control strategies are developed to help cope with spillback effects and handle congested conditions. In these papers, the research focus has mainly been on the urban environment where only passenger cars are present. However, in an urban environment, there are mixed traffic flows, such as LRVs and pedestrians. State-of-the-art RTCS have been tested with vehicles and the addition of priority for public transit, such as SCOOT with bus priority (Hounsell & Shrestha, 2005). Transit signal priority can improve the overall network performance of an urban environment. In the next section, Transit signal priority will be explained further.

2.3. Transit Signal priority

There are many benefits to using transit signal priority control in traffic control systems. These benefits include improved transit schedule reliability, reduced transit travel times, improved level of service, and reduced stops for all modes, leading to increased travel comfort for both cars and transit users. Furthermore, reduction in emissions and, above all, increases the attractiveness of public transit, which is the consequence of priority competitiveness between public transit and cars.

In general, a physical TSP system comprises three main components – first, the vehicle detection system, which detects transit vehicles and generates priority requests. Secondly, receiving and processing the priority request at signalized intersections with the traffic signal control system. Lastly, the communication system connects the detection system with the traffic signal control system (Ding et al., 2013).

Strategies for controlling TSP depend on the type of priority given to the traffic modes. Some strategies modify normal signal operations to allow transit vehicles to travel through a signalized intersection with delay; other systems are optimized, taking multiple modes into account for signal optimization. In the upcoming subsections, the fundamentals are explained based on the clear overview of Baker et al. (2002). First, the different priority types are explained, as the difference between local TSP and area-wide TSP, the detection of transit in TSP, and lastly, the links between real-time control and TSP.

2.3.1. Priority types

First, the difference between priority and preemption should be clear. The terms priority and preemption are different processes but are often confused: signal priority *modifies* the normal signal operation process to accommodate transit vehicles better, and preemption *interrupts* the standard procedure for special events (Baker et al., 2002). In the case of urban intersections, these special events typically are the arrivals of emergency vehicles.

In TSP, multiple strategies exist to modify signal operations to allow transit vehicles to travel through a signalized intersection with a reduced delay. These can be distinguished mainly into three types: passive priority, active priority, and real-time priority, where the latter is the case when TSP is facilitated with improved information by enabling real-time detection information to be used for purposes other than real-time control. A schematic overview of priority types can be found in Figure 2.7.

Passive priority

When transit operations are predictable and reliable, characterized by consistent dwell times and a high schedule adherence, in combination with high frequencies and low traffic volumes, passive priority strategies can be an efficient form of TSP. The signals coordinate transit vehicles' flow, promoting straight-through public transit. However, the consequence of traffic signals being coordinated for transit and not for other traffic modes is that these other may experience unnecessary stops or delays, which could lead to annoyance by other road users.

Active priority

Active priority is possible when public transit is detected in real-time. According to this detection, modifications are made to the traffic signal plan. These modifications are *early green*, which can be applied when the signal is red for the approaching vehicle. The green times for previous phases are often reduced to early green. The second strategy is *green extension*, where the downstream traffic light is green, and the method logically extends the green time to benefit transit priority. Optionally, early green and green extensions are combined for additional priority. *Actuated transit phases* detects transit vehicles at intersections. An actuated transit phase is a dedicated phase for transit vehicles. An actuated transit phase could be realized in two ways, either by *phase insertion*, in which the actuated transit phase is inserted in the normal signal sequence. The other way is to use *phase rotation* to provision TSP. An example of phase rotation would be a northbound left-turning bus requesting priority before the start of the green phase of the opposing through movement, which was the 'normal' phase structure (Baker et al., 2002).

Real-time control

When TSP strategies provide priority while simultaneously optimizing given performance criteria, such as person delay, transit delay, vehicle delay, or a combination dependent on the configuration of the real-time control system, generally, these systems require travel information about public transit for early detection to provide transit priority while minimizing traffic impacts for other modes. It is important to note that TSP does not end when the vehicle has passed through the signal. In priority strategies where the traffic system must detect the transit beforehand, most signal controllers implement a recovery operation where phases transition back to regular signal operation as stages were cut short or skipped during the priority strategy (Baker et al., 2002). This is the case because transit provision could negatively impact traffic operations of other modes.

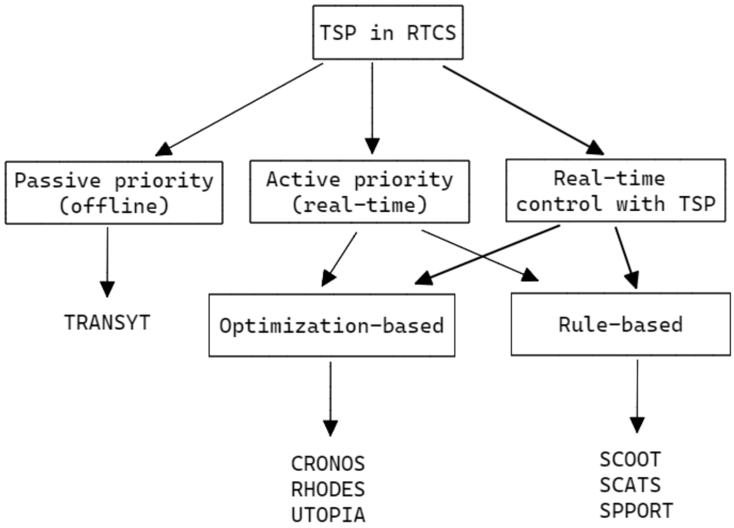


Figure 2.7: Overview of priority strategies (adapted from (Yagar & Han, 1994))

2.3.2. Local TSP vs Network TSP

By detecting approaching transit vehicle upstream of signalized intersection TSP could be accomplished at local intersection levels. The upcoming bus or LRV sends a call or message to the traffic signal controller to check in. After the vehicle has passed through the intersection, it can be detected again when it sends a call or message to check out.

At the network level, a traffic system uses an automated vehicle location and control (AVLC) system to determine if the transit vehicle travels on schedule. When the public transit is not travelling on schedule, the traffic signal controller could respond to request priority for the transit vehicle.

2.3.3. Transit detection

Transit vehicle detection systems can be distinguished into four categories: driver actuated, point detectors, area detectors, and zone detectors (Baker et al., 2002). The first category *driver actuated* is desirable for vehicle detection. Preemption of emergency vehicles could be very beneficial; however, in a real-life study in Washington, experience learned that drivers of transit vehicles keep the transmitter on, even when priority was not needed or desired. *Point detectors* are used frequently to detect TSP. The detectors work well, but the limitations concern the limited information of the transit vehicles between the point detectors. *Area detectors* can monitor the movement of a vehicle through an area and, therefore, can be used to predict the arrivals of transit vehicles at intersections. The last category is *zone detectors*; these detectors know when a system is somewhere on the approach of an intersection (e.g. 150 meters) and is requesting priority.

2.3.4. Strategies for Real-time control and TSP

Various strategies exist to implement adaptive/real-time traffic signal control with TSP. Although details of how each system implements adaptive control vary. In general, real-time signal control assesses the status of the network. With traffic flow predictions for cars, buses, and light-rail vehicles, traffic systems with TSP can modify signal timings to accommodate traffic demand efficiently. Real-time control requires more sophisticated detectors methods, communication, and processing capabilities than actuated signal control. Furthermore, when all modes are included in the real-time control, RTCS can optimize traffic in multiple ways – for example, the delay experienced by each vehicle or the delay experienced by each traffic participant. This is further explained in section 2.4.

TSP, in combination with real-time control, has been tested in real life, with critical performance criteria for transit identified as regularity and punctuality. For example, SCOOT bus priority, with inductive loop detection, proved to be effective and reliable. With more advanced information available, due to roadside beacons for the bus, TSP proved even more effective (Hounsell & Shrestha, 2005). Systems that focus on special priority for modes other than the bus, such as a system with a particular priority for Light Rail Vehicles, have also been developed that control traffic in combination with a Genetic Algorithm formulation. The genetic algorithm optimizes traffic control for multimodal operations in large urban networks. Solutions are constrained to preserve existing (and well-performing) Light Rail Transit predictive priority strategies in a Software-in-the-Loop environment (A. Stevanovic, Kergaye, & Martin, 2009; A. Stevanovic et al., 2015). Basic signal timing for passenger cars is the most essential measure to optimize traffic signal control, compared to optimizing signal timing for vehicle transit or a combination. Additionally, this is the case when the objective criterion is for passenger cars, personal delay, or transit vehicle delay (J. Stevanovic, 2011).

Multiple real-time urban traffic control systems in literature have been developed to regulate global traffic, and extensions to these models have been made to include public transit priority in multimodal optimization. These multimodal real-time controlled systems will be described in the following section.

2.4. Multimodal real-time controlled systems

Multimodal RTCS with multimodal optimization control all traffic by an objective function that optimizes all vehicle modes. While the traffic demand for private cars is still growing, the growing number of users of buses, light-rail vehicles, cyclists, and pedestrians, increases the complexity of finding the optimal signal control solution for an urban traffic environment (Christofa et al., 2013; Bhouri et al., 2015; Mein et al., 2022). Although signal control and multimodal priority systems have been widely deployed over the last few decades, these two systems often conflict with each other due to different control objectives (He et al., 2014). One of the identified issues in these systems is providing equity between modes. Another is estimating the vehicle delay, often based on existing real-time control systems.

In the following subsections, the used traffic detectors, control, queuing model, and objective function of multimodal real-time controlled systems are described.

2.4.1. Traffic sensors

Multimodal RTCS use multiple traffic sensors, as not only passenger cars but also LRVs, buses, bicycles, and pedestrians must be identified. Which can be done with conventional traffic sensors, such as magnetic loop detectors, with upstream and downstream possibilities for passenger cars, but prescribes a detector for each traffic mode. Data-driven systems use more sophisticated laser or machine vision sensors. These sensors make it possible to identify multiple traffic modes with a single sensor, possible with LiDAR sensors (J. Wu et al., 2020; Mein et al., 2022), or machine vision (Albiol et al., 2011). Additionally, queue lengths can be measured in real-time, or the traffic system can count the number of vehicles in the inner junction of an intersection (Boillot et al., 2006). However, these sensors are more prone to sensor faults when the weather is bad – for example, when it is dark or it is misty. Furthermore, less sophisticated are cheaper in terms of purchasing costs.

2.4.2. Traffic signal control

In terms of utilized traffic signal control, three types are found. The first is a (traffic responsive) fixed timing control with transit signal priority (Yagar & Han, 1994; Bhouri et al., 2015), here transit signal priority interrupts the proposed signal plan to provide priority for public transit. An alternative is adaptive traffic control; the traffic light switches dynamically when the option provides a better alternative than the current phase plan (Zeng et al., 2019; Christofa et al., 2016), adhering to safety constraints but mainly focused on minimizing vehicle or personal delay, regardless of the type of road user. The last type is adaptive control, which uses a predefined signal set: a collection of phase plans is generated and optimized based on car delay using a genetic algorithm. This results in a collection of phase diagrams. During the prediction horizon of the multimodal RTCS, the adaptive control evaluates different green options for cars and public transit and chooses the plan that leads to the minimum or maximum of the objective criterion (He et al., 2014; A. Stevanovic et al., 2015; Mein et al., 2022).

2.4.3. Modelling

For the estimation or prediction of traffic variables, older systems (Yagar & Han, 1994) to newer methods (He et al., 2014; Xie et al., 2014; Bhouri et al., 2015; Mein et al., 2022) use the delay to optimize multiple road users. For passenger cars, the delay is calculated according to a VQM. The VQM is easily implemented, and is computational fast. Yet, as previously mentioned, a VQM does not take spatial characteristics into account and delays are underestimated when queues are long. On the other hand, two identified systems apply shockwave theory to estimate delays or queue lengths, the system from Zeng et al. (2019) which uses connected vehicle to estimate the number of vehicles in the queue. Secondly, the multimodal system from Christofa et al. (2016) estimates car delay based on shock wave theory, comparable to the method in subsection 2.1.2. However, the queue length is not considered explicitly. In these multimodal systems, queue model are only used for the delay calculation. The minimum of the delays is then used to find the optimal signal plan.

2.4.4. Optimization

Multimodal RTCSs optimize based on either personal or vehicle delay. The personal delay is defined as the delay experienced by an individual road user, the vehicle delay is the experienced delay per vehicle. The researched multimodal system developed by Christofa et al. (2016) made use of personal delay, and the articles of He et al. (2014), Mein et al. (2022) use vehicle delay and include a vehicle priority list to give the possibility to provide additional priority for specific modes. A. Stevanovic et al. (2015) tested multiple configurations and concluded that optimizing a predefined collection of signals plans based on vehicle-delay-optimization yields the best results, comparing this to transit-delay-optimization or a combination of transit- and vehicle-delay-optimization.

Using personal delay was found successful for objective optimization functions (J. Stevanovic, 2011). Consequently, the higher the passenger occupancy of a transit vehicle, the higher the priority and the higher the benefit for transit users. However, when the car traffic demand is very high, personal or vehicle delay optimization converge to the same outcome. In addition, when transit vehicles such as LRVs have high occupancy, the reduction in personal delays grows until the system operates close to saturation; at this point, the optimization leads to the same solution as with a lower passenger occupancy. Providing additional priority for other traffic modes in such situations causes a lack of flexibility. Therefore, it is advised that experiments should incorporate different weights for various transportation modes applied in the person-delay optimization.

Using vehicle delay also has benefits with special priority for LRV. The priority is often defined as a user-specified list of priority weights. Public transit, such as LRVs or buses, receive a higher priority than passenger cars. This has the benefit that policymakers could include their decision-making goals directly in the priority weights of traffic modes. However, one of the identified issues in these systems is providing equity between traffic modes and the lack of flexibility in providing additional priority when the network demand grows during peak hours.

Providing additional priority also lacks in the traffic control of multimodal RTCS that use an objective function that optimizes all traffic modes. However, additional priority could be justified as spillback effects, such as spillover, can obstruct other traffic direction, or could lead to unsafe situations when right-of-way is given to a higher priority LRV.

2.5. Spillback control in MM real-time control systems

Little research has been done on spillback modelling in multimodal real-time controlled systems. Regarding unimodal RTCS, Noaeen et al. (2021) developed a control strategy that avoids and handles spillback effects, suggesting that more research is needed to include more modes and test transit priority. In the context of multimodal RTCS, it is suggested that a more sophisticated queue estimation model is used He et al. (2014). Christofa et al. (2016) developed a multimodal RTCS with a more sophisticated queue model that applies shockwave theory but neglects the queue lengths in the traffic control and suggests that non-recurrent congestion, such as spillover and/or lane blockage should be included in the control strategies of multimodal real-time traffic control. A multimodal RTCS (SURTRAC) that detect and handles spillback is designed by Xie et al. (2014). The system uses a vertical queuing model, and based on the state identification in this standing queue (Perez-Montesinos et al., 2011), spillback can be detected and handled. However, SURTRAC is a patented multimodal RTCS (Xie et al., 2015).

The results lead to insight about the effects on the performance of a multimodal RTCS. First, in terms of throughput, (transit) vehicles could achieve lower delays and a higher throughput when bottlenecks are solved sooner. Second, in control strategies where oversaturated traffic phenomena, such as spillover and lane blockage, are avoided or controlled, unsafe situations are avoided or solved faster so that less conflicts occur between different road users. For example, passenger cars spill over to an upstream intersection when an approaching light-rail vehicle crosses the street or when passenger cars halt pedestrians at the crosswalk due to downstream congestion.

The researched literature led to a conceptual framework that summarizes key aspects of researched articles. Namely, the included road users in the RTCS, whether priority is provided, if an objective function is included, the utilized traffic signal control, the traffic sensors, and the queue length estimation. Lastly, the spillback detection and control strategies of researched articles. A complete overview of the conceptual framework (Table 2.2) with mentioned contributions can

Table 2.2: Literature overview (full table in Appendix A,Table A.2)

Reference	Road users	Priority	Objective funct	Signal control	detectors	Spillback detection Queue model	Type	method	SB Control
Y. Zhang & Tong (2008)	PC	-	-	FT	S	S	LB	LC	None
X. Wu et al. (2010)	PC	-	-	FT	US	SWT	SO	OSI	None
Y. Liu & Chang (2011)	PC	-	MinTTS,MaxTP	AC	S	S	SO,LB	LC	OF
Chen & Chang (2014)	PC,B,T	-	MinTT,MaxTP	AC	S	S	SO,LB	LC	OF
Christofa et al. (2013)	PC	-	-	FT	CV	SWT,Gap-based	SO,(LB)	QT	M-US
Han & Gayah (2015)	PC	-	MaxTP,MinD	FT	S	SWT	SO,LB	LC	OF
Ramezani et al. (2014)	PC	-	-	Act	CV	SWT	SO	Prob(SO)	None
Ramezani et al. (2016)	PC	-	D	AC	S	S	SO, (LB)	LC	M-US,DS
Wong & Lee (2020)	PC	-	CF	AC	S	CTM	SO	QT	OF
Noaeen et al. (2021)	PC	-		AC	US	SWT	SO	QT	OF
Mohajerpoor & Cai (2020)	PC	-	-	AC	S	SWT	SO,LB	QT	M-US
H. Zhang et al. (2020)	PC	-	MinQL	FT	CV	SWT	SO	QT	OF
Ren et al. (2017)	PC	-	-	AC	US,SB	SWT	SO	SD	M-US,DS,SS
Cao et al. (2019)	PC	-	-	FT	CV	CV	LB	Prob(LB)	M-US,DS
Yagar & Han (1994)	PC,B	BP	VD	AC	US,SB	VQM	-	-	-
Xie et al. (2014)	PC,B,P	-	-	AC	MV	VQM	SO	LC	M-DS
Zeng et al. (2019)	PC,B	BP	PD	AC	CV	SWT	-	-	-
Bhouri et al. (2015)	PC,B	W	VD	FT	S	VQM	-	-	-
Christofa et al. (2016)	B, PC, (LRV,P,C,T)	(W)	PD	AC	US	SWT	-	-	-
A. Stevanovic et al. (2015)	LRV,B,PC,P	LRVP	PD,VD,PDVD	Set	US/SB	S	-	-	-
He et al. (2014)	PC, B,P, (BC,T)	W	VD	Set	SB	VQM	-	-	-
Mein et al. (2022)	PC,LRV,T,P,(BC,B)	W	VD	Set	MV	VQM	-	-	-
Proposed model	PC, LRV, T, P(BC,P)	W	VD	Set	MV	SWT	LB, (SO)	QT	Penalty

Legend. (brackets): Mentioned as possible extension of the model. Max: Maximize. Min: Minimize
Road users: PC (Passenger cars), B (Bus), T (Truck), LRV (Light-rail vehicle), BC (Bicycle), P (Pedestrian). Priority: BP (Bus priority), W (Weighted), LRVP (LRV priority).
Objective: TT (Travel time), TP (Throughput), D (Delay), QL (Queue length), CF (Common Flow), VD (Vehicle delay), PD (Personal delay).
Signal Control: FT (Fixed timing), Set (AC with signal plans predefined with genetic algorithm), AC (Adaptive control)
Detector placement: S (Measured from simulation software), US (upstream), CV (Connected vehicles), SB (Stopbar), MV (Machine vision)
Queue model: S (Measured from simulation software), SWT (Shock wave theory), I/O (Input/output method), CTM (Cell transmission model), CV (Connected vehicles), VQM (Vertical queuing model)
SB type: LB (lane-blocking), SO (Spillover). Detection: LC (Link capacity), OSI (Oversaturation Severity Index), QT (Queue Threshold), Prob() (Probability of spillback type), SD (Speed detection).
SB control: OF (Objective function), PinOF (Penalty in objective function), M- (Metering from US and/or DS direction), US (Upstream), DS (Downstream), SS (Sidestreet)

be found in Table A.2.

2.6. Conclusion

In the literature, control strategies have been developed that detect or control ocurring spillback effects. In this chapter the aim was to answer the first two subquestions of RQ1: *How could spillback be detected?* And *how could spillback be avoided or handled?*. First, the findings of current research is described, after that, implications for future research are made

Findings

It was found that the spillback detection approach was dependent on the utilized traffic sensors, and whether a queue method was used for detection. Two types of spillback are detected in literature, namely, lane blockage or spill over to an upstream intersection.

A commonly used approach in literature for spillback detection was using the link capacity of a lane. When the capacity was defined in terms of the number of vehicles, the traffic system counts the number of incoming vehicles, the number of vehicles are then compared against the link capacity, assuming a fixed vehicle length and vehicle gap. This method is often paired with a VQM. When the capacity was defined in terms of meters, the queue length was estimated in real-time using a queue model. For the queue length estimation, in most cases, shock wave theory was applied. Also, in some cases the queue length was used in spillback detection, but it was retrieved directly from the test environment. For both approaches, when the queue exceeds the link threshold, spillback is detected. Other cases that detect spillback, include a speed threshold, which detects spillback when the speed is low enough at the location an advance detector, another identification of the type of spillback, namely, the time a vehicle spends in the queue, and the queue length determined whether spillback is sustained or should be dealt with. The most pragmatic approach was the use of sophisticated traffic sensors that can supervise if spillback occurs at an inner junction, or when lane blockage occurs. This method performs well in good weather conditions.

Regarding spillback control strategies, mainly two approaches were found. The first approach was a form of metering by limiting the inflow with a green time reduction for critical phases at upstream intersections, promoting the traffic flow with green time extension for the congested link, or both. The second approach is with the optimization of an objective function. The optimization minimizes queue length, or maximizes of the congested link or, to solve spillback queues.

In terms of avoiding spillback, objective functions were used to find an overall optimal flow of the intersection, or to find the maximum average throughput for the whole intersection.

The researched literature led to a conceptual framework that summarizes key aspects of researched articles, depicted in Table A.2. Namely, the included road users in the RTCS, whether priority is provided, if an objective function is included, the utilized traffic signal control, parameters for the spillback detection method, and control strategies of researched articles.

Implications for future research

Regarding RTCS with a multimodal optimization algorithm, spillback detection and control strategies are almost never included in the traffic light control. The systems often utilize a VQM for delay estimation, therefore queues are not incorporated explicitly. As spillback detection is almost never incorporated in the system control, little research has been done on the effects of spillback control strategies in a multimodal RTCS on the traffic and network performance.

Insight is given for spillback control strategies, whether benefits are found for traffic participants, such as lower delays for congested links and the delay performance for the whole intersection. Secondly, when spillback effects, such as spillover and lane blockage, are handled, this leads to less direct conflicts between different road users which decreases unsafe situations.

This is realized by developing a spillback control strategy when spillback is detected. In research there was found that in many approaches the queue length was used for spillback detection, furthermore, when the queue length was measured almost always shock wave theory was applied. This comes with that advantage that for the calculation of delay, the constructed shock wave profile can also be used for a more accurate calculation for incoming traffic. Therefore, a queue method will be designed for the detection of spillback. The approach for the control strategy there will be looked at what can be integrated in the system under study. The description of this system is described in the next section.

3

MobiMaestro-Flow – System under study

The utilized traffic system for the thesis is MobiMaestro-Flow, a multimodal real-time controlled traffic system. MM-Flow continuously optimizes individual intersections by minimizing the waiting costs, which consist of the multiplications of the waiting time per vehicle, the movement, and object priority. Furthermore, upstream and downstream intersections exchange information so the optimization algorithm can consider this in successive optimization iterations. The utilized algorithm is referred to as 'TFE'.

Individual intersections are made up of agents exhibiting intelligent behaviour and a drive to cooperate, as proposed in Van Katwijk (2008). The optimization approach is multimodal, meaning that the traffic light control optimization includes multiple modes. Objects and movements can be assigned different priorities so that TFE can favour traffic objects in green time allocation. Furthermore, V2I technologies can provide preemption so that an emergency vehicle receives a green wave in emergency (He et al., 2014). Traffic flow predictions are made by free-flow travel time between an upstream intersection to the stopbar of an intersection, and predictions have a planning horizon of 120 seconds and an update frequency of 1 to 5 seconds. The following section describes the architecture. After that, the utilized traffic sensors, the operated traffic signal control, the queuing method, and the optimization algorithm are described.

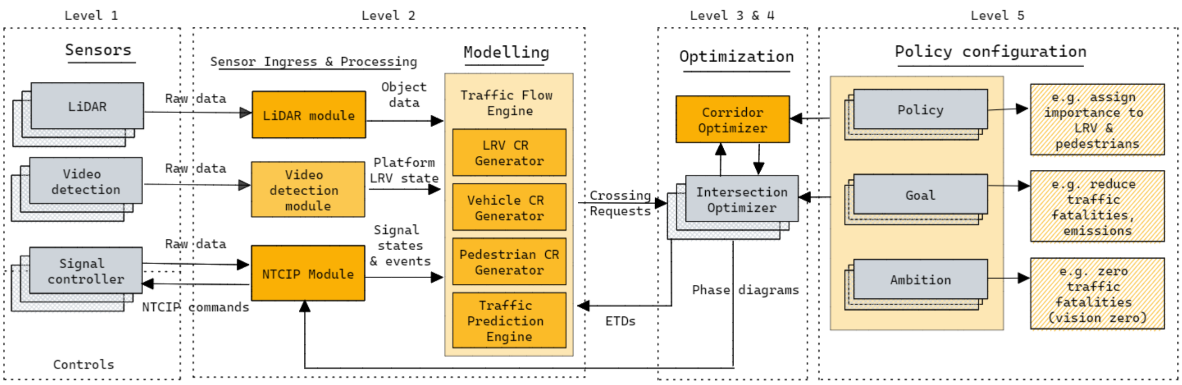


Figure 3.1: The logical structure from TFE (adapted from Mein et al. (2022))

3.1. Architecture

The architecture from MobiMaestro flow consists of five levels, in which the first level is the system's input from the traffic sensor. The corresponding traffic sensor modules handle and process the information in level two. The module processes the data into a suitable format for the traffic flow engine (TFE). Data delivered to the TFE are object data from vehicles travelling on the road, platform and LRV-states, and infrastructure states, such as traffic light signals. The traffic flow engine creates crossing requests for every mode and predicts traffic flows, serving as input for the optimization in levels 3 and 4. Level 5, the policy configuration, is also an input for the optimization. The policy configuration provides additional priority for particular traffic objects or movements in the network. In level 3, local intersections are optimized using the objective function. In level 4, the corridor optimization, the traffic flow predictions are also included in the optimization. An overview of the logical structure is depicted in Figure 3.1.

3.2. Traffic sensors

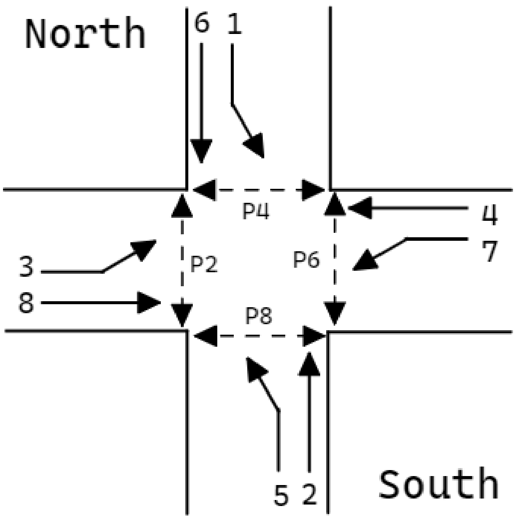
The traffic sensors provide input so the traffic flow engine can digitally reconstruct cars, public transit, cyclists, and pedestrians. Hardware and software modules classify objects, determine vehicle speeds, positions, and vehicle lengths, and are placed upstream and downstream of the intersection. In a previous test case in San Francisco, the utilized traffic sensors were LiDAR sensors; however, other traffic sensors, such as video detection units, are also applicable. In the case of LiDAR sensors, Qortex software transforms the point cloud data from LiDARs into real-time object information.

Regarding public transit, additional sensors are placed on public transit platforms to measure the number of waiting passengers and predict dwell times and departure times of Light-rail vehicles. The traffic lights utilize D4 signal controllers for the real-time management of traffic signal lights. Here, NTCIP retrieves controller status and actual phase information and sends desired plans. Generated phase plans are bound to safety constraints, such as clearance time, minimum green time, and local rules, such as the phase structure used—the next section elaborates on the traffic signal control in MobiMaestro-Flow.

3.3. Traffic signal control

3.3.1. Phase structure

The traffic signal control uses a ring-and-barrier structure, following the NEMA phasing convention, meaning that at a signalized intersection, such as the one depicted in Figure 3.2a, eight phases are used. These phases can be used by various users, such as cars, public transit, and pedestrians. Therefore, pedestrian phases P2, P4, P6, and P8 can receive green simultaneously as phases 2, 4, 6, and 8, respectively.Furthermore, turning right follows the same phase as the straight – for example, phase 8 for the west side also serves the right turn for that direction. The intersection in Figure 3.2a leads to the conflict matrix in Figure 3.2b.



(a) Phases at intersection

	1	2	3	4	5	6	7	8
1	■	x	x	x			x	x
2	x	■	x	x			x	x
3	x	x	■	x	x	x		
4	x	x	x	■	x	x		
5			x	x	■	x	x	x
6			x	x	x	■	x	x
7	x	x			x	x	■	x
8	x	x			x	x	x	■

(b) Conflict matrix car phases

Figure 3.2: Phases and resulting conflict matrix profiles at the intersection

3.3.2. Ring-barrier diagram

The ring-and-barrier structure groups phases in a continuous 'ring' and separates the conflicting traffic phases by making them sequential in a ring or by adding a barrier between the movements (Office of Operations, 2021). Multiple configurations of signal plans are generated, in which separate rings in the same barrier can receive green similarly; otherwise, the directions are conflicting. Following the conflict matrix in Figure 3.2b, this could lead to the phase diagram depicted in Figure 3.3. This phase diagram is similar to the phasing configuration of the intersection of 3rd Street & 16th Street in San Francisco. The phase plans are generated based on minimizing the waiting costs, calculated by the sum of crossing and virtual crossing requests. Among other things, these requests depend on the time the vehicle waits at the traffic light, which the queuing model determines.

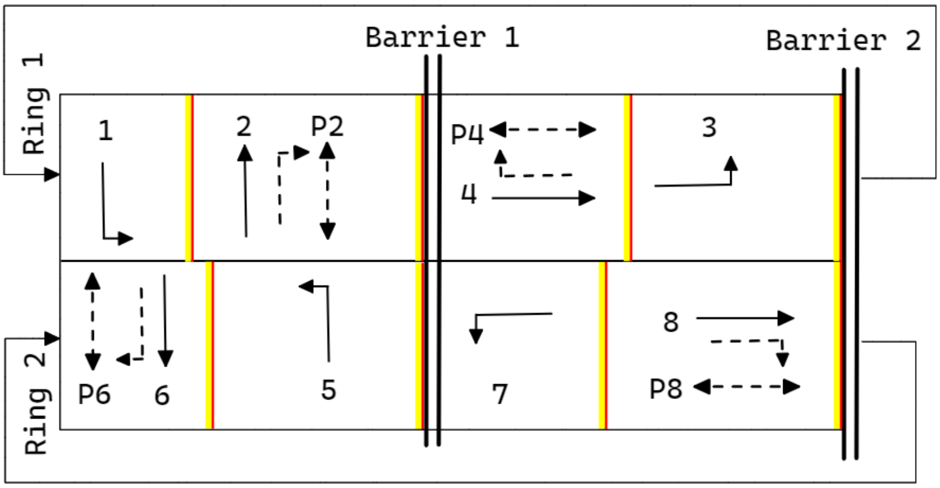


Figure 3.3: Example of phase diagram, similar to configuration of 3rd St. & 16th St.

3.4. Modelling

The prediction of traffic flows and the calculation of delays are used in the crossing requests. First, the elements of crossing requests are explained, after that, the delay alculation is explained.

3.4.1. Crossing requests

All possible movements and intersection crossings are described using crossing requests. A crossing request is defined as any traffic object n with the intention of crossing the road at an intersection. Traffic objects can be any road user, such as an LRV, passenger cars, buses, cyclists, and pedestrians, but also an emergency vehicle, such as a firetruck. These requests are weighted and are determined with the following function:

$$\text{Crossing request}(i) = \text{Waiting-time}(i)^{\gamma} \cdot (\alpha \cdot \text{object-priority}) \cdot (\beta \cdot \text{ movement-priority}) \tag{3.1}$$

The *Waiting-time* represents the red-light delay of the traffic object, which is measured as the time stopped in front of a red light in seconds. The *object-priority* is a preset priority weight assigned to traffic objects to accommodate additional for specific modes, such as a higher priority for the Light Rail Vehicle to promote transit priority. *Movement-priority* is a preset priority assigned to the road network to configure the additional priority for directions. Parameters, such as α, β, and γ, control the impact of individual terms of the formula. The *Waiting-time* is set to the power of γ to give an exponential penalty for waiting costs. Consequently, when a vehicle waits before a red-light, the penalty for the waiting time grows exponentially after three seconds, so that long waiting times are avoided. For the experiments performed in San Francisco and this thesis, γ was configured as 1, therefore, it is left out in further descriptions and equations. Furthermore, starvation prevention is implemented, which accounts for possible sensor faults. When a phase is skipped for multiple cycles and has not received a green light status for three minutes, a crossing request is made for that direction with a high priority to establish a green phase in the next minute.

For vehicles approaching the intersection, a virtual crossing request is made for the downstream direction of the intersection. The reason for a virtual crossing request is that it is less accounted for in the optimization than an actual crossing request, as the outcome of the prediction is not certain. The structure of virtual crossing requests is similar to the standard crossing requests. However, the request is multiplied by the probability of a turn ratio based on historical traffic flow data and parameter θ so that the virtual crossing request is assigned fewer costs than regular crossing requests.

$$\text{Virtual crossing request}(i) = \text{Waiting-time}(i) \cdot (\alpha \cdot \text{object-priority}) \cdot (\beta \cdot \text{ movement-priority}) \cdot (\theta \cdot \text{turn-probability}) \tag{3.2}$$

3.4.2. Delay calculation

For the optimization algorithm, the arrival time of vehicles is predicted, and the delay is measured as the time stopped in front of a red light in seconds. Traffic flow arrivals are estimated by the free-flow travel time between an upstream intersection to the stopbar of an intersection, in a similar way as described in subsection 2.1.2. For the arrival prediction, the time instant of the upstream detector is used, in which the distance of the upstream detector, divided by the free-flow speed resemble the travel time from the upstream detector to the stop-bar, as shown in Equation 3.3. The departure time for the first vehicle is equal to the time instant the traffic light turns green, T_g, plus the start-up delay. For successive vehicles, the departure time is dependent on the configured headway H. In the case of MM-flow, this is configured as two seconds, meaning that every two seconds a vehicle discharges when the light is green.

$$\text{A}(i) = \text{Upstream detector arrival}(i) + \text{distance of upstream-detector}/v_{freeflow} \tag{3.3}$$

The delay is also calculated using the expected arrival and departure time. Vehicles are expected to depart according to an assumed vehicle headway of two seconds. The total waiting time is then equal to the number of vehicles, multiplied by the headway, and summed with the waiting time of the first vehicle. The waiting time calculation for the first vehicle is dependent on the expected arrival departure time, and the start-up delay, as shown in Equation 3.5. The departure time is equal to the time instant the vehicle receives green, T_g.

$$\text{Total Waiting time of queue} = \text{Waiting time (1)} + \sum_{i=2}^{I} (i-1) \cdot H \tag{3.4}$$

$$\text{Waiting time(1)} = \text{Startup-delay} + (D(1) - A(1)) \tag{3.5}$$

$$D(1) = T_g \tag{3.6}$$

Figure 3.4 depicts a numerical example: the waiting time of the second vehicle in the queue is Waitingtime$(2) = H +$ Waiting time$(1) = 33s$, assuming a headway of 2 seconds and a waiting time of 31 seconds for the previous vehicle. The waiting time of a car can be calculated according to Equation 3.4.

For longer queues, more uncertainty could occur compared to a queue that consists of only three cars. The delay computation are efficient; however, in congested cases, the queue discharge rate is overestimated. The spatial queue length is not considered in the queue discharge and is discharged assuming a fixed headway H between the vehicles. This way, the cars are modelled leaving the queue for every H seconds.

The calculated waiting times for vehicles are used in the TFE for finding a minimum delay for all approaches with an accompanying signal plan. This will be explained in the next section.

3.5. Optimization algorithm

The TFE continuously minimizes the total weight of crossing requests of all road users, given the waiting time and the preconfigured mode and movement priority. With the national rules and possible phase timing, a predefined set of phase timings are generated using a genetic algorithm, in which the basic signal timings are optimized. The generated set of phase diagrams results in a collection of 20.000 phase diagrams. The height of the waiting costs determine which direction is allocated green time, in which the waiting costs is the result from the sum of crossing and virtual crossing requests.

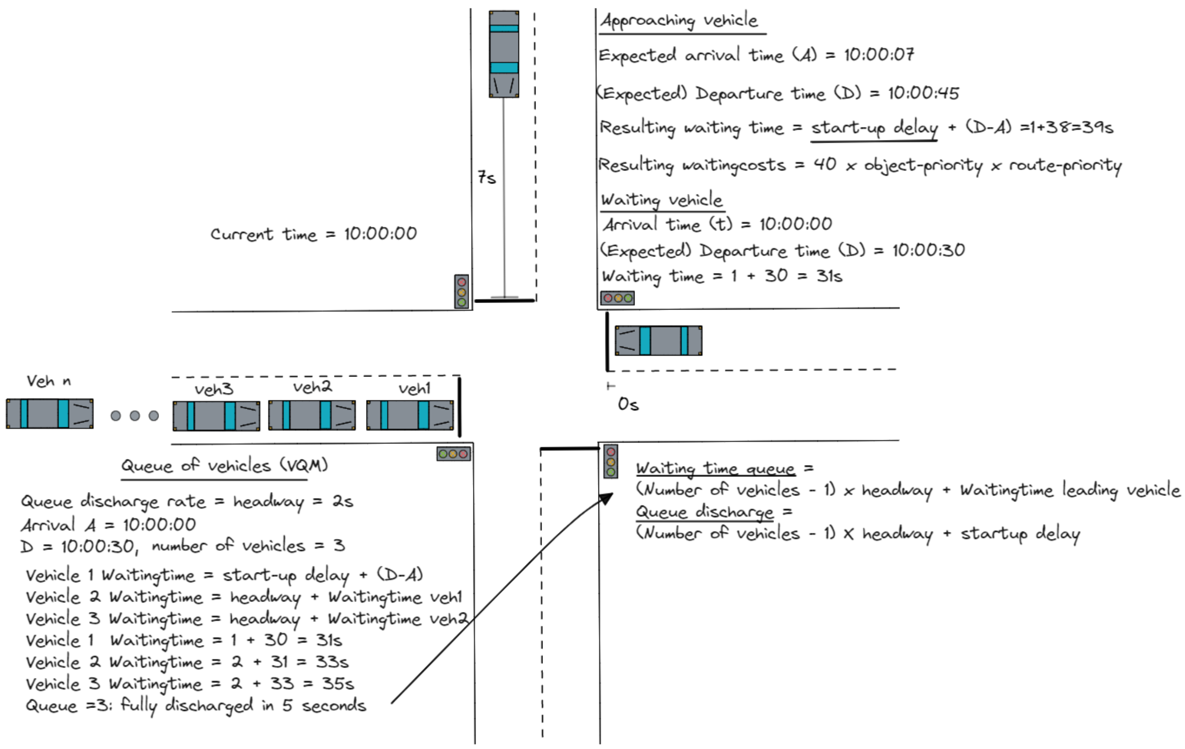


Figure 3.4: Example of waiting time calculations

3.5.1. Local intersections costs

When in operation, the TFE creates and updates crossing requests for existing and entering traffic objects i. The waiting costs per direction at local intersections are the sum of crossing requests.

$$\text{Waiting costs of actual approaches} = \sum_{i=1}^{I} \text{Crossing request}(i) \tag{3.7}$$

With every predicted change in crossing requests, waiting costs are calculated by evaluating phase timings per second, constrained by the possible and applicable phase timings. The crossing requests per traffic object i are summed for the total number of vehicles I in the approach.

3.5.2. Network costs

When controlling multiple intersections, TFE generates virtual crossing requests for predicted downstream approaches. When a vehicle approaches an intersection, the prediction is made that the vehicle will continue downstream to the next intersection. Consequently, for a network consisting of multiple intersections, the waiting costs are determined by the sum of crossing requests per approach for vehicles i and the sum of virtual crossing requests for vehicles i. The total waiting costs are calculated for every phase and intersection, which is indicated in the next subsection.

$$\text{Total waiting costs} = \sum_{i=1}^{I} \text{Crossing request}(i) + \text{Virtual crossing request}(i) \tag{3.8}$$

3.5.3. Optimization

Every evaluation loop results in waiting costs for every crossing request at every intersection. The objective function is sum of the total waiting costs per intersections. The goal is to minimize the overall waiting costs per intersection over a planning horizon of 120 seconds with an update frequency every 1 to 5 seconds. To achieve this, a collection of predefined phase diagrams are generated, with a varying sequence of phases, varying green times, and the possibility of phase skipping, leading to a total of 20.000 phase diagram per intersection.

$$\begin{aligned} \text{minimize:} \quad & \sum_{\text{phase}}^{\text{Set of phases}} \text{Total waiting costs(phase,intersection)} \\ \text{subject to:} \quad & \text{Phase structure} \\ & \text{Safety constraints} \end{aligned} \tag{3.9}$$

The optimization algorithm evaluates each phase diagram with the resulting waiting cost over the period of the planning horizon. The optimization is subject to local regulations, such as the used phase structure, and safety constraints, such as the red time clearance. The phase structure entails that some phases can receive green simultaneously, such as when phase 8 is allocated green time, phases 3 or 4 can also receive green (see Figure 3.2b), dependent on the height of the waiting costs one of both is allocated green time. The result of the optimization leads to a designated signal diagram.

3.5.4. Policy configuration

The result of waiting costs also depend on the configured priorities in the algorithm, as explained in subsection 3.4.1. With traffic object priority and movement priority configuration, policy goals or ambitions, such as improving public transit by improving punctuality, can be implemented using a higher priority weight for public transit vehicles. Consequently, public transit, such as an LRV, receives more priority in green time allocation than a car. On the other hand, specific routes in the corridor can receive different priorities – for example, to promote the traffic flow on the arterial, routes on the arterial are assigned a higher priority than sidestreets.

Table 3.1 shows an example configuration used by the San Francisco case study. Here, the LRV was assigned a priority of 2,000, whereas cars were given a priority of 5. Additionally, an emergency vehicle is given a significantly higher weight than other vehicles (100.000) to allocate a green wave for a priority vehicle, such as a fire truck, in the case of an emergency.

Table 3.1: Example of mode prioritization in San Francisco case study

Object class	Priority weight
Emergency vehicle	100,000
LRV	2,000
Bus/truck	100
Pedestrian	10
Car	5
Other (e.g. bicycle)	1

To research the effects on traffic performance and network performance, a spillback detection method and control strategies are designed. The additional components are explained in the next chapter.

4

Design of spillback component

The previous chapter described the architecture and components of MobiMaestro-Flow. This chapter proposes the spillback component that extends the architecture. This way, spillback effects, such as lane blockage and spillover, can be detected, furthermore, a spillback control strategy so that the identified spillback effect is handled.

4.1. Spillback detection

In the literature was concluded that the spillback detection (and control strategy) was dependent on the utilized traffic sensors. In the next sections, first, the traffic sensors needed for the spillback detection method are described, and after that, the queue method for queue length estimation, lastly the spillback detection method.

4.1.1. Traffic sensors

MobiMaestro-Flow, described in the previous chapter uses sensors that detect lane areas and vehicle speed and location, comparable to a traffic sensor that uses machine vision or laser sensors. The advantage of these sensors is that the queue length can be measured directly, such as with the method of J. Wu et al. (2020). However, these sensors are vulnerable to adverse weather conditions and the sensors are far more expensive than magnetic loop detectors. Furthermore, approaches in the literature are also applicable when these sensors are used. Therefore, it is chosen to use magnetic loop detectors for spillback detection.

4.1.2. Detection with lane threshold

In combination with the chosen sensors, a threshold determines whether spillback is detected. The threshold is the length of the link (l_{link}) or the length of a turning bay ($l_{turningbay}$). Spillback is detected when the estimated maximum queue length (L^n_{max}) during a cycle n exceeds the queue threshold. Which leads to the following conditions:

$$\text{Spillover detection: } L^n_{max} \geq l_{link}$$
$$\text{Lane blockage detection: } L^n_{max} \geq l_{turningbay}$$

Consequently, spillover is detected when the queue length exceeds a link length in which the vehicles spill over to an upstream intersection. Furthermore, lane blockage is detected when the queue length is exceeds the turning bay length. When one of these conditions does not hold, spillback is communicated as true to the RTCS. The queue length is estimated according to a queue definition and a queue model, explained in the next sections.

4.1.3. Queuing model for estimation of maximum queue length

The maximum queue length during a cycle is estimated for spillback detection. This can be done using the approach by H. Liu et al. (2009) that describes the queue dynamics at congested intersections. The LWR shockwave theory from Lighthill & Whitham (1955) is applied to estimate queues and the cycle-based method estimates maximum (and

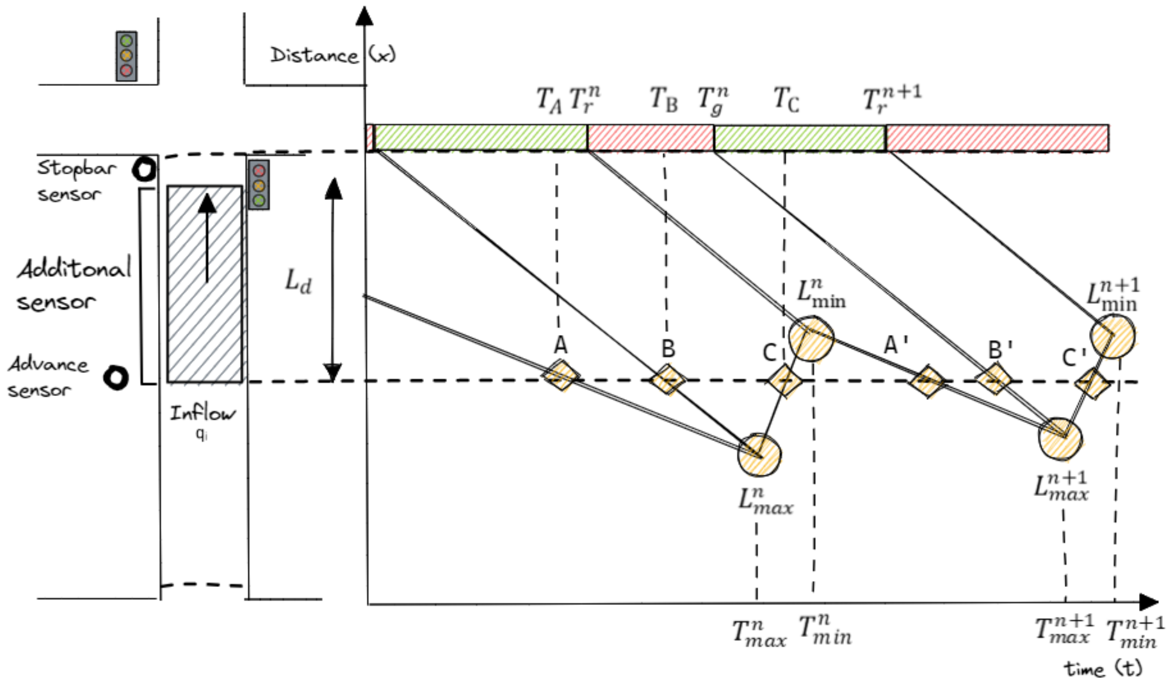


Figure 4.1: Sensor configuration

residual) queue length in real-time at the end of each traffic light cycle. The approach assumed that event-based traffic signal data is available for identifying traffic state changes, distinguishing vehicle queue discharge flows from upstream traffic arrivals so that even long queues can be estimated (H. Liu et al., 2009).

Queue definition

A queue consists of a head and a tail, the head being the first vehicle at the stopbar. The tail is the last vehicle in the queue. It is chosen to include a vehicle in the queue length when an arriving car drives slower than 18 km/h (5 m/s). This value is chosen, as in the test environment, 5 m/s was a speed where the vehicle almost always ended in a total standstill. For higher values, the car was part of heavy traffic and started accelerating again after a period.

Fundamental diagram

Several assumptions are made in the real-time estimation of the maximum queue length. In applying shockwave theory, the derivation of shockwave speeds uses the relations between macroscopic flow characteristics, called fundamental diagrams, as a basis. The variables density k, speed u, and flow q, represent the same information. Density is defined as the number of vehicles per unit of distance, flow is defined as the number of vehicles per unit of time, and speed is measured in the distance per unit of time. These three variables are referred to as traffic states, where vehicles can transition from uncongested to congested states. This can be summarized in four points indicated in a fundamental diagram and will be used in the queue length estimation (Lighthill & Whitham, 1955; Hoogendoorn & Knoop, 2016a,b).

On the left side of Figure 4.2, these points are schematized and represent the traffic states occurring at signalized intersections.

State (1) Inflow q_i, represents the inflow of the traffic at point (q_i, k_i).
State (2) Jam density k_j, represents the density in which the traffic has come to a full standstill with flow 0, at point $(0, k_j)$.
State (3) represents an empty road, at point $(0, 0)$.
State (4) The maximum flow q_{max} represents the maximum flow of the traffic, where the critical density is the density where the traffic flow switches from the maximum flow to a decreased flow. The maximum flow with the critical density is at point (q_{max}, k_c)

There is assumed that vehicles act according to the fundamental diagram, and depart with the maximum possible flow

(q_{max} when possible. For example, a traffic light turns green after being red for an extended period.

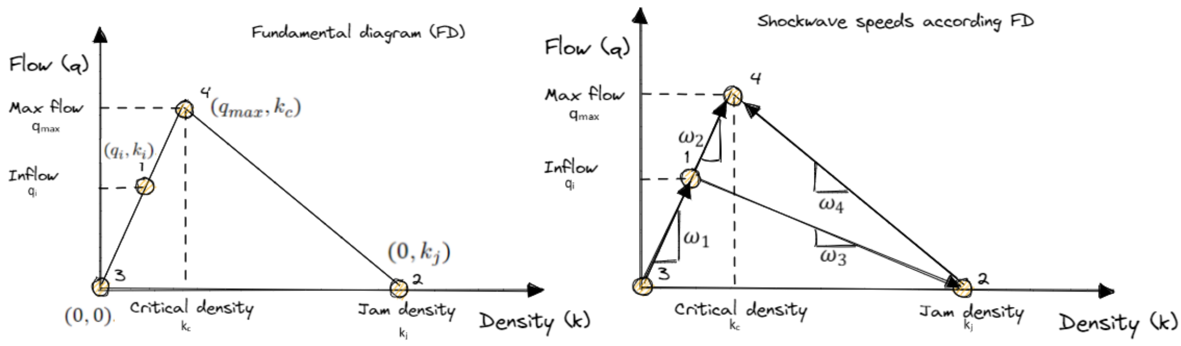


Figure 4.2: Critical points in FD (left), and shockwave speeds in FD (right)

Basic shockwave profile

With a known fundamental diagram of the used road, signalized intersections can apply SWT to estimate queue lengths and propagation. In Figure 4.3 the estimated traffic states are shown, corresponding to the traffic states in the fundamental diagram. For example, if the traffic state changes between 1 and 2, the tangent of the line is equal to ω_3 from the fundamental diagram (Figure 4.2). The shockwave speed is calculated according to the formulas Equation 4.1 - Equation 4.4.

$$\omega_1 = v_{free} = \frac{q_i^n - 0}{k_i^n - 0} = \frac{q_i^n}{k_i} \tag{4.1}$$

$$\omega_2 = \frac{q_{max} - q_i^n}{k_c - k_i^n} \tag{4.2}$$

$$\omega_3 = -\frac{q_i^n}{k_j^n - k_i^n} \tag{4.3}$$

$$\omega_4 = -\frac{q_{max}}{k_j - k_c} = \tag{4.4}$$

For the maximum queue length estimation, other variables, such as the green time (T_g^n) and red time (T_r^n) are needed to estimate the maximum queue length (L_{max}^n) and the time it occurs (T_{max}^n), during cycle n. But also variables from the advance detector are needed, such as the time instant the queue builds up to the advance detector (T_A), the time instant the queue starts propagating forward (T_B), and the time instant the queue is discharging (T_C). All these variables are depicted in Figure 4.3.

Maximum queue length estimation

The shockwave speeds in combination with detector data (points A,B, and C) are used to estimate the maximum queue length (L_{max}^n) and when it occurs (T_{max}^n). As was indicated above, between the diamond breakpoints T_B and T_C, the traffic state is at maximum flow: (q_{max}, k_c). State (q_i, k_i) is after T_C but before the next traffic light cycle (T_r^{n+1}). With ω_2 and ω_4 known, time instances T_B and T_C, and the detector length L_d can be used to estimate L_{max}^n and T_{max}^n:

$$L_{max}^n = L_d + (T_C - T_B) / \left(\frac{1}{\omega_2} + \frac{1}{\omega_4} \right) \tag{4.5}$$

$$T_{max}^n = T_B + (L_{max}^n - L_d) / \omega_4 \tag{4.6}$$

The current example assumes a homogeneous road and a constant inflow. However, the traffic variables density, flow and speed can also be estimated with event-based data from loop detectors, furthermore, a residual queue can also be estimated. As designing a queue model is not the main focus of the thesis, this is explained in Appendix A. Nonetheless, the outcome of the queue length is compared against the lane threshold, in which the outcome is that spillback is detected or not. In the next section, it is explained what strategies are developed to control the identified spillback effects.

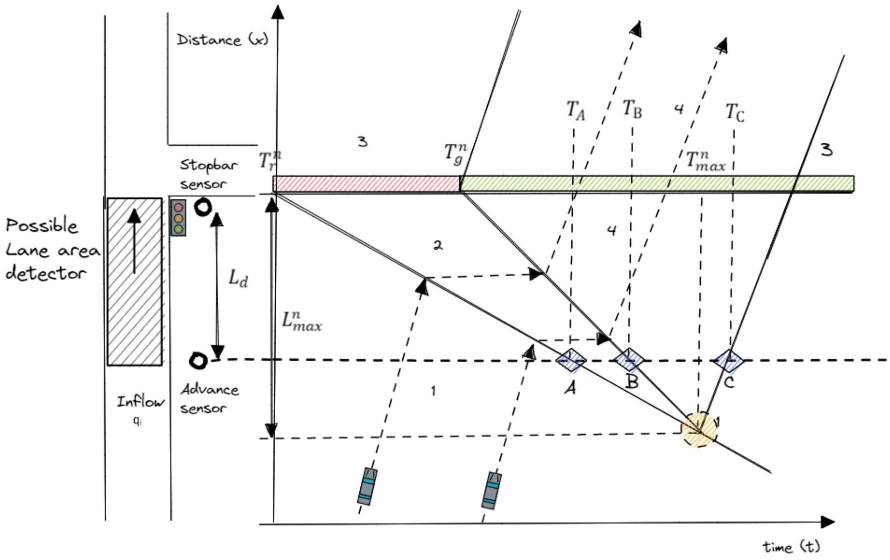


Figure 4.3: Applied SWT at signalized intersection

4.2. Spillback control strategies

Two spillback control strategies are designed, and are depicted in the logical structure of the TFE in Figure 4.4. Components that already are implemented in the TFE are blurred to highlight the additional spillback components. The main difference between the two control strategies, is that the first strategy alters the optimization outcome, and the second strategy influences the optimization outcome. The strategies are explained more in detail in the next sections.

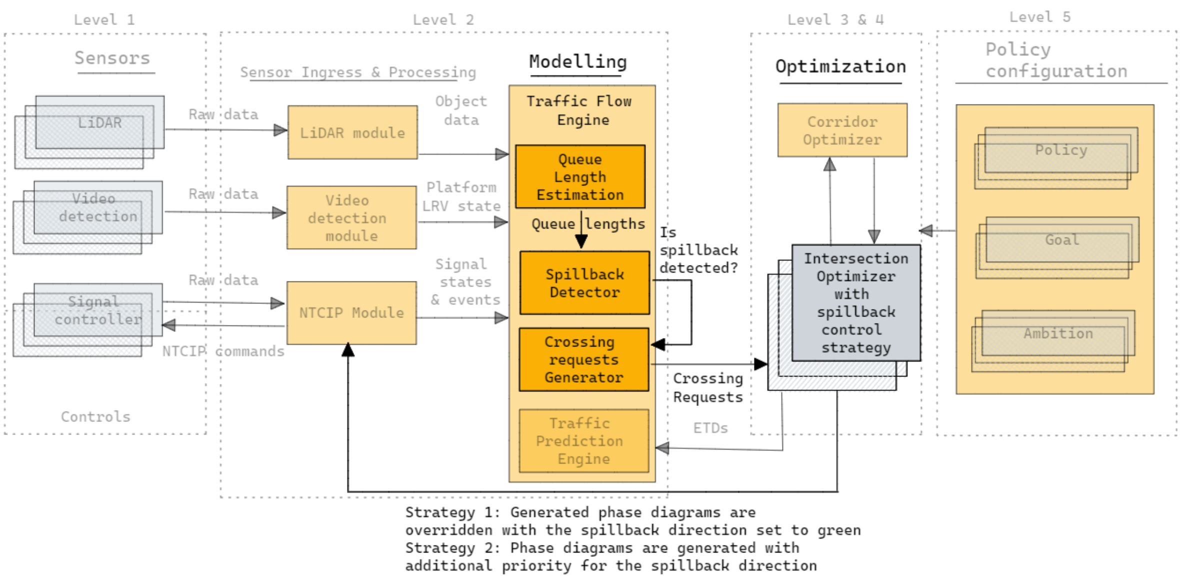


Figure 4.4: Spillback control strategies in the TFE framework

4.2.1. Control strategy 1: override

The first spillback control strategy is a rather abrupt method that enforces the congested link to a maximum amount of green time so that when spillback is detected it is solved as soon as possible. The strategy has a high advantage for the congested direction; however, other directions may suffer unnecessary delays. In Figure 4.4, the approach is depicted, the queue length is estimated for every cycle and communicated to the spillback detector. The spillback detectors compare the queue length to the queue threshold, and when the threshold is exceeded, spillback is communicated to the crossing requests generator. The crossing requests generator consists of the existing LRV CR Generator, Vehicle CR Generated, and Pedestrians CR generator (see Figure 3.1). In this strategy, it is communicated to the intersection optimizer that spillback is detected, but no additional calculations are done.

The intersection optimizer generates the phase diagrams as usual (as explained in chapter 3). Just before the generated phase diagrams are communicated to the NTCIP Module, the spillback direction of a phase, which is the direction in which the spillback effect occurs, is set to green and conflicting directions are set to red. The green time of the spillback direction is continued until it is communicated that no spillback is detected anymore. In this strategy, the phase constraints of the system, such as the phase structure and safety constraints are not taken into account, meaning that the order of ring-and-barrier structure is neglected, and safety constraints, such as the minimum green time of non-spillback directions. The strategy illustrates a theoretical gain, in terms of a proactive spillback control approach.

4.2.2. Spillback strategy 2: penalty factor

The second spillback control strategy penalizes the direction affected by spillback so that when spillback is detected, the direction receives higher priority, compared to other directions. This leads to an earlier green and advantages for the congested direction; however, less absolute priority is given compared to the 'override' strategy, and fewer unnecessary delays occur for disadvantaged directions. The spillback penalty factor induces a trade-off between higher prioritized public transit or a direction affected by spillback. Furthermore, a trade-off is induced for a higher prioritized spillback direction and possibly longer waiting cars in a disadvantaged direction.

For every cycle, the queue length is estimated, and the queue length is communicated to the spillback detector. The spillback detector compares the queue length to the queue threshold, and spillback is detected when the length exceeds the threshold. Then, a binary variable ϵ is passed as a 1 to the crossing requests generator. The crossing requests generator consists of the existing LRV CR Generator, Vehicle CR Generated, and Pedestrians CR generator (see Figure 3.1). In this strategy, additional priority is given to spillback directions in the crossing requests. This leads to an alternative calculation:

$$\text{Crossing request}(i) = \text{Waiting-time}(i) \cdot (\alpha \cdot \text{object-priority}) \cdot (\beta \cdot \text{movement-priority}) \cdot \text{spillback-priority}^{\epsilon} \quad (4.7)$$

The generated crossing requests are communicated to the intersection optimizer, which optimizes the traffic as usual. The generated phase diagrams are communicated to the NTCIP module.

In the next chapter, it is described how the designed spillback detection method and control strategies are implemented in the test environment.

5

Implementation of spillback component

5.1. Multimodal RTCS test framework

In section 3.1, the architecture of MobiMaestro-Flow has been described. The test framework is a Software-In-The-Loop simulation (SILS). A SILS consists of a microscopic simulation, a virtual traffic controller running on the same computer, and a communication interface for information exchange between the microscopic simulation and the virtual controller (A. Stevanovic, Abdel-Rahim, et al., 2009). The overview of the SILS is depicted in Figure 5.1.

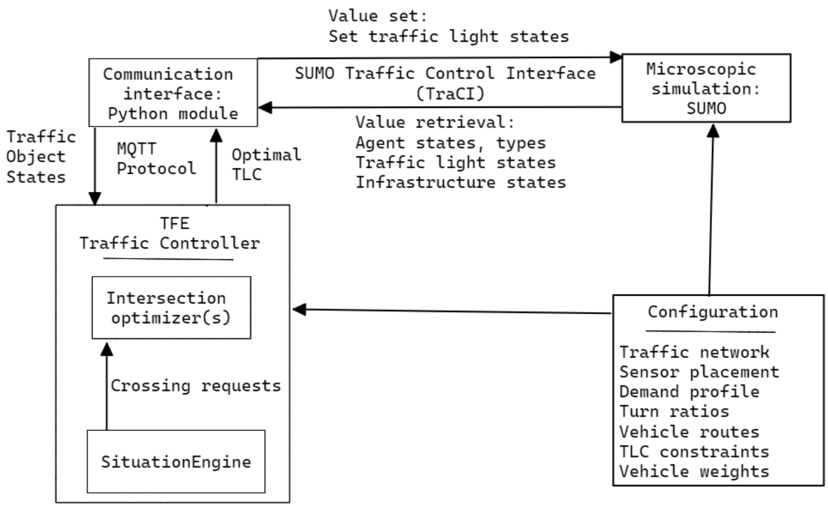


Figure 5.1: Test framework SILS

The used simulation environment is SUMO (Lopez et al., 2018), an open-source traffic simulation environment capable of executing microsimulations with individual vehicle behaviour. A demand profile and turning ratios are configured to run scenarios with varying traffic demand; in addition, traffic light control constraints provide the (legal) framework in which the traffic light optimization may optimize. Vehicle routes are generated using the given traffic volumes and turning ratios. Other configurable parameters are the weights of the vehicle priority and the route priority and all are used in the optimization of the virtual traffic controller 'TFE'.

The TFE generates crossing requests and, based on those crossing requests, optimizes the intersections, as is explained in chapter 3. The communication interface retrieves traffic states from SUMO using the SUMO Traffic Control Interface (TraCI). For example, the interface retrieves the vehicle speed, length, and position using placed traffic sensors; in addition, traffic and traffic light states from SUMO, such as the green times. The communication interface then communicates the values to the virtual controller using the MQTT-protocol (Light, 2017). The types of messages sent and received are traffic light states, vehicle locations, and requested and current traffic light phase states. In the TFE controller, the optimal signal control is calculated and communicated back to the communication interface, which then sets the new traffic light states in SUMO using TraCI. The test framework provides an environment to test traffic experiments and based on these experiments, generates output. The output data is then used for analysis purposes to describe effects of configured methods on the traffic and network performance.

In the test framework a spillback detection method is added, and two spillback control strategies. These components are described in the following sections.

5.2. Spillback detection

A queue threshold detects spillback effects, a common approach among the researched literature (Wang et al., 2016; Noaeen et al., 2021; Mohajerpoor & Cai, 2020; H. Zhang et al., 2020). In the framework, the estimated queue length is compared to the lane threshold of the traffic network. When the queue length exceeds the lane threshold, spillback is detected, for example, when the queue length exceeds the turning bay length or traffic spills over to the upstream intersection.

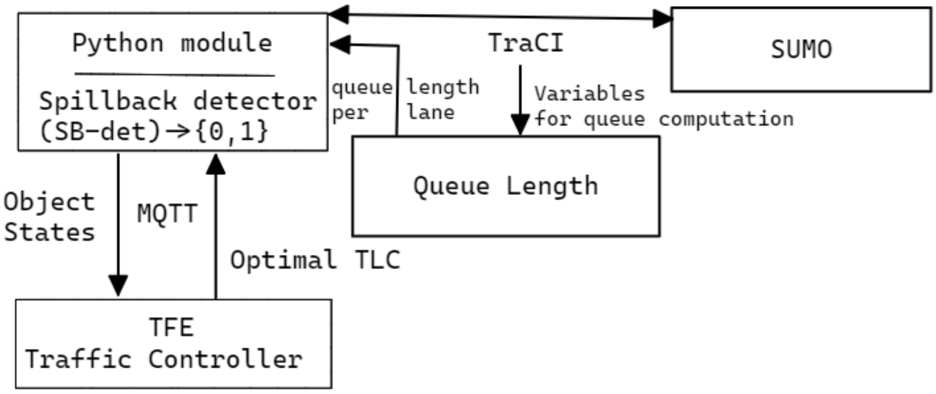


Figure 5.2: Queue length estimation with spillback detection

In the communication interface, the spillback detector is called, the spillback detector runs every timestep for every intersection-lane. In the function, the queue length estimation function is called which returns the queue length in meters, the front-lane id, which lane has the longest queue, and the total lane length. The queue length is compared to the lane threshold, which is similar to the lane length. If the queue exceeds the threshold, *isSpillbackDetected* is set to True (or 1) for that lane. Otherwise, the value of that *isSpillbackDetected* is False (or 0).

After that, every phase is coupled with the value of *isSpillbackDetected* and processed. The result is an intersection Id with a list of phases and a true or false related to the spillback state. Depending on the spillback control strategy, the result is processed further.

5.2.1. Queuing method

The queues are retrieved from the SUMO environment. The reason for this is to narrow the research scope, a queuing model requires calibration and verification to work correctly. The operation of the queue model is important, as the queue length is used for the spillback detection. When the queue length is overestimated spillback could be perceived as true when it is not the case. On the other hand, when the queue is underestimated spillback can be perceived as false when in reality spillback occurs. The queue function calculated the queue for every time step for every lane in all intersection approaches. SUMO distinguishes lanes and edges: an edge can consist of multiple lanes. An intersection approach often exists of multiple consecutive edges.

The algorithm's input is the id-number of an intersection, and is needed to retrieve the lane Ids so that other variables can be retrieved. For every timestep, the vehicles currently on the lane, the vehicle speeds, vehicle lengths, and the vehicle positions are retrieved. The vehicle positions are retrieved using the SUMO function *getLanePosition(vehicle-Id)*. As the outcome of this function is the beginning of the link approach to the vehicle's front bumper. To actual queue length is calculated by the sum of the lane position and the vehicle length is subtracted from the lane length. After that, the partial queue of the lane is calculated by iterating through the list of current vehicles and comparing the vehicle speed to a speed threshold. After calibration, it was found that 18 km/h (5 m/s) was a value where vehicles were nearing a halt in the simulation due to queues, instead of a temporary deceleration. The tail of the queue is identified as the lane length minus the furthest car plus the vehicle length.

The queue length is calculated for every lane. However, when no queue detected is on the front lane, no queues are found for the other lanes. When the lane is downstream, first is checked whether the front lane is saturated. When this is the case, the queue length is the sum of the lane queues. The algorithm returns the queue length for every intersection direction in meters, the front intersection lane with the longest queue (phase), and the lane threshold's total length.

Algorithm 1 Queue length estimation

```
Retrieve all lanes of intersection
for lane do
  Get:
  VEHICLE: Id, speed, length, position.
  LANE: Id, length.
  Calculate queue:
  if vehicle speed < speed threshold then
    queue = lane length − min(vehicle position) + vehicle length
  end if
  if front-lane saturated then
    Total queue = front-lane queue + upstream-queue
  else
    Total queue = front-lane queue
  end if
end for
return  total queue, Id of congested front-lane, length of front-lane
```

The spillback detector uses this output to compare the total queue to the queue threshold (length of the fron-lane). If the queue threshold is exceeded, the Id of the congested front-lane is communicated to the TFE. The TFE then applies a spillback control strategy for detected spillback.

5.3. Spillback control strategies

Two types of strategies were implemented. The first is an override function, which immediately sets the congested lane to green. The second strategy includes a spillback component in the optimization algorithm so that a spillback direction receives a higher priority and receives green earlier, compared to the situation without the spillback component.

5.3.1. Spillback strategy 1: override

In the control strategy is override, the spillback detector retrieves whether spillback is detected. When this occurs, the overflowing phases are communicated to the TFE (Figure 5.3). The TFE generates a collection of phase diagrams for optimal traffic signal control, after that, the phase diagrams of the intersections with spillback effects are overridden. The spillback direction is allocated green time, until the spillback state is controlled, meaning that it is communicated that no spillback is detected anymore. Furthermore, during this process, conflicting directions are allocated red time. When the spillback effects are solved, the traffic light control follows the conventional signal plan again. It should be mentioned that this strategy affects the proposed phase plan and traffic light constraints, such as the phase structure and safety constraints, are not taken into account. Therefore, the approach does not lead to signal plans that are valid in real life.

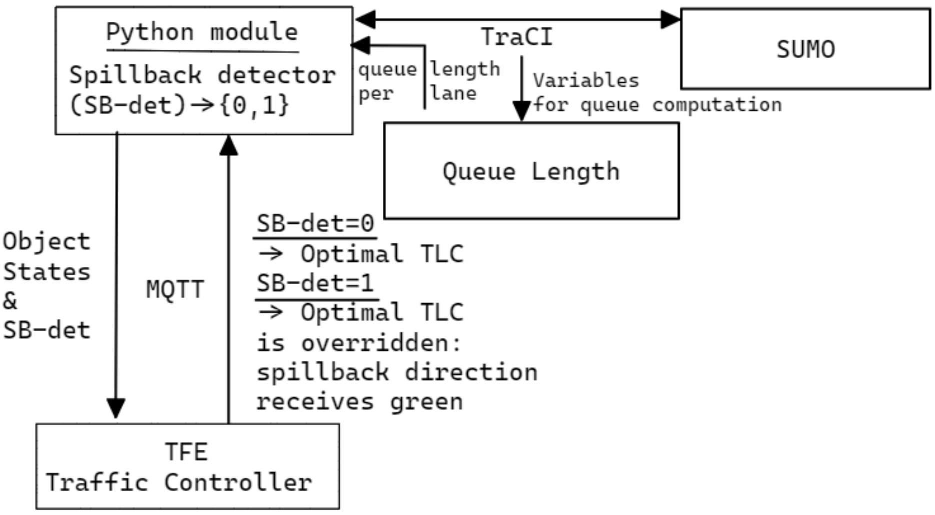


Figure 5.3: Congested lane is set to green

5.3.2. Spillback strategy 2: Penalty factor in objective

In the control strategy with a penalty factor in the objective function (Figure 5.4), the spillback states identified by the spillback detector are messaged through the MQTT-protocol. The intersection optimizer processes the received data.

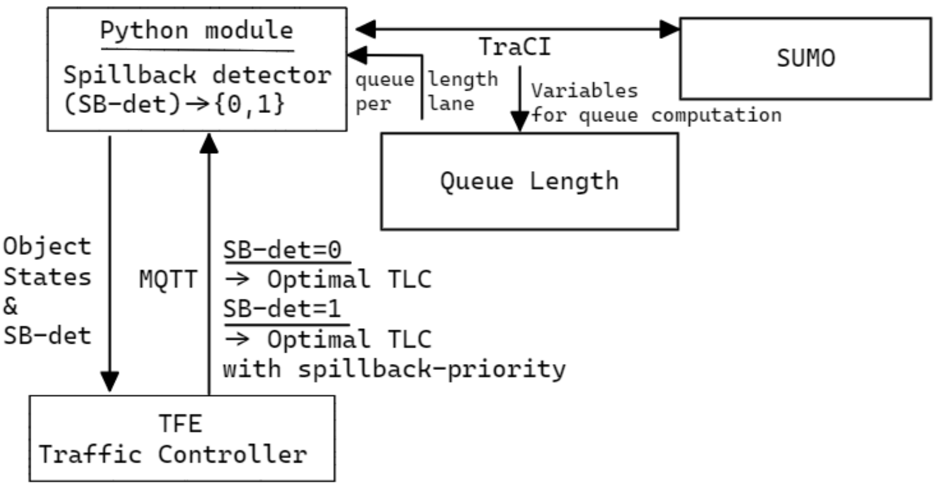


Figure 5.4: When spillback is detected, a penalty factor is activated in the saturated lane

Algorithm 2 Spillback penalty algorithm

```
Objective min(waiting costs)
Waiting cost calculation for every movement:
if queue length > lane length (spillback) then
    return Optimization result · Penalty-factor
else
    return Optimization result
end if
```

The waiting costs for a spillback direction are multiplied by 'spillback-priority', leading to increased costs. For the experiments, the height of the penalty-factor is configured as 5, 10, or 1000. The increase in waiting costs has the effect that in the optimization, green time is allocated earlier to the spillback direction as it leads to the lowest overall waiting costs in the optimization horizon.

Figure 5.5: Case where spillback is detected, communicated, and processed by TFE (penalty X1000)

Example of a send/received spillback-state MQTT message from the Python module to the TFE traffic controller: {phase: 2, isSpillbackDetected: false,phase: 4, isSpillbackDetected: true, phase: 6, isSpillbackDetected: false}

5.4. Verification of implementation

To verify the implementation of spillback detection. Singular experiments were executed to verify whether the queue length matches with the spillback detection Figure 5.5, using the interactive mode of SUMO. When spillback is detected, a print statement is logged on the TFE side, including the calculated waiting costs. On the Python side, a print statement was sent to the terminal. The print statement included the phases, the queue length, the lane threshold, and whether spillback was detected as true or false.

Example of logging: Is Spillback detected: true. Cost of direction: 2144939.4129999997

The interactive mode of SUMO was also used to verify the override handling strategies and a penalty factor. In the same way, as with the spillback detection verification, spillback was enforced. After that, the override handling strategy was applied and analyzed whether the affected direction received green as soon as possible. When the penalty costs were incorporated, a penalty factor of times 1000 was used to analyze whether the waiting costs showed a significantly higher result than when a non-spillback queue was present at the intersection. In addition, an experiment was performed to validate whether more green time was allocated to a spillback directionTable 5.1). The table shows that the amount of green time allocated increases when spillback occurs in the run on the west-side, and a spillback penalty is included.

Table 5.1: Green time allocation with and without spillback penalty

		Green time allocated [s]	
	Direction	Basecase	Penalty X1000
	North	330.4	331.4
	South	286.4	287.4
	East	510	440
	West	703.8	755.8
Turning-bay	East	151.8	139.8
	West	361	457.6

In the case of the override strategy, the method first had trouble with allocating green and red to the correct locations, as the method allocated green to the affected direction without changing the traffic light in other directions. After this was addressed, the verification showed that when multiple directions were affected by spillback simultaneously, the override method had difficulties allocating green to the correct movement. The constraints of the override strategy were changed, so that only the spillback direction in combination with one other non-conflicting direction (instead of two) was allocated green time.

5.5. Calibration of penalty factor in objective function

As the simulation runtime per scenario is long, a decision has been made to either include the spillback penalty factor X5 or factor X10 in the corridor scenarios. This choice is made based on the total delay, and the spillback durations of the isolated intersection scenarios.

5.5.1. Calibration scenarios

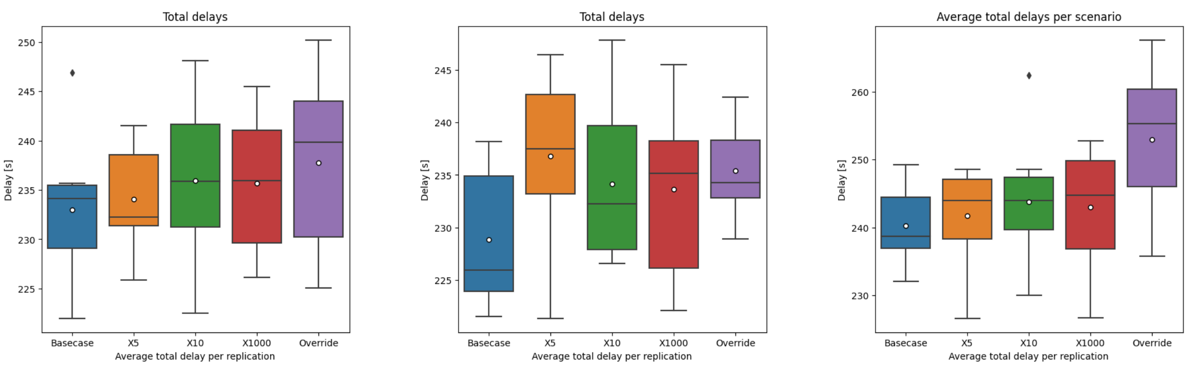
For the calibration of the penalty factor, experiments 1 to 12 (see Table 5.2) were used, and are similar to the first few experiments used to research effects at an isolated intersection, described in chapter 6. First, in the base case no penalty factor was added when spillback is detected (experiments 1-3). Second, the spillback penalty factor was 5 (experiments (4-6), third, a penalty factor of 10 (7-9). Lastly, a penalty of 1000 (experiments 10-12), which resembles a maximum penalty when spillback is detected. The used simulation network for the calibration is similar to the intersection used for isolated intersection experiments. The configurations, regarding the simulation network and demand profile, are explained in more detail in section 6.2.

Table 5.2: Overview calibration experiments

Experiment	Demand factor	Spillback control	Note
1	1	None	TFE
2	1.5	None	TFE
3	1	None	Turning fraction (Turn) east 50/50
4	1	Spillback penalty	Result X5
5	1.5	Spillback penalty	Result X5
6	1	Spillback penalty	Turn east 50/50 (X5)
7	1	Spillback penalty	Result X10
8	1.5	Spillback penalty	Result X10
9	1	Spillback penalty	Turn east 50/50 (X10)
10	1	Spillback penalty	Result X1000
11	1.5	Spillback penalty	Result X1000
12	1	Spillback penalty	Turn east 50/50 (X1000)

5.5.2. Choice of penalty factor

The results of average total delay, depicted in Figure 5.6, show five scenarios. The base case, the outcome of penalty factors X5, X10, X1000, and the control strategy override. The choice is made to include either the penalty factor X5 or the factor X10 into the corridor scenarios. Results showed an increase in total delay for all scenarios with a spillback control strategy, as depicted in Figure 5.6. When the demand is increased with factor 1.5 the delay of the scenario with a factor of x5 increased more compared to the other scenarios. In the scenario with conflicting competing directions (see Figure 5.6c) the overall delays do not show a significant difference between the spillback control strategy of a penalty factor of x10.



(a) Demand factor 1

(b) Demand factor 1.5

(c) Alternative turn fractions

Figure 5.6: Overview average overall delays calibration scenarios

The spillback duration is improved when the penalty factor is X10 with demand factor 1.5, and spillback occurs (only) at the west side of the intersection. When comparing spillback durations of the calibration scenarios (see Table 5.3), penalty factor X10 has lower spillback durations for the maximum affected direction (west), while disadvantaged direction do not have a significant decline, compared to penalty X5, except for the scenario with competing approaches. In further analyses, other modes are included, and the network size is increased to a corridor; the spillback control strategy is chosen as X10 as it showed promise on an isolated intersection and will have a more competing penalty with other types of road users in the corridor.

Table 5.3: Spillback duration calibration results

		Demand factor 1			Demand factor 1.5			Turnratio 50/50	
Direction	Base	Penalty X5	Penalty X10	Base	Penalty X5	penalty X10	Base	Penalty X5	Penalty X10
North	5.362	6%	2%	5.537	1%	-11%	10.632	1%	7%
South	8.245	-9%	-9%	6.066	17%	28%	9.364	13%	43%
East	8.311	60%	-21%	7.654	-29%	-18%	131.742	6%	22%
West	197.115	-6%	-11%	173.808	6%	4%	358.42	-7%	-12%
Total	219.033	-3%	-11%	193.065	5%	3%	510.158	-3%	-1%

6

Experimental design

6.1. Test environment

The traffic system is translated into a software-in-the-loop simulation (SILS) to perform experiments. A SILS consists of a microscopic simulation, a virtual traffic controller running on the same computer, and a communication interface for information exchange between the microscopic simulation and the virtual controller (A. Stevanovic, Abdel-Rahim, et al., 2009). The virtual traffic controller runs the same software as the actual traffic controller. Information exchange between the microscopic simulation and the virtual controller is done by a communication module. The microscopic simulation is SUMO (Lopez et al., 2018), and the communication module retrieves traffic states, such as speed, position and traffic light states, using the SUMO Traffic Control Interface (TraCI). The retrieved data is then communicated to the traffic controller with an MQTT protocol. The communicated data is received and handled by the virtual traffic controller. After the traffic control optimization of this controller is complete, the proposed phase plan is communicated back to SUMO, which updates the traffic light states if necessary.

To verify the simulation runs, the total distance travelled for vehicles between the replications was compared to make a fair comparison between the alternatives (Table 6.1); these values were closely the same, as the simulation experiments is filled up for the first quarter (half demand), the demand was at peak level for the second and third quarter, and the last quarter the simulation was emptied again (half demand).

The utilized traffic system had random parameters; runs were compared with similar seeds to verify whether the results were the same. In the experiments, multiple random-seed numbers were used for vehicle arrivals, which departed according to a Poisson Arrival Process. Furthermore, ten replications per scenario were performed. For the prediction component in the utilized system, the results varied too much to analyze whether the difference in performance was due to a new random seed or the added spillback component. Because of the long simulation runtime, it was chosen to set

Table 6.1: Total vehicle kilometers travelled in [km], base-case versus penalty times 10

	Isolated intersection		Corridor		
Seed	Basecase	Penalty x10	Basecase	Penalty x10	Difference
1	599175	599175	1356879	1356917	0.003%
2	598970	598970	1347057	1347027	-0.002%
3	598935	598935	1366455	1366389	-0.005%
4	597432	597432	1331257	1331233	-0.002%
5	598458	598458	1358714	1358674	-0.003%
6	600253	600253	1355917	1355935	0.001%
7	597534	597534	1349654	1349649	0.000%
8	597944	597944	1384078	1384058	-0.002%
9	598868	598868	1356890	1384704	2.050%
10	598150	598150	1347065	1363525	1.222%

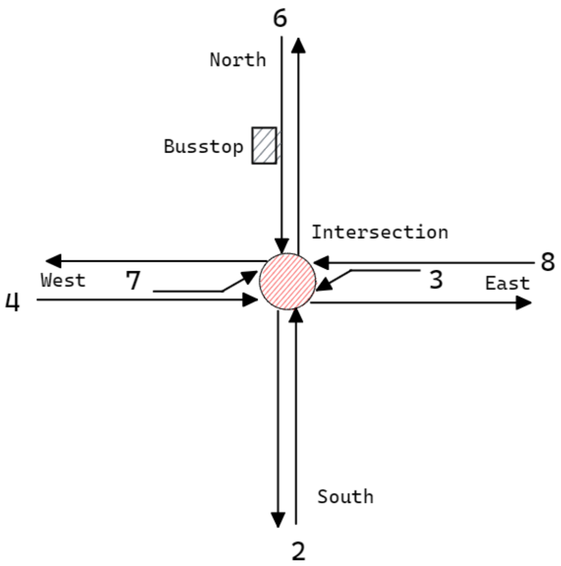
a fixed random seed for the traffic controller component.

The experimental scenarios are distinguished by the used simulation network model, the included modes, demand, and the spillback handling method. The experiments are performed on two simulation networks. The first is an isolated intersection; the second network is a corridor consisting of ten intersections. In the following sections, the experimental design of these set-ups is described. Information about specific characteristics, such as measurements of link lengths and traffic control times, are reported in Appendix B.

6.2. Isolated intersection

6.2.1. Simulation model

The first test network is an isolated intersection with a left turn and straight direction for east and westbound traffic and two straight directions for north and southbound traffic. This way, effects such as lane-blocking are enforced in a more controlled environment and create a more isolated view of the effects of handling spillback effects modelling in traffic control. Further experiments also include a bus line configured with a stop 100 meters upstream of the intersection. The simulation model is depicted in Figure 6.1a.



(a) Configuration for isolated intersection

	Direction	Demand factor 1	1.5	TF50/50
	North	300	450	300
	South	300	450	300
	East	270	405	300
	West	600	900	600
Turning bay	East	90	135	300
	West	200	300	200
	Bus	12	18	

(b) Demand profiles at peak-hour

Figure 6.1: Simulation model and demand profile

6.2.2. Traffic light control and sensors

In the current set-up, the traffic lights are constrained to the ring-and-barrier structure, as is explained in section 3.3. Because in this structure, the right and the straight direction are served green simultaneously, a left-turn bay is included in the network. Every traffic light is given a specific minimum and maximum green time, an extended green time of 2 seconds, a yellow time of 2 seconds, and a red clearance of 2 seconds. These specifications can be found in subsection B.1.2 in Appendix B. Lower minimum and maximum green time is allocated to the left turn due to lower demand than the straight directions. The same ring-and-barrier constraints apply to the adaptive control of the TFE. Consequently, four stage pairs can receive green at the same time: [2,6], [3,8], [4,8], and [4,7], the left turns cannot receive green at the same time in the corridor, that is why there is configured that they cannot receive green at the same time in the isolated intersection.

In the case of the TFE, additional traffic sensors are used. These sensors are constructed in SUMO by polygons (SUMO, 2022) and can detect the exact vehicle position, speed, and length. Every lane has a specific polygon in the TFE. In the case of the isolated intersection, all polygons have the same lengths as the turning bays.

6.2.3. Modes and demand

In the first several experiments the only road users are passenger cars, with varying demand. In further experiments, a bus service is added to see the effects of the optimization module on the traffic flow when multiple traffic modes are included. Furthermore, to see how the module copes with conflicting priorities in the optimization.

The bus service is set up as a bus that travels from north to south and halts for 20 seconds at the bus stop, 100 meters upstream of the intersection, indicated in Figure 6.1a. Unless indicated otherwise, the turning fractions are determined at 75 percent for the straight directions and 25 percent for the left turns at the isolated intersection. The resulting demand profile for the scenarios is depicted in Figure 6.1b.

The demand profiles with factor 1 and 1.5 were chosen because spillback is enforced multiple times in the west side (on average 197 seconds for factor 1, and 174 for factor 1.5), while other direction still have tolerable queuing durations (5 seconds on average for north). The results showed large delays for the turning-bay on the east-side, it was suspected that the high delay was due to a low demand, consequently, a third demand profile was created in which the turning fraction of the east side was changed to 50% straight and 50% turn traffic, in addition, the demand for the was increased to 600 vehicles per hour.

6.2.4. Spillback handling

Spillback occurs at least at one side of the intersection with the chosen demands. Every network configuration is tested without a spillback handling method, the override spillback method, and the penalty factor handling method. In the calibration in section 5.5, there was chosen to continue with a spillback priority of 10 for the 'minor' spillback penalty for the corridor.

6.3. Corridor

6.3.1. Simulation model

The corridor is divided into ten signalized intersections and has an arterial from north to south. The network is depicted in Figure 6.2 in which the corridor is cut in half, a full-size figure is depicted in section B.2. Intersection 3, Mission Bay, consists of a North-side and a South-side, named Mission Bay-North, and Mission Bay-South. Intersection 5, 3rd Campus, is located on the road's west side. Therefore, only traffic on the west side can travel over and turn right at this intersection. The LRV is indicated with a striped blue line, enters the corridor at intersection 1, and travels from north to south. The LRV leaves the network on the south side of the corridor. The LRV travels both ways.

6.3.2. Traffic light control and sensors

Figure 6.2 indicates the directions in which cars can travel. Most directions follow the prescribed ring-barrier phasing, as indicated in Figure 3.2a in chapter 3. The phase times per intersection are depicted in the Table B.4.

In the adaptive traffic light control of TFE, additional traffic sensors are used. In SUMO, these sensors are constructed with polygon zones and can retrieve the exact vehicle position, speed, and length inside the zone. Every lane has a specific polygon so that TFE can recognize which vehicle enters and leave a specific lane. In the same way, not only are LRV states retrieved on the dedicated lane but also pedestrians are identified at the corner of an intersection. Pedestrians can ask permission to cross the road by a push button.

6.3.3. Modes and demand

In the corridor, cars, LRVs, and pedestrians enter and leave the network. Later scenarios simulate a mixed traffic flow by including trucks in the demand profile. Regarding the traffic demand, during the first quarter, the traffic participants enter the network with half the specified demand factor to fill up the network. In the second and third quarters, the demand factor is the specified demand, and in the last quarter, the demand factor is halved again.

For the corridor, the demand profile and the turning fractions per intersection (Table B.7 and Table B.6 in Appendix B) are configured based on historical data, provided by Technolution.

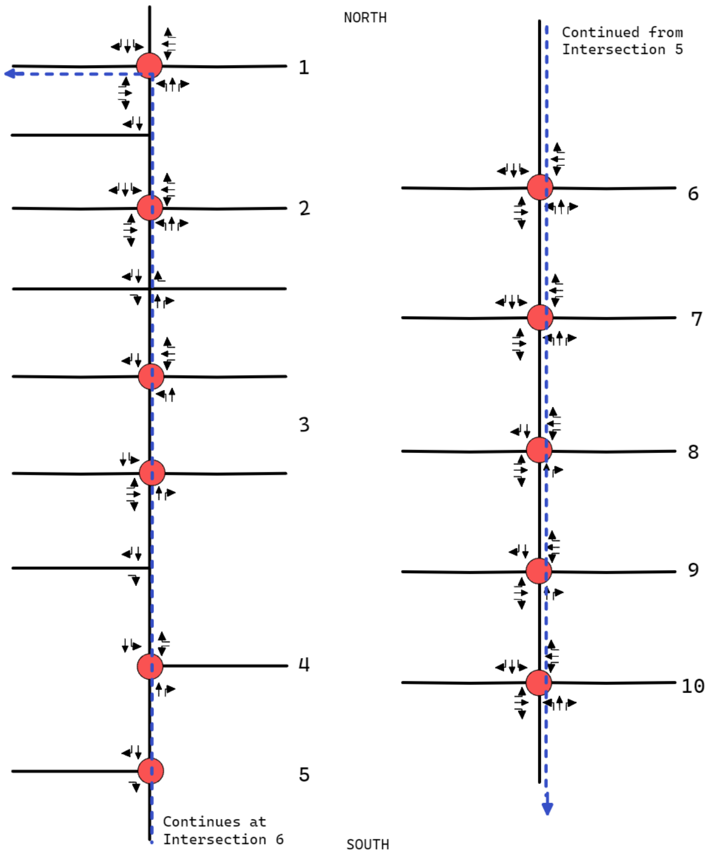


Figure 6.2: Corridor San Francisco

6.4. Simulation experiments

6.4.1. Route generation

In SUMO, vehicle routes are generated based on demand definitions and junction turning percentages. In the router, a random-seed number determines the routes and the random departure times for flow input. The same seed numbers (1 to 10) are used between the replications for the departure profiles.

For the verification of the simulation runs, the total distance travelled for vehicles between the replications is compared. As the turning fractions cause a difference in routes per replication, the total distance travelled differs slightly in a more extensive network. However, this is not the case at an isolated intersection; in (Table 6.1), an example of the comparison is depicted.

6.4.2. Priority weights

In the TFE algorithm, configurable parameters, such as the movement and object priority, influence the optimization, therefore, the outcome of the optimal signal plan. The object priority remains the same throughout the experiments and the chosen networks. For the corridor the standard the movement priority is indicated as 1 for every direction, in the corridor-priority scenario, additional priority was given to the corridor, as shown in Table 6.2.

6.4.3. Randomness

In the model, two random components provide a different output every time. Therefore, a seed is specified for these parameters. The first is the predictive component of TFE, in which the model predicts whether the vehicle will go straight or turn in another direction based on the turning fraction. In the validation of the model, it was seen that the outcome was inconsistent with the same input. Therefore, the predictive component was configured with a fixed seed

Table 6.2: Object-priority and movement-priority configuration

(a) Movement-priority configuration

Traffic object	Mode-priority
LRV	2000
Truck/bus	100
Pedestrian	10
Car	5

(b) Movement-priority configuration

Movement	Route-priority	Corridor-priority
Along Corridor	1	1.2
From sidestreet left turn	1	1.0
From corridor left turn	1	1.1
From sidestreet	1	1.1

number.

The second random component is the arrival flow departures. Poisson arrivals are used between the different runs. The seed-number increases by one with each new replication and ten replications are made.

6.5. Network scenarios and experimental design

Table 6.3: Generated network scenarios

#	Simulation network	Modes	Spillback control
1	Isolated intersection	Car	None
2	Isolated intersection	Car	Spillback penalty
3	Isolated intersection	Car	Override
4	Isolated intersection	Car, bus	None
5	Isolated intersection	Car, bus	Spillback penalty
6	Isolated intersection	Car, bus	Override
7	Corridor	LRV, car,pedestrians	none
8	Corridor	LRV, car,pedestrians	Spillback penalty
9	Corridor	LRV, car,pedestrians	override
10	Corridor	LRV, bus,car,pedestrians	none
11	Corridor	LRV, bus,car,pedestrians	Spillback penalty
12	Corridor	LRV,bus,car,pedestrians	override

During each experiment, spillback is enforced somewhere in the simulation model. For the isolated intersection, this results in the demand profiles in Figure 6.1b, for the corridor the demand profile is depicted in Table B.7. An overview of the experiments is written in the next section in Table 6.4.

6.6. Analysis

6.6.1. Number of replications

The number of runs depends on the uncertainty of the outcome; the number of replications should accomplish a statistical significance of 5 percent when comparing the means of a key performance indicator. However, a simulation run with MobiMaestro-Flow operates in real-time: 1 hour of simulation time is 1 hour in real-time. Therefore, ten replications are performed per scenario, leading to a runtime of ten to twelve hours per scenario.

Every run generates multiple output files by detectors placed in SUMO or SUMO generates the data itself. The key-performance indicators travel time, delay, spillback time, and network performance are calculated from these output files. The method of data collection and generation depend on the simulation network.

6.6.2. Additional sensors

Instantaneous (E1) loop detectors are placed around the researched intersection for the detection of spillback duration upstream of turning bays (Figure 6.3). These sensors can detect vehicles standing still or travelling over the detector at

Table 6.4: Overview performed experiments

Experiment	Network scenario	Demand factor	Spillback control	Note
Isolated intersection experiments				
1	1	1	None	TFE
2		1.5	None	TFE
3		1	None	Turning fraction (Turn) east 50/50
4	2	1	Spillback penalty	Result X5
5		1.5	Spillback penalty	Result X5
6		1	Spillback penalty	Turn east 50/50 (X5)
7		1	Spillback penalty	Result X10
8		1.5	Spillback penalty	Result X10
9		1	Spillback penalty	Turn east 50/50 (X10)
10		1	Spillback penalty	Result X1000
11		1.5	Spillback penalty	Result X1000
12		1	Spillback penalty	Turn east 50/50 (X1000)
13	3	1	Override	TFE
14		1.5	Override	TFE
15		1	Override	Turn east 50/50
16	4	1	None	TFE with bus
17		1.5	None	TFE with bus
18	5	1	Spillback penalty	with bus (X5)
19		1.5	Spillback penalty	with bus (X5)
20		1	Spillback penalty	with bus (X10)
21		1.5	Spillback penalty	with bus (X10)
22		1	Spillback penalty	with bus (X1000)
23		1.5	Spillback penalty	with bus (X1000)
24	6	1	Override	TFE with bus
25		1.5	Override	TFE with bus
Corridor experiments				
26	7	1	None	TFE
27		1	None	TFE with corridor priority
28	8	1	Spillback penalty	Result X10
29		1	Spillback penalty	Result X1000
30		1	Spillback penalty	Corridorpriority (X10)
31		1	Spillback penalty	Corridorpriority (X1000)
32	9	1	Override	TFE
33		1	Override	TFE with corridor priority
34	10	1	None	TFE with bus
35	11	1	Spillback penalty	with bus (X10)
36		1	Spillback penalty	with bus (X1000)
37	12	1	Override	TFE with bus

a specific speed. The detector gathers data from the travelling cars and assigns one of three states: *enter*, *stay*, or *leave*. The period of entering, staying, and leaving the E1 detector is measured. At direction where spillback could occur (sidestreets), E1 detectors are placed at an equal distance from the intersection, to calculate the queue durations at a certain distance for disadvantaged directions.

6.7. Key performance indicators (KPIs)

The experiments collect data for three performance indicators at each replication. These three KPIs give insight into the effects of spillback modelling on the network's performance. The mean, standard deviation, and statistical significance

Figure 6.3: Loop detector placed upstream of turning-bay

are measured for these indicators.

6.7.1. Spillback duration [s]

The first performance indicator is the time spillback is experienced around the intersection, measured with an E1-detector in SUMO upstream of an intersection. When the vehicle queue flows over the detector with a speed lower than three m/s, the duration is calculated by the time the car enters until the car leaves the detector. The duration is measured in seconds. The total spillback time per direction is calculated as the sum of these durations.

At the isolated intersection, the detectors are placed just upstream of the turning bays on the east and west side of the intersection. The detectors are placed at an equivalent distance for the north and south of the intersection. Important to note that spillback duration is measured in the north and south directions; however, it is used for measurements and in every scenario, no spillback control strategy is applied in the north and south directions.

In the corridor, E1-detectors are placed upstream of the northernmost intersection 3rd-Channel; furthermore, the detectors are placed at the north, south, east and west sides of the intersection 3rd and 16th Street. In the same way as the isolated intersection, just upstream of the turning bay or at the directions with no turning bay: at a similar distance.

6.7.2. Delay

The second performance indicator is vehicle delay in seconds, which is a derivative of the travel time. The travel time is measured using vehicle route duration. At the isolated intersection, this leads to six routes: vehicles travelling from **(1)** east to west, **(2)** west to east, vehicles travelling from **(3)** east to south or **(4)** west to north, and vehicles travelling from **(5)** north to south or **(6)** south to north. For the corridor, six routes are selected that are affected by spillback or by the spillback control strategy, indicated in Figure 6.4. Routes 1-4 are for passenger cars; routes 5 and 6 are the LRVs travelling from south to north or from south to north, respectively.

The individual delay is measured as the vehicle's travel time to complete its route minus the travel time of the route when the vehicle is travelling with free-flow speed. As the free-flow speed travel time is a fixed variable per route, the data distribution of the travel time and the delays are similar. The free-flow travel time is calculated by the route length divided by the free-flow speed (13.41 m/s).

$$\text{Vehicle delay} = \text{Traveltime} - \text{Free-flow traveltime} \tag{6.1}$$

6.7.3. Overall intersection delay

For the network indicator, the overall intersection delay is calculated. The method differs between the isolated intersection and the corridor. For the isolated intersection, the overall delay is calculated as the sum of the direction delay.

Calculating the total delay in the same way as the isolated intersection is rather complex, as it requires multiple additional sensors per intersection and a lot of data processing. Therefore, the total delay is calculated differently. The delay per intersection is estimated by SUMO, defined by the sum of the time loss and the waiting time. The waiting time is the time spent waiting for a vehicle. The time loss is the time a vehicle travels below the ideal speed during their trip. The disadvantage of these variables is that a vehicle stop at traffic lights is defined as a scheduled stop and is not considered in this delay calculation.

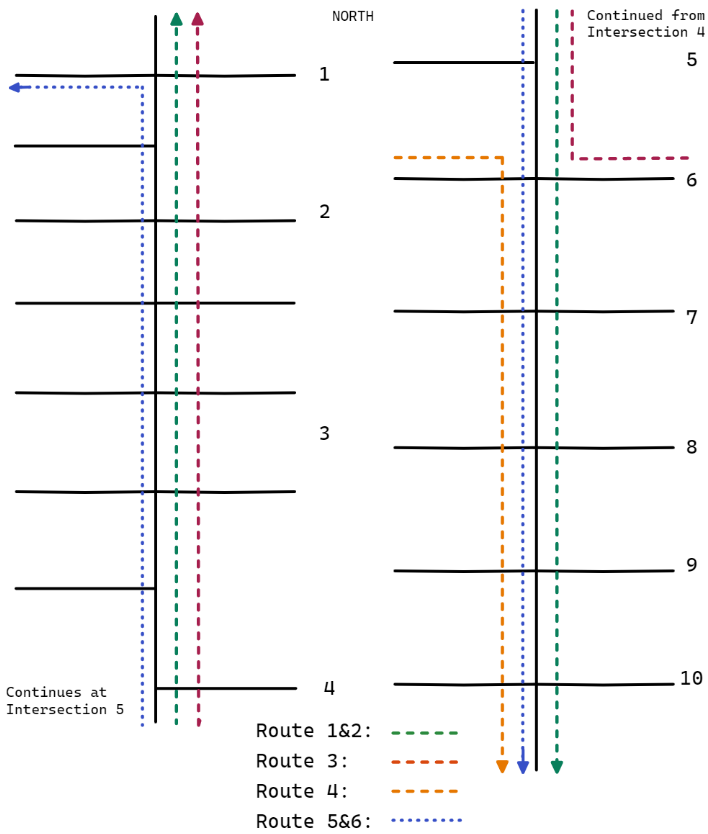


Figure 6.4: Routes compared in the analysis

6.7.4. Statistical significance

The statistical significance is calculated by a variation of the student t-test, namely the Welch t-test. Welch's test is regarded as the parametric equivalent of the Two-Sample t-test. This test is chosen, because the variances of the compared means are assumed not to be equal. This is compensated by a different method of approximating the degrees of freedom. The means of the two samples are compared and tested to determine whether a hypothesis is accepted or rejected. The following hypothesis is tested:

> H_0 : There is no difference between the means of scenario 1 (basecase) and scenario 2 (comparison-scenario).
> H_1 : The means of scenarios 1 (base case) and 2 (comparison-scenario) are different.

First, the means $\overline{x}_1$ and $\overline{x}_2$, and the variance s_1 and s_2 are calculated. After that, the difference of the variance between the means is calculated using the number of replications n_1 and n_2 as follows:

$$s_{\text{diff}} = \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}} \tag{6.2}$$

The t-value is then calculated as the difference in the scenario means, divided by s_{diff}:

$$t = \frac{\overline{x_1} - \overline{x_2}}{s_{\text{diff}}} \tag{6.3}$$

After that, the degrees of freedom df are calculated, using the following formula:

$$df = \frac{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2}{\frac{\left(\frac{s_1^2}{n_1}\right)^2}{n_1-1} + \frac{\left(\frac{s_2^2}{n_2}\right)^2}{n_2-1}} \tag{6.4}$$

The degrees of freedom lead to a t-value from the t-table. The null hypothesis is rejected if the calculated t exceeds the t-value from the t-table.

A two-tailed significance of $\alpha = 0.05$ is chosen, and the number of replications per scenario is 10. The following example table compares the base-case scenario with the scenario where a spillback penalty factor (x10) is included. When the significance of $\alpha = 0.05$ is not reached, and the result is $p < 0.1$ or $p < 0.25$ it is mentioned in the result tables. When the p-value is above 0.25, it is declared insignificant, meaning no difference is found between the means of the experiment compared to the base case.

Table 6.5: Outcome delays base-case (experiment 5)

Direction	Mean	Std.dev
North	31.248	2.469
South	36.296	2.532
East	22.549	2.120
West	22.111	0.808
TB: east	67.593	6.998
TB: west	53.221	1.971

Table 6.6: Overview KPIs experiment 11

	Direction	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	5.453	2.564	-0.232	9.819	No
	South	7.478	4.139	1.345	7.596	(p < 0.25)
	East	6.596	13.657	0.762	2.498	No
	West	174.586	27.395	4.604	1.597	(p < 0.1)
	Total	194.113	32.185	4.405	1.711	(p < 0.1)
Travel time	North	61.467	2.071	-2.385	12.851	Yes: (p < 0.05)
	South	65.933	1.581	-0.626	13.376	No
	East	59.446	1.113	0.275	19.240	No
	West	58.217	0.904	7.070	59.233	Yes: (p < 0.05)
	TB: East	105.122	5.944	-4.784	4.289	Yes: (p < 0.05)
	TB: West	84.862	2.297	4.950	13.978	Yes: (p < 0.05)
Delay	North	32.016	2.071	-2.385	12.851	Yes: (p < 0.05)
	South	36.483	1.581	-0.626	13.376	No
	East	22.483	1.113	0.275	19.240	No
	West	21.254	0.904	7.070	59.233	Yes: (p < 0.05)
	TB: East	71.986	5.944	-4.784	4.289	Yes: (p < 0.05)
	TB: West	51.723	2.297	4.950	13.978	Yes: (p < 0.05)

7

Results

The experimental scenarios led to quantitative results that indicate the effect on the traffic and network performance when spillback control strategies were incorporated in traffic light control optimization. A Welch t-test was used, as explained in subsection 6.7.4, to test the statistical significance of the hypothesis if there is a difference in means between the scenario without a spillback control strategy (base case) versus cases where a spillback control strategy was implemented. When a result is significant, the p-value results in a lower value than 5 percent. In the following sections, key results are described, first on the effects on the network performance at an isolated intersection and, after that, on the network performance in a corridor. An overview of the performed experiments is found in the previous chapter, in Table 6.4. The generated graphs and tables can be found in Appendix C for unimodal experiments at an isolated intersection, in Appendix D for isolated intersection scenarios with a busline, and in Appendix E for the results of the corridor scenarios.

7.1. Isolated intersection

The experiments performed at an isolated intersection (see Table 6.4) varied in the type of road users, the demand, and the spillback control strategy. In the next sections, the results of these experiments are described, first, the overall intersection delay is described, and then the spillback duration and delay performance. After describing the results of different scenarios, the results are discussed.

7.1.1. Passenger car experiments

For all scenarios, the overall intersection performance decreased when a spillback control strategy was applied. In the experiments with the turn ratio set to 50/50, the total intersection delay results were less spread, however, the overall delays still increased. The highest intersection delay in the scenarios was found for the strategy override.

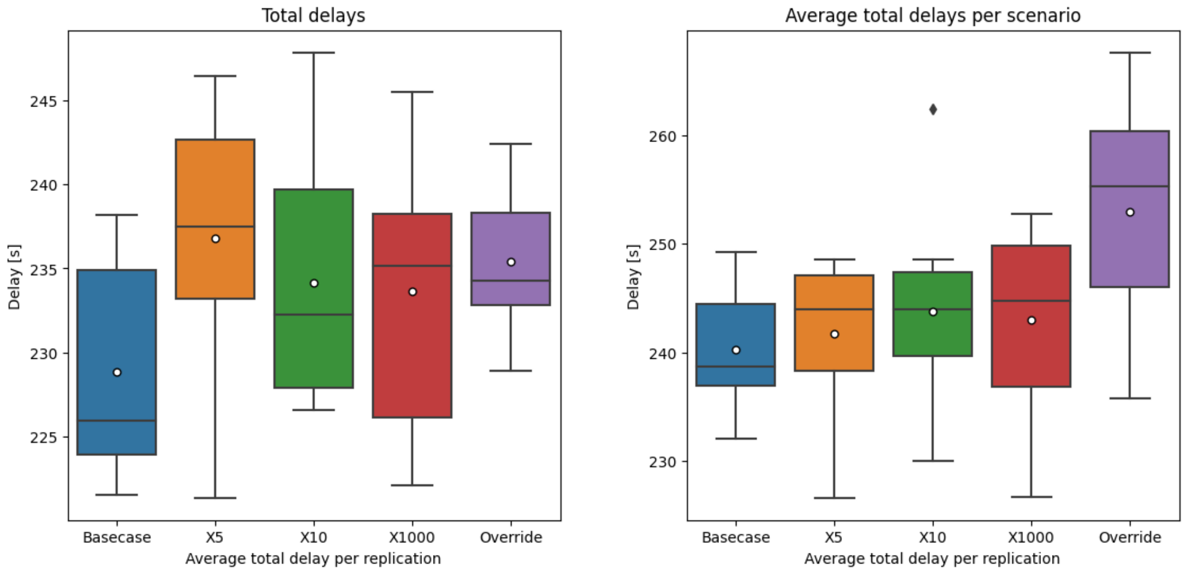
Spillback duration

In general, the override strategy showed the most significant reductions for all directions affected by spillback (p <0.05). However, in most cases, this was paired with an increase in delays for the directions that were not bound by spillback. For example, in the scenario turn ratio 50/50, increases showed increases of 146% and 86% in queue durations for the north and south.

With a demand factor of 1, all spillback penalty strategies showed a decrease in spillback duration for the west, with the most significant decrease for the penalty factor X10. The total spillback duration also decreased for factor X10, which is also the case for the larger factor x1000; however, the data of the replications are more spread out.

When the demand was increased with factor 1.5, the penalty strategies did not show a statistical difference compared to the base case; however, the data in Table 7.1 shows decreased spillback durations for the east side. The direction with the highest demand, the west, increased in spillback duration.

When the east-side demand was increased, and also turn ratio was altered to 50/50, improvements were found for the



(a) Experiments with increased demand x1.5

(b) Experiments east turning fraction 50/50 and higher demand

Figure 7.1: Overall mean average delay

Table 7.1: Results demand factor 1.5 and turnratio 50/50

				Mean x5		MeanX10		Mean X1000		Mean override	
	Direction	**1.5**	**Turnratio**	**1.5**	**Turnratio**	**1.5**	**Turnratio**	**1.5**	**Turnratio**	**1.5**	**Turnratio**
Spillback	North	5.537	10.632	0.7%	0.7%	-10.9%	7.2%	-20.0%	-10.0%	18.7%	146.4%
	South	2.667	17.513	17.1%	9.5%	28.5%	39.3%	16.6%	-1.5%	49.8%	363.4%
	East	7.654	131.742	-29.3%	6.1%	-18.2%	22.5%	-39.0%	38.8%	-42.6%	-30.3%
	West	173.808	358.42	5.8%	-7.1%	3.7%	-11.5%	0.5%	-11.0%	-39.0%	-33.8%
	Total	189.666	518.307	4.6%	-3.1%	3.2%	-1.3%	-1.1%	2.1%	-34.7%	-21.6%
Delay	North	32.404	36.092	-1.3%	4.1%	-1.0%	7.5%	-1.5%	1.5%	6.2%	12.5%
	South	34.572	40.004	4.5%	0.2%	8.3%	3.4%	4.7%	-1.0%	9.0%	23.7%
	East	23.707	24.404	-5.4%	1.3%	-4.7%	0.7%	-7.3%	0.1%	8.1%	18.3%
	West	21.237	29.903	-1.3%	-3.9%	-1.6%	-5.1%	-3.2%	-4.6%	-12.3%	-12.0%
	TB: East	64.398	48.132	12.8%	1.4%	7.3%	5.6%	8.3%	10.1%	1.8%	-2.5%
	TB: West	52.51	61.745	0.3%	0.1%	-1.0%	-3.1%	1.4%	-1.5%	1.9%	-1.6%

west side for all spillback control strategies ($p < 0.05$). However, this was paired with increased spillback durations for the east side. With a high penalty factor, the north side benefits with a reduced queue duration compared to the base case. However, duration at the south increased ($p < 0.05$).

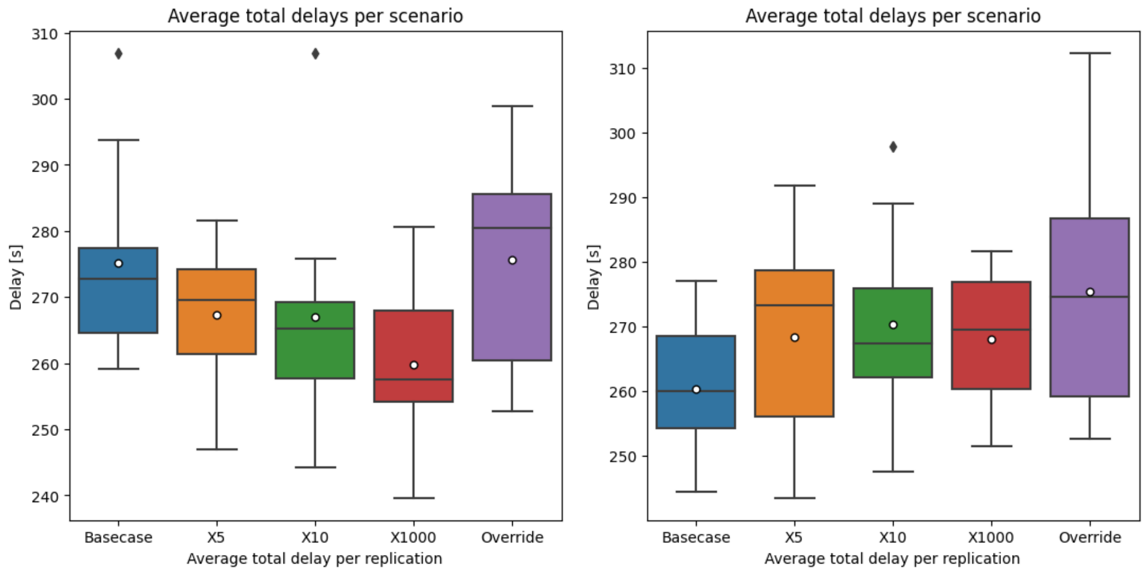
Delays

With low demand, the delay decreased with all spillback strategies and demand scenarios, for the direction in which spillback was enforced (west). With an increased demand factor of 1.5, the delays of the directions with a low traffic demand increased significantly (turning-bay east side, north and south side). In contrast to other directions, as with a minor penalty factor, the delays decreased for north, east, and west, while the turning-bay delay stayed similar.

In the scenario with a turning ratio of 50/50 on the east, a larger penalty factor shows more improvements for directions that are affected by spillback, but this is paired with increased delays for the north and the south. However, with a very high penalty factor (X1000), the turning bay of the east side is skipped more often.

7.1.2. Experiments with busline

In the experiments with low demand, the overall intersection delay was decreased when spillback penalty strategies were applied (p<0.05), as shown in Figure 7.2a. The most significant decrease is with the highest penalty factor of X1000. The decrease in overall intersection delay disappeared (see Figure 7.2b when the demand was increased with factor 1.5 (p < 0.05), the means of the spillback penalty strategies were comparable. For both demand profiles, the override strategy increased the overall intersection delay.



(a) Bus Experiments with demand 1.0

(b) Bus experiments with increased demand factor 1.5

Figure 7.2: Total mean delays from bus experiments

Spillback duration

In terms of spillback durations, the most considerable reductions are found with the override control strategy, as shown in Table 7.2. But this is also paired with the highest increase in queue durations for disadvantaged directions north and south.

With a demand factor of 1, the penalty strategies reduced spillback durations. The most significant decrease is found for the penalty factor X10. The benefit is decreased when the demand factor is increased to 1.5; however, spillback is still reduced for the west side. For other directions, the queue or spillback duration is increased.

Delays

Regarding the delays, reductions were found for the straight and turning bay of the west side with low demand and a penalty factor of X5 (see Table 7.2). Additionally, minor reductions for the north, south, and east side. Also a reduction was found for the bus delay. In general, with low demand, the delay of the bus was decreased for all spillback penalty strategies.

The benefit decreased when the demand was increased with factor 1.5. Then, the reductions in spillback duration were found to be the highest for the spillback penalty X10. No benefit is found for a smaller penalty factor of X5, only a slight decrease for the west side. Furthermore, the disadvantaged directions, the north and the south, have no significant decrease in performance, except for the east side, which has increased delays when the demand is higher, and also the delays of the bus increased with a spillback control strategy applied.

7.2. Interpretation results – isolated intersection

With a low demand, the overall intersection delay increases when spillback penalty factors are included in the traffic light control optimization. In a scenario where one direction has an apparent higher demand, the provided additional priority does does not compensate the loss in delays for other, disadvantaged, directions, leading to a lower intersection

Table 7.2: Result bus experiments isolated intersection

		Mean base case		Mean (X5)		Mean (X10		Mean (X1000)		Mean (Override)	
		1	1.5	1	1.5	1	1.5	1	1.5	1	1.5
Spillback	North	10.188	11.697	8.6%	-20.0%	10.8%	6.5%	-0.3%	19.3%	79.3%	64.9%
	South	6.846	7.982	5.8%	-2.7%	24.9%	13.2%	30.6%	11.8%	133.7%	121.7%
	East	13.381	14.735	72.5%	23.7%	30.8%	-0.7%	29.3%	32.5%	-41.3%	-25.3%
	West	205.849	227.57	-15.9%	-8.6%	-12.1%	-17.1%	-2.3%	-7.0%	-50.4%	-56.4%
	Total	236.264	261.984	-9.2%	-7.2%	-7.7%	-14.4%	0.5%	-3.1%	-39.4%	-44.6%
Delays	North	31.921	31.844	-0.9%	3.4%	0.2%	2.3%	1.7%	4.1%	7.7%	9.5%
	South	34.701	34.776	-0.3%	1.2%	0.2%	2.2%	3.4%	3.7%	14.3%	12.0%
	East	25.125	23.186	-1.1%	1.8%	-0.7%	7.9%	-5.0%	3.6%	-0.9%	16.4%
	West	22.523	22.933	-5.1%	-1.5%	-4.3%	-4.5%	-0.4%	-1.4%	-14.4%	-17.8%
	TB: East	68.376	64.018	2.8%	3.8%	-1.5%	3.8%	-6.1%	4.9%	1.3%	2.8%
	TB: West	54.551	54.93	-2.1%	2.6%	-5.9%	-4.5%	-4.6%	-2.3%	-4.4%	-2.0%
	Bus	37.9	28.72	-17.9%	8.7%	-7.6%	26.4%	-23.7%	9.5%	-5.1%	25.6%

performance. Furthermore, when a spillback penalty strategy is applied, the direction affected by spillback, receives green to minimize the waiting costs, the non-conflicting direction that is allocated green time is the direction with the highest demand, receiving priority over other non-conflicting directions. This caused high delays for directions with a low demand sharing a barrier with a direction where spillback occurred. For example, the turning-bay on the east side, with a low demand. chosen

With a high spillback penalty, a direction with spillback receives green as fast as possible; however, the penalty is already given when the traffic exceeds the turning bay; this way, absolute priority is given very fast, and the traffic light switches more often, while other direction also have logner queues. Switching the traffic light takes time due to providing sufficient clearance, which can lead to an increased spillback duration (10X versus X1000).

The override strategy showed promising results on spillback duration; even with approaches competing in demand, benefitss were shown for both the east and the west side. This is caused by the abrupt method. However, the method does not consider safety constraints, such as red clearance. This results in a dynamic phasing situation, switching traffic lights when spillback is detected as true. After that, the traffic light control works as usual. The absolute prioity also led to very high delays for disadvantaged directions.

When a busline is is included in the network, delays decrease for all directions when the traffic demand is low and one side is enforced with spillback. This caused the traffic lights to switch more often: when spillback is detected, the west side received green, and when a bus is detected at the north-side green is allocated faster as the object priority of a bus is twenty times higher. This caused a lower bus delay and lower delays for spillback directions. However, the benefits are lost when a conflict occurs in traffic control. For example, with a rising traffic demand: no difference with the base case or worse performance was found in delays and spillback durations. With a small penalty factor, improvements are still found for spillback and north and south directions, as the high object priority of the bus is more in balance with a queue of vehicles that overflows the turning bay. Though, the benefits are paired with an increase in bus delay. With increased penalty factors, traffic control leans into an advantage for spillback directions and larger delays for the bus (and non-spillback directions).

7.3. Corridor

In experiments 26 to 37, experiments were performed on a corridor. The experiments have the same demand profile, but vary in priority given to the corridor, the spillback control strategy, and the included traffic on the road. First, results are described for the scenario with cars, LRVs and pedestrians. Next, the corridor is assigned 10 percent additional movement priority. After that, the result are presented for the last scenario, when the traffic flow is more mixed with the inclusion of buses. First, the intersection performance and network performance are described. After that, the spillback duration is described for the intersection 3rd and 16th Street, which is measured by detectors placed around the intersection (see Table 7.3b). Furthermore, the delays for the LRV and different vehicle routes are described (see

Table 7.3a). An overview of the intersections on the corridor is shown in Table 7.4.

(a) Routes for delay analysis

Route	From	To	Length [m]
1	North corridor	South corridor	1826
2	South corridor	North corridor	1826
3	3rd 16th East	North corridor	1050
4	3rd 16th West	South corridor	913
5	LRV: South	North	1822
6	LRV: North	South	1917

(b) Detector locations

Detector name	Location
Overflow	3rd Campus
North	North of 3rd 16th
South	South of 3rd 16th
East	East of 3rd 16th
West	West of 3rd 16th

Table 7.3: Overview routes and detector locations

Table 7.4: Intersections in the corridor

Number in graph	**0**	**1**	**2**	**3**	**4**	**5**
Intersections	3rd Channel	3rd Mission Rock	3rd Mission Bay (north)	3rd Mission Bay (south)	3rd Warriors ways	3rd Campus
#	**6**	**7**	**8**	**9**	**10**	
Intersections	3rd 16th	3rd Mariposa	3rd 18th	3rd 19th	3rd 20th	

7.3.1. Traffic flow with car, LRV, and pedestrians

When spillback control strategies were applied, the network performance, which is the sum of all intersection performances, depicted in Table 7.5, showed increased performance when the spillback penalty was configured as X10. With a very high spillback penalty (X1000), the network performance decreased. The highest performance increase is with the control strategy override, however, this strategy neglects the ring-and-barrier structure when controlling the spillback effects.

Table 7.5: Network performance with normal demand in delay [s] and [%]

Period	Base case	X10	X1000	Override
Q1	329.0	-0.69%	2.17%	-2.10%
Q2/Q3	674.4	-0.72%	-0.22%	-4.80%
Q4	349.2	-0.21%	1.81%	-2.75%
Total	1352.7	-0.58%	0.88%	-3.62%

When looking at the individual intersection performance (see Table 7.6), intersections 6. 3rd 16th Street and 7. 3rd Mariposa have the highest delays compared to the other intersections. With a penalty strategy applied, benefits are found for 3rd Mariposa, which is the intersection directly south of 3rd and 16th Street. Furthermore, at the ends of the corridor, benefits were found, mainly during the peak period Q2/Q3. At the intersection where spillback was enforced, 3rd and 16th Street, the overall intersection delays increased when spillback control strategies were applied.

Outside the peak period (Q1 and Q4), a decreased performance was found for several intersections when a higher spillback penalty of X1000 was applied. These delays were higher compared to a lower spillback penalty – for example, in Q1, the delay of intersection 4. 3rd Warriors Way, increased 20.9% compared to 0.6 % when a spillback penalty of X10 was applied.

Regarding the spillback effects at 3rd and 16th (Table 7.7). With spillback penalty strategies were applied, the spillback duration of the north decreased, and decreased more with a higher spillback penalty. In contrast to the overflow, occurring upstream north of 3rd and 16th, is handled faster when no spillback penalty strategy was applied. With the current demand profile, there were increased queue durations for disadvantaged directions, however, these durations are not that long.

Regarding the route delays, routes travelling from north to south, such as routes 1 and 4 decreased when the penalty factor was X10 (p<0.05). These routes are the routes that benefited from the spillback control strategy. Route 2 also had a decreased delay and travelled from south to north. Only route 3, which travels from the east side of 3rd and 16th

Table 7.6: Intersection performance in delay [s] and [%]

	Base case			Result X10			Result X1000			Result Override		
Intersections	Mean Q1	Mean Q2/Q3	Mean Q4	Mean Q1	Mean Q2/Q3	Mean Q4	Mean Q1	Mean Q2/Q3	Mean Q4	Mean Q1	Mean Q2/Q3	Mean Q4
0. 3rd_channel	22.519	50.589	22.648	11.9%	0.2%	9.0%	-2.3%	-9.6%	8.0%	4.4%	-12.3%	-4.0%
1. 3rd_missionrock	17.281	37.667	15.765	-0.4%	-4.2%	28.4%	7.4%	-5.9%	28.9%	1.1%	-10.4%	19.5%
2. 3rd_missionbaynorth	13.553	26.548	13.918	-5.2%	-4.9%	8.2%	10.4%	-6.8%	7.1%	-2.6%	1.1%	-1.0%
3. 3rd_missionbaysouth	19.905	38.932	20.966	-0.8%	-1.7%	7.8%	-4.9%	2.2%	17.2%	6.0%	1.1%	-5.8%
4. 3rd_warriorsway	19.138	39.173	18.678	0.6%	3.1%	-9.2%	20.9%	4.7%	-4.7%	-8.1%	-11.5%	3.2%
5. 3rd_campus	36.226	69.542	33.962	-0.6%	0.2%	12.8%	-1.4%	1.2%	-4.1%	-7.4%	-5.7%	-1.9%
6. 3rd_16th	50.385	109.597	54.735	5.8%	5.4%	5.9%	4.3%	7.6%	5.7%	4.1%	2.4%	5.3%
7. 3rd_mariposa	55.729	124.208	72.581	-3.6%	-4.7%	-6.8%	2.1%	-4.6%	-5.1%	-4.4%	-11.9%	-9.1%
8. 3rd_18th	36.552	74.679	40.66	-3.8%	1.0%	-14.2%	-8.9%	3.7%	-0.9%	-2.6%	2.6%	-13.7%
9. 3rd_19th	28.652	48.843	28.084	-8.4%	-0.2%	-25.1%	10.9%	3.2%	-18.8%	1.1%	-4.1%	-2.8%
10. 3rd_20th	29.034	54.664	27.249	-3.7%	-6.3%	6.9%	-2.7%	-5.6%	14.5%	-12.6%	-4.4%	-1.2%

street, has an increased delay. The delay increased when the spillback penalty was high (X1000); furthermore, the benefit for route 4, travelling from the west of 3rd and 16th to the south of the corridor, is lost with a higher spillback penalty. The delays for the LRV are not statistically different from the basecase, however, the LRV travelling to north has a small decrease in delay for all cases where a spillback control strategy is applied.

Table 7.7: Results of experiments with normal demand

		Basecase	X10	X1000	Override
	KPI	Mean [s]	Mean [s]	Mean [s]	Mean [s]
Spillback	Overflow	7.208	118.9%	37.2%	-100.0%
	North	212.99	-29.5%	-35.5%	-84.1%
	South	2.363	29.4%	11.1%	40.6%
	East	3.143	33.1%	8.9%	78.5%
	West	5.981	-17.7%	-0.5%	-16.6%
	Total	224.477	-27.7%	-33.5%	-78.7%
Delay	Route 1	197.316	-6.3%	-9.0%	-21.0%
	Route 2	175.867	-1.8%	-3.3%	-8.8%
	Route 3	115.71	4.7%	12.5%	9.7%
	Route 4	116.986	-4.5%	1.5%	-7.2%
	LRV-north	225.823	0.2%	-1.3%	-0.7%
	LRV-south	207.86	0.5%	2.7%	2.9%

7.3.2. Corridor priority

When corridor priority is configured for the arterial, vehicles leaving, entering or travelling over the arterial receive an increased priority. The corridor in combination with a spillback penalty strategy reduced the network performance. For both spillback penalties X10 and X1000, the overall network delay increased, furthermore, a higher network delay was found when the spillback penalty was higher. However, applying the override strategy showed a slight improvement on the network performance.

Table 7.8: Network performance corridor priority in delay [s] and [%]

	Basecase	X10	X1000	Override
Q1	328.6	-0.84%	3.04%	-1.57%
Q2/Q3	664.1	0.45%	2.01%	1.03%
Q4	346.9	0.63%	6.51%	-2.28%
Total	1339.6	0.18%	3.43%	-0.46%

Regarding intersection performance, (see Table 7.9) the outer intersections still had an increased performance when spillback penalty strategies were applied. With a higher spillback penalty, the performance benefits were mainly found during the peak-demand in Q2, in comparison to Q4 which had decreased performances for all intersections. The increased corridor priority for the arterial, in combination with the additional spillback priority, did not lead to better performances than without the corridor priority.

Table 7.9: Intersection performance in delay [s] and [%]

	Base case			Result X10			Result X1000			Result Override		
Intersections	**Mean Q1**	**Mean Q2/Q3**	**Mean Q4**	**Mean Q1**	**Mean Q2/Q3**	**Mean Q4**	**Mean Q1**	**Mean Q2/Q3**	**Mean Q4**	**Mean Q1**	**Mean Q2/Q3**	**Mean Q4**
0. 3rd_channel	24.765	49.494	24.599	-4.1%	-2.7%	3.2%	-10.4%	-5.8%	5.1%	-9.9%	-11.6%	-2.5%
1. 3rd_missionrock	14.742	34.812	18.659	22.7%	8.6%	-2.3%	5.7%	9.5%	3.7%	5.6%	4.3%	-12.7%
2. 3rd_missionbaynorth	15.027	25.995	15.39	-9.6%	2.6%	-5.0%	-7.6%	-1.8%	0.1%	-10.0%	1.5%	-3.1%
3. 3rd_missionbaysouth	22.995	38.899	20.897	-17.0%	4.5%	1.8%	-5.9%	1.9%	7.2%	-2.4%	4.7%	-1.4%
4. 3rd_warriorsway	19.501	37.382	16.209	-16.2%	6.8%	-1.5%	-2.6%	8.6%	9.6%	-2.3%	2.3%	7.6%
5. 3rd_campus	33.22	66.779	32.973	8.8%	3.4%	-1.6%	9.4%	4.0%	7.8%	7.4%	-1.0%	5.1%
6. 3rd_16th	52.826	111.584	57.659	1.6%	1.7%	1.8%	1.4%	7.8%	9.3%	-8.3%	7.1%	-0.9%
7. 3rd_mariposa	54.89	120.981	68.442	1.8%	-0.6%	6.5%	7.7%	-1.7%	2.8%	1.0%	-8.4%	-11.0%
8. 3rd_18th	36.554	76.455	37.714	-2.5%	-6.7%	0.0%	7.5%	-0.6%	8.6%	5.1%	2.4%	-0.5%
9. 3rd_19th	26.757	47.603	23.746	-0.9%	-1.8%	0.4%	0.3%	4.0%	16.4%	-4.4%	15.3%	5.0%
10. 3rd_20th	27.356	54.079	30.641	-0.4%	-2.3%	-8.4%	13.8%	-2.5%	1.8%	-1.3%	3.3%	0.2%

In general, spillback durations were already reduced due to the increased corridor priority, at the north of 3rd and 16th Street. Nevertheless, the penalty factors have decreased the spillback durations even more for the north and south (see Table 7.10, also shorter queue durations were found in the east direction. The decrease in total spillback, had the effect that the west side of 3rd and 16th Street had a very high increase in queue duration. The duration increased even more when a higher spillback penalty was applied. Furthermore, for the override strategy, the biggest reduction in spillback duration, was paired with the highest increase in queue durations for the south, the east, and the west.

Table 7.10: Performance indicators with corridor priority

		Basecase	**X10**	**X1000**	**Override**
	KPI	**Mean [s]**	**Mean [s]**	**Mean [s]**	**Mean [s]**
Spillback	Overflow	16.541	-83.4%	-94.0%	-100.0%
	North	214.098	-17.8%	-36.7%	-88.6%
	South	2.954	-18.7%	-5.3%	241.3%
	East	4.043	-5.4%	-10.7%	530.2%
	West	6.09	173.3%	224.3%	408.5%
	Total	227.185	-12.5%	-28.9%	-59.9%
Delay	Route 1	177.913	1.5%	0.0%	-12.6%
	Route 2	163.742	-2.9%	6.3%	-4.1%
	Route 3	125.775	-1.3%	-1.4%	3.4%
	Route 4	115.501	-3.1%	0.6%	-5.1%
	LRV-north	222.266	1.3%	2.3%	1.2%
	LRV-south	209.821	-1.6%	-1.1%	0.8%

Regarding the route delays, all routes have received additional priority as they were travelling over the arterial. With a penalty factor of X10, routes 2 and 3, travelling to the north of the corridor had decreased delays, but also vehicle travelling from the east of 3rd and 16th Street to the south of the corridor (route 4). With a higher penalty factor (X1000), only a decrease in delay was found for the third route. Regarding the LRV delays, no high difference in delay was found. The LRVs travelling to the south had decreased delays when spillback penalties were applied, which was not the case when no corridor priority was applied in the previous scenario.

7.3.3. Mixed traffic flow with bus

For these scenarios with a mixed traffic flow, buses are included and travel on the same road as cars. A bus receives more priority than a normal passenger car, consequently, when a bus is in a queue for the trffic light, the queue has extra priority, compared to a queue consisting only of cars. Regarding the network performance (see Table 7.11), the spillback control strategies caused an increased network performance during the peak demand (Q2/Q3). With a higher spillback penalty, the benefit was also seen for the period after the peak in Q4. For the total network delay, there was no difference, or a small improvement in network performance for higher spillback penalties.

Table 7.11: Network performance mixed traffic flow in delay [s] and [%]

	Base case	X10	X1000	Override
Q1	363.6	3.43%	-0.02%	2.90%
Q2/Q3	774.7	-1.94%	-1.50%	-3.94%
Q4	393.6	1.54%	-2.35%	-1.52%
Total	1531.9	0.23%	-1.37%	-1.69%

Regarding the intersection performances, shown in Table 7.12, the increased performances are more found at intersections in the middle of the corridor, for example 7. 3rd Mariposa, and 3rd Warrior's Way, instead of outer intersections, such as 0. 3rd Channel, 1. 3rd Mission Rock, and 3rd and 9. 19th Street, which had increased performances in previous scenarios. However, when the spillback control strategy was override, the absolute priority did increase the network performance of the four northernmost intersections (p<0.05) paired with southernmost intersections 7. 3rd Mariposa, 8. 3rd 18th and 10. 3rd 20th ($p < 0.05$).

Table 7.12: Intersection performance with mixed vehicle flow, delay in [s] and [%]

	Base case			Result X10			Result X1000			Result Override		
Intersections	**Mean Q1**	**Mean Q2/Q3**	**Mean Q4**	**Mean Q1**	**Mean Q2/Q3**	**Mean Q4**	**Mean Q1**	**Mean Q2/Q3**	**Mean Q4**	**Mean Q1**	**Mean Q2/Q3**	**Mean Q4**
0. 3rd_channel	26.174	54.309	29.184	-2.2%	0.5%	8.0%	1.3%	-1.9%	2.8%	3.2%	-12.3%	-3.3%
1. 3rd_missionrock	17.187	39.648	21.864	13.1%	6.2%	0.2%	12.0%	10.1%	-7.0%	1.7%	-5.5%	-4.9%
2. 3rd_missionbaynorth	14.953	31.833	15.743	-2.0%	-3.9%	10.9%	0.4%	-4.4%	-4.3%	-1.9%	-6.9%	5.3%
3. 3rd_missionbaysouth	22.401	50.721	24.777	-3.0%	-9.1%	2.9%	0.4%	-9.9%	-1.3%	0.9%	-4.1%	0.6%
4. 3rd_warriorsway	22.798	41.354	19.998	-11.4%	5.8%	10.6%	-8.1%	2.3%	-9.6%	-8.4%	5.6%	-9.9%
5. 3rd_campus	35.227	78.418	37.686	11.3%	-4.5%	-2.2%	-1.4%	-7.0%	-1.4%	4.5%	-4.3%	4.7%
6. 3rd_16th	55.782	136.641	62.552	-0.9%	-2.5%	4.4%	1.1%	1.4%	2.5%	11.4%	0.3%	4.1%
7. 3rd_mariposa	62.859	137.685	76.758	14.7%	-1.9%	-7.4%	0.8%	-5.4%	-6.4%	1.0%	-10.2%	-8.0%
8. 3rd_18th	42.999	86.442	43.639	13.0%	-5.0%	-4.3%	-1.3%	-1.9%	-5.3%	8.2%	-4.4%	-9.7%
9. 3rd_19th	33.332	53.355	27.88	-13.7%	1.3%	5.8%	-3.3%	6.6%	-3.3%	-3.5%	7.7%	-2.5%
10. 3rd_20th	29.866	64.279	33.562	1.9%	-1.6%	9.2%	1.0%	0.0%	4.4%	1.6%	-4.8%	11.4%

In terms of spillback duration, shown at the top of Table 7.13, applying a spillback control strategy lead to high reductions in spillback duration on the side in which spillback was enforced (north-side of 3rd and 16th). But also, a high reduction was found for the west side, when a small spillback penalty of X10 was applied. Furthermore, a higher spillback penalty (X1000), did not lead to higher reduction, but caused longer queue durations for disadvantaged directions.

Table 7.13: Results of corridor experiments with bus

		Base case			
		Mean [s]	**X10**	**X1000**	**Override**
Spillback	Overflow	10.975	-32.9%	-32.0%	-92.4%
	North	259.073	-36.5%	-28.9%	-83.2%
	South	18.698	29.7%	94.6%	50.5%
	East	36.776	8.4%	134.0%	108.3%
	West	126.104	-31.2%	34.3%	-30.6%
	Total	440.651	-28.4%	8.0%	-19.8%
Delay	Route 1	191.617	-1.1%	-4.8%	-14.9%
	Route 2	169.601	-0.5%	2.7%	-5.1%
	Route 3	120.925	14.2%	14.2%	19.7%
	Route 4	121.84	-7.0%	-1.1%	-8.6%
	LRV-north	229.131	-0.2%	-0.6%	-0.6%
	LRV-south	204.852	0.7%	3.1%	2.8%

The delays of the routes are shown at the bottom of Table 7.13. The effect of spillback control strategies was negative for route 3, which is the route from the east side of 3rd and 16th Street to the north of the corridor. In contrast to vehicles travelling from north of the corridor to the south, or 3rd and 16th Streets to the south (routes 1 and 4). Regarding the LRV, there was little to no difference in delay for the line travelling to the north. The LRV travelling to the south did had increased delays for all spillback control strategies.

7.4. Interpretation results – Corridor

Every scenario had the same demand profile, in which spillback was enforced on the north side of 3rd and 16th Street and also overflow occurred in some instants at 3rd Campus, just north of 3rd and 16th Street. The results showed with a moderate vehicle flow on the road and a minor spillback penalty of X10, the overall network performance was increased. Furthermore, during the peak period (Q2/Q3), the network performance improved for all scenarios with spillback control strategies, except for the scenario with additional corridor priority. Furthermore, improved network performance was found when absolute priority was provided and the suggested phase plan was interrupted with the override strategy. Regarding intersection performance, intersections also benefit the most from the override strategy, provided that the traffic demand gradually reduces. Although, these promising results are due to the abrupt spillback control by neglecting phase constraints, in contrast to the 'TFE' spillback penalty control strategy.

Regarding the intersection performance, intersections with lower demand or fewer conflicting directions gain performance when spillback penalty strategies are applied. For example, 3rd Warriors Way or 3rd Campus, which are both three-legged intersections. Intersection decreased in performance when multiple directions had a higher demand. It can be said that the overall intersection delay decreases when the demand for conflicting directions is low, consequently, when the demand for conflicting directions is high, the gain in overall intersection performance is lost. Still, the spillback durations are reduced as these movements receive priority over other directions.

At the investigated intersection (3rd and 16th Street), spillback was reduced more with a stronger spillback control strategy. This was paired with increased delays for non-spillback directions. However, when spillback occurred more often on the north side, the control allocated green time more often to the north side, but the queue duration on the west side also decreased. The west side is in a separate phase barrier, and due to a higher demand the west receives priority over the other direction in the same barrier, the east side, consequently, the phases of the west side are always the successive phase of the spillback direction (north). Furthermore, the performance of the intersection south of 3rd and 16th improved when spillback control strategies were applied. The intersection downstream of 3rd and 16th has a long approach link, which meant that the vehicle platoons approaching 3rd Mariposa often received a green wave, compared to when no spillback control strategy was applied. This could be due to an increase in vehicle platoons, or in the case of no green wave, the lanes in front of the intersection are immediately detected with spillback when the vehicles arrived (overflow of turning-bay). Consequently, this direction receives high priority, compared to the other directions at the intersection.

Regarding the overflow measured upstream of 3rd and 16th Street, a small spillback penalty does not provide the proper priority to handle the spilled-over vehicles. This is because of a short link where the overflow occurs on. Consequently, in the scenarios it could be seen that only a larger spillback penalty (X1000) or providing absolute priority did reduce the overflow duration.

When interpreting the results of combining a spillback control strategy with a movement priority for the arterial (corridor priority), the 'extra' priority did not lead the more benefits when only a spillback control strategy was applied, as the additional priority led to higher delays for disadvantaged directions and the reduce in spillback duration was not significantly different compared without the corridor-priority.

In terms of public transit, the impact of spillback control strategies on the delay of Light Rail vehicles depend on the weight of the spillback penalty: passenger cars entering the network at 3rd Channel (with spillback priority) can be given the right of way when the spillback penalty is high, compared to the LRV with a significant higher object priority. A high spillback penalty or the override strategy leads to higher LRV delays. The average delay for the LRV is still manageable, as the highest LRV delay for the scenarios without a bus is 3.1% with a high spillback penalty (X1000). However, mainly the delay occurred at the north side of the corridor, as this was the only conflicting direction, in most cases the LRV benefited (or no difference), because same way as arterial. The same

When the traffic flow was mixed with a bus, low additional delays and spillback durations are found, as the bus promotes the traffic flow of the North with the additional vehicle priority. This was paired with higher delays for disadvantaged directions. As the bus shares the same infrastructure as the vehicles, effects are not that different from scenarios with only cars. However, it should be noted, that when a bus travels over a conflicting directions, for example from east of 3rd 16th Street to the west of 3rd 16th Street, this lead to conflicting control objectives due to a comparable waiting cost.

Consequently, these situations leads to a larger intersection delay.

The results at the corridor showed that a penalty factor effectively decreased the spillback durations, with a minor increase in delay for the public transit. When the spillback penalty was minor (X10), the cost for disadvantaged directions was a small increase in average delay. However, it should be mentioned that this is the effect when other directions have a relatively low demand, compared to the spillback direction. When multiple directions have high demand, the benefit is lost. Furthermore, when the demand was factor 1 during Q2/Q3, the performance of the whole network increased, but in half demand (Q1 and Q4), in most cases, the performance decreased a bit. The results also showed that having a fixed penalty factor throughout varying demands, the penalty factor may not always be the right weight. For example, overflow occurring at a short link does not receive the proper priority when a minor spillback penalty is applied. However, a minor spillback factor to add additional priority to spillback, but no absolute priority should be given.

In the next chapter, the results of the research are concluded, and the research questions from this thesis are answered. Furthermore, the limitations surrounding this research are discussed.

8 Conclusions and recommendations

This chapter answers the questions posed at the beginning of the thesis. It was found that little research was done on spillback control in multimodal RTCS system and knowledge was lacking on the effects of spillback control in a RTCS with multimodal optimization. This research focuses on gaining insight on the effects of spillback control in multimodal RTCS so that gap is filled. Therefore, the first question (RQ1) was:

1. *How can an existing RTCS be extended with spillback detection and spillback control strategies in a multimodal context?*

To research the effects of the spillback control strategy, simulation study was constructed, with the central research question being as follows:

2. *What is the effect of controlling spillback in a multimodal RTCS at signalized intersections on the traffic and network performance?*

The main research questions were divided into multiple subquestions. The following sections conclude the outcome of the literature review and the design choices for the component, followed by a discussion. After that, the effects of the spillback control strategy on an isolated intersection and a corridor are concluded and discussed (RQ2).

8.1. Research question 1 – Literature research

Research question 1 was divided into four subquestions. Namely how spillback could be detected (RQ1.1), how spillback could be controlled (RQ1.2), and the identification of the architecture of RTCS with multimodal optimization (RQ1.3). After that, there was explored on how a spillback detection method and control strategy could be implemented in a multimodal RTCS. The findings are concluded in the next sections.

8.1.1. Input for spillback component design

Spillback detection

In the literature was found that the spillback detection method depended on the utilized traffic sensors. The most pragmatic approach was using video sensors that supervise whether spillback occurs at an inner junction, or lane blockage at a turning bay, which performs well in good weather conditions. When sensors were used that can count vehicle arrivals and speeds (e.g. loop detectors), spillback was detected in the form of a threshold. In these approaches, a queue method was used to estimate whether the capacity was exceeded. More specifically, shock wave theory was applied to estimate queue lengths in real-time.

Spillback control strategies

The research papers described mainly two approaches to control spillback. The first approach was a form of metering by limiting the inflow with a reduction in green time for critical phases at upstream intersections, the green time extension for the congested link, or a combination. The second approach controls spillback with an optimization algorithm to minimize an objective function that avoids or handles spillback queues. Possible criteria are minimizing the queue length, maximizing the throughput, minimizing the delay, or finding an overall optimal flow for all approaches.

Multimodal RTCS architecture

A real-time controlled traffic system with multimodal optimization optimizes multiple vehicle flows based on an objective criterion. Traffic sensors measure traffic input, such as vehicle position and speed, for multiple modes. The sensor input is processed and used for modelling. The modelling part of the RTCS consists of estimation and prediction of traffic variables. For the estimation or prediction of traffic variables, the delay is used to optimize for multiple road users, which can be either personal delay or vehicle delay. For passenger cars, the delay is often calculated according to a input-output method with a vertical queuing model, but also systems were identified that apply shockwave theory to estimate delays. The delay calculation can be combined with a user-specified priority list for vehicles or routes to generate waiting-costs per direction. This way, the decision-making goals of policy-makers can be translated into the priority weights of traffic modes. The resulting costs per directions are then used in the optimization by calculating the overall costs per direction for different signal plans. With the optimization, it is ensured that the overall waiting costs are minimized per intersection, by allocating green time to the direction with the highest waiting-costs.

It was found, that in these multimodal RTCS, little research was been done on the detection of spillback effects and providing priority when spillback effects occur. When spillback can be detected and controlled in a multimodal RTCS, unsafe situation are avoided or handled faster, so that less conflicts occur between different road users.

8.1.2. Design of spillback component

For the thesis, it was chosen to design a spillback detection method that works with loop detectors in real-time applying shockwave theory. In most countries loop detectors are already placed in the road, furthermore, they are cheaper than using sensors that are able to measure areas around the intersection. However, in the test framework it was chosen to retrieve the queue length from the simulation software, due to a lack of time by the implementation complexity and calibration. Nevertheless, the queue length, measures cycle-by-cycle, and can be compared against a lane threshold in terms of meters. The approach detects either lane-blocking, spillover, or both. Another advantages is that the resulting shockwave profiles can also be used in the delay calculation for traffic light control.

With spillback detected, one of two designed control strategies were applied. The first designed strategy was a spillback penalty factor. The penalty factor multiplies the resulting costs with a weight to provide additional priority to the spillback direction. The second control strategy is an override strategy which interrupts the optimization algorithm to a phase plan in which the spillback direction receives green, neglecting the current phase plan.

8.2. Research question 2 – Effects on traffic and network performance

The second research question was divided into two subquestions, namely the effect of spillback control strategies on the traffic and network performance of an isolated intersection. RQ2.2 investigated the effect of spillback control strategies on the traffic and network performance of a corridor.

8.2.1. Traffic and intersection performance isolated intersection

In experiments, spillback was enforced on one side of the intersection. In general, the overall intersection delay increases when a spillback control strategy is applied in the traffic light control optimization. Regarding the height of the spillback penalty, only when the demand for disadvantaged directions is low enough, a higher spillback priority increases intersection performance. For higher demands, the height of the spillback penalty has no little to no difference in intersection performance.

In terms of delay, provision of additional priority for spillback also caused unbalanced allocation of green time. This occurred when multiple non-conflicting directions can receive green besides the spillback direction, and one of the directions clearly has higher demand. Therefore, individual vehicle wait exceptionally long at directions with low-demand, such as a left turn. When a conflicting busline is included in the traffic flow and the demand is low, the best overall results in delay are found with a small spillback penalty. With a higher demand, better are results not found with the application of a spillback penalty, however, it still reduced the delay of the spillback direction.

In terms of spillback duration, when the demand is higher a small spillback penalty (X5) leads to the best results. An increased penalty did decrease the duration of the spillback direction, however, it does not compensate for the increase in duration of other directions. When a conflicting busline is included, a low spillback penalty with a low demand has the best results for the spillback direction. The durations are more distributed among other directions when the spillback penalty is increased. With an increased demand and a low spillback penalty, improvements are still found for spillback directions in combination with a decrease in spillback for the bus direction. With increased penalty factors, traffic control leans into an advantage for spillback directions with higher delays for the bus and non-spillback directions.

The override strategy showed promising results on spillback duration; even with approaches competing in demand, benefits were shown for both the east and the west side. This is caused by the abrupt method, and neglecting safety constraints and phase structure. The benefits were paired very high delays for disadvantaged directions.

8.2.2. Traffic and network performance corridor

In the corridor experiments, spillback was enforced on the north side of 3rd and 16th Street, halfway through the corridor. With a minor spillback penalty and a moderate vehicle flow, the overall network performance increases. Additionally, the network performance increased for all scenarios during the peak period. Except, when apart from spillback priority, also corridor priority was provided. Regarding the intersection performance, it can be said that the overall intersection delay decreases when the demand for conflicting directions is low, consequently, when the demand for conflicting directions is high, the gain in overall intersection performance is lost. Intersection performance is most often increased at the ends of the corridor. But also, the performance of the intersection downstream of intersection affected by spillback increased.

A spillback priority works well in combination with higher prioritized public transit, a penalty factor effectively decreases spillback durations and at the same time, minor increases in delay were found for the LRV. However, at one location in the corridor, passenger cars could get right-of-way with spillback priority over an LRV, for other directions the LRV travelled along the arterial. When also a bus was included in the traffic flow, lower delays and spillback durations were found for spillback directions. However, the effect was paired with higher delays for disadvantaged directions. Additionally, when buses are included in the spillback direction, spillback priority lead to practically absolute priority.

In terms of the height of the spillback penalty, a too-high priority negatively impacts the intersection and network performance. However, in some cases, a (high) spillback priority is necessary to provide enough priority so that a growing unsafe situation is avoided. Therefore, it is crucial to determine the intended use and the applicabilities of assigning spillback priority. The spillback priority promotes traffic and network performance when a short peak demand is expected. In more moderate to congested traffic situations, it is advised to look at whether the delay for disadvantaged directions is permitted. Furthermore, when an unsafe situation emerges, a very high spillback priority can be feasible, for example, when preemption is needed for an emergency vehicle and vehicles are spillt over at an intersection.

8.3. Discussion

The researched literature and methods configuration were paired with several limitations, furthermore, the conclusions deduced from the performed experiments do not fully replicate real-life behaviour and are also paired with limitations. These are described in the next sections.

8.3.1. Designed methods

The first limitation regards the utilized queuing model. The designed queuing model can accurately estimate queue length but the queue length is fully estimated after the cycle has been set and therefore is not predicted. Which influences the effectiveness of the spillback detection, as spillback is detected after it occurs. Consequently, the traffic control cleans up instead of avoiding the spillback effect. Additionally, the control method assigns additional priority when the queue length exceeds the lane capacity, but the delay road users experience is not into account in the allocation of green time. Regarding non-recurrent situations, the queue method does not take these situation into account, which can cause faulty traffic light control. For example, when a truck parks on the road for unloading cargo, the upstream traffic is blocked, and the allocated green time does not serve the intended use, but also the capacity of a lane decreases.

It is important to note that the 'best' spillback detection method (and control strategy) is dependent on the utilized traffic sensors. For example, when probe data or lane change behaviour is available in the otpimization of traffic light control, more accurate control could be applied as more information is available.

8.3.2. Measured effects

The results were obtained using a software-in-the-loop simulation. However, widely accepted for evaluating traffic simulations, it is paired with limitations due to the test configuration and the TFE algorithm. In this test configuration, the prediction component of TFE, a stochastic module in the system, makes identical predictions in every replication. The simulation outcomes varied more than ten percent in between with identical input, meaning ten runs were needed for a base case with a single departure profile for a meaningful average. Because of a long runtime, the random uncertainty, and the research goal of finding the effect of spillback control strategies, it was decided not to investigate multiple random seeds for the prediction variable in the TFE algorithm. Furthermore, the performed experiments assumed an exact and correct queue length retrieved from the simulation, consequently, the spillback detection method does not take into account sensor faults or misestimation of queue length. Regarding the single intersection network, an *early-walk*-setting causes asynchronous green time. When north and southbound traffic both receive green at the isolated intersection, there is a lag of two seconds between the north and the south. This reduced the performance of the south side of the single intersections. However, this effect did not occur in the corridor.

Regarding the optimization module of TFE, the algorithm is set to evaluate every two seconds. The computational complexity increases when the demand is raised or the minimum green times are reduced for intersections. When the optimization exceeds the computational capacity to evaluate enough tasks few effects can occur. First, the simulation stalls until it is actively terminated, second, the simulation stalls for a while and then the run continues, causing massive delays and considerable differences between simulation runs. Third, a warning is provided for a short period of a few seconds to a minute, it is unclear if this has a large impact on the traffic control and the simulation outcomes.

Regarding the simulation environment and configuration, the improved performance at ends of the corridor can also be due to the vehicles leaving the network endlessly. Consequently, the network performance could be overestimated as no spillbacks occur from directions that leave the corridor. Furthermore, pedestrians are included in the simulation with fixed routes without adequate behaviour. In a few simulation runs, pedestrians got stuck on the side of crossings without a clear explanation. The effect is that in a few runs, the pedestrians do not cross the road and wait for a very long period before crossing a red light when no car is nearby. Therefore, no useful effect could be deduced from pedestrian behaviour. The behaviour of the drivers and the environment itself is limited in simulation, therefore, the effects may be underestimated or overestimated compared to a real-life setup. For example, minor disruptions such as a depart delay at intersection due to driver distraction, or more major disruptions such as lane closure upstream of an intersection due to roadworks or an incident.

Finally, the measured effects have been tested in undersaturated to moderate conditions, and demand profiles with lower demands at sidestreets and a higher demand along the mainstreets. Furthermore, the effects were tested with one set of vehicle priorities, providing priority to public transit. The measured effects should be seen in this light and could be different when an alternative demand profile is used, such as a higher demand for side streets or when vehicle priorities are configured differently. Consequently, additional spillback priority could have an increased influence on the delay performance of the LRV if public transit is assigned less priority in the network.

8.4. Recommendations

Based on the findings and limitations of the study recommendations are done. First, recommendations are done for Technolution regarding policy implications and TFE model aspects, in which some are related to future research directions, also new research directions and topics are proposed.

8.4.1. Model and policy

Recommendations are done for existing components of MM-Flow, but also for additional components. First, regarding the spillback detection method used in this thesis, in which spillback effects are coped with after they have occurred, it is advised to explore spillback prediction methods that avoid spillback occurrence instead of solving the occurred spillback. One of the approaches is calculating the probability of a spillover event, which has been developed by Ramezani & Geroliminis (2015). Second, in this thesis it was chosen to detect spillback by a queuing method. The queuing method used in the experiments is not applicable in real life, and the current queue model used in MM-Flow is insufficient for estimating queue lengths. If it is chosen in the future to include a queue method in the optimization, it can be useful to look into a more sophisticated queue model so that queue lengths can be processed inside the TFE algorithm. Examples are the one suggested by H. Liu et al. (2009), which has been extended with a Kalman filter by Horvath M. & Tettamanti T. (2021). Another advantage is that the generated shockwave profiles can also be used for delay calculation (see Christofa et al. (2013)). When sensors are used that can detect lane areas, real-time queue length measurement could be looked into, in which Albiol et al. (2011) developed a pragmatic approach.

Regarding the spillback control strategy, the suggested height of the spillback priority depends on the situation and the intended use. A relative low weight not only promoted the traffic flow, but also increased the network performance on a corridor, however this effect is found with vehicle priorities that were configured so that the LRV received priority for the most part. Therefore, looking into the balance of assigning priority in the objective function is recommended. Furthermore, to look into assigning multiple weights of spillback priorities for different situations – for example, overflow on a short link needs a large spillback priority to control the spillover, and when a potential unsafe situation emerges benefits are also found when it is controlled as fast as possible. However, a high spillback priority at an ordinary intersection causes unnecessary long delays for disadvantaged directions. An alternative approach is to just promote the traffic flow by assigning additional priorities (movement-priority) for critical lanes instead of implementing a spillback penalty in the optimization. The current developed approach of the control strategy is to assign additional priority until the queue length is below a spillback detection queue threshold, therefore, it is advised to also look into controlling spillback effects based on the delays experienced by other cars. However, if the goal is to include the delays experienced by all types of traffic participants, the delays used in the optimization should be configured as personal delay instead of vehicle delay.

In terms of the optimization algorithm in the TFE, it is advised to look into optimization algorithms that search for a local optimum instead of evaluating all solutions so that TFE can handle more complexity, such as a more extensive network, a higher demand or additional computations. Furthermore, a test configuration without the ring and barrier structure could also be looked at so that the algorithm's performance can be tested with dynamic phasing, as the most pragmatic approach that neglects phase structure (override strategy) showed the highest reduction in spillback reduction.

Regarding the policy configuration of MM-Flow, it is recommended to gain insight into the effects of policy goals on the network and traffic performance. For example, the current set up showed the effects when the policy goal was to assign importance to public transport. But also other goals lead to other effects on the network performance, such as prioritizing vehicles based on their emissions

8.4.2. Future research

During the thesis, other subjects and research directions emerged. In terms of spillback detection it is advised to further research the identification of non-recurrent congestion and the corresponding effects occurring from that congestion, such as the change in link capacity and handling that congestion in terms of traffic signal control. Second, regarding the priority provided to a spillback direction, it is advised to look further into how spillback should be prioritized in different types of traffic situations in a multimodal context. Additionally, more insight could be gained in the combination of different priorities, such as configuration of the vehicle priority in combination with additional spillback priority. What is the effect when only spillback priority is applied on the traffic and network performance. In terms of spillback control strategies, it is advised to look into the current strategy and vary with the weights given to the spillback penalty, dependent on specific traffic situations. Furthermore, the effect of the spillback control strategy with varying demand profiles. Furthermore, it is advised to further research other strategies to control spillback in a multimodal RTCS and the effect of that strategy on the traffic and network performance. Such approaches could include an alternative objective function when spillback is detected, or including downstream and upstream metering in the solve method. In terms of analyzing the effects of controlling spillback effects, it is advised to include speed contourplots to gain more insight per individual situation when a spillback control strategy is applied.

In terms of policy, it is recommended to gain insight into the effects of different combinations of priorities (vehicle, movement, and spillback) created to fulfill different policy goals, and the effects of these policy goals on the traffic and network performance. Altogether, when the policy goal is to reduce traffic fatalities to zero by 2024, it should come as no surprise that controlling an emerging unsafe situation as spillover at an upstream intersection should be highly prioritized in the traffic signal control.

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A

Literature review tables

Table A.1: Overview of considered papers

Reference	Citations	Search method
Mein et al. (2022)	0	MobiMaestro-Flow paper
Van Katwijk (2008)	74	Backward snowballing Mein et al. (2022)
He et al. (2014)	257	Backward snowballing Mein et al. (2022)
Yagar & Han (1994)	104	Backward snowballing from He et al. (2014)
Zeng et al. (2019)	25	Backward snowballing from He et al. (2014)
Christofa et al. (2016)	103	Forward snowballing from He et al. (2014)
Christofa (2012)	7	Backward snowballing from Christofa et al. (2016)
A. Stevanovic et al. (2015)	2	Forward snowballing Christofa (2012)
J. Stevanovic (2011)	32	Backward snowballing A. Stevanovic et al. (2015)
Noaeen et al. (2021)	3	Query
Tilg et al. (2021)	4	Query
Jovanović et al. (2021)	7	Query, out of scope
S. Liu et al. (2020)	5	Query, out of scope
Auld et al. (2016)	186	Query, out of scope
Wong & Lee (2020)	1	Query
H. Zhang et al. (2020)	28	Query
Mohajerpoor & Cai (2020)	0	Query
Ramezani et al. (2016)	18	Query
Ramezani & Geroliminis (2015)	133	Backward snowballing Ramezani et al. (2016)
Cao et al. (2019)	6	Query
H. Liu et al. (2009)	468	Backward snowballing from Cao et al. (2019)
Sharma et al. (2007)	232	Backward snowballing from H. Liu et al. (2009)
X. Wu et al. (2010)	157	Forward snowballing from H. Liu et al. (2009)
Amini et al. (2016)	26	Forward snowballing from H. Liu et al. (2009)
Ren et al. (2017)	56	Forward snowballing from X. Wu et al. (2010)
Zheng et al. (2017)	32	Query
Flötteröd & Osorio (2017)	19	Query, out of scope
Di Gangi et al. (2016)	44	Query, out of scope
Han & Gayah (2015)	41	Query
Chen & Chang (2014)	19	Query
Yang et al. (2014)	1	Query
Ramezani & Geroliminis (2015)	16	Query
Christofa et al. (2013)	67	Query
Y. Liu & Chang (2011)	184	Query
Y. Zhang & Tong (2008)	61	Query
Xie et al. (2014)	10	Google Scholar (untraced)
Bhouri et al. (2015)	17	Google Scholar (untraced)

Table A.2: Overview of researched paper literature

Reference	Road users	Priority	Objective funct	Signal control	detectors	Spillback detection: Queue model	Spillback detection: Type	Spillback detection: method	SB Control	Contribution
Y. Zhang & Tong (2008)	PC	-	-	FT	S	S	LB	LC	None	Left-turn SB detection
X. Wu et al. (2010)	PC	-	-	FT	US	SWT	SO	OSI	None	Oversaturation severity index
Y. Liu & Chang (2011)	PC	-	MinTTS,MaxTP	AC	S	S	SO,LB	LC	OF	Lane-change interaction among lanes at intersections with CV
Chen & Chang (2014)	PC,B,T	-	MinTT,MaxTP	AC	S	S	SO,LB	LC	OF	Optimization with mixed vehicle flows
Christofa et al. (2013)	PC	-	-	FT	CV	SWT,Gap-based	SO,(LB)	QT	M-US	SB detection control strategies with CV
Han & Gayah (2015)	PC	-	MaxTP,MinD	FT	S	SWT	SO,LB	LC	OF	handling of SB using continuum model
Ramezani et al. (2014)	PC	-	-	Act	CV	SWT	SO	Prob(SO)	None	Queue estimation with CV without known signal settins
Ramezani et al. (2016)	PC	-	D	AC	S	S	SO, (LB)	LC	M-US,DS	Proactive SC for SB, integrated with potential SB risks
Wong & Lee (2020)	PC	-	CF	AC	S	CTM	SO	QT	OF	Optimization of SC including red green duration, cycle times and lane markings
Noaeen et al. (2021)	PC	-		AC	US	SWT	SO	QT	OF	Dynamic SC with SB
Mohajerpoor & Cai (2020)	PC	-	-	AC	S	SWT	SO,LB	QT	M-US	SB SC short links
H. Zhang et al. (2020)	PC	-	MinQL	FT	CV	SWT	SO	QT	OF	QE, SB with (very) low penetration rates
Ren et al. (2017)	PC	-	-	AC	US,SB	SWT	SO	SD	M-US,DS,SS	SB detection with veh speed
Cao et al. (2019)	PC	-	-	FT	CV	CV	LB	Prob(LB)	M-US,DS	Left-turn SB probability with CV
Yagar & Han (1994)	PC,B	BP	VD	AC	US,SB	VQM	-	-	-	Traffic-responsive SC with TSP
Xie et al. (2014)	PC,B,P	-	-	AC	MV	VQM	SO	LC	M-DS	SB in multimodal RTCS (patented)
Zeng et al. (2019)	PC,B	BP	PD	AC	CV	SWT	-	-	-	More accurate PD using CV
Bhouri et al. (2015)	PC,B	W	VD	FT	S	VQM	-	-	-	Review paper
Christofa et al. (2016)	B, PC, (LRV,P,C,T)	(W)	PD	AC	US	SWT	-	-	-	Multimodal RTCS along arterial
A. Stevanovic et al. (2015)	LRV,B,PC,P	LRVP	PD,VD,PDVD	Set	US/SB	S	-	-	-	Comparison of SC optimization
He et al. (2014)	PC, B,P, (BC,T)	W	VD	Set	SB	VQM	-	-	-	(Virtual) priority requests for mulitmodal RTCS
Mein et al. (2022)	PC,LRV,T,P,(BC,B)	W	VD	Set	MV	VQM	-	-	-	
Proposed model	PC, LRV, T, P(BC,P)	W	VD	Set	MV	SWT	LB, (SO)	QT	Penalty	Spillback in multimodal RTCS

Legend. (brackets): Mentioned as possible extension of the model. Max: Maximize. Min: Minimize
Road users: PC (Passenger cars), B (Bus), T (Truck), LRV (Light-rail vehicle), BC (Bicycle), P (Pedestrian). Priority: BP (Bus priority), W (Weighted), LRVP (LRV priority).
Objective: TT (Travel time), TP (Throughput), D (Delay), QL (Queue length), CF (Common Flow), VD (Vehicle delay), PD (Personal delay).
Signal Control: FT (Fixed timing), Set (AC with signal plans predefined with genetic algorithm), AC (Adaptive control)
Detector placement: S (Measured from simulation software), US (upstream), CV (Connected vehicles), SB (Stopbar), MV (Machine vision)
Queue model: S (Measured from simulation software), SWT (Shock wave theory), I/O (Input/output method), CTM (Cell transmission model), CV (Connected vehicles), VQM (Vertical queuing model)
SB type: LB (lane-blocking), SO (Spillover). Detection: LC (Link capacity), OSI (Oversaturation Severity Index), QT (Queue Threshold), Prob() (Probability of spillback type), SD (Speed detection).
SB control: OF (Objective function), PinOF (Penalty in objective function), M- (Metering from US and/or DS direction), US (Upstream), DS (Downstream), SS (Sidestreet)

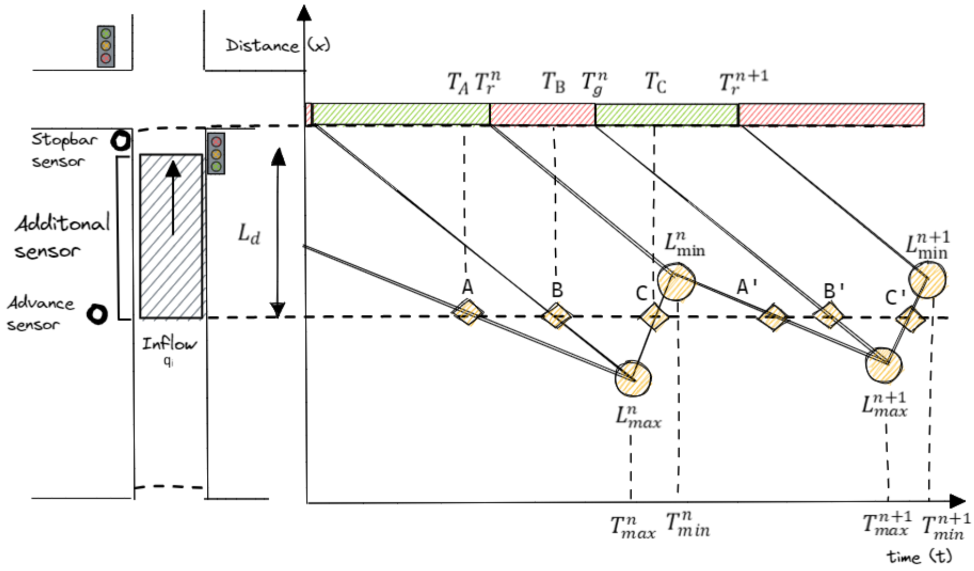

Figure A.1: Residual queue shockwave profile

A.1. Queue length estimation

When the traffic light control allocates insufficient green time, or when the traffic conditions are oversaturated, a residual queue L^n_{min} could form at time instant T^n_{min}. Using shockwave speed ω_4 and the queue discharging process between T^n_{max} and T^n_{min}, defined by ω_2, this can be estimated. The maximum queue length and the time instant it occurs is already estimated (see chapter 4).

$$L^n_{min} = \left(\frac{L^n_{max}}{\omega_2} + T^n_{max} - T^{n+1}_r\right) / \left(\frac{1}{\omega_2} + \frac{1}{\omega_4}\right) \tag{A.1}$$

$$T^n_{\text{min}} = T^{n+1}_t + L^n_{min}/\omega_4 \tag{A.2}$$

The last queue state is derivable from the maximum queue length, the time it occurs, and the time instant T_A. ω_3 can be estimated, assuming a constant shockwave speed, by:

$$\omega_3 = (L^n_{max} - L_d)/(T^n_{max} - T_A) \tag{A.3}$$

A.1.1. Estimation of shockwave variables

For the estimation of ω_1, the current inflow q_i and current density k_i should be known, which is possible by traffic state estimation of the upstream detector, as the vehicles pass the sensor with the state q_i and k_i. For ω_3, only the jam density should be configured; after that, it is possible to estimate ω_3, with **??**. The advance detectors deliver data to estimate ω_2 and ω_4. This way, ω_4 is calculated using the distance between the stopbar and the advance sensor: L_d, and the time difference between the green time start T^n_g and discharge wave reaching advance sensor: T_s. Another option would be with an assumed saturation flow q_max, jam density k_j, and critical density k_c.

$$\omega_4 = L_d/(T_s - T^n_g) \tag{A.4}$$

Shock wave speed ω_2 is estimated by identifying the states maximum flow q_{max}, critical density k_m, and the current inflow q_i and current density k_i. However, to estimate ω_2, event-based data should be available to record the detector occupancy time. The detector occupancy time $t_{o,i}$, and the sum of the vehicle length plus the detector length l_e are used to estimate individual vehicle speed u_i (Equation A.5). Then, with the number of vehicles n known, the sum of the individual vehicle speed u_i, divided by the number of vehicles, calculates the space mean speed u_{space}, according to Equation A.6.

These conditions can be estimated using the equations Equation A.5 to Equation A.8 to calculate shockwave ω_2.

Now, the sum of headways h_i of the vehicles estimates the average flow. The sum of the detector time occupancy o of vehicle i: $t_{o,i}$ and the time gap g of vehicle i with its predecessor: $t_{o,i}$, divided by the number of cars (Equation A.7) calculates the headway per vehicle. Lastly, the average density is calculated using the relationship between the density, flow, and speed ($q = ku$), as shown in Equation A.8.

$$u_i = l_e/t_{o,i} \tag{A.5}$$

$$u_{space} = 1/(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{u_i}) \tag{A.6}$$

$$q = 1/(\frac{1}{n}\sum_{i=1}^{n}(h_i)) \tag{A.7}$$

$$k = q/u_{space} \tag{A.8}$$

A.1.2. Estimation points A, B, and C

Point A, indicated by T_A, is the time instant that queue shockwave ω_3 propagates backwards to the location of the advance detector. Between the beginning of red in cycle n and T_A, the vehicles travel over the loop detector with the traffic state (q_i, k_i). After passing the loop detector, between T_A and T^n_{max}, no flow is possible due to the jam density: $(0, k_j)$. Point A identifies whether there is a long queue; when point A does not exist, the queue does not propagate further than the advance detector or outside the lane area detector range. A detector occupancy threshold is used to detect point A, or in the case of a lane area detector, the sensor range that still provides an accurate queue length.

B is the time instant T_b in which the queue discharge shockwave passed the advance detector with a shockwave speed of ω_4. The traffic state is also a jammed state of $(0, k_j)$ between the green start T^n_g and the time instant T_b. The vehicles discharge according to the maximum flow assumption of (q_{max}, k_c). Because the traffic density is 0 after T^n_g and in advance of T_b, the time occupancy of the detector is high. After that, the queue discharge over the detector or inside the lane area range, and the occupancy time and the time gap between vehicles drop significantly. It is advisable to use sensor data to estimate the (q_{max}, k_c), as the saturation flow could decrease due to busy downstream intersections.

T_C is the time instant in which the tail of the queue travels over the detector. Point C estimates the maximum queue length, combined with the queue discharge shock wave ω_4 to describe the queuing process. ω_2 is the shockwave between the arrival flow state (q_i, k_i) and (q_{max}, k_c) and describes the vehicle discharge in which occurs between T^n_{max} and T_C. After the wave propagates to point C, the traffic state changes to (q_i, k_i), which means that the discharge rate at the advance detector location is less than the maximum flow. The time gap between two successive vehicles is sensitive to the change in traffic state: before T_C, the time gap is smaller than 2.5 seconds with a small variance. After that, the gaps increase in combination with the variance. In addition, a time lag usually occurs between the queue discharge flow and newly arrived traffic (H. Liu et al., 2009). Based on their observations, when the time gap exceeds 2.5 seconds, the queue's end propagates forward, the detector line is reached, and T_C is identified. For verification, the system could check for multiple occasions where the time gap exceeds 2.5 seconds.

B

Network configuration measurements

B.1. Isolated intersection

B.1.1. Network dimensions

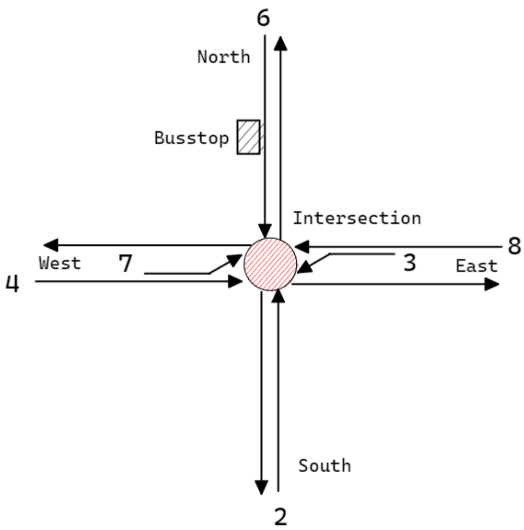

Figure B.1: Network model

Table B.1: Table with network specifications

		Node		
Edge	**Length [m]**	**From**	**To**	**Lanes**
north	200.03	source	intersection	1
south	200.03	source	intersection	1
west	170.06	source	west-front	1
west-front	80.13	west	intersection	2
east	170.06	source	east-front	1
east-front	80.13	east	intersection	2
-north	200.03	main-intersection	sink south	1
-south	200.03	main-intersection	sink north	1
-west	250.01	main-intersection	sink east	1
-east	250.01	main-intersection	sink west	1

B.1.2. Traffic light control specification

Table B.2: Phase durations isolated intersection

Phase	Min green [s]	Max green [s]
2	8	24
3	6	12
4	8	24
6	8	24
7	6	12
8	8	24

B.2. Corridor

B.2.1. Network dimensions

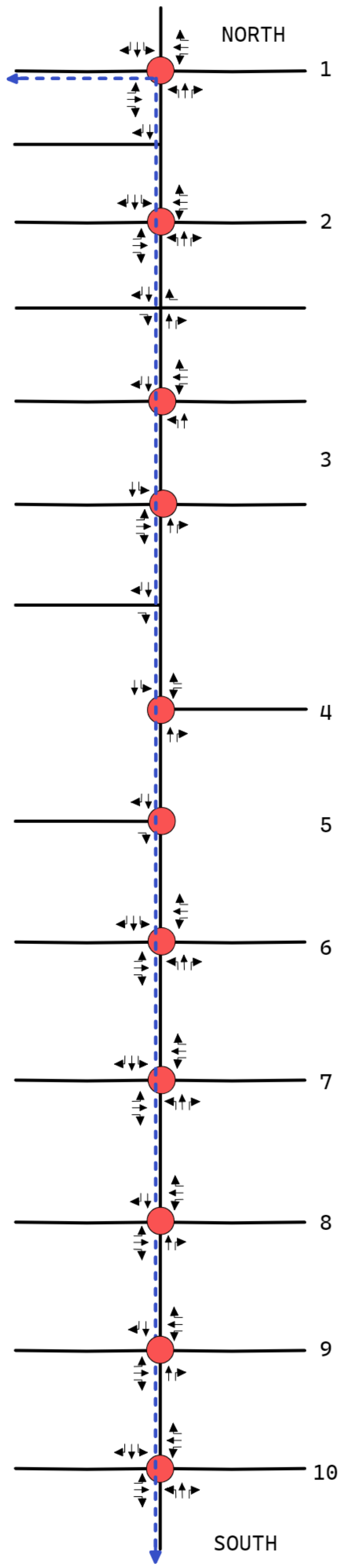

Figure B.2: Corridor network

Table B.3: Overview of edge measurements between intersection nodes

Intersection	Incoming	Length [m]	Lanes	Outgoing	Length [m]	Lanes
	3rd_missionrock.3rd_channel	101.74	2	3rd_channel.North	126.16	2
	3rd_missionrock.3rd_channel_TB	55.62	3	3rd_channel.East	156	2
1. 3rd Channel	North.3rd_channel	93.27	2	3rd_channel.West	143.73	2
	North.3rd_channel_TB	34	3			
	West.3rd_channel	143.56	2			
	East.3rd_channel	156.01	1			
3rd Longbridge	West.3rd_longbridge	133.53	1	3rd_longbridge.West	133.53	1
	3rd_channel.3rd_missionrock_1	71.42	2	3rd_missionrock.East	193.54	1
	3rd_channel.3rd_missionrock_2	27.16	2	3rd_missionrock.West	134.25	1
	3rd_channel.3rd_missionrock_TB	44.55	3	3rd_missionrock.3rd_channel	101.74	2
2. 3rd Mission Rock	West.3rd_missionrock	134.25	1			
	East.3rd_missionrock	193.54	2			
	3rd_missionbaynorth.3rd_missionrock	52.44	2			
	3rd_missionbaynorth.3rd_missionrock_TB	35.18	3	3rd_missionrock.3rd_missionbaynorth.1	86.96	2
	3rd_missionrock.3rd_missionbaynorth.1	86.96	2	3rd_missionrock.3rd_missionbaynorth.2	64.55	2
3rd Chinabasin	West.3rd_chinabasin	136.91	1	3rd_chinabasin.East	133.75	1
	East.3rd_chinabasin	133.75	1	3rd_chinabasin.West	136.91	1
	3rd_missionbaynorth.3rd_missionrock.1	86.64	2	3rd_missionbaynorth.3rd_missionrock.2	52.44	2
	3rd_missionrock.3rd_missionbaynorth.2	64.55	2	3rd_missionbaynorth.3rd_missionrock	86.64	2
3. Mission Bay (north)				3rd_missionbaynorth.3rd_missionrock.1	86.64	2
	3rd_missionrock.3rd_missionbaynorth_TB	23.09	3	3rd_missionbaynorth.West	90.31	1
	East.3rd_missionbaynorth	124.26	2	3rd_missionbaynorth.3rd_missionbaysouth	34.96	3
	3rd_missionbaynorth.3rd_missionbaysouth	34.96	3	3rd_missionbaysouth.3rd_missionbaynorth	34.77	3
	West.3rd_missionbaysouth	96.89	1	3rd_missionbaysouth.3rd_warriorsway.1	89.03	2
3. Mission Bay (south)	West.3rd_missionbaysouth_TB	38.1	2	3rd_missionbaysouth.East	124.26	1
	3rd_warriorsway.3rd_missionbaysouth	163.51	2			
	3rd_warriorsway.3rd_missionbaysouth_TB	22.58	3			
3rd Nelson Rising	3rd_missionbaysouth.3rd_warriorsway.1	89.03	2	3rd_nelsonrising.West	133.38	1
	West.3rd_nelsonrising	133.38	1	3rd_missionbaysouth.3rd_warriorsway	52.39	2
	3rd_missionbaysouth.3rd_warriorsway	52.39	2	3rd_warriorsway.3rd_missionbaysouth	163.51	2
	3rd_missionbaysouth.3rd_warriorsway_TB	30.09	3	3rd_warriorsway.East_TB	58.59	2
4. 3rd Warriors Way	East.3rd_warriorsway	69.39	2	3rd_warriorsway.East	77.78	1
	East.3rd_warriorsway_TB	67	3			
	3rd_campus.3rd_warriorsway	95.96	2	3rd_warriorsway.3rd_campus	87.19	2
	3rd_warriorsway.3rd_campus	87.19	2	3rd_campus.3rd_16th	47.31	2
5. 3rd Campus	West.3rd_campus	82.86	1			
	West.3rd_campus_TB	52.77	2			
	3rd_campus.3rd_16th	47.31	2	3rd_16th.3rd_campus	92.85	2
	3rd_campus.3rd_16th_TB	35.03	3	3rd_16th.West	80.9	2
	3rd_mariposa.3rd_16th	184.88	2	3rd_16th.East	65.28	2
6. 3rd 16th Street	3rd_mariposa.3rd_16th_TB1	42.28	3			
	3rd_mariposa.3rd_16th_TB2	37.24	4			
	West.3rd_16th	80.95	3			
	East.3rd_16th	65.28	3	3rd_16th.3rd_mariposa	218.41	2
	3rd_16th.3rd_mariposa	218.41	2	3rd_mariposa.3rd_16th	184.88	2
	3rd_16th.3rd_mariposa_TB	45.66	3	3rd_mariposa.West_TB	56.62	2
	3rd_18th.3rd_mariposa	81.51	2	3rd_mariposa.West	47.75	3
7. 3rd Mariposa	3rd_18th.3rd_mariposa_TB	39.9	3	3rd_mariposa.East	65.95	1
	East.3rd_mariposa	65.97	3			
	West.3rd_mariposa	42.23	2			
	West.3rd_mariposa_TB	65.23	3	3rd_mariposa.3rd_18th	120.58	2
	3rd_mariposa.3rd_18th	120.58	2	3rd_18th.3rd_mariposa	81.51	2
8. 3rd 18th Street	3rd_19th.3rd_18th	127.21	2	3rd_18th.West	68.14	1
	West.3rd_18th	62.06	1	3rd_18th.East	62.06	1
	East.3rd_18th	68.14	1	3rd_18th.3rd_19th	127.06	2
	3rd_18th.3rd_19th	127.06	2	3rd_19th.3rd_18th	127.21	2
9. 3rd 19th Street	3rd_20th.3rd_19th	125.71	2	3rd_19th.East	74.84	1
	West.3rd_19th	65.87	1	3rd_19th.West	65.87	1
	East.3rd_19th	74.84	1	3rd_19th.3rd_20th	64.37	2
	3rd_19th.3rd_20th	64.37	2	3rd_20th.3rd_19th	125.71	2
	3rd_19th.3rd_20th_TB	61.78	3	3rd_20th.South	118.13	2
10. 3rd 20th Street	South.3rd_20th	59.66	2	3rd_20th.West	65.29	1
	South.3rd_20th_TB	58.42	3	3rd_20th.East	71.56	1
	West.3rd_20th	65.29	1			
	East.3rd_20th	71.59	1			

B.2.2. Traffic light control specification

Table B.4: Traffic light time configuration (part 1)

	Phase							
# Intersection name	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min Green	The minimum green time [s] given to this phase							
Extended green	The extended green time [s] given to this phase							
Max green	The maximum green time [s] given to this phase							
Yellow	Four seconds for all phases							
Red Clearance	The minimum red time for this phase [s] given							
Walk	Green time for pedestrians							
Pedestrian clearance	The clearance red time for pedestrians							
Barrier groups:	[Barrier 1: [RING 1],[RING 2]], [Barrier 2: [RING 1],[RING 2]]							
1. 3rd Channel	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min Green	5	13		15	5	18		15
Extended green	2	0		3	2	0		3
Max green	15	30		20	15	30		20
Red Clearance	2	2		4	2	2		4
Walk	0	4		6	0	5		8
Pedestrian clearance	0	13		23	0	18		21
Barrier groups:		[[2,1],[5,6]], [[4],[8]]						
2. 3rd Mission Rock	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min Green	5	10		21	5	10		21
Extended green	2	0		0	2	0		0
Max green	14	30		20	15	30		20
Red Clearance	1.5	1		2.5	1	1.5		2.5
Walk	0	7		4	0	7		4
Pedestrian clearance	0	10		25	0	10		25
Barrier groups:		[[2,1],[5,6]], [[4],[8]]						
3. Mission Bay (N+S)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min Green	5	6	6	24	5	6		
Extended green	3	0	0	3	3	0		
Max green	15	30	45	30	15	30		
Red Clearance	1.5	3.5	3.5	2.5	3.5	1		
Walk	0	7	0	4	0	7		
Pedestrian clearance	0	6	0	24	0	6		
Barrier groups:		[[1,2],[6,5],[3]], [[4],[],[]]						
4. 3rd Warriors Way	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min Green	5	11		16		11		16
Extended green	3	0		0		0		3
Max green	15	30		30		30		30
Red Clearance	4	4		4		4		4
Walk	2	1		2		1		2
Pedestrian clearance	0	11		23		0		23
Barrier groups:		[[1,2],[6]], [[4],[8]]						
5. 3rd Campus	**1**	**2**	**3**	**4**	**5**	**6**	**10**	**12**
Min Green		10		5		10	8	8
Extended green		0		3		0	0	0
Max green		30		20		30	0	0
Red Clearance		5		5		1.5	0	0
Walk		0		0		4	7	7
Pedestrian clearance		0		0		10	30	30
Barrier groups:		[[2],[6,4]], [[10],[12]]						
6. 3rd 16th Street	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min Green	5	10	5	19	5	10	5	19
Extended green	3	0	3	3	3	0	3	3
Max green	10	30	10	30	20	30	10	30
Red Clearance	2.5	2	2.5	2.5	2.5	2	2	2.5
Walk	0	7	0	4	0	7	0	4
Pedestrian clearance	0	21	0	25	0	22	0	26
Barrier groups:		[[1,2],[6,5]], [[4,3],[7,8]]						

Table B.5: Traffic light time configuration (part 2)

7. 3rd Mariposa	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min Green	4	15	5	22	6	18	5	28
Extended green	2	0	3	0	2	0	3	0
Max green	8	30	6	30	10	30	6	30
Red Clearance	2	2.5	2.5	2.5	2.5	1.5	2.5	2.5
Walk	0	4	0	5	0	5	0	4
Pedestrian clearance	0	15	0	22	0	18	0	28
Barrier groups:			[[1,2],[6,5]], [[4,3],[7,8]]					
8. 3rd 18th Street	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min Green	0	10		15		10		15
Extended green	0	0		3		0		3
Max green	0	34		15		34		15
Red Clearance	0	1		2		1		2
Walk	0	6		6		6		6
Pedestrian clearance	0	10		21		10		21
Barrier groups:			[[[2],[6]], [[4],[8]]]					
9. 3rd 19th Street	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min Green	0	10		10		10		10
Extended green	0	0		3		0		3
Max green	0	34		15		34		15
Red Clearance	0	1		2		1		2
Walk	0	7		6		7		6
Pedestrian clearance	0	10		21		10		21
Barrier groups:			[[2],[6]], [[4],[8]]					
10. 3rd 20th Street	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min Green	5	10		18	5	10		18
Extended green	2	0		0	2	0		0
Max green	14	30		24	14	34		24
Red Clearance	2	1.5		2	2	2		2
Walk	0	7		6	0	7		6
Pedestrian clearance	0	10		22	0	10		22
Barrier groups:			[[[2,1],[5,6]],[[4],[8]]]					

B.2.3. Turning fractions

Table B.6: Turning fractions corridor

From edge:	To edge:	Probability [%]
3rd_16th.3rd_mariposa.2	3rd_mariposa.3rd_18th.1	85
3rd_16th.3rd_mariposa.2	3rd_mariposa.East	5
3rd_16th.3rd_mariposa.2	3rd_mariposa.West.1	10
3rd_18th.3rd_19th.1	3rd_19th.3rd_20th.1	90
3rd_18th.3rd_19th.1	3rd_19th.West	10
3rd_18th.3rd_mariposa.2	3rd_mariposa.3rd_16th.1	75
3rd_18th.3rd_mariposa.2	3rd_mariposa.East	5
3rd_18th.3rd_mariposa.2	3rd_mariposa.West.1	20
3rd_19th.3rd_18th.1	3rd_18th.3rd_mariposa.1	85
3rd_19th.3rd_18th.1	3rd_18th.East	5
3rd_19th.3rd_20th.2	3rd_20th.East	5
3rd_19th.3rd_20th.2	3rd_20th.South.1	85
3rd_19th.3rd_20th.2	3rd_20th.West	10
3rd_20th.3rd_19th.1	3rd_19th.3rd_18th.1	90
3rd_20th.3rd_19th.1	3rd_19th.East	10
3rd_campus.3rd_16th.3	3rd_16th.3rd_mariposa.1	85
3rd_campus.3rd_16th.3	3rd_16th.East	5
3rd_campus.3rd_16th.3	3rd_16th.West	10

3rd_campus.3rd_warriorsway.1	3rd_warriorsway.3rd_missionbaysouth.1	90
3rd_campus.3rd_warriorsway.1	3rd_warriorsway.East.1	10
3rd_channel.3rd_missionrock.1	3rd_channel.3rd_missionrock.2	90
3rd_channel.3rd_missionrock.1	3rd_longbridge.West	10
3rd_channel.3rd_missionrock.3	3rd_missionrock.3rd_missionbaynorth.1	85
3rd_channel.3rd_missionrock.3	3rd_missionrock.East	10
3rd_channel.3rd_missionrock.3	3rd_missionrock.West	5
3rd_mariposa.3rd_16th.3	3rd_16th.3rd_campus.1	75
3rd_mariposa.3rd_16th.3	3rd_16th.East	5
3rd_mariposa.3rd_16th.3	3rd_16th.West	20
3rd_mariposa.3rd_18th.1	3rd_18th.3rd_19th.1	95
3rd_mariposa.3rd_18th.1	3rd_18th.West	5
3rd_missionbaynorth.3rd_missionbaysouth.1	3rd_missionbaysouth.3rd_warriorsway.1	90
3rd_missionbaynorth.3rd_missionbaysouth.1	3rd_missionbaysouth.East	10
3rd_missionbaynorth.3rd_missionrock.1	3rd_chinabasin.East	5
3rd_missionbaynorth.3rd_missionrock.1	3rd_missionbaynorth.3rd_missionrock.2	95
3rd_missionbaynorth.3rd_missionrock.3	3rd_missionrock.3rd_channel.1	85
3rd_missionbaynorth.3rd_missionrock.3	3rd_missionrock.East	10
3rd_missionbaynorth.3rd_missionrock.3	3rd_missionrock.West	5
3rd_missionbaysouth.3rd_missionbaynorth.1	3rd_missionbaynorth.3rd_missionrock.1	90
3rd_missionbaysouth.3rd_missionbaynorth.1	3rd_missionbaynorth.West	10
3rd_missionbaysouth.3rd_warriorsway.1	3rd_missionbaysouth.3rd_warriorsway.2	90
3rd_missionbaysouth.3rd_warriorsway.1	3rd_nelsonrising.West	10
3rd_missionbaysouth.3rd_warriorsway.3	3rd_warriorsway.3rd_campus.1	90
3rd_missionbaysouth.3rd_warriorsway.3	3rd_warriorsway.East.1	10
3rd_missionrock.3rd_channel.2	3rd_channel.East	5
3rd_missionrock.3rd_channel.2	3rd_channel.North.1	85
3rd_missionrock.3rd_channel.2	3rd_channel.West	10
3rd_missionrock.3rd_missionbaynorth.3	3rd_missionbaynorth.3rd_missionbaysouth.1	90
3rd_missionrock.3rd_missionbaynorth.3	3rd_missionbaynorth.West	10
3rd_missionrock.3rd_missionbaynorth.4	3rd_chinabasin.West	10
3rd_missionrock.3rd_missionbaynorth.4	3rd_missionrock.3rd_missionbaynorth.2	90
3rd_warriorsway.3rd_campus.1	3rd_campus.3rd_16th.1	90
3rd_warriorsway.3rd_campus.1	3rd_campus.West.1	10
3rd_warriorsway.3rd_missionbaysouth.2	3rd_missionbaysouth.3rd_missionbaynorth.1	90
3rd_warriorsway.3rd_missionbaysouth.2	3rd_missionbaysouth.East	10
East.3rd_16th	3rd_16th.3rd_campus.1	25
East.3rd_16th	3rd_16th.3rd_mariposa.1	25
East.3rd_16th	3rd_16th.West	50
East.3rd_18th	3rd_18th.3rd_19th.1	33.33333333
East.3rd_18th	3rd_18th.3rd_mariposa.1	33.33333333
East.3rd_18th	3rd_18th.West	33.33333333
East.3rd_19th	3rd_19th.3rd_18th.1	33.33333333
East.3rd_19th	3rd_19th.3rd_20th.1	33.33333333
East.3rd_19th	3rd_19th.West	33.33333333
East.3rd_20th	3rd_20th.3rd_19th.1	33.33333333
East.3rd_20th	3rd_20th.South.1	33.33333333
East.3rd_20th	3rd_20th.West	33.33333333
East.3rd_channel	3rd_channel.3rd_missionrock.1	33
East.3rd_channel	3rd_channel.North.1	32
East.3rd_channel	3rd_channel.West	35
East.3rd_mariposa	3rd_mariposa.3rd_16th.1	25
East.3rd_mariposa	3rd_mariposa.3rd_18th.1	25
East.3rd_mariposa	3rd_mariposa.West.1	50
East.3rd_missionbaynorth	3rd_missionbaynorth.3rd_missionbaysouth.1	25
East.3rd_missionbaynorth	3rd_missionbaynorth.3rd_missionrock.1	50

East.3rd_missionbaynorth	3rd_missionbaynorth.West	25
East.3rd_missionrock	3rd_missionrock.3rd_channel.1	32
East.3rd_missionrock	3rd_missionrock.3rd_missionbaynorth.1	33
East.3rd_missionrock	3rd_missionrock.West	35
East.3rd_warriorsway.2	3rd_warriorsway.3rd_campus.1	50
East.3rd_warriorsway.2	3rd_warriorsway.3rd_missionbaysouth.1	50
North.3rd_channel.3	3rd_channel.3rd_missionrock.1	85
North.3rd_channel.3	3rd_channel.East	10
North.3rd_channel.3	3rd_channel.West	5
South.3rd_20th.2	3rd_20th.3rd_19th.1	80
South.3rd_20th.2	3rd_20th.East	10
South.3rd_20th.2	3rd_20th.West	10
West.3rd_16th	3rd_16th.3rd_campus.1	30
West.3rd_16th	3rd_16th.3rd_mariposa.1	40
West.3rd_16th	3rd_16th.East	30
West.3rd_18th	3rd_18th.3rd_19th.1	33.33333333
West.3rd_18th	3rd_18th.3rd_mariposa.1	33.33333333
West.3rd_18th	3rd_18th.East	33.33333333
West.3rd_19th	3rd_19th.3rd_18th.1	33.33333333
West.3rd_19th	3rd_19th.3rd_20th.1	33.33333333
West.3rd_19th	3rd_19th.East	33.33333333
West.3rd_20th	3rd_20th.3rd_19th.1	33.33333333
West.3rd_20th	3rd_20th.East	33.33333333
West.3rd_20th	3rd_20th.South.1	33.33333333
West.3rd_channel	3rd_channel.3rd_missionrock.1	32
West.3rd_channel	3rd_channel.East	35
West.3rd_channel	3rd_channel.North.1	33
West.3rd_mariposa.2	3rd_mariposa.3rd_16th.1	28
West.3rd_mariposa.2	3rd_mariposa.3rd_18th.1	36
West.3rd_mariposa.2	3rd_mariposa.East	36
West.3rd_missionbaysouth.2	3rd_missionbaysouth.3rd_missionbaynorth.1	25
West.3rd_missionbaysouth.2	3rd_missionbaysouth.3rd_warriorsway.1	50
West.3rd_missionbaysouth.2	3rd_missionbaysouth.East	25
West.3rd_missionrock	3rd_missionrock.3rd_channel.1	33
West.3rd_missionrock	3rd_missionrock.3rd_missionbaynorth.1	32
West.3rd_missionrock	3rd_missionrock.East	35

B.2.4. Demand profile

Table B.7: Resulting demand profile

Mode	Flow [veh/hour]	From edge
Car	360	North.3rd_channel.1
Car	20	East.3rd_channel
Car	60	East.3rd_missionrock
Car	20	East.3rd_chinabasin
Car	77	East.3rd_missionbaynorth
Car	20	East.3rd_warriorsway.1
Car	240	East.3rd_16th
Car	144	East.3rd_mariposa
Car	31	East.3rd_18th
Car	20	East.3rd_19th
Car	45	East.3rd_20th
Car	360	South.3rd_20th.1
Car	57	West.3rd_20th
Car	20	West.3rd_19th
Car	82	West.3rd_18th
Car	144	West.3rd_mariposa.1
Car	240	West.3rd_16th
Car	144	West.3rd_campus.1
Car	20	West.3rd_nelsonrising
Car	144	West.3rd_missionbaysouth.1
Car	20	West.3rd_chinabasin
Car	41	West.3rd_missionrock
Car	71	West.3rd_longbridge
Car	20	West.3rd_channel
Bus	32	North.3rd_channel.1
Bus	4.5	East.3rd_channel
Bus	4.5	East.3rd_missionrock
Bus	4.5	East.3rd_chinabasin
Bus	4	East.3rd_missionbaynorth
Bus	5	East.3rd_warriorsway.1
Bus	20	East.3rd_16th
Bus	15	East.3rd_mariposa
Bus	4.5	East.3rd_18th
Bus	45	East.3rd_20th
Bus	52	South.3rd_20th.1
Bus	10	West.3rd_18th
Bus	21	West.3rd_mariposa.1
Bus	44	West.3rd_16th
Bus	6	West.3rd_campus.1
Bus	24	West.3rd_missionbaysouth.1
Bus	22	West.3rd_missionrock
Bus	4.5	West.3rd_longbridge
Bus	5	West.3rd_channel
LRV	12	south.3rd_20th.1.LRV
LRV	12	West.3rd_channel.LRV

C

TFE results isolated intersection cars

C.1. TFE Demand factor 1

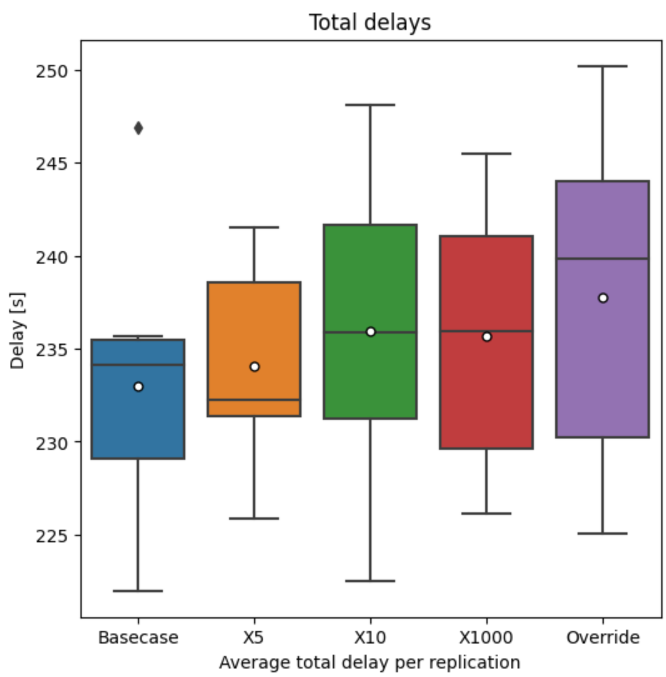

Figure C.1: Average total delay in [s]

Table C.1: Average total delay per scenario [s]

Direction	Mean	Std.dev	t-value	dF	Significant?
Base case	233.019	6.576	0.000	5.540	No
Result x5	234.080	5.026	-1.282	3.841	No
Result x10	235.945	8.013	-2.823	6.841	Yes: ($p < 0.05$)
Result x1000	235.709	6.922	-2.817	5.893	Yes: ($p < 0.05$)
Result override	237.764	8.358	-4.462	7.082	Yes: ($p < 0.05$)

C.1.1. Resulting graphs of KPIs

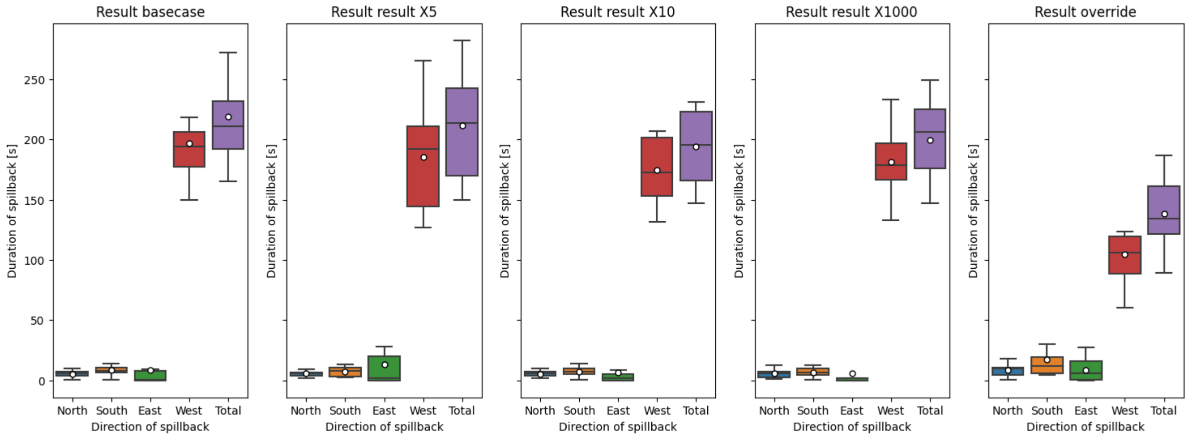

Figure C.2: Spillback duration in [s]

C.1.2. Base case scenario

Table C.2: Overview KPIs of basecase

Direction	Mean	Std.dev
North	5.362	2.959
South	8.245	3.921
East	8.311	17.874
West	197.115	40.546
Total	219.033	46.526
North	60.698	2.469
South	65.747	2.532
East	59.512	2.120
West	59.074	0.808
TB: East	100.730	6.998
TB: West	86.360	1.971
North	31.248	2.469
South	36.296	2.532
East	22.549	2.120
West	22.111	0.808
TB: East	67.593	6.998
TB: West	53.221	1.971

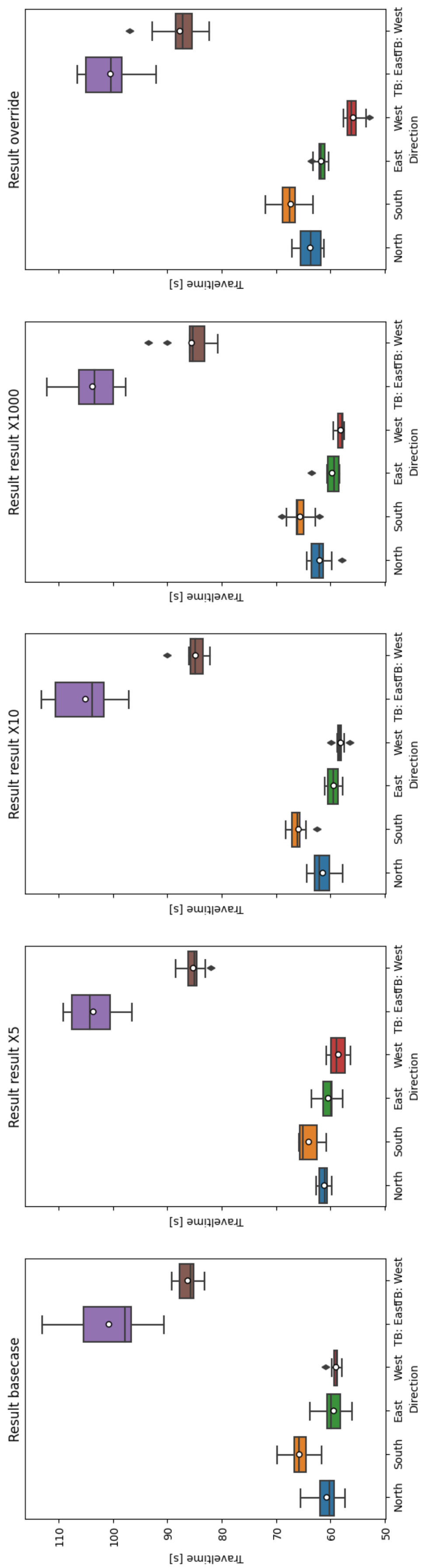

Figure C.3: Travel time [s]

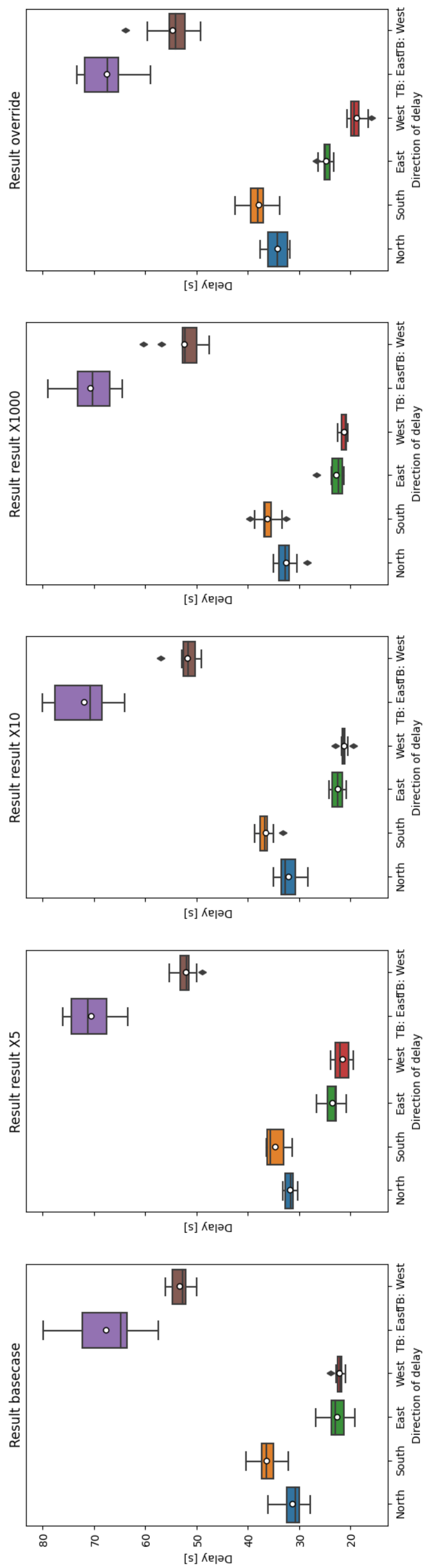

Figure C.4: Delay [s]

C.1.3. Result X5

Table C.3: Overview KPIs

	Directions	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	5.663	2.300	-0.803	9.939	No
	South	7.522	4.107	1.273	7.572	(p < 0.25)
	East	13.307	23.753	-1.681	6.883	(p < 0.25)
	West	185.080	43.998	2.011	5.252	(p < 0.1)
	Total	211.572	49.203	1.102	5.020	No
Travel time	North	61.146	1.082	-1.663	14.553	(p < 0.25)
	South	64.088	1.874	5.268	12.878	Yes: (p < 0.05)
	East	60.499	1.755	-3.585	16.499	Yes: (p < 0.05)
	West	58.558	1.604	2.870	16.790	Yes: (p < 0.05)
	TB: East	103.663	4.554	-3.513	2.927	Yes: (p < 0.05)
	TB: West	85.228	1.907	4.129	16.552	Yes: (p < 0.05)
Delay	North	31.696	1.082	-1.663	14.553	(p < 0.25)
	South	34.637	1.874	5.268	12.878	Yes: (p < 0.05)
	East	23.536	1.755	-3.585	16.499	Yes: (p < 0.05)
	West	21.595	1.604	2.870	16.790	Yes: (p < 0.05)
	TB: East	70.527	4.554	-3.513	2.927	Yes: (p < 0.05)
	TB: West	52.089	1.907	4.129	16.552	Yes: (p < 0.05)

C.1.4. Result X10

Table C.4: Overview KPIs

	Direction	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	5.453	2.564	-0.232	9.819	No
	South	7.478	4.139	1.345	7.596	(p < 0.25)
	East	6.596	13.657	0.762	2.498	No
	West	174.586	27.395	4.604	1.597	(p < 0.1)
	Total	194.113	32.185	4.405	1.711	(p < 0.1)
Travel time	North	61.467	2.071	-2.385	12.851	Yes: (p < 0.05)
	South	65.933	1.581	-0.626	13.376	No
	East	59.446	1.113	0.275	19.240	No
	West	58.217	0.904	7.070	59.233	Yes: (p < 0.05)
	TB: East	105.122	5.944	-4.784	4.289	Yes: (p < 0.05)
	TB: West	84.862	2.297	4.950	13.978	Yes: (p < 0.05)
Delay	North	32.016	2.071	-2.385	12.851	Yes: (p < 0.05)
	South	36.483	1.581	-0.626	13.376	No
	East	22.483	1.113	0.275	19.240	No
	West	21.254	0.904	7.070	59.233	Yes: (p < 0.05)
	TB: East	71.986	5.944	-4.784	4.289	Yes: (p < 0.05)
	TB: West	51.723	2.297	4.950	13.978	Yes: (p < 0.05)

C.1.5. Result X1000

Table C.5: Overview KPIs

	Direction	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	6.031	3.905	-1.365	9.318	($p < 0.25$)
	South	6.803	3.700	2.675	7.245	Yes: ($p < 0.05$)
	East	5.459	13.928	1.259	2.631	No
	West	187.789	45.300	1.534	5.503	($p < 0.25$)
	Total	199.257	33.903	3.435	2.012	($p < 0.1$)
Travel time	North	62.576	1.469	-6.537	14.117	Yes: ($p < 0.05$)
	South	66.001	1.888	-0.806	12.851	No
	East	59.454	1.710	0.213	16.740	No
	West	58.180	0.730	8.204	86.330	Yes: ($p < 0.05$)
	TB: East	102.507	6.807	-1.820	5.221	($p < 0.25$)
	TB: West	86.092	3.636	0.649	10.126	No
Delay	North	33.126	1.469	-6.537	14.117	Yes: ($p < 0.05$)
	South	36.551	1.888	-0.806	12.851	No
	East	22.491	1.710	0.213	16.740	No
	West	21.218	0.730	8.204	86.330	Yes: ($p < 0.05$)
	TB: East	69.370	6.807	-1.820	5.221	($p < 0.25$)
	TB: West	52.953	3.636	0.649	10.126	No

C.1.6. Result override

Table C.6: Overview KPIs

	Direction	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	8.242	5.213	-4.805	9.120	Yes: ($p < 0.05$)
	South	16.969	16.639	-5.103	8.990	Yes: ($p < 0.05$)
	East	8.667	9.670	-0.175	0.970	No
	West	104.694	30.892	18.131	2.309	Yes: ($p < 0.05$)
	Total	138.572	30.468	14.468	1.433	Yes: ($p < 0.05$)
Travel time	North	63.711	2.250	-9.019	12.410	Yes: ($p < 0.05$)
	South	67.331	2.644	-4.328	11.303	Yes: ($p < 0.05$)
	East	61.719	1.066	-9.298	19.357	Yes: ($p < 0.05$)
	West	55.795	1.555	18.704	17.745	Yes: ($p < 0.05$)
	TB: East	100.576	4.872	0.180	3.200	No
	TB: West	87.733	4.436	-2.828	9.532	Yes: ($p < 0.05$)
Delay	North	34.260	2.250	-9.019	12.410	Yes: ($p < 0.05$)
	South	37.881	2.644	-4.328	11.303	Yes: ($p < 0.05$)
	East	24.756	1.066	-9.298	19.357	Yes: ($p < 0.05$)
	West	18.833	1.555	18.704	17.745	Yes: ($p < 0.05$)
	TB: East	67.440	4.872	0.180	3.200	No
	TB: West	54.594	4.436	-2.828	9.532	Yes: ($p < 0.05$)

C.2. TFE Demand factor 1.5

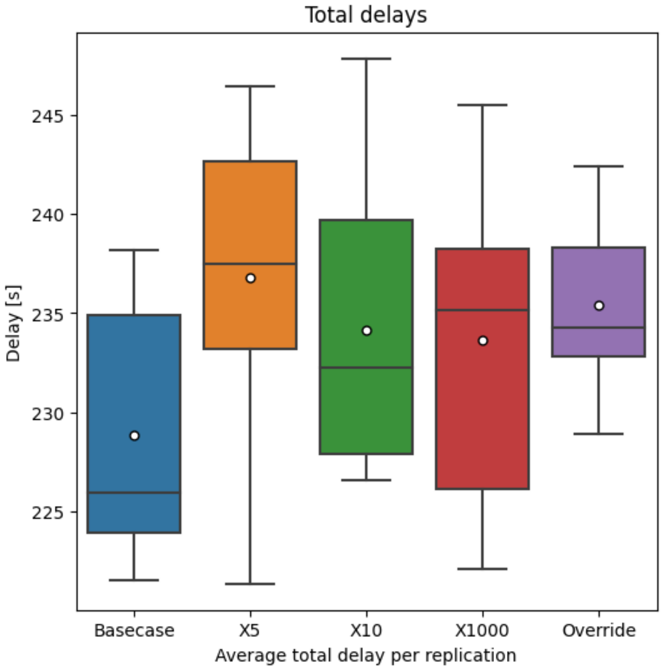

Figure C.5: Average total delay in [s]

Table C.7: Average total delay per scenario [s]

Scenario	Mean	Std.dev	t-value	dF	Significant?
Base case	228.828	6.696	0.000	5.504	No
Result x5	236.794	7.719	-7.796	6.471	Yes: ($p < 0.05$)
Result x10	234.146	7.598	-5.250	6.369	Yes: ($p < 0.05$)
Result x1000	233.631	8.162	-4.549	6.820	Yes: ($p < 0.05$)
Result override	235.393	4.220	-8.294	2.959	Yes: ($p < 0.05$)

C.2.1. Resulting graphs of KPIs

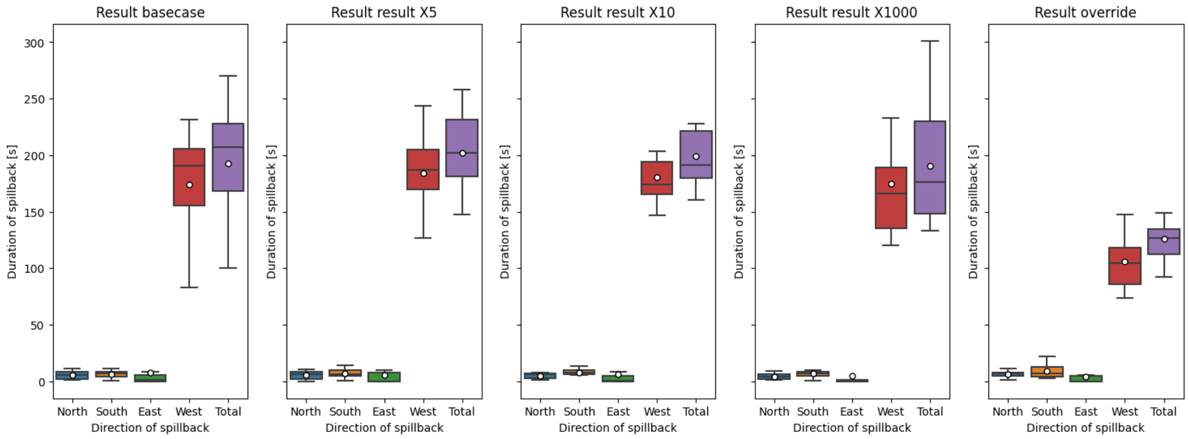

Figure C.6: Spillback duration in [s]

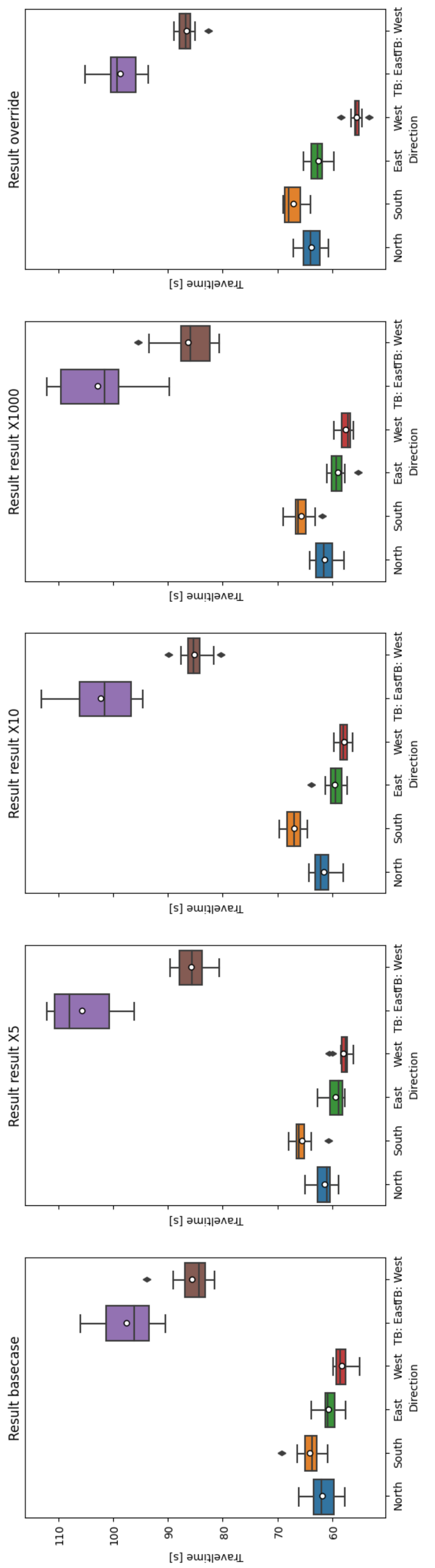

Figure C.7: Travel time [s]

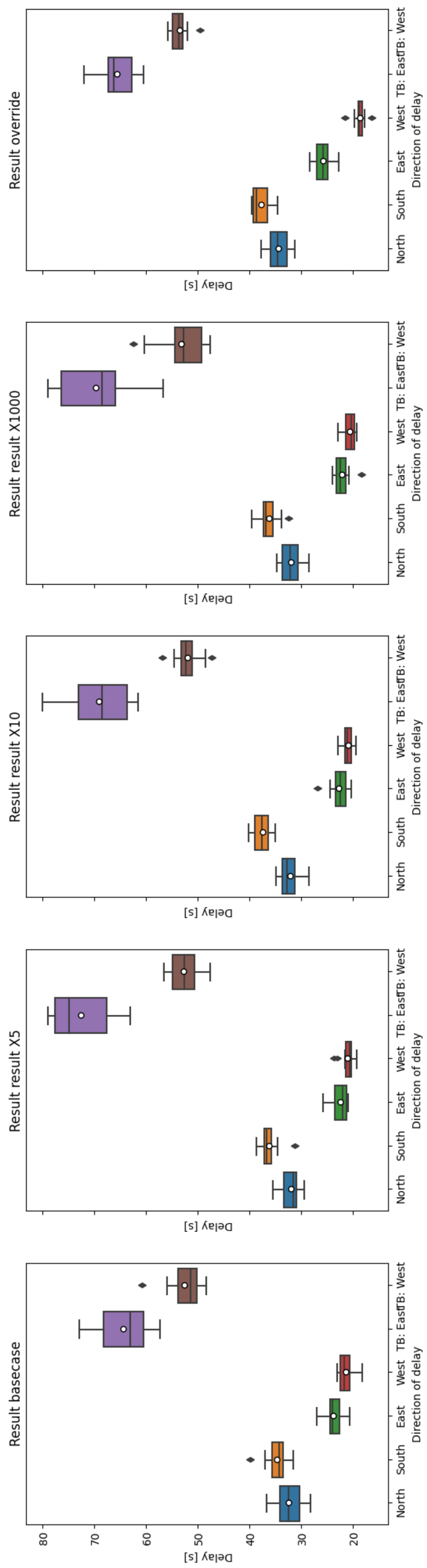

Figure C.8: Delay [s]

C.2.2. Basecase

Table C.8: Overview KPIs of basecase

	Direction	Mean	Std.dev
Spillback	North	5.537	3.591
	South	6.066	3.584
	East	7.654	17.777
	West	173.808	49.356
	Total	193.065	55.114
Travel time	North	61.854	2.750
	South	64.023	2.456
	East	60.669	1.849
	West	58.200	1.485
	TB: East	97.535	5.127
	TB: West	85.649	3.664
Delay	North	32.404	2.750
	South	34.572	2.456
	East	23.707	1.849
	West	21.237	1.485
	TB: East	64.398	5.127
	TB: West	52.510	3.664

C.2.3. Result X5

Table C.9: Overview KPIs

	Direction	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	5.573	3.972	-0.067	8.190	No
	South	7.105	4.070	-1.916	8.251	(p < 0.1)
	East	5.415	9.340	1.115	0.902	No
	West	183.933	33.802	-1.693	1.653	No
	Total	202.026	37.244	-1.347	1.577	No
Travel time	North	61.431	1.867	1.274	11.390	(p < 0.25)
	South	65.588	2.083	-4.860	12.905	Yes: (p < 0.05)
	East	59.389	1.623	5.204	19.867	Yes: (p < 0.05)
	West	57.926	1.375	1.352	27.331	(p < 0.25)
	TB: East	105.747	6.011	-10.395	7.070	Yes: (p < 0.05)
	TB: West	85.816	2.937	-0.355	7.375	No
Delay	North	31.980	1.867	1.274	11.390	(p < 0.25)
	South	36.137	2.083	-4.860	12.905	Yes: (p < 0.05)
	East	22.426	1.623	5.204	19.867	Yes: (p < 0.05)
	West	20.963	1.375	1.352	27.331	(p < 0.25)
	TB: East	72.610	6.011	-10.395	7.070	Yes: (p < 0.05)
	TB: West	52.677	2.937	-0.355	7.375	No

C.2.4. Result X10

Table C.10: Overview KPIs

	Direction	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	4.935	2.657	1.348	7.444	($p < 0.25$)
	South	7.794	3.599	-3.402	8.011	Yes: ($p < 0.05$)
	East	6.264	13.541	0.622	2.480	No
	West	180.214	49.443	-0.917	4.534	No
	Total	199.207	50.674	-0.820	3.768	No
Travel time	North	61.523	2.097	0.956	11.166	No
	South	66.895	1.722	-9.575	13.773	Yes: ($p < 0.05$)
	East	59.565	1.940	4.123	16.835	Yes: ($p < 0.05$)
	West	57.863	1.026	1.867	34.913	($p < 0.1$)
	TB: East	102.255	6.628	-5.633	7.530	Yes: ($p < 0.05$)
	TB: West	85.147	2.743	1.097	7.254	No
Delay	North	32.073	2.097	0.956	11.166	No
	South	37.444	1.722	-9.575	13.773	Yes: ($p < 0.05$)
	East	22.602	1.940	4.123	16.835	Yes: ($p < 0.05$)
	West	20.900	1.026	1.867	34.913	($p < 0.1$)
	TB: East	69.119	6.628	-5.633	7.530	Yes: ($p < 0.05$)
	TB: West	52.008	2.743	1.097	7.254	No

C.2.5. Result X1000

Table C.11: Overview KPIs

	Direction	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	4.429	2.722	2.459	7.479	Yes: ($p < 0.05$)
	South	7.073	3.818	-1.923	8.128	($p < 0.1$)
	East	4.670	11.556	1.407	1.605	No
	West	174.730	52.870	-0.127	5.131	No
	Total	190.902	56.320	0.274	4.709	No
Travel time	North	61.353	1.999	1.475	11.266	($p < 0.25$)
	South	65.661	2.096	-5.075	12.870	Yes: ($p < 0.05$)
	East	58.947	1.658	6.932	19.516	Yes: ($p < 0.05$)
	West	57.531	1.162	3.548	32.137	Yes: ($p < 0.05$)
	TB: East	102.878	7.172	-6.061	7.845	Yes: ($p < 0.05$)
	TB: West	86.363	4.922	-1.164	8.461	No
Delay	North	31.902	1.999	1.475	11.266	($p < 0.25$)
	South	36.211	2.096	-5.075	12.870	Yes: ($p < 0.05$)
	East	21.985	1.658	6.932	19.516	Yes: ($p < 0.05$)
	West	20.568	1.162	3.548	32.137	Yes: ($p < 0.05$)
	TB: East	69.741	7.172	-6.061	7.845	Yes: ($p < 0.05$)
	TB: West	53.224	4.922	-1.164	8.461	No

C.2.6. Result override

Table C.12: Overview KPIs

	Direction	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	6.573	3.054	-2.198	7.672	($p < 0.1$)
	South	9.087	6.332	-4.152	8.814	Yes: ($p < 0.05$)
	East	4.395	7.355	1.694	0.533	No
	West	106.085	23.900	12.350	0.504	($p < 0.25$)
	Total	126.140	22.710	11.227	0.281	No
	North	63.851	2.127	-5.745	11.135	Yes: ($p < 0.05$)
	South	67.144	1.966	-9.922	13.201	Yes: ($p < 0.05$)
	East	62.595	1.734	-7.597	18.770	Yes: ($p < 0.05$)
	West	55.595	1.312	13.145	28.770	Yes: ($p < 0.05$)
	TB: East	98.675	3.492	-1.839	4.411	($p < 0.25$)
	TB: West	86.633	1.842	-2.401	6.843	Yes: ($p < 0.05$)
	North	34.401	2.127	-5.745	11.135	Yes: ($p < 0.05$)
	South	37.693	1.966	-9.922	13.201	Yes: ($p < 0.05$)
	East	25.632	1.734	-7.597	18.770	Yes: ($p < 0.05$)
	West	18.632	1.312	13.145	28.770	Yes: ($p < 0.05$)
	TB: East	65.539	3.492	-1.839	4.411	($p < 0.25$)
	TB: West	53.495	1.842	-2.401	6.843	Yes: ($p < 0.05$)

C.3. TFE alternative turning fractions east

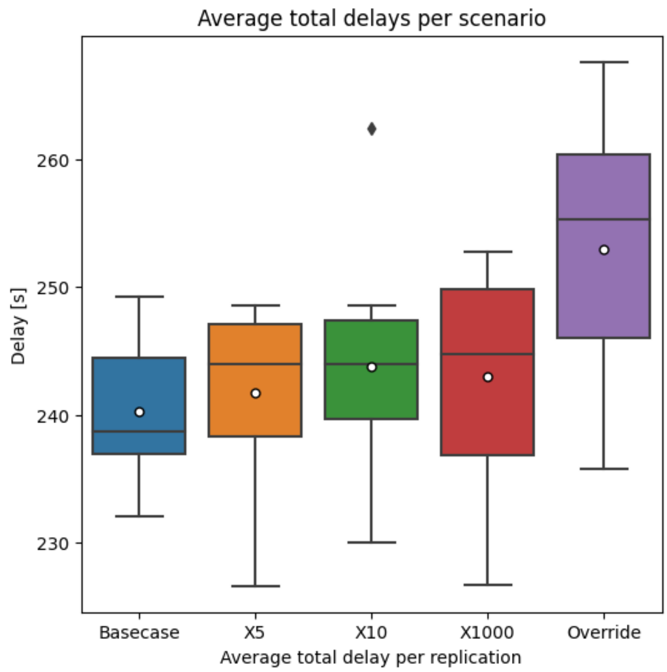

Figure C.9: Average total delay in [s]

Table C.13: Average total delay per scenario [s]

Direction	Mean	Std.dev	t-value	dF	Significant?
Baseccase	240.280	5.899	0.000	5.793	No
Result x5	241.724	7.111	-1.563	6.939	($p < 0.25$)
Result x10	243.732	8.989	-3.210	7.996	Yes: ($p < 0.05$)
Result x1000	242.987	8.469	-2.622	7.778	Yes: ($p < 0.05$)
Result override	252.992	10.497	-10.557	8.418	Yes: ($p < 0.05$)

C.3.1. Resulting graphs of KPIs

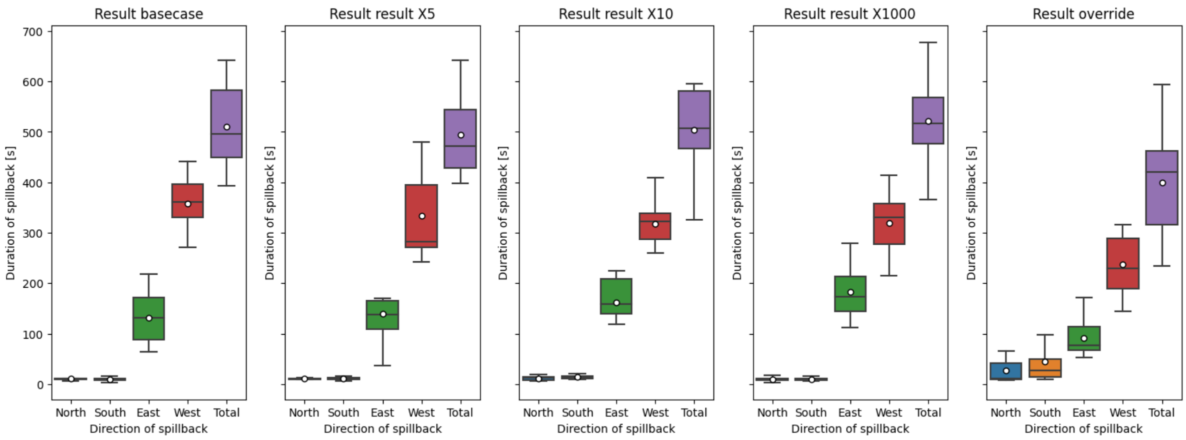

Figure C.10: Duration of spillback in [s]

C.3.2. Base case

Table C.14: Overview KPIs of basecase

	Direction	Mean	Std.dev
Spillback	North	10.632	4.495
	South	9.364	3.469
	East	131.742	51.955
	West	358.420	52.940
	Total	510.158	81.921
Travel time	North	65.543	2.077
	South	69.455	2.058
	East	61.366	1.707
	West	66.866	1.669
	TB: East	81.268	2.594
	TB: West	94.884	3.442
Delay	North	36.092	2.077
	South	40.004	2.058
	East	24.404	1.707
	West	29.903	1.669
	TB: East	48.132	2.594
	TB: West	61.745	3.442

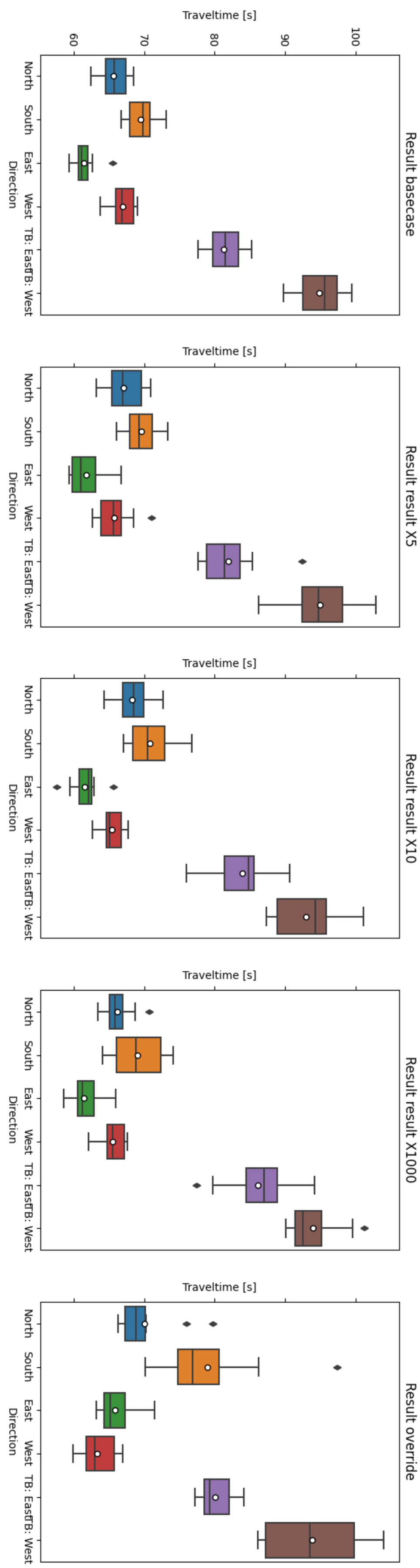

Figure C.11: Travel time [s]

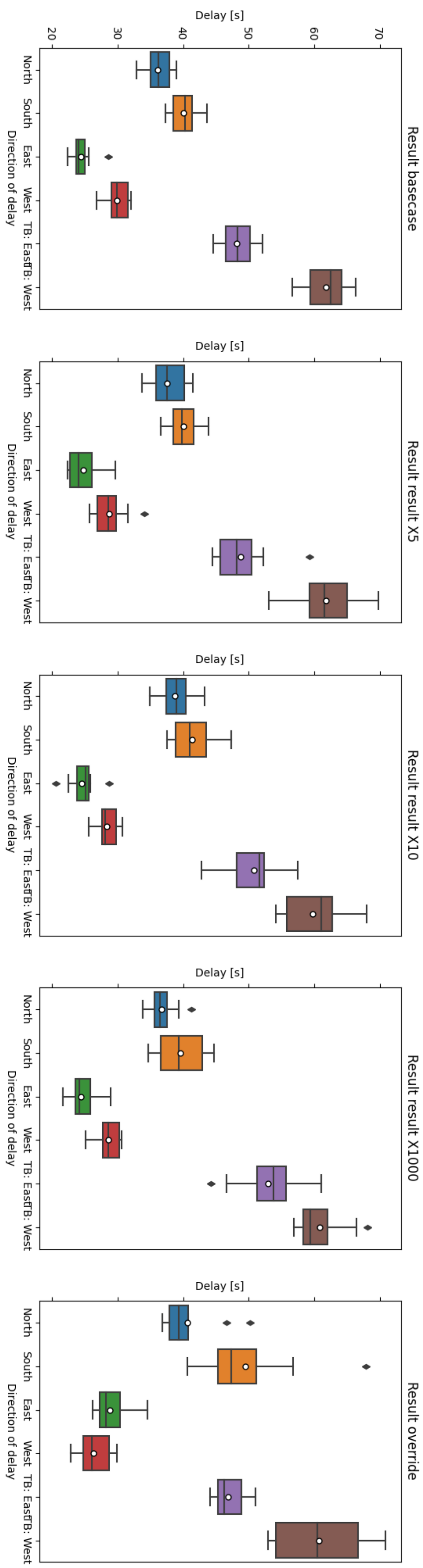

Figure C.12: Delay [s]

C.3.3. Result X5

Table C.15: Overview KPIs

	Direction	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	10.710	4.252	-0.126	6.476	No
	South	10.546	3.116	-2.535	8.078	Yes: (p < 0.05)
	East	139.814	59.908	-1.018	5.760	No
	West	333.092	88.748	2.451	7.992	Yes: (p < 0.05)
	Total	494.162	83.808	1.365	4.711	(p < 0.25)
Travel time	North	67.020	2.755	-4.283	11.897	Yes: (p < 0.05)
	South	69.532	2.408	-0.243	13.260	No
	East	61.684	2.645	-1.009	12.237	No
	West	65.711	2.571	3.768	12.515	Yes: (p < 0.05)
	TB: East	81.939	4.526	-1.284	9.426	(p < 0.25)
	TB: West	94.940	4.649	-0.098	8.675	No
Delay	North	37.570	2.755	-4.283	11.897	Yes: (p < 0.05)
	South	40.081	2.408	-0.243	13.260	No
	East	24.721	2.645	-1.009	12.237	No
	West	28.748	2.571	3.768	12.515	Yes: (p < 0.05)
	TB: East	48.802	4.526	-1.284	9.426	(p < 0.25)
	TB: West	61.802	4.649	-0.098	8.675	No

C.3.4. Result X10

Table C.16: Overview KPIs

	Direction	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	11.393	4.011	-1.263	6.219	No
	South	13.423	3.858	-7.823	8.398	Yes: (p < 0.05)
	East	161.369	59.072	-3.766	5.643	Yes: (p < 0.05)
	West	317.143	44.701	5.957	3.054	Yes: (p < 0.05)
	Total	503.328	87.272	0.571	5.072	No
Travel time	North	68.242	2.671	-7.978	12.176	Yes: (p < 0.05)
	South	70.813	3.136	-3.622	10.917	Yes: (p < 0.05)
	East	61.531	2.165	-0.596	15.098	No
	West	65.354	1.642	6.458	21.028	Yes: (p < 0.05)
	TB: East	83.945	4.316	-5.315	9.505	Yes: (p < 0.05)
	TB: West	92.949	4.548	3.392	8.653	Yes: (p < 0.05)
Delay	North	38.791	2.671	-7.978	12.176	Yes: (p < 0.05)
	South	41.363	3.136	-3.622	10.917	Yes: (p < 0.05)
	East	24.568	2.165	-0.596	15.098	No
	West	28.391	1.642	6.458	21.028	Yes: (p < 0.05)
	TB: East	50.808	4.316	-5.315	9.505	Yes: (p < 0.05)
	TB: West	59.811	4.548	3.392	8.653	Yes: (p < 0.05)

C.3.5. Result X1000

Table C.17: Overview KPIs

	variable	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	9.565	4.908	1.603	7.123	(p < 0.25)
	South	9.490	3.166	-0.268	8.101	No
	East	182.903	52.937	-6.898	4.684	Yes: (p < 0.05)
	West	319.121	59.493	4.935	5.544	Yes: (p < 0.05)
	Total	521.079	98.749	-0.851	6.112	No
Travel time	North	66.100	2.201	-1.842	14.249	(p < 0.1)
	South	69.035	3.616	1.007	10.163	No
	East	61.399	2.270	-0.114	14.305	No
	West	65.479	1.733	5.763	19.777	Yes: (p < 0.05)
	TB: East	86.135	4.881	-8.805	9.323	Yes: (p < 0.05)
	TB: West	93.939	3.780	1.847	8.427	(p < 0.25)
Delay	North	36.650	2.201	-1.842	14.249	(p < 0.1)
	South	39.585	3.616	1.007	10.163	No
	East	24.436	2.270	-0.114	14.305	No
	West	28.516	1.733	5.763	19.777	Yes: (p < 0.05)
	TB: East	52.999	4.881	-8.805	9.323	Yes: (p < 0.05)
	TB: West	60.801	3.780	1.847	8.427	(p < 0.25)

C.3.6. Result override

Table C.18: Overview KPIs

	Direction	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	26.201	22.595	-6.758	8.993	Yes: (p < 0.05)
	South	44.647	47.269	-7.444	9.000	Yes: (p < 0.05)
	East	91.795	40.112	6.086	2.384	Yes: (p < 0.05)
	West	237.128	60.793	15.046	5.726	Yes: (p < 0.05)
	Total	399.771	105.379	8.270	6.596	Yes: (p < 0.05)
Travel time	North	70.063	4.405	-9.282	9.559	Yes: (p < 0.05)
	South	78.947	7.877	-11.660	9.057	Yes: (p < 0.05)
	East	65.820	2.463	-14.863	13.103	Yes: (p < 0.05)
	West	63.292	2.459	12.027	13.083	Yes: (p < 0.05)
	TB: East	80.056	2.486	3.374	11.375	Yes: (p < 0.05)
	TB: West	93.915	6.811	1.270	8.914	(p < 0.25)
Delay	North	40.613	4.405	-9.282	9.559	Yes: (p < 0.05)
	South	49.497	7.877	-11.660	9.057	Yes: (p < 0.05)
	East	28.858	2.463	-14.863	13.103	Yes: (p < 0.05)
	West	26.329	2.459	12.027	13.083	Yes: (p < 0.05)
	TB: East	46.920	2.486	3.374	11.375	Yes: (p < 0.05)
	TB: West	60.776	6.811	1.270	8.914	(p < 0.25)

D
TFE results isolated intersection with bus

D.1. TFE with bus, experiment demand factor 1

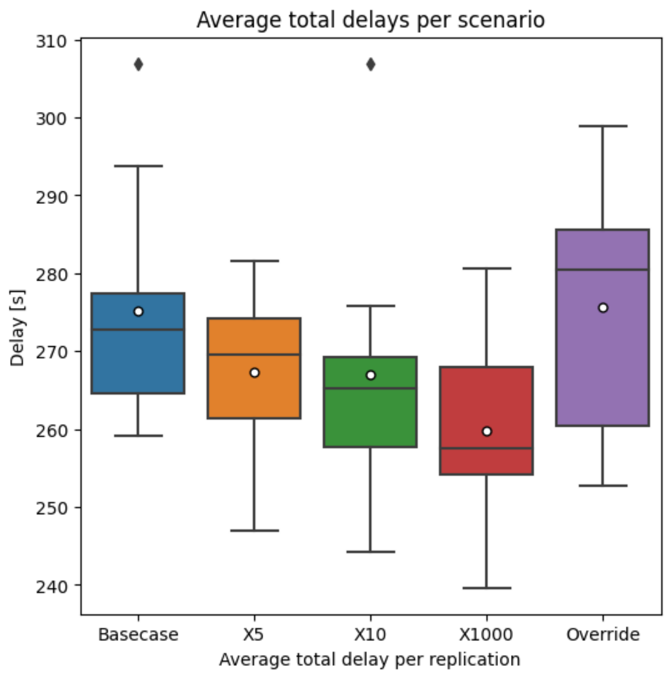

Figure D.1: Average total delay in [s]

Table D.1: Average total delay per scenario [s]

	Scenario	Mean	Std.dev	t-value	dF	Significant?
0	Base case	275.096	14.913	0.000	4.702	No
1	Result x5	267.286	10.431	4.291	2.065	Yes: ($p < 0.05$)
2	Result x10	266.940	16.627	3.652	5.623	Yes: ($p < 0.05$)
3	Result x1000	259.822	13.295	7.645	3.732	Yes: ($p < 0.05$)
4	Result override	275.598	15.741	-0.231	5.165	No

D.1.1. Resulting graphs of KPIs

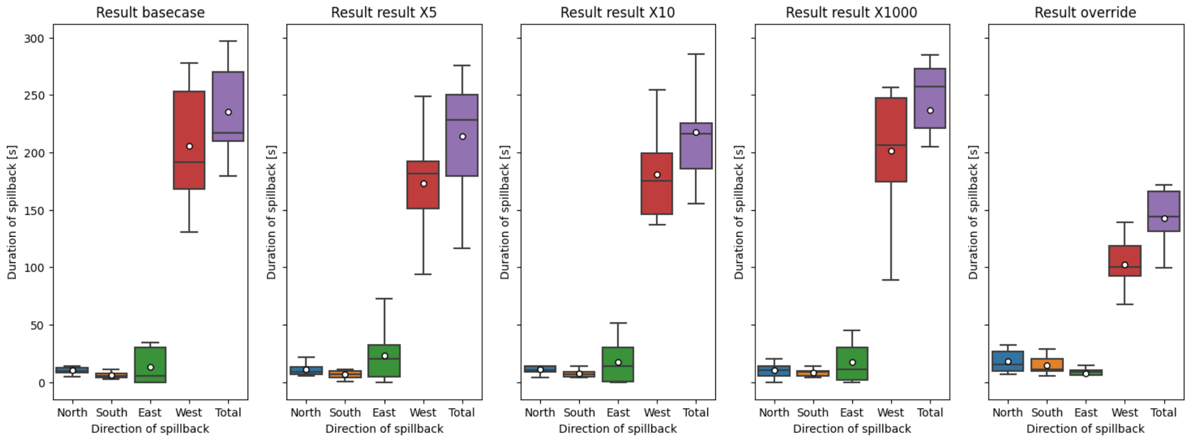

Figure D.2: Spillback duration in [s]

D.1.2. Base case scenario

Table D.2: Overview KPIs of basecase

	Direction	Mean	Std.dev
Spillback	North	10.188	3.190
	South	6.208	2.755
	East	13.381	15.721
	West	205.849	50.641
	Total	235.626	41.675
Travel time	North	61.372	2.257
	South	64.151	2.214
	East	62.088	2.527
	West	59.485	1.443
	TB: East	101.512	7.295
	TB: West	87.689	4.572
	Bus	67.194	13.221
Delays	North	31.921	2.257
	South	34.701	2.214
	East	25.125	2.527
	West	22.523	1.443
	TB: East	68.376	7.295
	TB: West	54.551	4.572
	Bus	37.900	13.221

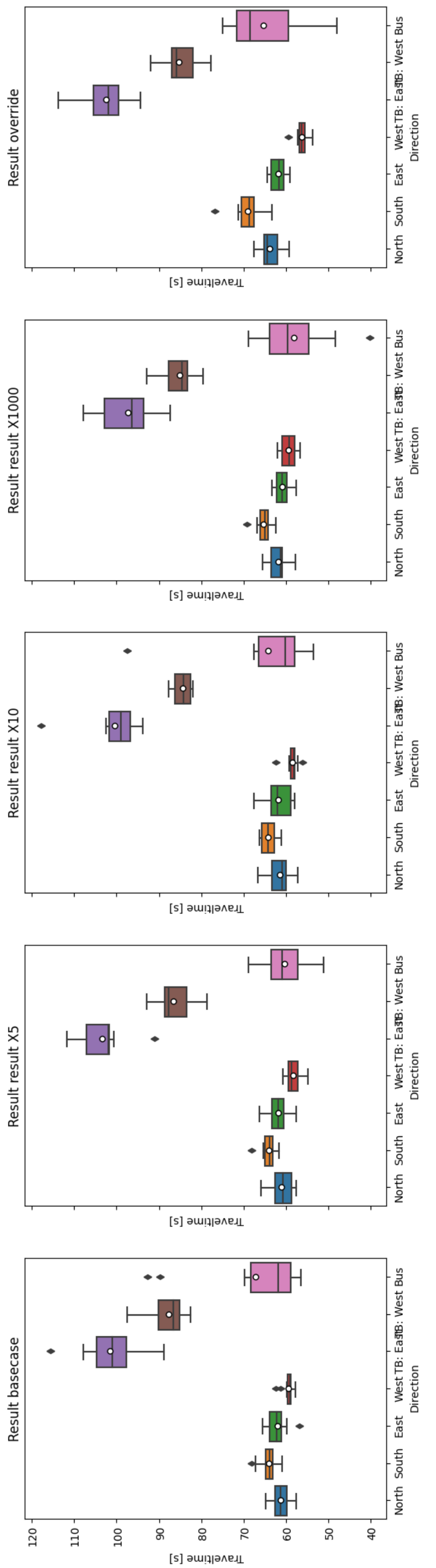

Figure D.3: Travel time [s]

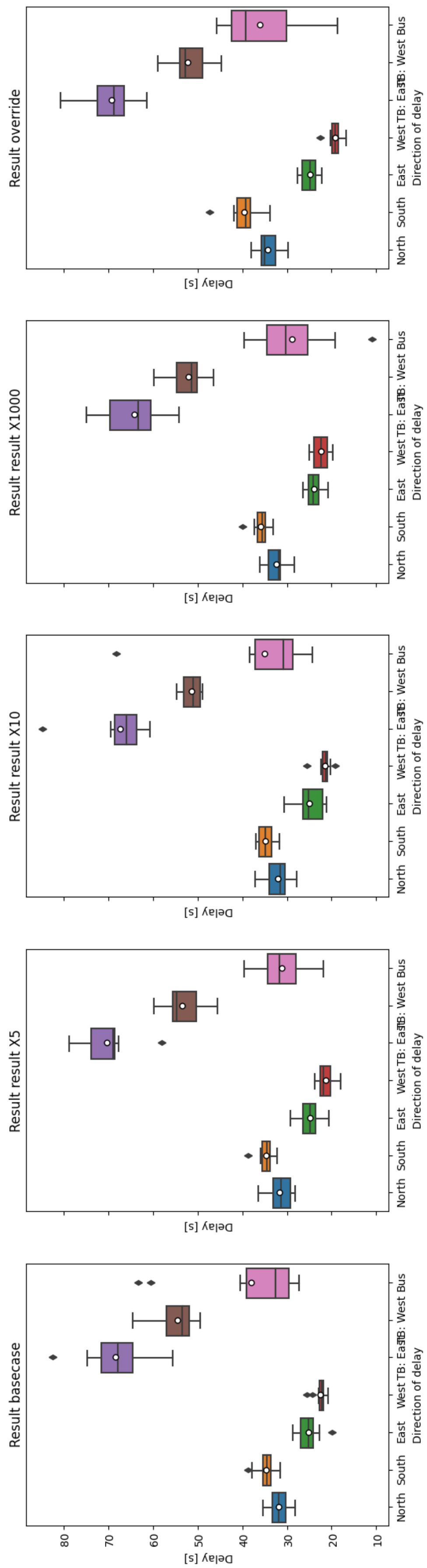

Figure D.4: Delay [s]

D.1.3. Result X5

Table D.3: Overview KPIs

	Direction	Mean	Std.dev	t-value	dF	Significant?
0	North	11.062	5.776	-1.325	8.987	(p < 0.25)
Spillback	South	6.565	3.326	-0.827	9.915	No
2	East	23.087	22.439	-3.543	7.323	Yes: (p < 0.05)
3	West	173.187	50.837	4.552	4.552	Yes: (p < 0.05)
4	Total	213.901	53.676	3.197	6.615	Yes: (p < 0.05)
Travel time	North	61.099	2.900	0.742	11.327	No
1	South	64.064	1.887	0.298	15.123	No
2	East	61.812	2.478	0.777	11.647	No
3	West	58.329	1.707	5.176	20.574	Yes: (p < 0.05)
4	TB: East	103.423	5.900	-2.036	3.881	(p < 0.25)
5	TB: West	86.552	4.338	1.804	6.407	(p < 0.25)
6	Bus	60.402	5.277	4.771	0.725	(p < 0.25)
Delay	North	31.648	2.900	0.742	11.327	No
1	South	34.614	1.887	0.298	15.123	No
2	East	24.850	2.478	0.777	11.647	No
3	West	21.366	1.707	5.176	20.574	Yes: (p < 0.05)
4	TB: East	70.286	5.900	-2.036	3.881	(p < 0.25)
5	TB: West	53.414	4.338	1.804	6.407	(p < 0.25)
6	Bus	31.108	5.277	4.771	0.725	(p < 0.25)

D.1.4. Result X10

Table D.4: Overview KPIs

	Direction	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	11.293	5.231	-1.803	8.981	(p < 0.25)
	South	7.756	3.585	-3.424	9.739	Yes: (p < 0.05)
	East	17.501	18.442	-1.700	6.016	(p < 0.25)
	West	180.958	42.561	3.763	3.019	Yes: (p < 0.05)
	Total	217.508	44.478	2.973	5.105	Yes: (p < 0.05)
Travel time	North	61.427	2.766	-0.156	11.663	No
	South	64.205	1.784	-0.191	15.580	No
	East	61.913	3.236	0.426	10.381	No
	West	58.515	1.636	4.449	21.911	Yes: (p < 0.05)
	TB: East	100.491	6.745	1.028	4.777	No
	TB: West	84.465	2.106	6.406	4.508	Yes: (p < 0.05)
	Bus	64.320	12.511	1.579	4.291	(p < 0.25)
Delay	North	31.977	2.766	-0.156	11.663	No
	South	34.755	1.784	-0.191	15.580	No
	East	24.950	3.236	0.426	10.381	No
	West	21.552	1.636	4.449	21.911	Yes: (p < 0.05)
	TB: East	67.354	6.745	1.028	4.777	No
	TB: West	51.326	2.106	6.406	4.508	Yes: (p < 0.05)
	Bus	35.026	12.511	1.579	4.291	(p < 0.25)

D.1.5. Result X1000

Table D.5: Overview KPIs

	Direction	Mean	Std.dev	t-value	dF	Significant?	Delays [s]
Spillback	North	10.159	6.500	0.040	8.991	No	
	South	8.106	2.975	-4.681	10.212	Yes: ($p < 0.05$)	
	East	17.306	17.989	-1.643	5.819	($p < 0.25$)	
	West	201.130	53.844	0.638	5.065	No	
	Total	236.701	55.661	-0.155	6.860	No	
Travel time	North	61.909	2.287	-1.672	13.217	($p < 0.25$)	
	South	65.334	1.840	-4.108	15.333	Yes: ($p < 0.05$)	
	East	60.841	1.918	3.929	12.824	Yes: ($p < 0.05$)	
	West	59.389	1.935	0.401	17.081	No	
	TB: East	97.338	6.785	4.190	4.819	Yes: ($p < 0.05$)	
	TB: West	85.193	4.259	3.996	6.322	Yes: ($p < 0.05$)	
	Bus	58.214	8.889	5.637	1.954	Yes: ($p < 0.05$)	
Delay	North	32.458	2.287	-1.672	13.217	($p < 0.25$)	
	South	35.884	1.840	-4.108	15.333	Yes: ($p < 0.05$)	
	East	23.878	1.918	3.929	12.824	Yes: ($p < 0.05$)	
	West	22.426	1.935	0.401	17.081	No	
	TB: East	64.202	6.785	4.190	4.819	Yes: ($p < 0.05$)	
	TB: West	52.054	4.259	3.996	6.322	Yes: ($p < 0.05$)	
	Bus	28.920	8.889	5.637	1.954	Yes: ($p < 0.05$)	

D.1.6. Result Override

Table D.6: Overview KPIs

	variable	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	18.270	10.238	-7.536	8.999	Yes: ($p < 0.05$)
	South	14.511	7.545	-10.337	9.050	Yes: ($p < 0.05$)
	East	7.849	4.802	3.365	0.439	No
	West	102.158	23.038	18.638	0.403	($p < 0.25$)
	Total	142.788	25.226	19.058	1.111	Yes: ($p < 0.05$)
Travel time	North	63.814	2.499	-7.253	12.463	Yes: ($p < 0.05$)
	South	69.104	3.522	-11.905	10.264	Yes: ($p < 0.05$)
	East	61.864	1.938	0.702	12.785	No
	West	56.236	1.573	15.220	23.182	Yes: ($p < 0.05$)
	TB: East	102.426	5.811	-0.980	3.789	No
	TB: West	85.269	4.429	3.803	6.504	Yes: ($p < 0.05$)
	Bus	65.280	8.664	1.211	1.836	No
Delay	North	34.363	2.499	-7.253	12.463	Yes: ($p < 0.05$)
	South	39.654	3.522	-11.905	10.264	Yes: ($p < 0.05$)
	East	24.901	1.938	0.702	12.785	No
	West	19.273	1.573	15.220	23.182	Yes: ($p < 0.05$)
	TB: East	69.290	5.811	-0.980	3.789	No
	TB: West	52.130	4.429	3.803	6.504	Yes: ($p < 0.05$)
	Bus	35.986	8.664	1.211	1.836	No

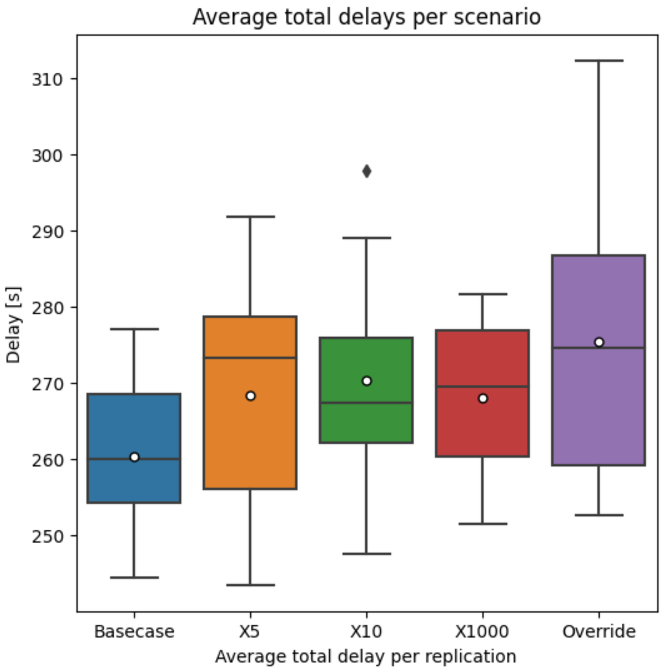

Figure D.5: Average total delay in [s]

D.2. TFE with bus, experiment demand factor 1.5

Table D.7: Average total delay per scenario [s]

Direction	Mean	Std.dev	t-value	dF	Significant?
Base case	260.407	10.749	0.000	4.889	No
Result x10	270.266	14.642	-5.427	7.150	Yes: ($p < 0.05$)
Result x1	268.093	10.337	-5.154	4.568	Yes: ($p < 0.05$)
Result override	275.429	18.540	-7.009	8.165	Yes: ($p < 0.05$)

D.2.1. Resulting graphs of KPIs

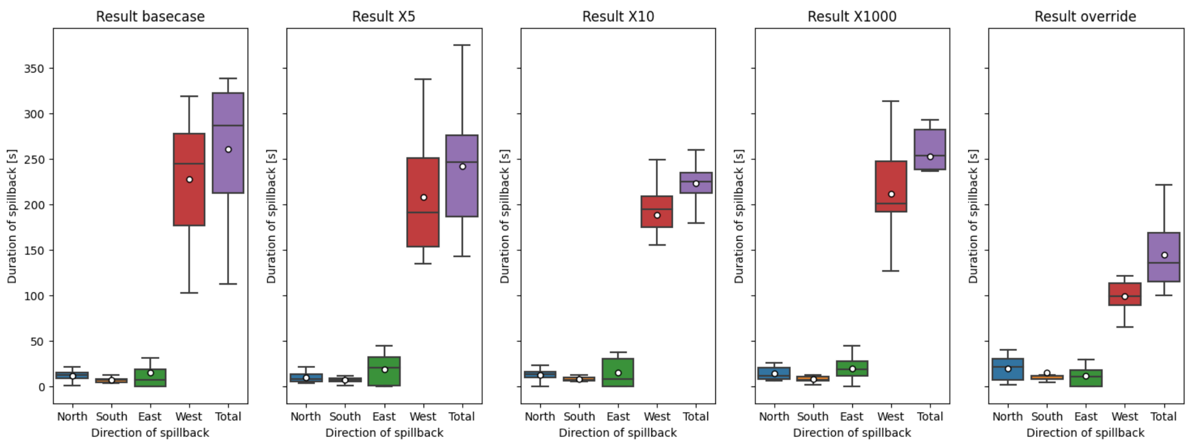

Figure D.6: Spillback duration in [s]

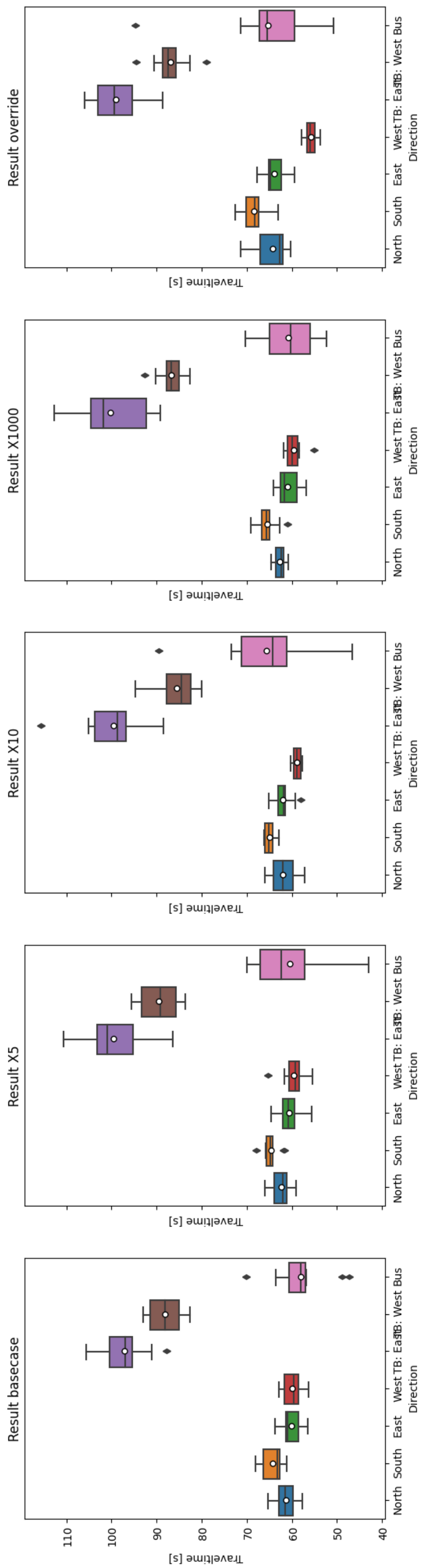

Figure D.7: Travel time [s]

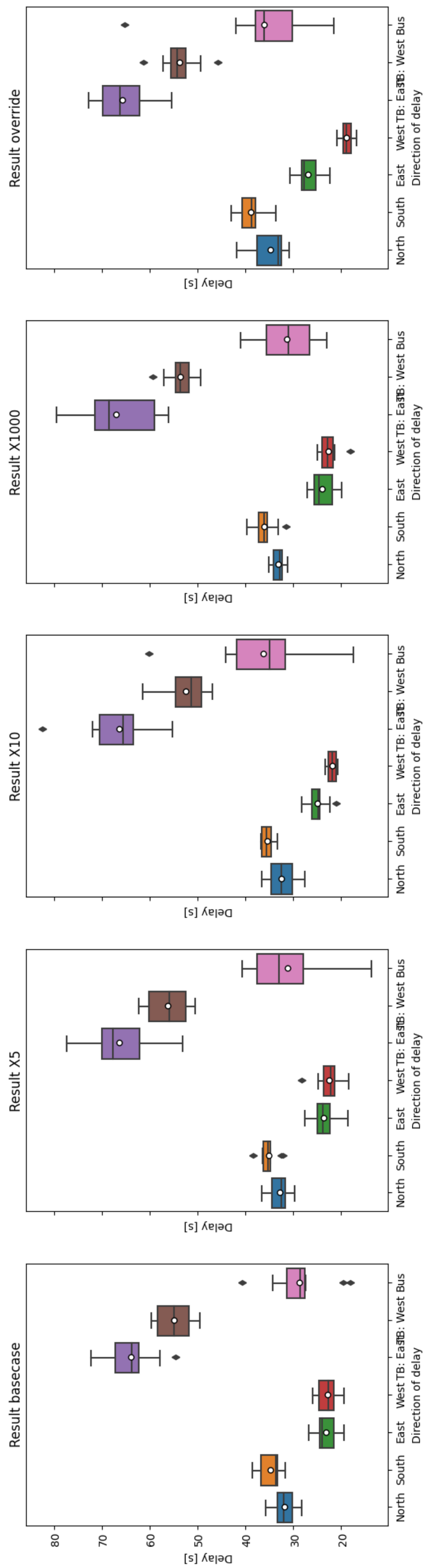

Figure D.8: Delay [s]

D.2.2. Base case scenario

Table D.8: Overview KPIs of basecase

	Direction	Mean	Std.dev
Spillback	North	11.697	5.884
	South	6.772	3.007
	East	14.735	21.266
	West	227.570	69.591
	Total	260.774	78.789
Travel time	North	61.294	2.407
	South	64.226	2.351
	East	60.148	2.329
	West	59.896	2.151
	TB: East	97.155	5.290
	TB: West	88.069	3.830
	Bus	58.014	6.559
Delay	North	31.844	2.407
	South	34.776	2.351
	East	23.186	2.329
	West	22.933	2.151
	TB: East	64.018	5.290
	TB: West	54.930	3.830
	Bus	28.720	6.559

D.2.3. Result X5

Table D.9: Overview KPIs

	Direction	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	9.352	5.753	2.850	5.655	Yes: ($p < 0.05$)
	South	6.587	3.139	0.426	9.435	No
	East	18.233	16.767	-1.292	2.652	No
	West	207.946	65.870	2.048	4.018	($p < 0.25$)
	Total	242.118	71.435	1.754	3.638	($p < 0.25$)
Travel time	North	62.366	2.128	-3.337	13.059	Yes: ($p < 0.05$)
	South	64.640	1.866	-1.378	14.215	($p < 0.25$)
	East	60.571	2.397	-1.264	12.577	($p < 0.25$)
	West	59.554	2.690	0.993	12.033	No
	TB: East	99.594	6.936	-2.796	7.538	Yes: ($p < 0.05$)
	TB: West	89.485	4.437	-2.416	7.977	Yes: ($p < 0.05$)
	Bus	60.500	8.520	-2.312	7.204	($p < 0.1$)
Delay	North	32.916	2.128	-3.337	13.059	Yes: ($p < 0.05$)
	South	35.189	1.866	-1.378	14.215	($p < 0.25$)
	East	23.608	2.397	-1.264	12.577	($p < 0.25$)
	West	22.591	2.690	0.993	12.033	No
	TB: East	66.458	6.936	-2.796	7.538	Yes: ($p < 0.05$)
	TB: West	56.346	4.437	-2.416	7.977	Yes: ($p < 0.05$)
	Bus	31.206	8.520	-2.312	7.204	($p < 0.1$)

D.2.4. Result X10

Table D.10: Overview KPIs

Direction	Mean	Std.dev	t-value	dF	Significant?
North	12.455	6.377	-0.874	6.311	No
South	7.664	2.267	-2.369	9.720	Yes: (p < 0.05)
East	14.629	16.316	0.040	2.464	No
West	188.596	37.674	4.925	0.729	(p < 0.25)
Total	223.344	36.325	4.314	0.403	No
North	62.028	2.931	-1.936	11.043	(p < 0.1)
South	64.986	1.145	-2.907	15.896	Yes: (p < 0.05)
East	61.985	2.265	-5.655	13.008	Yes: (p < 0.05)
West	58.868	0.938	4.381	19.087	Yes: (p < 0.05)
TB: East	99.595	7.702	-2.612	7.947	Yes: (p < 0.05)
TB: West	85.588	4.588	4.151	8.063	Yes: (p < 0.05)
Bus	65.610	11.714	-5.658	8.382	Yes: (p < 0.05)
North	32.578	2.931	-1.936	11.043	(p < 0.1)
South	35.536	1.145	-2.907	15.896	Yes: (p < 0.05)
East	25.022	2.265	-5.655	13.008	Yes: (p < 0.05)
West	21.905	0.938	4.381	19.087	Yes: (p < 0.05)
TB: East	66.459	7.702	-2.612	7.947	Yes: (p < 0.05)
TB: West	52.449	4.588	4.151	8.063	Yes: (p < 0.05)
Bus	36.316	11.714	-5.658	8.382	Yes: (p < 0.05)

D.2.5. Result X1000

Table D.11: Overview KPIs

	Direction	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	13.955	7.299	-2.408	7.100	Yes: (p < 0.05)
	South	7.569	3.355	-1.769	9.374	(p < 0.25)
	East	19.527	13.859	-1.888	1.544	(p < 0.25)
	West	211.715	54.607	1.792	2.488	(p < 0.25)
	Total	252.766	55.594	0.830	1.799	No
Travel time	North	62.614	1.306	-4.819	15.017	Yes: (p < 0.05)
	South	65.523	2.415	-3.847	12.445	Yes: (p < 0.05)
	East	60.975	2.475	-2.432	12.335	Yes: (p < 0.05)
	West	59.584	1.991	1.063	15.025	No
	TB: East	100.262	8.305	-3.155	8.183	Yes: (p < 0.05)
	TB: West	86.797	3.050	2.598	6.956	Yes: (p < 0.05)
	Bus	60.734	6.216	-3.010	5.177	Yes: (p < 0.05)
Delay	North	33.163	1.306	-4.819	15.017	Yes: (p < 0.05)
	South	36.073	2.415	-3.847	12.445	Yes: (p < 0.05)
	East	24.012	2.475	-2.432	12.335	Yes: (p < 0.05)
	West	22.622	1.991	1.063	15.025	No
	TB: East	67.125	8.305	-3.155	8.183	Yes: (p < 0.05)
	TB: West	53.658	3.050	2.598	6.956	Yes: (p < 0.05)
	Bus	31.440	6.216	-3.010	5.177	Yes: (p < 0.05)

D.2.6. Result Override

Table D.12: Overview KPIs

	Direction	Mean	Std.dev	t-value	dF	Significant?
Spillback	North	19.293	13.771	-5.072	8.794	Yes: ($p < 0.05$)
	South	15.011	18.963	-4.291	9.001	Yes: ($p < 0.05$)
	East	11.000	11.193	1.554	0.826	No
	West	99.224	16.879	17.923	0.050	No
	Total	144.528	38.410	13.262	0.495	($p < 0.25$)
Travel time	North	64.322	3.673	-6.894	10.017	Yes: ($p < 0.05$)
	South	68.399	2.835	-11.330	11.339	Yes: ($p < 0.05$)
	East	63.945	2.625	-10.819	11.905	Yes: ($p < 0.05$)
	West	55.822	1.260	16.343	18.353	Yes: ($p < 0.05$)
	TB: East	98.977	5.371	-2.417	6.196	($p < 0.1$)
	TB: West	86.991	4.249	1.884	7.860	($p < 0.1$)
	Bus	65.368	12.207	-5.307	8.468	Yes: ($p < 0.05$)
Delay	North	34.871	3.673	-6.894	10.017	Yes: ($p < 0.05$)
	South	38.949	2.835	-11.330	11.339	Yes: ($p < 0.05$)
	East	26.982	2.625	-10.819	11.905	Yes: ($p < 0.05$)
	West	18.860	1.260	16.343	18.353	Yes: ($p < 0.05$)
	TB: East	65.841	5.371	-2.417	6.196	($p < 0.1$)
	TB: West	53.852	4.249	1.884	7.860	($p < 0.1$)
	Bus	36.074	12.207	-5.307	8.468	Yes: ($p < 0.05$)

E

TFE results corridor

E.1. TFE demand factor 1

E.1.1. Base case scenario

Table E.1: Overview KPIs of basecase

	KPIs	Mean	Std.dev
Spillback	Overflow	7.208	15.144
	North	212.990	63.458
	South	2.363	1.849
	East	3.143	1.954
	West	5.981	2.454
	Total	224.477	63.113
Traveltime	Route 1	333.517	17.599
	Route 2	312.031	13.523
	Route 3	194.039	15.389
	Route 4	185.089	8.880
	LRV-north	361.688	8.415
	LRV-south	350.804	9.966
Delay	Route 1	197.316	17.599
	Route 2	175.867	13.523
	Route 3	115.710	15.389
	Route 4	116.986	8.880
	LRV-north	225.823	8.415
	LRV-south	207.860	9.966

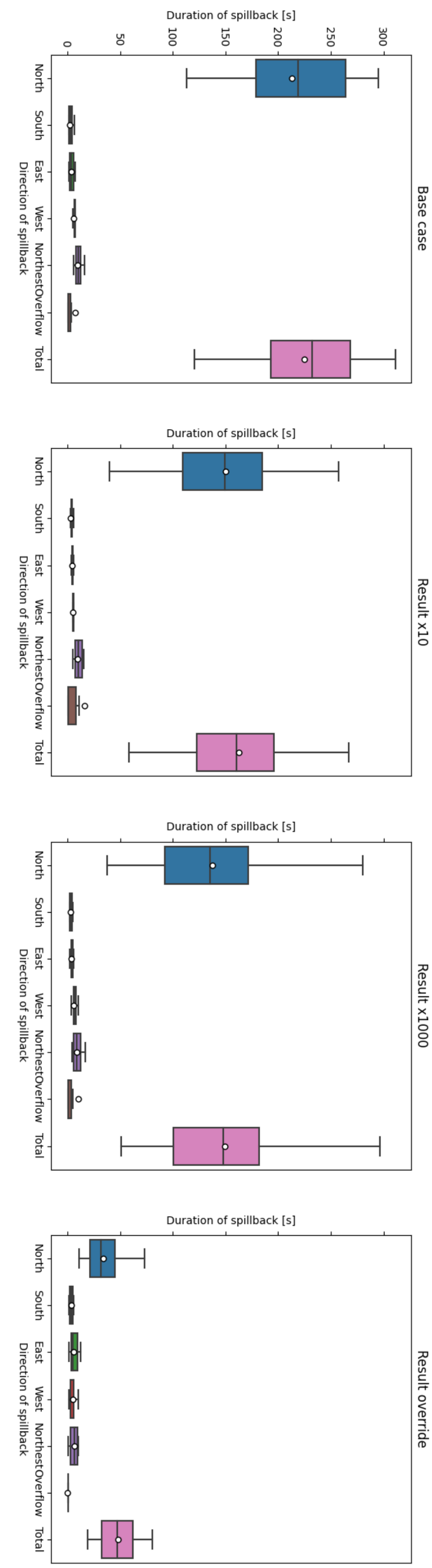

Figure E.1: Spillback duration [s]

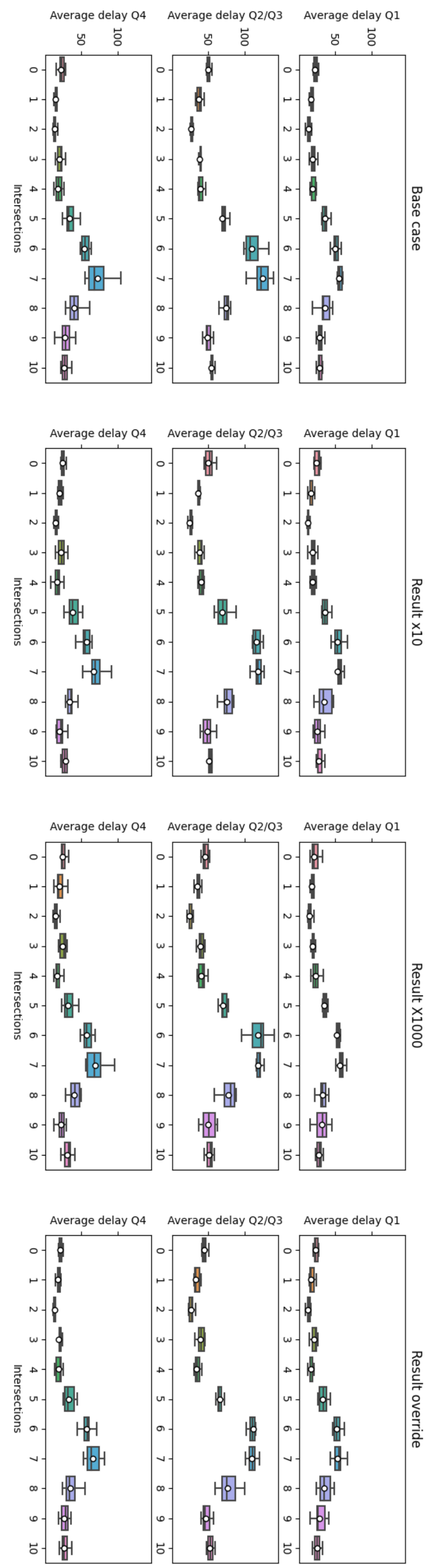

Figure E.2: Intersection delays [s]

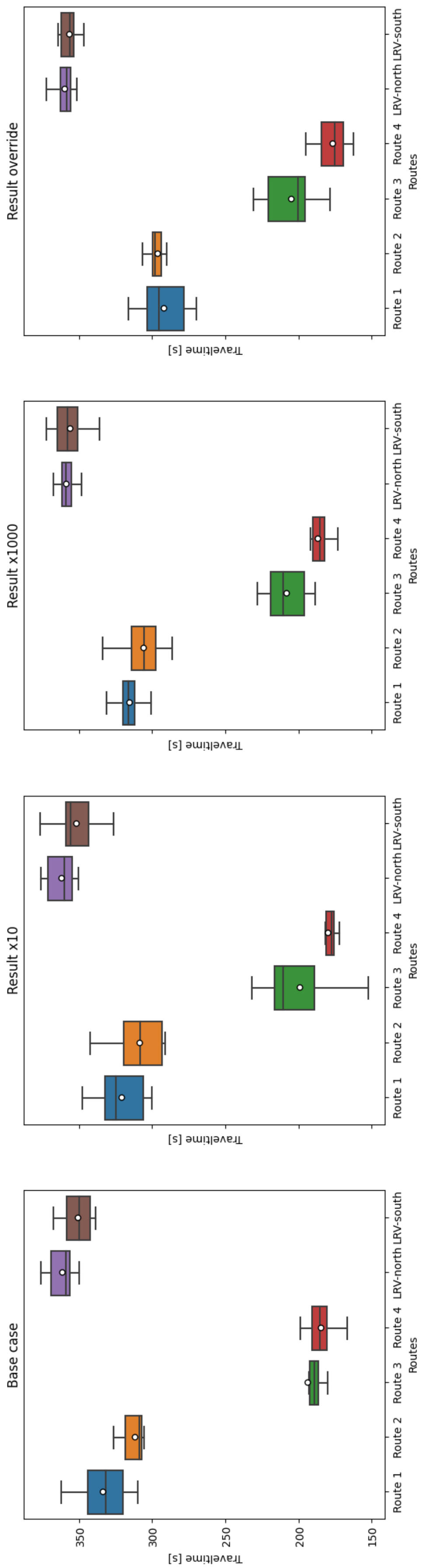

Figure E.3: Travel time [s]

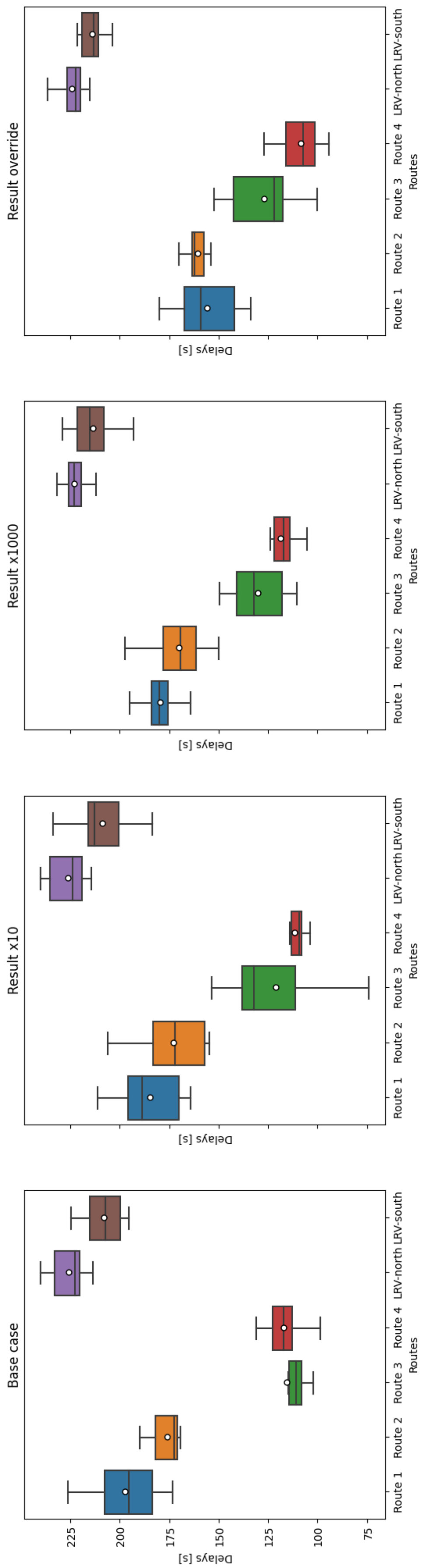

Figure E.4: Delay [s]

Table E.2: Basecase delay per intersection [s]

	Mean Q1	Std.dev	Mean Q2/Q3	Std.dev	Mean Q4	Std.dev
0. 3rd_channel	22.519	2.770	50.589	5.409	22.648	4.350
1. 3rd_missionrock	17.281	3.378	37.667	3.790	15.765	2.918
2. 3rd_missionbaynorth	13.553	2.442	26.548	1.433	13.918	2.351
3. 3rd_missionbaysouth	19.905	3.948	38.932	2.635	20.966	4.124
4. 3rd_warriorsway	19.138	3.009	39.173	3.814	18.678	4.501
5. 3rd_campus	36.226	5.553	69.542	5.674	33.962	7.202
6. 3rd_16th	50.385	4.506	109.597	11.330	54.735	5.395
7. 3rd_mariposa	55.729	2.937	124.208	16.296	72.581	16.995
8. 3rd_18th	36.552	10.746	74.679	7.445	40.660	9.385
9. 3rd_19th	28.652	3.419	48.843	4.691	28.084	8.549
10. 3rd_20th	29.034	5.203	54.664	1.739	27.249	4.522

E.1.2. Result X10

Table E.3: Overview KPIs

	KPIs	Mean	Std.dev	t-value	dF	Significant?
Spillback	Overflow	15.780	31.003	-2.484	8.536	Yes: ($p < 0.05$)
	North	150.155	66.698	6.825	4.957	Yes: ($p < 0.05$)
	South	3.058	1.075	-3.250	24.551	Yes: ($p < 0.05$)
	East	4.182	1.447	-4.273	20.198	Yes: ($p < 0.05$)
	West	4.923	2.268	3.166	12.438	Yes: ($p < 0.05$)
	Total	162.318	64.597	6.883	4.720	Yes: ($p < 0.05$)
Travel time	Route 1	321.052	15.927	5.252	3.787	Yes: ($p < 0.05$)
	Route 2	308.889	17.208	1.436	6.651	($p < 0.25$)
	Route 3	199.520	26.666	-1.780	8.139	($p < 0.25$)
	Route 4	179.806	10.231	3.899	6.155	Yes: ($p < 0.05$)
	LRV-north	362.208	9.199	-0.416	5.817	No
	LRV-south	351.800	14.789	-0.559	7.616	No
Delay	Route 1	184.850	15.927	5.252	3.787	Yes: ($p < 0.05$)
	Route 2	172.725	17.208	1.436	6.651	($p < 0.25$)
	Route 3	121.191	26.666	-1.780	8.139	($p < 0.25$)
	Route 4	111.704	10.231	3.899	6.155	Yes: ($p < 0.05$)
	LRV-north	226.343	9.199	-0.416	5.817	No
	LRV-south	208.856	14.789	-0.559	7.616	No

Table E.4: Delays per intersection [s]

	Mean	Std.dev	t-value	dF	Significant?
0. 3rd_channel	25.195	3.923	-5.572	9.543	Yes: (p < 0.05)
1. 3rd_missionrock	17.207	3.302	0.157	8.417	No
2. 3rd_missionbaynorth	12.855	1.427	2.468	14.457	Yes: (p < 0.05)
3. 3rd_missionbaysouth	19.748	4.324	0.269	7.676	No
4. 3rd_warriorsway	19.259	2.653	-0.301	9.585	No
5. 3rd_campus	35.993	4.327	0.331	4.557	No
6. 3rd_16th	53.332	6.961	-3.554	8.318	Yes: (p < 0.05)
7. 3rd_mariposa	53.734	7.289	2.539	9.037	Yes: (p < 0.05)
8. 3rd_18th	35.174	9.595	0.957	3.974	No
9. 3rd_19th	26.259	5.457	3.716	8.826	Yes: (p < 0.05)
10. 3rd_20th	27.962	4.293	1.589	5.123	(p < 0.25)
0. 3rd_channel	50.712	5.297	-0.163	5.915	No
1. 3rd_missionrock	36.093	2.518	3.461	6.712	Yes: (p < 0.05)
2. 3rd_missionbaynorth	25.259	2.247	4.836	13.944	Yes: (p < 0.05)
3. 3rd_missionbaysouth	38.280	4.012	1.359	9.622	(p < 0.25)
4. 3rd_warriorsway	40.399	3.101	-2.495	7.043	Yes: (p < 0.05)
5. 3rd_campus	69.670	9.109	-0.119	8.188	No
6. 3rd_16th	115.513	5.816	-4.645	1.240	(p < 0.1)
7. 3rd_mariposa	118.337	7.512	3.272	0.713	No
8. 3rd_18th	75.392	14.191	-0.445	8.481	No
9. 3rd_19th	48.730	7.579	0.126	8.372	No
10. 3rd_20th	51.216	3.740	8.358	9.926	Yes: (p < 0.05)
0. 3rd_channel	24.683	3.495	-3.647	6.004	Yes: (p < 0.05)
1. 3rd_missionrock	20.239	3.593	-9.666	9.476	Yes: (p < 0.05)
2. 3rd_missionbaynorth	15.059	2.926	-3.040	11.142	Yes: (p < 0.05)
3. 3rd_missionbaysouth	22.593	5.489	-2.369	8.104	Yes: (p < 0.05)
4. 3rd_warriorsway	16.963	4.981	2.555	7.177	Yes: (p < 0.05)
5. 3rd_campus	38.309	8.356	-3.941	6.417	Yes: (p < 0.05)
6. 3rd_16th	57.971	12.298	-2.409	8.789	Yes: (p < 0.05)
7. 3rd_mariposa	67.647	13.357	2.282	2.711	(p < 0.25)
8. 3rd_18th	34.879	5.230	5.381	1.724	Yes: (p < 0.05)
9. 3rd_19th	21.044	5.007	7.106	2.049	Yes: (p < 0.05)
10. 3rd_20th	29.137	7.936	-2.067	8.562	(p < 0.1)

E.1.3. Result X1000

Table E.5: Overview KPIs

	KPIs	Mean	Std.dev	t-value	dF	Significant?
Spillback	Overflow	9.890	21.272	-1.027	7.241	No
	North	137.279	69.282	8.059	5.291	Yes: ($p < 0.05$)
	South	2.626	1.130	-1.214	24.209	($p < 0.25$)
	East	3.422	1.408	-1.158	20.472	No
	West	5.949	2.226	0.097	12.545	No
	North Corridor	8.669	4.639	1.716	8.635	($p < 0.25$)
	Total	149.276	70.550	7.944	5.495	Yes: ($p < 0.05$)
Travel time	Route 1	315.756	8.733	9.040	0.788	($p < 0.25$)
	Route 2	306.224	14.450	2.934	5.307	Yes: ($p < 0.05$)
	Route 3	208.445	13.447	-7.049	3.554	Yes: ($p < 0.05$)
	Route 4	186.878	10.139	-1.327	6.089	($p < 0.25$)
	LRV-north	358.742	5.677	2.902	2.598	($p < 0.1$)
	LRV-south	356.450	10.807	-3.841	5.603	Yes: ($p < 0.05$)
Delay	Route 1	179.554	8.733	9.040	0.788	($p < 0.25$)
	Route 2	170.060	14.450	2.934	5.307	Yes: ($p < 0.05$)
	Route 3	130.116	13.447	-7.049	3.554	Yes: ($p < 0.05$)
	Route 4	118.775	10.139	-1.327	6.089	($p < 0.25$)
	LRV-north	222.877	5.677	2.902	2.598	($p < 0.1$)
	LRV-south	213.506	10.807	-3.841	5.603	Yes: ($p < 0.05$)

Table E.6: Delays per intersection [s]

	Mean	Std.dev	t-value	dF	Significant?
3rd_channel	22.008	5.267	0.858	9.194	No
3rd_missionrock	18.552	3.033	-2.800	8.324	Yes: (p < 0.05)
3rd_missionbaynorth	14.962	2.735	-3.842	11.367	Yes: (p < 0.05)
3rd_missionbaysouth	18.921	2.952	1.995	6.542	(p < 0.1)
3rd_warriorsway	23.147	5.746	-6.180	9.066	Yes: (p < 0.05)
3rd_campus	35.730	5.986	0.608	6.413	No
3rd_16th	52.534	5.163	-3.137	7.323	Yes: (p < 0.05)
3rd_mariposa	56.910	6.179	-1.726	9.070	(p < 0.25)
3rd_18th	33.315	7.744	2.444	2.525	(p < 0.25)
3rd_19th	31.772	9.433	-3.109	8.978	Yes: (p < 0.05)
3rd_20th	28.250	4.400	1.150	5.245	No
3rd_channel	45.752	4.010	7.184	4.451	Yes: (p < 0.05)
3rd_missionrock	35.449	3.289	4.421	7.256	Yes: (p < 0.05)
3rd_missionbaynorth	24.746	2.497	6.259	12.406	Yes: (p < 0.05)
3rd_missionbaysouth	39.788	3.752	-1.867	9.776	(p < 0.1)
3rd_warriorsway	41.021	5.427	-2.786	8.448	Yes: (p < 0.05)
3rd_campus	70.360	4.352	-1.145	4.391	No
3rd_16th	117.904	12.911	-4.836	5.911	Yes: (p < 0.05)
3rd_mariposa	118.461	6.107	3.303	0.506	No
3rd_18th	77.457	9.798	-2.257	7.156	(p < 0.1)
3rd_19th	50.411	8.891	-1.560	8.647	(p < 0.25)
3rd_20th	51.594	4.886	5.920	9.328	Yes: (p < 0.05)
3rd_channel	24.468	4.458	-2.922	6.982	Yes: (p < 0.05)
3rd_missionrock	20.315	5.272	-7.552	9.135	Yes: (p < 0.05)
3rd_missionbaynorth	14.905	2.761	-2.722	11.509	Yes: (p < 0.05)
3rd_missionbaysouth	24.569	4.259	-6.076	7.266	Yes: (p < 0.05)
3rd_warriorsway	17.791	4.022	1.470	6.217	(p < 0.25)
3rd_campus	32.556	8.036	1.303	6.152	(p < 0.25)
3rd_16th	57.835	6.733	-3.593	7.276	Yes: (p < 0.05)
3rd_mariposa	68.847	12.119	1.789	2.097	(p < 0.25)
3rd_18th	40.290	7.632	0.305	3.450	No
3rd_19th	22.800	7.273	4.708	3.903	Yes: (p < 0.05)
3rd_20th	31.202	5.737	-5.411	7.720	Yes: (p < 0.05)

E.1.4. Result override

Table E.7: Overview KPIs

	KPIs	Mean	Std.dev	t-value	dF	Significant?
Spillback	Overflow	0.000	0.000	4.760	0.392	No
	North	33.894	19.772	26.945	0.106	No
	South	3.323	2.983	-2.736	11.230	Yes: $(p < 0.05)$
	East	5.611	3.778	-5.802	9.973	Yes: $(p < 0.05)$
	West	4.988	3.664	2.252	9.995	Yes: $(p < 0.05)$
	Total	47.816	20.713	26.595	0.126	No
Travel time	Route 1	292.156	16.101	17.340	3.878	Yes: $(p < 0.05)$
	Route 2	296.594	6.215	10.372	0.856	$(p < 0.1)$
	Route 3	205.206	17.082	-4.857	5.577	Yes: $(p < 0.05)$
	Route 4	176.679	10.602	6.081	6.408	Yes: $(p < 0.05)$
	LRV-north	360.115	7.504	1.395	4.266	$(p < 0.25)$
	LRV-south	356.738	5.919	-5.120	1.802	Yes: $(p < 0.05)$
Delay	Route 1	155.955	16.101	17.340	3.878	Yes: $(p < 0.05)$
	Route 2	160.430	6.215	10.372	0.856	$(p < 0.1)$
	Route 3	126.877	17.082	-4.857	5.577	Yes: $(p < 0.05)$
	Route 4	108.576	10.602	6.081	6.408	Yes: $(p < 0.05)$
	LRV-north	224.250	7.504	1.395	4.266	$(p < 0.25)$
	LRV-south	213.794	5.919	-5.120	1.802	Yes: $(p < 0.05)$

Table E.8: Delays per intersection [s]

	Mean	**Std.dev**	**t-value**	**dF**	**Significant?**
0. 3rd_channel	23.499	2.499	-2.628	10.641	Yes: (p < 0.05)
1. 3rd_missionrock	17.478	3.597	-0.399	8.512	No
2. 3rd_missionbaynorth	13.207	2.139	1.065	12.836	No
3. 3rd_missionbaysouth	21.092	3.580	-2.228	7.074	(p < 0.1)
4. 3rd_warriorsway	17.590	3.364	3.429	9.366	Yes: (p < 0.05)
5. 3rd_campus	33.543	5.996	3.283	6.423	Yes: (p < 0.05)
6. 3rd_16th	52.438	5.894	-2.768	7.837	Yes: (p < 0.05)
7. 3rd_mariposa	53.282	7.076	3.193	9.041	Yes: (p < 0.05)
8. 3rd_18th	35.585	8.009	0.721	2.718	No
9. 3rd_19th	28.966	7.678	-0.374	8.951	No
10. 3rd_20th	25.390	5.529	4.800	6.506	Yes: (p < 0.05)
0. 3rd_channel	44.380	3.214	9.869	3.733	Yes: (p < 0.05)
1. 3rd_missionrock	33.751	3.502	7.590	7.419	Yes: (p < 0.05)
2. 3rd_missionbaynorth	26.838	3.125	-0.845	10.474	No
3. 3rd_missionbaysouth	39.377	4.808	-0.812	9.328	No
4. 3rd_warriorsway	34.651	3.256	9.018	7.163	Yes: (p < 0.05)
5. 3rd_campus	65.610	5.637	4.916	5.858	Yes: (p < 0.05)
6. 3rd_16th	112.244	12.509	-1.568	5.661	(p < 0.25)
7. 3rd_mariposa	109.456	6.357	8.434	0.535	(p < 0.25)
8. 3rd_18th	76.646	14.251	-1.224	8.489	No
9. 3rd_19th	46.826	5.794	2.705	7.524	Yes: (p < 0.05)
10. 3rd_20th	52.275	4.075	5.392	9.666	Yes: (p < 0.05)
0. 3rd_channel	21.747	3.416	1.630	5.925	(p < 0.25)
1. 3rd_missionrock	18.847	2.488	-8.038	10.028	Yes: (p < 0.05)
2. 3rd_missionbaynorth	13.773	2.473	0.425	12.273	No
3. 3rd_missionbaysouth	19.760	3.355	2.269	6.422	(p < 0.1)
4. 3rd_warriorsway	19.270	4.341	-0.947	6.557	No
5. 3rd_campus	33.324	7.527	0.612	5.688	No
6. 3rd_16th	57.630	8.204	-2.948	8.069	Yes: (p < 0.05)
7. 3rd_mariposa	65.984	10.340	3.316	1.359	(p < 0.25)
8. 3rd_18th	35.071	9.637	4.155	5.222	Yes: (p < 0.05)
9. 3rd_19th	27.294	5.855	0.762	2.633	No
10. 3rd_20th	26.931	6.080	0.420	7.923	No

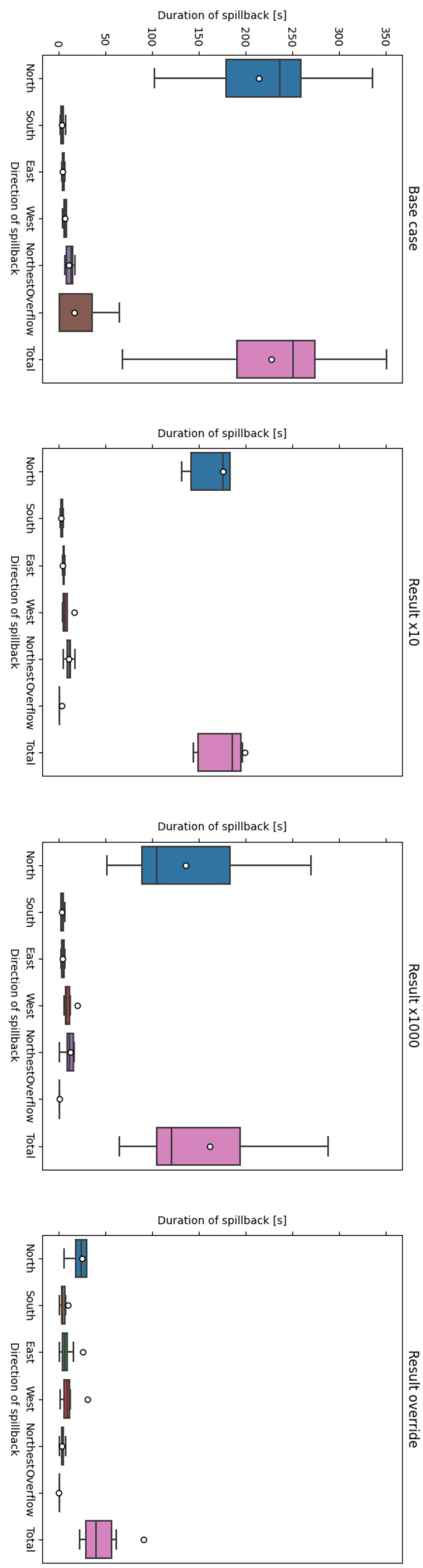

Figure E.5: Spillback duration [s]

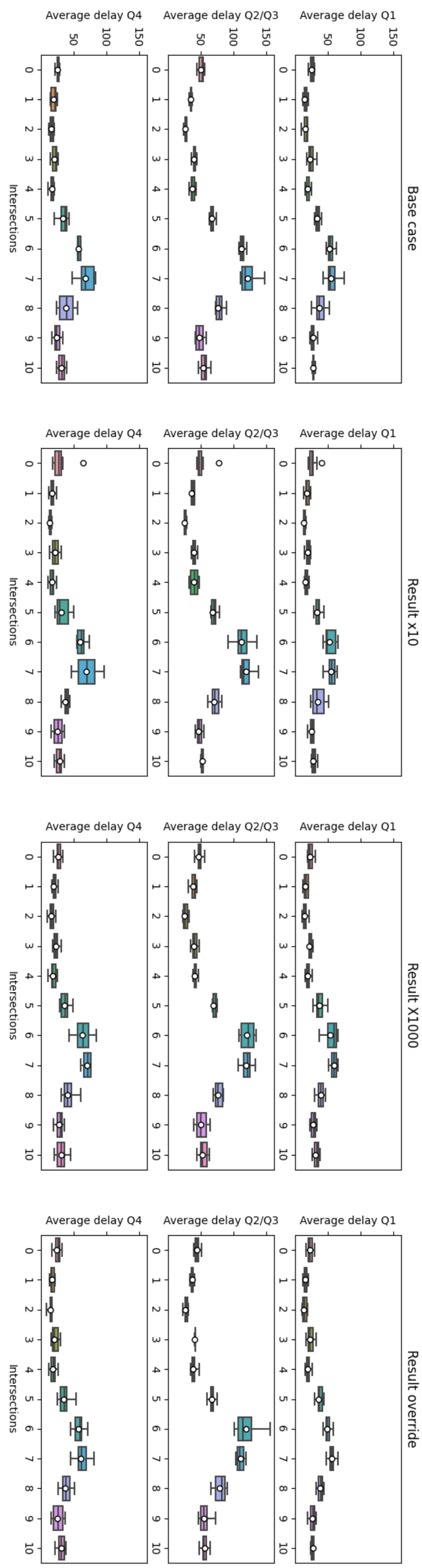

Figure E.6: Intersection delays [s]

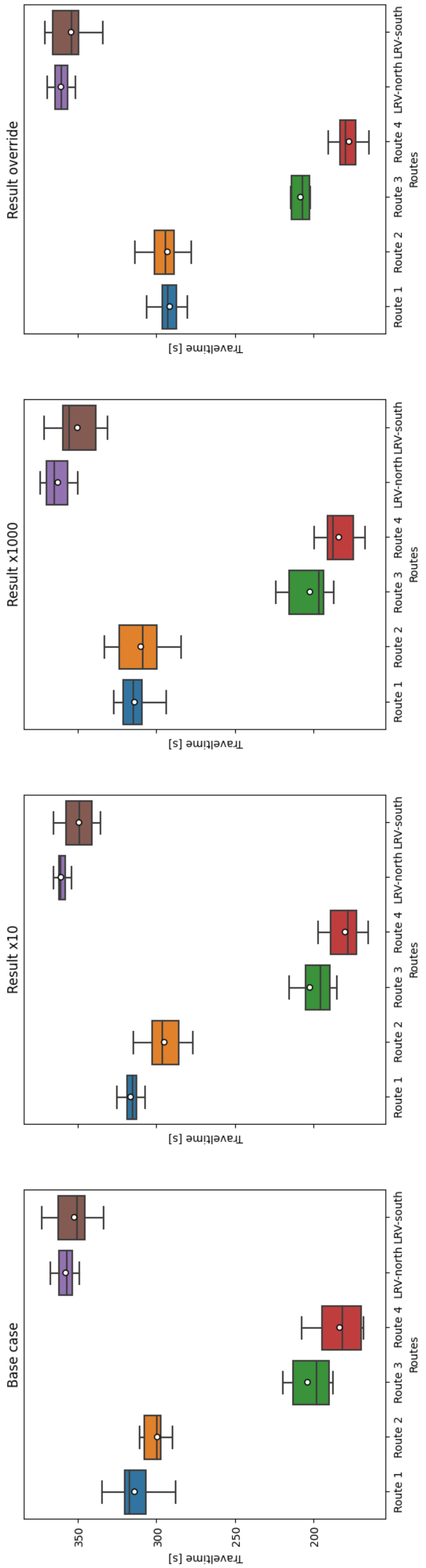

Figure E.7: Travel time [s]

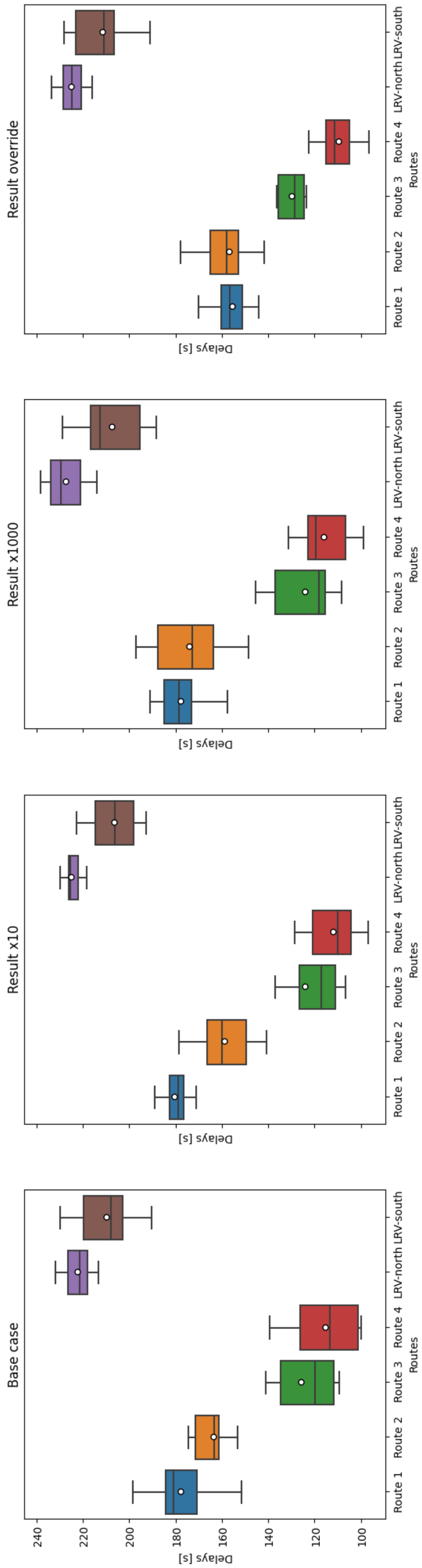

Figure E.8: Delay [s]

E.2. TFE demand 1.0 corridor priority

Table E.9: Overview KPIs of basecase

	KPIs	Mean	Std.dev
Spillback	Overflow	16.541	26.147
	North	214.098	85.964
	South	2.954	1.718
	East	4.043	1.300
	West	6.090	1.893
	North Corridor	10.988	3.994
	Total	227.185	86.732
Travel time	Route 1	314.114	12.905
	Route 2	299.906	9.268
	Route 3	204.104	19.214
	Route 4	183.603	14.843
	LRV-north	358.131	6.351
	LRV-south	352.765	13.027
Delay	Route 1	177.913	12.905
	Route 2	163.742	9.268
	Route 3	125.775	19.214
	Route 4	115.501	14.843
	LRV-north	222.266	6.351
	LRV-south	209.821	13.027

Table E.10: Basecase delay per intersection [s]

	Mean Q1	Std.dev	Mean Q2/Q3	Std.dev	Mean Q4	Std.dev
0. 3rd_channel	24.765	3.222	49.494	3.511	24.599	2.391
1. 3rd_missionrock	14.742	2.554	34.812	3.450	18.659	4.212
2. 3rd_missionbaynorth	15.027	3.356	25.995	2.367	15.390	3.193
3. 3rd_missionbaysouth	22.995	5.116	38.899	2.590	20.897	5.019
4. 3rd_warriorsway	19.501	3.995	37.382	4.619	16.209	4.723
5. 3rd_campus	33.220	4.787	66.779	7.004	32.973	8.161
6. 3rd_16th	52.826	5.051	111.584	4.488	57.659	10.413
7. 3rd_mariposa	54.890	9.747	120.981	11.577	68.442	11.949
8. 3rd_18th	36.554	8.557	76.455	8.111	37.714	12.076
9. 3rd_19th	26.757	4.790	47.603	6.283	23.746	5.133
10. 3rd_20th	27.356	2.949	54.079	5.468	30.641	5.660

E.2.1. Result X10

Table E.11: Overview KPIs

	KPIs	Mean	Std.dev	t-value	dF	Significant?
Spillback	Overflow	2.750	8.696	5.005	0.239	No
	North	175.981	70.486	3.429	2.810	Yes: ($p < 0.05$)
	South	2.401	1.353	2.528	24.514	Yes: ($p < 0.05$)
	East	3.823	1.192	1.247	34.920	($p < 0.25$)
	West	16.647	35.467	-2.972	9.	Yes: ($p < 0.05$)
	North Corridor	10.731	4.294	0.438	7.562	No
	Total	198.852	91.331	2.250	4.969	($p < 0.1$)
Travel time	Route 1	316.771	8.179	-1.739	1.716	($p < 0.25$)
	Route 2	295.183	12.833	2.984	7.299	Yes: ($p < 0.05$)
	Route 3	202.514	22.578	0.536	5.988	No
	Route 4	180.074	11.467	1.882	2.665	($p < 0.25$)
	LRV-north	361.073	8.076	-2.864	7.128	Yes: ($p < 0.05$)
	LRV-south	349.481	10.125	1.991	2.795	($p < 0.25$)
Delay	Route 1	180.570	8.179	-1.739	1.716	($p < 0.25$)
	Route 2	159.019	12.833	2.984	7.299	Yes: ($p < 0.05$)
	Route 3	124.186	22.578	0.536	5.988	No
	Route 4	111.971	11.467	1.882	2.665	($p < 0.25$)
	LRV-north	225.208	8.076	-2.864	7.128	Yes: ($p < 0.05$)
	LRV-south	206.537	10.125	1.991	2.795	($p < 0.25$)

Table E.12: Delays per intersection [s]

	Mean	Std.dev	t-value	dF	Significant?
0. 3rd_channel	23.740	3.651	2.104	8.876	(p < 0.1)
1. 3rd_missionrock	18.086	3.059	-8.392	10.569	Yes: (p < 0.05)
2. 3rd_missionbaynorth	13.587	1.044	4.098	7.998	Yes: (p < 0.05)
3. 3rd_missionbaysouth	19.075	3.449	6.353	4.391	Yes: (p < 0.05)
4. 3rd_warriorsway	16.339	2.879	6.420	6.352	Yes: (p < 0.05)
5. 3rd_campus	36.135	7.126	-3.395	8.142	Yes: (p < 0.05)
6. 3rd_16th	53.665	9.265	-0.795	8.556	No
7. 3rd_mariposa	55.867	7.193	-0.807	2.790	No
8. 3rd_18th	35.624	10.631	0.682	6.703	No
9. 3rd_19th	26.519	8.164	0.252	8.462	No
10. 3rd_20th	27.251	2.974	0.252	9.664	No
0. 3rd_channel	48.137	5.285	2.138	8.723	(p < 0.1)
1. 3rd_missionrock	37.800	2.766	-6.758	7.983	Yes: (p < 0.05)
2. 3rd_missionbaynorth	26.681	3.071	-1.769	10.842	(p < 0.25)
3. 3rd_missionbaysouth	40.659	6.104	-2.654	9.139	Yes: (p < 0.05)
4. 3rd_warriorsway	39.932	5.466	-3.564	7.385	Yes: (p < 0.05)
5. 3rd_campus	69.068	4.109	-2.819	2.594	(p < 0.1)
6. 3rd_16th	113.536	15.883	-1.183	8.971	No
7. 3rd_mariposa	120.306	10.101	0.439	3.727	No
8. 3rd_18th	71.307	5.726	5.185	2.886	Yes: (p < 0.05)
9. 3rd_19th	46.743	4.299	1.130	3.488	No
10. 3rd_20th	52.854	3.178	1.938	3.623	(p < 0.25)
0. 3rd_channel	25.379	6.256	-1.164	9.141	No
1. 3rd_missionrock	18.226	5.040	0.658	7.712	No
2. 3rd_missionbaynorth	14.616	3.124	1.732	8.911	(p < 0.25)
3. 3rd_missionbaysouth	21.269	5.653	-0.491	6.920	No
4. 3rd_warriorsway	15.971	4.149	0.378	5.888	No
5. 3rd_campus	32.459	9.908	0.401	6.590	No
6. 3rd_16th	58.694	10.415	-0.703	4.917	No
7. 3rd_mariposa	72.865	14.314	-2.373	6.264	(p < 0.1)
8. 3rd_18th	37.730	5.765	-0.012	1.031	No
9. 3rd_19th	23.840	8.407	-0.096	8.319	No
10. 3rd_20th	28.069	8.142	2.594	7.828	Yes: (p < 0.05)

E.2.2. Result X1000

Table E.13: Overview KPIs

	KPIs	Mean	Std.dev	t-value	dF	Significant?
Spillback	Overflow	0.987	3.121	5.907	0.133	No
	North	135.464	75.456	6.875	3.360	Yes: ($p < 0.05$)
	South	2.797	1.460	0.696	23.118	No
	East	3.609	1.342	2.323	29.712	Yes: ($p < 0.05$)
	West	19.749	29.120	-4.681	9.000	Yes: ($p < 0.05$)
	North Corridor	12.287	10.392	-1.167	8.928	No
	Total	161.619	88.121	5.303	4.649	Yes: ($p < 0.05$)
Travel time	Route 1	314.101	9.624	0.008	2.539	No
	Route 2	310.179	15.622	-5.656	8.124	Yes: ($p < 0.05$)
	Route 3	202.391	13.608	0.727	2.004	No
	Route 4	184.245	10.679	-0.351	2.224	No
	LRV-north	363.196	8.623	-4.730	7.461	Yes: ($p < 0.05$)
	LRV-south	350.454	13.620	1.226	5.141	No
Delay	Route 1	177.900	9.624	0.008	2.539	No
	Route 2	174.015	15.622	-5.656	8.124	Yes: ($p < 0.05$)
	Route 3	124.063	13.608	0.727	2.004	No
	Route 4	116.142	10.679	-0.351	2.224	No
	LRV-north	227.331	8.623	-4.730	7.461	Yes: ($p < 0.05$)
	LRV-south	207.510	13.620	1.226	5.141	No

Table E.14: Delays per intersection [s]

	Mean	Std.dev	t-value	dF	Significant?
0. 3rd_channel	22.184	4.024	5.005	8.904	Yes: (p < 0.05)
1. 3rd_missionrock	15.575	3.417	-1.953	10.141	(p < 0.1)
2. 3rd_missionbaynorth	13.885	2.797	2.615	8.318	Yes: (p < 0.05)
3. 3rd_missionbaysouth	21.639	3.779	2.131	4.714	(p < 0.1)
4. 3rd_warriorsway	18.996	3.316	0.973	6.720	No
5. 3rd_campus	36.359	6.461	-3.903	7.825	Yes: (p < 0.05)
6. 3rd_16th	53.572	10.138	-0.659	8.682	No
7. 3rd_mariposa	59.136	7.575	-3.440	3.100	Yes: (p < 0.05)
8. 3rd_18th	39.313	9.758	-2.126	6.112	(p < 0.1)
9. 3rd_19th	26.839	3.577	-0.137	5.127	No
10. 3rd_20th	31.120	4.061	-7.501	9.294	Yes: (p < 0.05)
0. 3rd_channel	46.647	4.380	5.073	8.504	Yes: (p < 0.05)
1. 3rd_missionrock	38.125	4.075	-6.205	8.513	Yes: (p < 0.05)
2. 3rd_missionbaynorth	25.530	3.531	1.094	10.186	No
3. 3rd_missionbaysouth	39.633	4.485	-1.416	9.442	(p < 0.25)
4. 3rd_warriorsway	40.609	2.506	-6.142	4.599	Yes: (p < 0.05)
5. 3rd_campus	69.456	4.547	-3.205	2.916	(p < 0.1)
6. 3rd_16th	120.333	10.119	-7.904	8.831	Yes: (p < 0.05)
7. 3rd_mariposa	118.873	7.830	1.508	2.112	No
8. 3rd_18th	75.965	5.909	0.488	3.045	No
9. 3rd_19th	49.512	9.188	-1.715	7.794	(p < 0.25)
10. 3rd_20th	52.741	5.985	1.651	6.540	(p < 0.25)
0. 3rd_channel	25.847	3.944	-2.705	9.803	Yes: (p < 0.05)
1. 3rd_missionrock	19.351	3.635	-1.244	6.473	No
2. 3rd_missionbaynorth	15.403	3.830	-0.026	8.944	No
3. 3rd_missionbaysouth	22.412	4.160	-2.323	5.312	(p < 0.1)
4. 3rd_warriorsway	17.763	4.339	-2.423	6.101	(p < 0.1)
5. 3rd_campus	35.534	6.447	-2.462	3.495	(p < 0.1)
6. 3rd_16th	63.022	11.970	-3.380	6.025	Yes: (p < 0.05)
7. 3rd_mariposa	70.388	9.452	-1.277	2.986	No
8. 3rd_18th	40.971	9.275	-2.139	2.781	(p < 0.25)
9. 3rd_19th	27.634	5.343	-5.248	6.433	Yes: (p < 0.05)
10. 3rd_20th	31.204	10.924	-0.457	8.584	No

E.2.3. Result override

Table E.15: Overview KPIs

	KPIs	Mean	Std.dev	t-value	dF	Significant?
Spillback	Overflow	0.000	0.000	6.326	0.132	No
1	North	24.473	14.901	21.735	0.020	No
2	South	10.081	21.089	-3.368	9.001	Yes: ($p < 0.05$)
3	East	25.479	63.019	-3.401	9.000	Yes: ($p < 0.05$)
4	West	30.968	58.970	-4.217	9.000	Yes: ($p < 0.05$)
5	North Corridor	3.127	2.066	17.481	5.866	Yes: ($p < 0.05$)
6	Total	91.001	123.047	9.046	7.221	Yes: ($p < 0.05$)
Travel time	Route 1	291.624	13.603	11.994	5.214	Yes: ($p < 0.05$)
1	Route 2	293.188	13.944	4.013	7.702	Yes: ($p < 0.05$)
2	Route 3	208.347	25.600	-1.326	6.891	($p < 0.25$)
3	Route 4	177.741	8.298	3.448	1.173	($p < 0.25$)
4	LRV-north	360.908	5.896	-3.204	5.116	Yes: ($p < 0.05$)
5	LRV-south	354.512	12.731	-0.959	4.570	No
Delay	Route 1	155.423	13.603	11.994	5.214	Yes: ($p < 0.05$)
1	Route 2	157.024	13.944	4.013	7.702	Yes: ($p < 0.05$)
2	Route 3	130.018	25.600	-1.326	6.891	($p < 0.25$)
3	Route 4	109.638	8.298	3.448	1.173	($p < 0.25$)
4	LRV-north	225.043	5.896	-3.204	5.116	Yes: ($p < 0.05$)
5	LRV-south	211.567	12.731	-0.959	4.570	No

Table E.16: Delays per intersection [s]

	Mean	Std.dev	t-value	dF	Significant?
0. 3rd_channel	22.320	4.332	4.528	8.923	Yes: ($p < 0.05$)
1. 3rd_missionrock	15.572	4.401	-1.631	9.489	($p < 0.25$)
2. 3rd_missionbaynorth	13.520	2.981	3.359	8.377	Yes: ($p < 0.05$)
3. 3rd_missionbaysouth	22.453	5.758	0.704	6.865	No
4. 3rd_warriorsway	19.044	4.019	0.807	7.338	No
5. 3rd_campus	35.691	5.974	-3.227	7.519	Yes: ($p < 0.05$)
6. 3rd_16th	48.435	4.707	6.359	5.880	Yes: ($p < 0.05$)
7. 3rd_mariposa	55.436	6.878	-0.458	2.547	No
8. 3rd_18th	38.423	5.920	-1.797	2.678	($p < 0.25$)
9. 3rd_19th	25.586	4.093	1.858	5.687	($p < 0.25$)
10. 3rd_20th	27.004	4.656	0.640	9.187	No
0. 3rd_channel	43.731	4.982	9.455	8.664	Yes: ($p < 0.05$)
1. 3rd_missionrock	36.304	4.433	-2.657	8.615	Yes: ($p < 0.05$)
2. 3rd_missionbaynorth	26.396	3.454	-0.957	10.276	No
3. 3rd_missionbaysouth	40.713	3.630	-4.066	9.908	Yes: ($p < 0.05$)
4. 3rd_warriorsway	38.259	5.083	-1.277	7.062	($p < 0.25$)
5. 3rd_campus	66.087	5.479	0.778	3.787	No
6. 3rd_16th	119.498	19.232	-4.008	8.987	Yes: ($p < 0.05$)
7. 3rd_mariposa	110.852	8.758	6.978	2.726	Yes: ($p < 0.05$)
8. 3rd_18th	78.297	8.456	-1.572	5.501	($p < 0.25$)
9. 3rd_19th	54.907	8.158	-7.093	7.251	Yes: ($p < 0.05$)
10. 3rd_20th	55.869	7.861	-1.869	7.864	($p < 0.1$)
0. 3rd_channel	23.972	5.337	1.072	9.261	No
1. 3rd_missionrock	16.296	2.820	4.661	5.729	Yes: ($p < 0.05$)
2. 3rd_missionbaynorth	14.920	4.326	0.874	8.961	No
3. 3rd_missionbaysouth	20.610	4.989	0.406	6.254	No
4. 3rd_warriorsway	17.442	4.597	-1.871	6.383	($p < 0.25$)
5. 3rd_campus	34.662	8.488	-1.434	5.476	($p < 0.25$)
6. 3rd_16th	57.160	8.390	0.373	3.252	No
7. 3rd_mariposa	60.896	10.764	4.692	3.953	Yes: ($p < 0.05$)
8. 3rd_18th	37.523	8.551	0.129	2.301	No
9. 3rd_19th	24.930	8.047	-1.241	8.207	($p < 0.25$)
10. 3rd_20th	30.710	7.978	-0.071	7.749	No

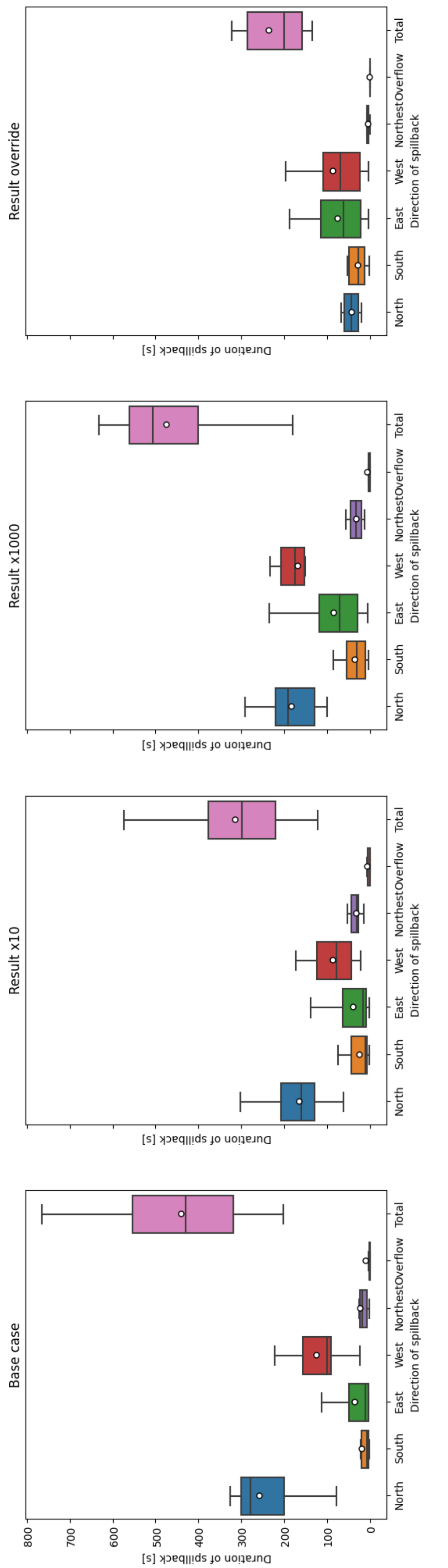

Figure E.9: Spillback duration [s]

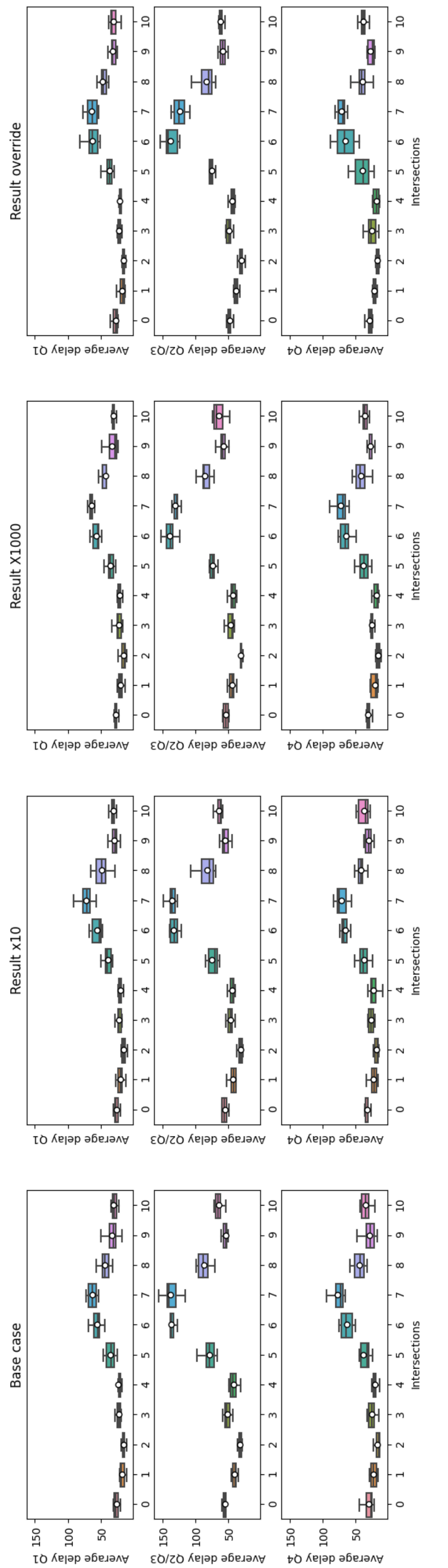

Figure E.10: Intersection delays [s]

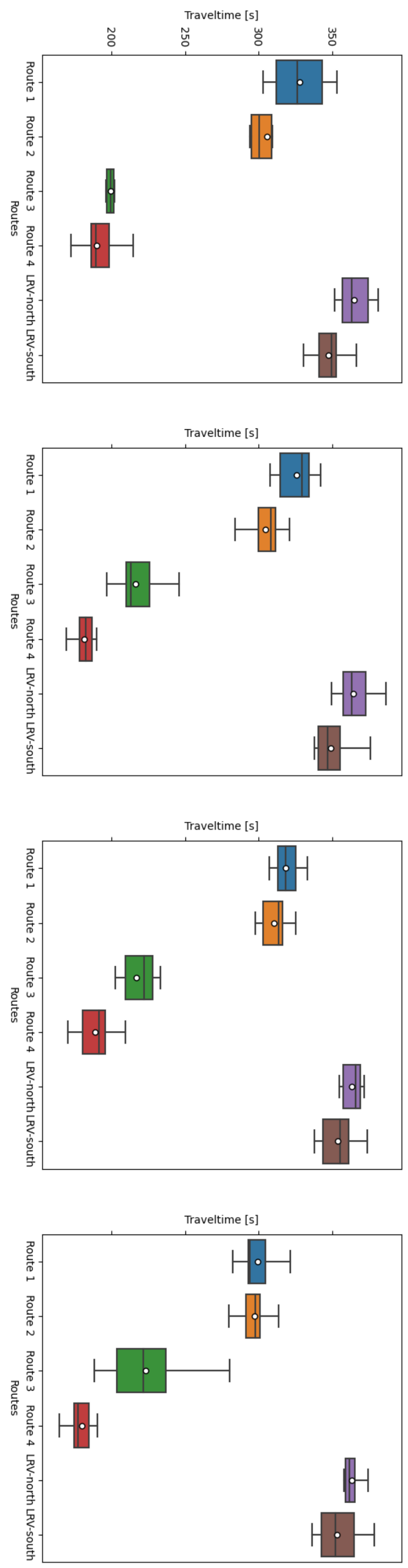

Figure E.11: Travel time routes [s]

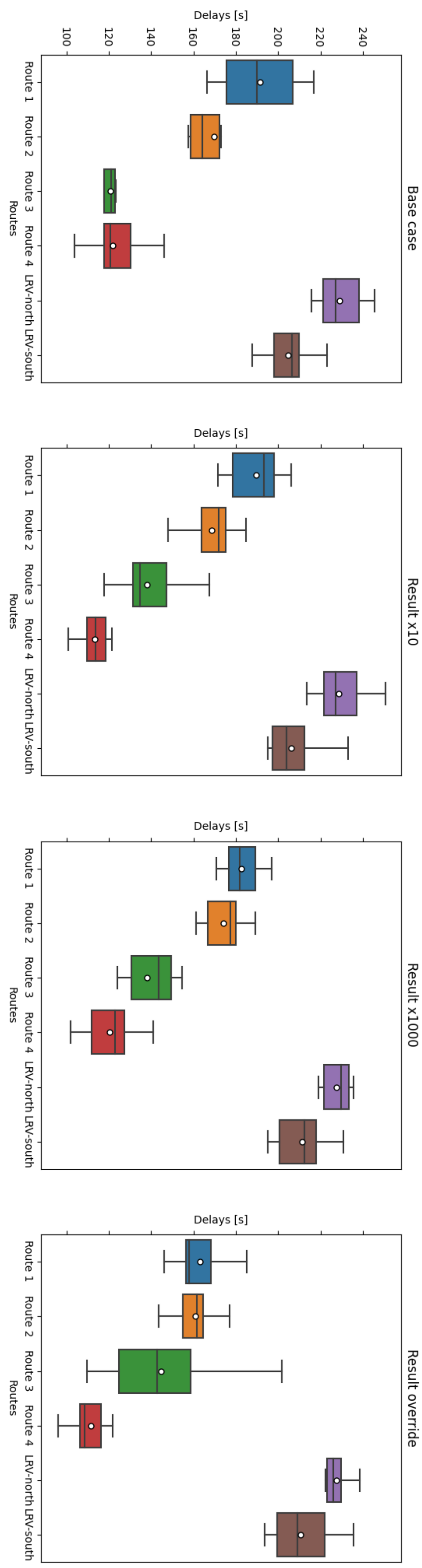

Figure E.12: Delay routes [s]

E.3. TFE demand 1.0 with additional bus mode

E.3.1. Base case scenario

Table E.17: Overview KPIs of basecase

	variable	Mean	Std.dev
Spillback	Overflow	10.975	26.905
	North	259.073	105.519
	South	18.698	25.003
	East	36.776	46.863
	West	126.104	84.328
	Total	440.651	174.616
Travel time	Route 1	327.819	18.762
	Route 2	305.765	15.194
	Route 3	199.254	18.371
	Route 4	189.943	12.984
	LRV-north	364.996	11.177
	LRV-south	347.796	10.329
Delay	Route 1	191.617	18.762
	Route 2	169.601	15.194
	Route 3	120.925	18.371
	Route 4	121.840	12.984
	LRV-north	229.131	11.177
	LRV-south	204.852	10.329

Table E.18: Base case delay per intersection [s]

	Mean Q1	Std.dev	Mean Q2/Q3	Std.dev	Mean Q4	Std.dev
0. 3rd_channel	26.174	3.777	54.309	6.113	29.184	6.681
1. 3rd_missionrock	17.187	3.666	39.648	3.560	21.864	5.084
2. 3rd_missionbaynorth	14.953	2.491	31.833	2.541	15.743	3.505
3. 3rd_missionbaysouth	22.401	3.267	50.721	5.021	24.777	5.657
4. 3rd_warriorsway	22.798	5.233	41.354	5.826	19.998	3.428
5. 3rd_campus	35.227	6.974	78.418	9.259	37.686	14.419
6. 3rd_16th	55.782	8.320	136.641	10.307	62.552	9.633
7. 3rd_mariposa	62.859	6.903	137.685	12.497	76.758	12.151
8. 3rd_18th	42.999	7.381	86.442	9.598	43.639	9.363
9. 3rd_19th	33.332	11.701	53.355	5.158	27.880	9.255
10. 3rd_20th	29.866	6.729	64.279	5.572	33.562	7.888

E.3.2. Result X10

Table E.19: Overview KPIs

	variable	**Mean**	**Std.dev**	**t-value**	**dF**	**Significant?**
Spillback	Overflow	7.365	15.659	1.160	1.038	No
	North	164.590	69.788	7.468	1.452	Yes: (p < 0.05)
	South	24.257	26.705	-1.520	5.152	(p < 0.25)
	East	39.874	48.118	-0.461	4.757	No
	West	86.701	52.041	3.976	1.151	(p < 0.25)
	Total	315.422	137.631	5.632	2.508	Yes: (p < 0.05)
Travel time	Route 1	325.672	12.334	0.956	1.632	No
	Route 2	304.897	10.694	0.467	2.086	No
	Route 3	216.421	14.193	-7.395	2.560	Yes: (p < 0.05)
	Route 4	181.423	6.455	5.876	1.021	(p < 0.25)
	LRV-north	364.631	11.305	0.230	4.955	No
	LRV-south	349.258	11.909	-0.927	6.053	No
Delay	Route 1	189.471	12.334	0.956	1.632	No
	Route 2	168.733	10.694	0.467	2.086	No
	Route 3	138.092	14.193	-7.395	2.560	Yes: (p < 0.05)
	Route 4	113.320	6.455	5.876	1.021	(p < 0.25)
	LRV-north	228.766	11.305	0.230	4.955	No
	LRV-south	206.314	11.909	-0.927	6.053	No

Table E.20: Delays per intersection [s]

	Mean	Std.dev	t-value	dF	Significant?
0. 3rd_channel	25.592	3.154	1.183	7.188	No
1. 3rd_missionrock	19.438	5.037	-3.613	8.495	Yes: (p < 0.05)
2. 3rd_missionbaynorth	14.658	3.399	0.699	10.233	No
3. 3rd_missionbaysouth	21.723	4.074	1.299	8.835	(p < 0.25)
4. 3rd_warriorsway	20.203	2.920	4.330	3.792	Yes: (p < 0.05)
5. 3rd_campus	39.217	6.159	-4.289	4.555	Yes: (p < 0.05)
6. 3rd_16th	55.304	7.849	0.418	4.703	No
7. 3rd_mariposa	72.110	10.698	-7.266	7.950	Yes: (p < 0.05)
8. 3rd_18th	48.601	11.040	-4.219	7.776	Yes: (p < 0.05)
9. 3rd_19th	28.766	5.768	3.500	1.123	(p < 0.25)
10. 3rd_20th	30.437	4.611	-0.700	3.254	No
0. 3rd_channel	54.603	4.293	-0.394	3.698	No
1. 3rd_missionrock	42.099	5.110	-3.936	8.638	Yes: (p < 0.05)
2. 3rd_missionbaynorth	30.596	3.327	2.953	10.253	Yes: (p < 0.05)
3. 3rd_missionbaysouth	46.082	4.573	6.831	5.783	Yes: (p < 0.05)
4. 3rd_warriorsway	43.750	3.446	-3.540	3.344	Yes: (p < 0.05)
5. 3rd_campus	74.917	13.887	2.098	7.688	(p < 0.1)
6. 3rd_16th	133.178	9.646	2.454	4.386	(p < 0.1)
7. 3rd_mariposa	135.046	6.400	1.880	1.118	No
8. 3rd_18th	82.080	12.645	2.747	7.001	Yes: (p < 0.05)
9. 3rd_19th	54.045	6.487	-0.832	7.395	No
10. 3rd_20th	63.271	4.489	1.409	4.707	(p < 0.25)
0. 3rd_channel	31.533	3.908	-3.036	2.748	(p < 0.1)
1. 3rd_missionrock	21.916	5.778	-0.068	6.932	No
2. 3rd_missionbaynorth	17.462	2.984	-3.734	7.901	Yes: (p < 0.05)
3. 3rd_missionbaysouth	25.504	4.060	-1.045	4.110	No
4. 3rd_warriorsway	22.114	6.675	-2.820	8.913	Yes: (p < 0.05)
5. 3rd_campus	36.872	8.108	0.492	1.211	No
6. 3rd_16th	65.326	10.906	-1.907	5.961	(p < 0.25)
7. 3rd_mariposa	71.044	9.381	3.722	2.809	Yes: (p < 0.05)
8. 3rd_18th	41.782	5.600	1.702	1.931	(p < 0.25)
9. 3rd_19th	29.488	5.573	-1.489	1.975	No
10. 3rd_20th	36.651	8.284	-2.700	5.592	Yes: (p < 0.05)

E.3.3. Result X1000

Table E.21: Overview KPIs

	KPIs	Mean	Std.dev	t-value	dF	Significant?
Spillback	Overflow	7.467	16.034	1.120	1.119	No
	North	184.137	63.098	6.095	1.027	($p < 0.1$)
	South	36.383	29.985	-4.530	6.114	Yes: ($p < 0.05$)
	East	86.045	75.220	-5.559	7.827	Yes: ($p < 0.05$)
	West	169.420	76.691	-3.800	3.663	Yes: ($p < 0.05$)
	Total	475.985	135.926	-1.597	2.419	($p < 0.25$)
Travel time	Route 1	318.650	9.512	4.359	0.798	($p < 0.25$)
	Route 2	310.391	8.987	-2.620	1.329	($p < 0.25$)
	Route 3	216.465	16.146	-7.037	3.530	Yes: ($p < 0.05$)
	Route 4	188.579	11.610	0.783	3.835	No
	LRV-north	363.535	6.448	1.133	1.546	No
	LRV-south	354.154	12.618	-3.899	6.473	Yes: ($p < 0.05$)
Delay	Route 1	182.448	9.512	4.359	0.798	($p < 0.25$)
	Route 2	174.227	8.987	-2.620	1.329	($p < 0.25$)
	Route 3	138.136	16.146	-7.037	3.530	Yes: ($p < 0.05$)
	Route 4	120.476	11.610	0.783	3.835	No
	LRV-north	227.670	6.448	1.133	1.546	No
	LRV-south	211.210	12.618	-3.899	6.473	Yes: ($p < 0.05$)

Table E.22: Delays per intersection [s]

	Mean	Std.dev	t-value	dF	Significant?
0. 3rd_channel	26.514	2.550	-0.747	6.771	No
1. 3rd_missionrock	19.247	3.702	-3.955	7.870	Yes: ($p < 0.05$)
2. 3rd_missionbaynorth	15.012	3.892	-0.129	9.791	No
3. 3rd_missionbaysouth	22.487	5.059	-0.143	8.916	No
4. 3rd_warriorsway	20.949	2.770	3.122	3.703	Yes: ($p < 0.05$)
5. 3rd_campus	34.718	5.886	0.558	4.258	No
6. 3rd_16th	56.406	6.185	-0.602	3.102	No
7. 3rd_mariposa	63.333	5.035	-0.555	3.458	No
8. 3rd_18th	42.435	9.246	0.476	6.878	No
9. 3rd_19th	32.223	9.072	0.749	2.872	No
10. 3rd_20th	30.171	3.619	-0.398	2.529	No
0. 3rd_channel	53.301	3.517	1.429	3.059	($p < 0.25$)
1. 3rd_missionrock	43.652	4.047	-7.428	8.289	Yes: ($p < 0.05$)
2. 3rd_missionbaynorth	30.440	2.774	3.703	11.041	Yes: ($p < 0.05$)
3. 3rd_missionbaysouth	45.724	5.075	7.001	6.343	Yes: ($p < 0.05$)
4. 3rd_warriorsway	42.286	4.337	-1.283	4.143	No
5. 3rd_campus	72.943	4.444	5.332	1.451	($p < 0.1$)
6. 3rd_16th	138.582	10.878	-1.295	5.361	($p < 0.25$)
7. 3rd_mariposa	130.191	9.297	4.811	2.551	Yes: ($p < 0.05$)
8. 3rd_18th	84.789	9.146	1.246	4.603	No
9. 3rd_19th	56.859	7.205	-3.954	7.831	Yes: ($p < 0.05$)
10. 3rd_20th	64.267	8.562	0.011	8.072	No
0. 3rd_channel	29.988	5.008	-0.963	3.691	No
1. 3rd_missionrock	20.324	5.313	2.094	6.483	($p < 0.1$)
2. 3rd_missionbaynorth	15.073	3.037	1.443	7.928	($p < 0.25$)
3. 3rd_missionbaysouth	24.463	3.604	0.468	3.688	No
4. 3rd_warriorsway	18.070	3.820	3.755	8.472	Yes: ($p < 0.05$)
5. 3rd_campus	37.170	8.380	0.310	1.310	No
6. 3rd_16th	64.145	9.090	-1.203	4.521	No
7. 3rd_mariposa	71.832	9.610	3.180	2.969	($p < 0.1$)
8. 3rd_18th	41.309	9.294	1.766	4.954	($p < 0.25$)
9. 3rd_19th	26.967	5.143	0.862	1.743	No
10. 3rd_20th	35.038	4.879	-1.592	2.411	($p < 0.25$)

E.3.4. Result override

Table E.23: Overview KPIs

	KPIs	Mean	Std.dev	t-value	dF	Significant?
Spillback	Overflow	0.835	2.641	3.751	0.125	No
	North	43.572	17.678	20.142	0.015	No
	South	28.147	20.450	-2.925	2.882	($p < 0.1$)
	East	76.614	68.262	-4.811	7.372	Yes: ($p < 0.05$)
	West	87.559	85.171	3.216	4.596	Yes: ($p < 0.05$)
	North Corridor	5.271	4.190	5.878	0.094	No
	Total	235.892	112.434	9.859	1.323	Yes: ($p < 0.05$)
Travel time	Route 1	299.192	12.388	12.733	1.652	Yes: ($p < 0.05$)
	Route 2	297.114	10.472	4.688	1.975	Yes: ($p < 0.05$)
	Route 3	223.055	27.139	-7.262	7.484	Yes: ($p < 0.05$)
	Route 4	179.484	12.077	5.898	4.158	Yes: ($p < 0.05$)
	LRV-north	363.585	6.537	1.090	1.588	No
	LRV-south	353.581	14.671	-3.224	7.391	Yes: ($p < 0.05$)
Delay	Route 1	162.991	12.388	12.733	1.652	Yes: ($p < 0.05$)
	Route 2	160.950	10.472	4.688	1.975	Yes: ($p < 0.05$)
	Route 3	144.726	27.139	-7.262	7.484	Yes: ($p < 0.05$)
	Route 4	111.381	12.077	5.898	4.158	Yes: ($p < 0.05$)
	LRV-north	227.720	6.537	1.090	1.588	No
	LRV-south	210.637	14.671	-3.224	7.391	Yes: ($p < 0.05$)

Table E.24: Delays per intersection [s]

	Mean	**Std.dev**	**t-value**	**dF**	**Significant?**
0. 3rd_channel	27.006	5.275	-1.281	8.439	(p < 0.25)
1. 3rd_missionrock	17.476	4.315	-0.510	8.211	No
2. 3rd_missionbaynorth	14.673	2.204	0.840	12.414	No
3. 3rd_missionbaysouth	22.605	4.043	-0.393	8.831	No
4. 3rd_warriorsway	20.890	3.790	2.953	4.519	Yes: (p < 0.05)
5. 3rd_campus	36.829	6.048	-1.736	4.434	(p < 0.25)
6. 3rd_16th	62.120	9.914	-4.896	6.447	Yes: (p < 0.05)
7. 3rd_mariposa	63.510	8.357	-0.601	6.741	No
8. 3rd_18th	46.514	7.923	-3.246	5.843	Yes: (p < 0.05)
9. 3rd_19th	32.168	6.689	0.863	1.463	No
10. 3rd_20th	30.340	6.285	-0.514	5.018	No
0. 3rd_channel	47.654	3.246	9.614	2.893	Yes: (p < 0.05)
1. 3rd_missionrock	37.461	2.895	4.766	7.678	Yes: (p < 0.05)
2. 3rd_missionbaynorth	29.635	3.487	5.093	10.086	Yes: (p < 0.05)
3. 3rd_missionbaysouth	48.645	4.373	3.119	5.553	Yes: (p < 0.05)
4. 3rd_warriorsway	43.683	4.410	-3.188	4.221	Yes: (p < 0.05)
5. 3rd_campus	75.055	5.286	3.155	1.813	(p < 0.1)
6. 3rd_16th	137.081	10.305	-0.302	4.922	No
7. 3rd_mariposa	123.685	9.872	8.791	2.937	Yes: (p < 0.05)
8. 3rd_18th	82.611	11.602	2.544	6.441	Yes: (p < 0.05)
9. 3rd_19th	57.439	5.301	-5.521	6.344	Yes: (p < 0.05)
10. 3rd_20th	61.207	5.419	3.952	5.779	Yes: (p < 0.05)
0. 3rd_channel	28.215	5.469	1.121	4.181	No
1. 3rd_missionrock	20.788	3.715	1.709	4.706	(p < 0.25)
2. 3rd_missionbaynorth	16.573	4.395	-1.477	8.517	(p < 0.25)
3. 3rd_missionbaysouth	24.917	7.467	-0.150	7.467	No
4. 3rd_warriorsway	18.021	4.314	3.587	8.617	Yes: (p < 0.05)
5. 3rd_campus	39.445	13.260	-0.898	4.005	No
6. 3rd_16th	65.086	15.382	-1.396	7.929	(p < 0.25)
7. 3rd_mariposa	70.645	6.663	4.411	1.305	(p < 0.1)
8. 3rd_18th	39.420	10.413	3.012	5.848	Yes: (p < 0.05)
9. 3rd_19th	27.172	8.995	0.548	4.799	No
10. 3rd_20th	37.393	5.358	-4.017	2.773	Yes: (p < 0.05)