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by

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**MULTILINE HOLDING CONTROL AND INTEGRATION OF
COOPERATIVE ITS**

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Acknowledgments

I still cannot believe it I made it this far. When I was taking the exams for the second time in order to enter to a university with transport related studies, I would never imagine writing the last words of my PhD dissertation. And here I am! These are the last lines of this thesis and the last words of a chapter that comes to an end and opens the door to the new one. It was back in April 2016 that everything started and now seems that all these happened in a blink of an eye. These years have been roller coaster with ups and downs but a journey worth taken and remembering for its every single moment. Last thing to be done is to express to my gratitude to all the people accompanied me to this journey.

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Σας ευχαριστώ από καρδιάς πάρα πολύ όλους!

Georgios Laskaris

Preface

Transportation is an important sector of the global economy. The rapid urbanization and urban sprawl comes with continuous demand for additional transportation infrastructure in order to satisfy the increasing and variable demand. Public transportation is a major contributor in alleviating traffic congestion in the modern megacities and provide a sustainable alternative to car for accessibility.

Public transport operation is inherently stochastic due to the high variability in travel times and passenger demand. This yields to disruptions and undesired phenomena such as vehicles arriving in platoons at stops. Due to the correlation between the headway between vehicles and passenger demand, bunching leads to long waiting time at stops, overcrowded vehicles, discomfort for the passengers and from the operators side poor management of available resources and overall a low of service of the system. The introduction of intelligent transport systems provided innovative applications in order to monitor the operation, collect data and react dynamically to any disruption of the transit system. Advanced Public Transport Systems extended the range of control strategies and their objectives beyond schedule adherence and reliance on historical data alone. Among strategies, holding is a thoroughly investigated and applicable control strategy. With holding, a vehicle is instructed to remain at a designated stop for an additional amount of time after the completion of dwell time, until a criterion is fulfilled. Depending on the characteristics of the line the criterion aim for schedule adherence or regularity or minimization of passenger costs and its components.

So far, holding is used for regulating single line operation. Beyond single line, it has been used for transfer synchronization at transfer hubs and recently has been extended to regulate the operation on consecutive stops that are served by multiple lines. The first part of this dissertation is dedicated to real time holding control of multiple lines. A rule based holding criterion is formulated based on the passenger travel time that accounts for the passengers experiencing the control action. Total holding time is estimated based on the size of all passenger groups that interact. The formulated criterion can be applied on all different parts of trunk and branch network. Additionally, the criterion is coupled with a rule based criterion for synchronization and the decision between the two is taken based on the passenger cost. The criterion has been tested for different trunk and branch networks and compared with different control schemes and its performance has been assessed using regularity indices as well as passenger cost indicators for the network in total but also per passenger group. Finally, an analysis has been conducted in order to define under which network and demand configuration multiline control can be preferred over single line control. Results

shown that under specific demand distributions multiline control can outperform single line control in network level.

Continuously new technologies are introduced to transit operation. Recently, Cooperative Intelligent Transport Systems utilized in the form of Driver Advisory Systems (DAS) shown that can provide the same level of priority with transit signal priority without changing the time and the phases of a traffic light. However, until now the available DASs focus exclusively on public transport priority neglecting completely the sequence of the vehicles and the effects on the operation. In the second part of the dissertation, two widely used DASs are combined with holding in order to meet both the objective of reducing the number of stops at traffic signals and at the same time maintain regularity. Two hybrid controllers are introduced, a combination of two holding criteria and a combination of holding and speed advisory. Both controllers are tested using simulation in comparison to the independent application of the controllers and different levels of transit signal priority. The hybrid controllers can drastically reduce transit signal priority requests while they manage to achieve both objectives.

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Notation

Acronyms:

AFC=Automated Fare Collection

APC=Automatic Passenger Counts

APTS=Advanced Public Transport Systems

AVL=Automatic Vehicle Location

C-ITS=Cooperative Intelligent Transport Systems

CV=Connected Vehicles

DAS=Driver Advisory Systems

DSRC=Dynamic Short Range Communication

GLODTA=Green Light Optimal Dwell Time Advisory

GLOSA=Green Light Optimal Speed Advisory

ITS=Intelligent Transport Systems

PT=Public Transport

SPaT=Signal Phase and Timing

TCP=Time Control Points

TSP=Transit Signal Priority

V2I=Vehicle to Infrastructure

V2V=Vehicle to Vehicle

Notations:*Sets*

I	set of lines;
J_i	set of stops served by line i ;
K_i	set of trips of line i ;
N_i	number of stops of line i ; and
N_i^w	number of stops of the subset w of line i .

Network related labels

c	index for the shared transit corridor;
b	index for the branches;
cb	index for the shared transit corridor to branch variables.

Time related variables

t_{ijk}^{arrival}	Arrival time at stop j of trip k of line i in [time units];
$t_{ijk}^{\text{arr,tl}}$	Arrival time at signalized intersection after stop j of trip k of line i in [time units];
t_{ijk}^{dwell}	Dwell time at stop j of trip k of line i in [time units];
t_{ijk}^{exit}	Exit (departure) time at stop j of trip k of line i in [time units];
τ^{transfer}	Transferring coefficient in [time units];
$\tau_{j-1,j}^{\text{riding}}$	Scheduled riding time between stops $j-1$ and j in [time units];
$t_{j-1,j}^{\text{riding}}$	Actual riding time between stops $j-1$ and j in [time units];
t_{ijk}^{hold}	Holding time at stop j of trip k of line i in [time units];
t^{Green}	Green time in [time units];
t^{Red}	Red time in [time units];
t^{GLODTA}	time assigned with GLODTA in [time units];
t^{TSP}	time
$h_{i,j,k,k-1}$	Actual headway at stop j between trips k and $k-1$ of line i in [time units];

\hat{h}_i	Planned headway of line i in [time units];
\hat{h}^{join}	Planned joint headway in [time units];
t_{ijk}^{wait}	Waiting time at stop j of trip k of line i in [time units];
$t_{ijk}^{\text{wait,tl}}$	Waiting time at traffic light after stop j of trip k of line i in [time units];
t_{ijk}^{inveh}	In vehicle time between stop j and $j+1$ of trip k of line i in [time units];
t_{ijk}^{travel}	Travel time between stop j and $j+1$ of trip k of line i in [time units];

Vehicle Related

V_k	Actual speed of vehicle k in [km/h];
V_k^{GLOSA}	GLOSA speed of vehicle k in [km/h];

Passenger related variables

o	origin stop;
d	destination stop;
$\lambda_{o,d}$	arrival rate between origin o and destination d in [passengers per hour];
q_{ijk}	passengers on board on trip k of line i at stop j in [passengers].

1

Introduction

Public transport is a main contributor on easing severe traffic congestion in cities, providing a sustainable alternative for the commuters. Beyond tactical planning, public transport control is essential to react to the disturbances occurring during operation and, thanks to the availability of information in real time, operators can dynamically respond to maintain a high level of service. The absence of public transport control can lead to a series of undesired phenomena such as bunching and poor administration of available resources, which reduce the efficiency and the attractiveness of the system.

This dissertation focuses on extending real time holding based control beyond single line level and additionally complements existing traffic signal priority strategies to account for the regularity of the line by fully utilizing newly introduced C-ITS technology.

This Chapter introduces the context of this thesis, real time control for public transport, the contributions of this dissertation and its outline.

1.1. Context and background

1.1.1. Context

Transportation is a crucial sector and key component of global economy. In European Union alone, the transportation sector constitutes 5% of the gross domestic product (GDP), employing 11.2 million people corresponding to 5.2% of the total workforce of the Union (European Union, 2017). Simultaneously, the 21st century is characterized by massive urbanization. According to United Nations (UN) the shift from rural to urban areas shows a steady and high increase rate resulting in a growth of urban areas by 1.8% annually (United Nations, 2018). The extreme urban sprawl changes rapidly the traditional form of a city transforming it into a polycentric system with more specialized areas and heterogeneity in population distribution. The results of urbanization come together with changes in transportation via the wide range in demand patterns emerging, the excessive need of transportation infrastructure and mobility alternatives. The impacts in infrastructure are reflected via the severe congestion observed in all modern megacities. Commuters lose a considerable amount of time in congestion, exceeding 70h in cities such as London and Paris (INRIX, 2018), a cost impacting 1% of the EU Gross Domestic Product (GDP).

The incorporation of public transport services in urban environments can help to alleviate congestion and reduce travel times. Public transport (PT) is a sustainable alternative to car, providing accessibility and promoting social equity. In 2014, PT ridership in EU showed an upward trend since 2008, a figure which is in line with economic growth and stability (UITP, 2014). More than half of local public transport trips in 2012 were conducted by bus (UITP, 2014). The bus is one of the main contributors to a city's public transport network with the most important objective to provide efficient and reliable transport to the users (Rohani et al., 2013). The foundation to meet their objective lies in proper tactical planning and addressing all four activities from route and timetable design to fleet and crew scheduling (Ceder, 2007). However, the nature of operations is inherent with stochasticity.

During operation deviations from schedule are observed, as well as variation of headways. The main result of this is bus bunching. Firstly observed and documented by Newell and Potts (1964), bus bunching occurs when the headway between consecutive vehicles drastically shortens or vehicles run prior to schedule and as a result arrive together at stops. This phenomenon propagates along the route with extremely long times for the passengers arriving after the platoon of buses, unevenly distributed demand on the buses and lost transfers. The causes of bunching are classified to internal and external (Feng and Figliozzi, 2011). The first are caused by poor tactical planning, while the latter on the actual conditions during operation. The most important external conditions that can cause bunching are the variability of travel time and passenger demand. Therefore, in order to maintain reliability of the system, public transport control is essential during operation.

The most recent breakthrough in public transport control is the introduction of Intelligent Transport Systems (ITS). A broad range of applications in the transportation sector allows to monitor the traffic conditions, provide information and manage the network. ITS applications were adopted by PT operators in order to improve the level of service of the PT system. This group of applications is known as Advanced Public Transportation Systems (APTS). Based on their application, APTS can be divided into four main categories (Ceder, 2007). The first category is the monitoring systems. In this category technologies such as Automatic Vehicle Location (AVL) and Automatic Passenger Counts (APC) can be found. AVL is used to monitor the position of the PT vehicles in a network, while with APC the number of passengers boarding and alighting at each stop. The second category is fare payment systems. The introduction of smart cards and automated payment methods made easier the data collection and increased the availability of data, assisting in identifying demand patterns and important locations in networks (transport hubs) (Jang, 2010). Next

category is the traveler information system. Information can be provided pre-trip, at stops or in-vehicle to the passengers, who can also utilize them and adapt their travel behavior. Similar to the previous category, multi-purpose information systems include the technology for communicating information between vehicles (Vehicle to Vehicle (V2V) Information) and between vehicle and infrastructure (V2I). Information for travel times, position of vehicles as well as signal times can be communicated and utilized in different ways. Finally, the last category is traffic signal control. Traffic lights can adjust their cycle in order to provide priority to PT after request. Operators can utilize all the aforementioned technologies in PT control in order to react to potential disruptions. APTS widen the range of control strategies and the objectives.

1.1.2. Real time PT control

It is vital for the passenger a PT service to be reliable, underlining the importance of consistency of performance (Transit Development Cooperation et al., 2007). Real time PT control is the procedure of reacting to potential disruption or loss of level of service utilizing real time information to benefit both the systems and its users. Prior to control, the stage of tactical planning is of great importance, providing a well-designed schedule including the determination of the frequency, fleet size and driver roster. Furthermore, there are infrastructure solutions that provide the right of way to PT such as traffic segregation with dedicated lanes and transit signal priority.

PT control initiated with schedule adherence as main objective. Firstly, vehicles were monitored manually at stops and if they were running prior to schedule they were delayed until their scheduled departure time. Gradually, different slack times were added based on the planned headway. In the late 90's, researchers started assuming the availability of the position not only of the preceding but also for the first time the succeeding vehicle in real time. From that point, in parallel with schedule adherence, regularity of high frequency lines was introduced as an objective. Different strategies have been deployed in order to maintain regularity, increase the number of synchronization events and optimize the passenger cost.

Control has been applied independently on transit lines, with recent attempts to coordinate multiple lines. Operators can achieve a lower variability of headways, reduction of excess waiting times and on-board delays as well as reduced travel times. The stability of travel times can assist in administering the available resources in terms of fleet and driver roster. Additionally, regulating PT operation leads also to substantial savings. The annual savings from the application of holding control at the high frequency lines of the city of Stockholm, Sweden were approximately 3.87 million Euros, the greatest share of which was in operational cost ("Real Time Control Summary.", Cats, O.).

The integration of intelligent transport systems in support to control strategies incorporated the new technologies and the information acquired to improve their effectiveness. From manually monitoring the arrival of buses at stops and holding the vehicle based on the departure of the preceding vehicle, operators can now account for the expected arrival of the succeeding vehicle as the position of all buses is monitored in real time by a centralized control center. While passenger cost is estimated in real time based on historical data, nowadays, control decisions are gradually taken based on the actual demand of a line or of a specific vehicle. Passenger counting devices assisted in mapping the routes and decisions taken in the network, in monitoring passengers waiting at stops, on board, waiting for a transfer or failed to board and in estimating different types of penalties such lost connections and overcrowding.

Control strategies keep evolving with the continuous deployment of APTS and availability of data. Being always be up to date can achieve multiple objectives, mitigate the negative side effects and improve the level of service. This dissertation deals with real time PT control in the era of APTS. In

particular, how specific control strategies can be further extended to regulate the operation on specific networks and how existing strategies can be further extended incorporating newer applications on ITS.

1.2. Objective and Scope

1.2.1. Objective

The main objective of this thesis lies within the framework of real time public transport control. Holding is a thoroughly investigated strategy in the literature and applied on different networks with different objectives. Recent work focuses on controlling multiple lines via holding. So far, the findings are limited in the shared transit corridor, disregarding the effects of the control on the remaining parts of the network. In addition, the analysis for the passenger cost is conducted at a network level, neglecting the interactions between different passenger groups affected by different control decisions regarding regularity or synchronization or regularity for the line or joint operation. The first part of this dissertation is dedicated to the extension of a rule based holding strategy for multiline control. The formulated criterion should be applicable in every part of a multiline network and account for the passengers that are experiencing any control decision.

The second part of the dissertation involves the integration and utilization of cooperative ITS in holding strategy. Currently from the APTS applications operators have in their disposal, cooperative ITS have been used in control independently to reduce the number of stops at traffic lights instead of resorting to transit signal priority. At the same time, a major drawback of holding strategy is the additional time added due to control. Hybrid controllers with combinations of holding and speed adjustment have been proposed focusing on minimizing the overall travel time and reduce the effects of holding actions. The second objective of this thesis is to integrate C-ITS based applications to holding strategy in order to combine their objectives and try to utilize or mitigate the impact of the latter to the travel time.

The aforementioned objectives are reflected into four research questions that will be addressed in the current dissertation:

R.Q.1: How can single line rule-based criteria be extended to account for multiple lines?

There is still ongoing research on holding strategies for single line, exploring different directions in order to adhere to the schedule of the line or to maintain regularity. However, the contributions to the strategy that account for multiline control (excluding holding for synchronization) is limited. It is common that transit routes serve the same sequence of stops extending the options for passengers. However, the interaction between lines is neglected and phenomena during the operation of a single line can also be observed and cascaded between lines. For instance, platooning may occur on shared stops from buses of different lines. In this dissertation, rule-based criteria are formulated in order to be applied on networks with sets of consecutive common stops and account for regularity for both single line and multiline control and include all actions to traverse between different stop sets such as coordination, branching to single line operation and potential synchronization at the common part.

R.Q.2: What are the consequences of applying multiline control to the different passenger groups?

In the concept of single line operation, passengers share the same objectives, which are limited within the level of the line. On complex networks of multiple lines sharing a transit corridor,

passengers have different and conflicting interests which depend on their origin and destination. Each group seeks to minimize its travel time, while the overall benefit of a system cannot guarantee the same gains to all passenger groups. Additionally, control decisions affect differently each passenger group. Moreover, synchronization decisions on a series of consecutive stops has not been addressed together with its effects on the regularity of the system. This dissertation will try to record all the interactions between passenger groups that co-exist on each part of the network during control and how the magnitude of each control action should be reflected to the corresponding passenger group.

R.Q.3: Which are the conditions for applying single or multiline control?

In literature, different control strategies can be found that can be applied to single line. An operator can choose between control strategies based on the source of the stochasticity of a line. Recently, control strategies start to extend beyond the line level offering additional alternative to control a transit network. Once the operator has the option between single and multiline control the factors that should he take into consideration must be addressed in order to choose between the two. The two main factors that will be assessed are the topology of the network and the demand distribution between different passenger groups. Furthermore, synchronization as an extension of single line control will also be taken into account answering under which conditions can be feasible.

R.Q.4: To which extent C-ITS can enhance holding as a strategy?

Undeniably, transit signal priority is an effective measure to provide the right of way to public transport but excessive use can cause problems to the rest of the traffic. Driver Advisory Systems can shift the action from signal heads to vehicles (private and PT) to reduce TSP requests. However, they still do not account for operational disturbances, which can be covered by strategies such as holding. The challenge of this research question is to combine the objective of the DAS to reduce stop and go action at stops and to maintain even spaced headways via holding strategy.

1.2.2. Scope

Public transport control can be applied in form of different strategies on different parts of the network. This dissertation is focusing exclusively on holding strategy. The applications of holding strategy are quite extensive with various objectives, decision rules and solution approaches. Rule based holding strategies are formulated and assessed in this dissertation, which are extended to account also for the interaction between lines. The integration and utilization of real time data is considered available but within the limits of the thesis only historical data is taken into consideration. Additionally, networks with shared transit corridor are under investigation. On sets of consecutive stops passengers can take different decisions based on the nature of the trip. Travel behavior of passengers travelling on such networks in out of the scope of the thesis.

On the combination of DAS with holding, the contribution of the controllers to the rest of the traffic is not taken into consideration. The impact of green extension or green recall is to private vehicles is not taken into consideration.

1.3. Thesis Contribution

The contributions of this dissertation are in two main directions:

Multiline Holding Control: A rule based holding criterion is formulated that accounts for multiple lines and can be applied at any part of a network. The criterion is based on the minimization of the additional time due to holding. The final holding time takes into account how the control decision impacts passengers waiting at the current and the downstream stops and the passengers on board. In addition, the criterion is based on all different control actions that take place in multiline control beyond the regularization of the headway of the line. Finally, the holding criterion is paired with a rule based synchronization criterion to account for transferring passengers in the network. Multiline control is compared with single line control in order to analyze all the interactions between passenger groups and find out when is it beneficial to apply single or multiline control.

Integration of Cooperative ITS in Holding Strategy: Holding strategy is combined with two Driver Advisory Systems available thanks to Cooperative ITS into two hybrid controllers. The new controllers combine the objectives of maintaining regularity and reduce the number of stops at traffic signals without resorting to Transit Signal Priority. When holding is combined with GLODTA, holding time is decided based on the current position between consecutive vehicles and the time needed in order to traverse during the next green phase. Combined with the second DAS, GLOSA, apart from holding time vehicle is also instructed for the cruising speed on the next segment between stop and traffic light.

1.4. Thesis Outline

This dissertation consists of three main parts. Chapter 2 presents the literature review of the dissertation providing the state of the art on the topic. The remaining two parts constitute the main contributions of the current work. The final chapter summarizes the main findings and the conclusions are drawn together with directions and recommendations for further research. The outline of the dissertation is depicted in Figure 1-1.

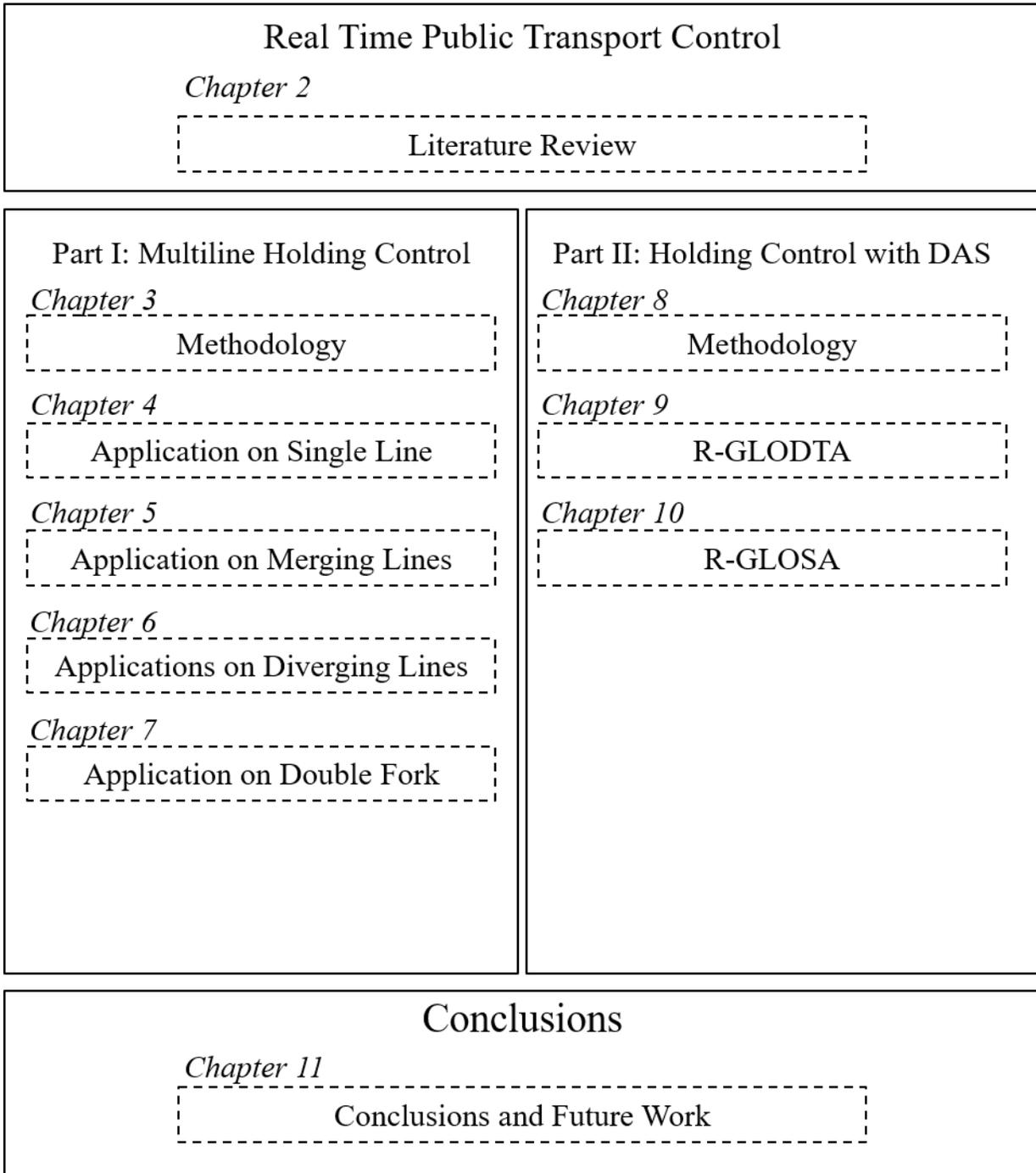


Figure 1-1 Thesis Outline

Literature Review

The second chapter provides an overview on real time public transport control. After presenting the main classification of control strategies, the most important contributions on each one are documented. A preferential treatment is given to holding strategy. Furthermore, the integration and utilization of Driver Advisory Systems is discussed. Finally, the chapter ends with a synthesis and the research gaps that will be filled in the current thesis.

Part I: Multiline Holding Control

The first part of the dissertation is dedicated to the formulation of rule based real time holding criteria to regulate high frequency lines at networks where lines share a significant number of consecutive stops. The criteria account for passenger cost of the passengers that will experience any potential control action. In the first chapter of this part the methodology is documented, followed by the application and the assessment of the criterion in different network structures. The experimental setup and the results are documented in different chapters. The final chapter of this part discusses under which conditions multiline holding control can be more beneficial than single line control.

Part II: Holding Control with DAS

In the second part of the dissertation, DASs are integrated with rule based holding strategies in order to combine the objectives of reducing the number of stops at traffic lights without TSP requests and maintain the regularity of the line. The first chapter describes the integration of the two driver advisory systems and the results of each are documented in the remaining chapters of this part.

Chapter 11 finally concludes this dissertation with a summary of the main findings and recommendations for future research directions.

2

Literature Review

This chapter provides the State of the Art. After a brief presentation and classification of real time control, the literature review on holding control strategy will be presented and on Driver Advisory Systems. The last section of this Chapter comprises a synthesis of the findings and focuses on the research gaps that will be addressed in this thesis.

2.1. Real Time Public Transport Control

Real time public transport control is the action of reacting dynamically on disturbances occurring during operation in a transit system. This has become feasible thanks to the introduction of Advanced Public Transport Systems (APTS), ITS-based applications utilized by the public transport sector. According to Ceder (2007) all the different control strategies an operator can use to maintain a specific level of service:

- Holding;
- Stop Skipping;
- Reserved Vehicle Addition;
- Speed Adjustment;
- Signaling;
- Deadheading;
- Short turning; and
- Short cutting.

With holding a vehicle is instructed to wait at a stop for additional time to achieve evenly spaced headways and eliminate platooning between vehicles. Holding is the control strategy used in this thesis and it will be analyzed thoroughly in a dedicated section. With stop-skipping one or several stops can be skipped in order to restore headway between services accounting for the alighting passengers and the passengers waiting at a stop. In cases of sudden change in demand, reserved vehicles can be added to the network in order to satisfy it. Speed adjustment can save travel time and reduce bunching between vehicles. Transit Signal Priority (TSP) for public transport systems can provide additional gains in terms of both operational efficiency and reduced energy consumption (Hu et al., 2015). With deadheading, a vehicle is dispatched to serve another route after the completion of each trip. With short turning and short cutting vehicles change their route at a specific point in order to provide denser frequencies at a specific location of the network.

Eberlein et al. (2001) classified the control strategies based on where they are applied. The two main categories of this classification are the station-based strategies. In this category belong strategies such as holding, stop skipping, short turning and short cutting. The second category is the interstation strategies, with actions taken between stops. Speed adjustment and signaling belong to interstation strategies. Eberlein also included a last category of other strategies which include the remaining of the aforementioned strategies (Reserve vehicle addition, deadheading) as well as strategies applied on railways.

Given the characteristics of the network and the availability of data, operators can apply one of the aforementioned strategies to regulate the operation of one or more transit lines. The next two sections focus on the two main topics of this thesis namely the holding strategy and the driver advisory systems.

2.2. Holding Strategy

The main elements of holding control are the holding criterion and the stops where control should be applied. As far as the criterion is concerned, Zolfaghari et al. (2004) categorized the criteria based on the solution approach, differentiating between rule-based and optimization models. A final classification depends on the characteristics of the line; the criterion may focus on reducing headway variability or minimizing passenger cost (Ibarra-Rojas et al., 2015). The stops where control can be applied are defined as Time Control Points (TCPs). Theoretically, all stops can be used as time control points. Studies have investigated the position and the number of control points. Cats et al., (2014) concluded that the location is a more crucial factor than the number of control points. Early studies used a single control point located at the beginning of the route, considering it sufficient (Eberlein et al., 2001). Later on, Puong and Wilson, (2008) contradicted this finding by arguing that multiple control points are needed. Fu and Yang (2002) compared

an all-stop control scenario to a two-stop one, finding that the all-stop scenario performed marginally better with significant increase in in-vehicle time, bus travel time and control frequency. On the location of TCPs, several studies concluded that control should be applied prior to a sequence of high demand stops (Turnquist and Blume, 1980; Abkowitz and Engelstein, 1984; Liu and Wirasinghe, 2001) or important transfer hubs (Cats et al., 2012). Finally, Hickman, (2001) suggested that high demand stops should be used as TCPs to avoid unnecessary increase of on-board delays due to control.

2.2.1. Single Line Holding Control

Considering holding strategies, different approaches have been developed based on line characteristics and availability of information. For lines operated with long headways, it is conventional to use holding strategies aiming at schedule adherence, while for lines with short headways the aim is to maintain service regularity. The criterion for the former category is that a vehicle should not depart earlier than its scheduled time. In the concept of the first category, Rossetti and Turitto (1998) applied different slack times each time a bus is controlled at a stop reducing the delay for the on-board passengers at the expense of an increase in the system's travel time. For the latter category, holding time is calculated by taking into account the headway between consecutive vehicles. Fu and Yang (2002) compared threshold-based holding rules subject to preceding and succeeding vehicles, concluding that the optimal holding time lies between 60% and 80% of the planned headway of the line. Daganzo (2009) proposed a dynamic holding scheme that reduces or increases the speed of a succeeding vehicle depending on the headway with the preceding vehicle. Xuan et al. (2011), based on the work of Daganzo, formulated a family of dynamic holding strategies to maintain schedule reliability and maximize commercial speed.

Cats et al. (2011) compared schedule- and headway-based control with limitation on the maximum allowed headway. They concluded that headway-based control that considers both forward and backward headways outperforms the other strategies and brings substantial benefits for the passengers. Bartholdi and Eisenstein (2012) proposed a self-coordinating control method, which adjusts dynamically headways depending on the actual bus capacity utilizations and a minimum headway to be maintained to avoid bunching. In the same context, Liang et al (2016) formulated a self-adaptive control scheme to regulate headways with fast headway recovery time and as a result they showed substantial benefits in terms of travel times. On the same track, Zhang and Lo (2018) analyzed a framework of equalizing headways subject to preceding and succeeding vehicles accounting for both deterministic and stochastic travel times as well as the number of vehicles in the network.

Holding time can be determined as the decision variable in passenger cost optimization problems. Barnett (1974) formulated a single stop holding model that minimizes the main components of travel cost, namely waiting times and in-vehicle delays. Zhao et al. (2003) treated stops and buses as agents and developed a negotiation algorithm based on marginal costs to determine the optimal conditions for applying holding. Zolfaghari et al. (2004) added waiting times induced by capacity constraints in the objective function. Yu and Yang (2007) determined the optimal holding times by minimizing the total users cost using a Genetic Algorithm. In addition, the authors developed a forecasting model for early departures, based on a support vector machine (SVM) approach. Delgado et al. (2009) combined holding based on minimizing the travel time of individual users with boarding limits and found that the combination should be applied when the preceding vehicle closes in. More recently, Berrebi et al. (2015) used holding in the dispatching policy aiming to reduce passenger waiting time by minimizing the sum of square headways, while Sánchez-Martínez et al. (2016) formulated a holding control optimization accounting for time-dependent changes in passenger demand and running times. Wu et al. (2017) introduced the effects of overtaking and queue swapping behavior to schedule based and headway based holding control strategies. As all holding

strategies also increase the travel time of the trips Gkiotsalitis and Cats (2019) introduced time windows within which the holding times of all buses are calculated and optimized based on the minimization of passenger in vehicle time and level of bunching.

2.2.2. Hybrid Control Strategies

Holding has been also combined with other control strategies to reinforce its performance. For instance Eberlein et al., (1999) and Sáez et al., (2012) combined holding with stop skipping. Chandrasekar et al., (2002) and Koehler et al. (2018) combined holding with transit signal priority to minimize the total delay of passengers on board and at stops. Finally, Nesheli and Ceder, (2017) tested combinations of holding, stop skipping, boarding limits and speed adjustment in order to minimize total passenger travel time and increase the number of direct transfers.

2.2.3. Holding for Synchronization

Holding strategies have also been used for transfer synchronization, starting from the work of Abkowitz et al., (1987), which compared four simple holding-based rules on a single transfer point. Hall et al (2001) examined a set of dispatching policies for transfer stops based on minimizing the expected travel time of all passengers. Delgado et al., (2013) used a rolling horizon for comparison in order to decide for transfer synchronization. Nesheli and Ceder (2015) presented a framework to maximize the number of direct transfers and minimize the total passenger travel time. Additionally, Wu et al., (2016) combined holding strategy from operation's perspective with schedule coordination from tactical planning to further assist transfer events, a combination not explored in existing work. Daganzo and Anderson, (2016) introduced a dynamic holding strategy for transfer coordination. The decision to coordinate depended on estimated bus arrivals and passengers in real time. Recently, (Gavriilidou and Cats, 2018) introduced a controller which calculates holding time for regularity and synchronization and the controller decision is taken based on minimization of passenger cost given different levels of passenger information. Based on the state of the network, an optimal set of operational tactics was chosen and validated using simulation, showing to achieve a considerable improvement to the network performance.

2.2.4. Multiline Holding Control

User cost minimization in transit network design problems often result in offering a number of overlapping lines (Baaj and Mahmassani, 1995). However, this design solution does not explicitly take into account service reliability and the related operational challenges. Early work on corridors with overlapping routes focused on modelling waiting time behavior of passengers that can be served by multiple lines (Chriqui and Robillard, 1975; Marguier and Ceder, 1984). Han and Wilson (1982) investigated the allocation of additional buses on busy networks, which included a shared transit corridor. In the area of tactical design, Ibarra-Rojas and Muñoz, (2016, 2015) introduced a timetable optimization problem for maximizing the synchronization events of different bus lines at common stops on overlapping segments and later they extended their problem to ensure even headways between consecutive vehicles of different lines while limiting diversions from a given timetable .

Only recently the control of transit corridors has gained the attention of the research community. The most relevant work to be mentioned is that of Hernandez et al (2015), who tested holding on a shared transit corridor comparing different operation schemes. However, service performance outside of the corridor was not considered in their study. Argote-Cabanero et al. (2015) extended the single line holding control strategy by Xuan et al (2011) to multiline control, and tested it on the real network of San Sebastian. They proved that the single line control can also be applied to more complex systems with multiple lines with resilient results with line and inter-line metrics with or without the addition of driver guidance, which was also a

part of the study. Fabian and Sánchez-Martínez (2017) compared scheduled- and headway-based holding for the trunk and multi-branch light rail network of Boston. The control was applied for each line independently, while satisfying rail infrastructure limitations. Based on their findings, they concluded that headway-based holding based on a joint headway and applied at the shared transit corridor itself can be more beneficial than obeying to the line headway. Schmöcker et al. (2016) formulated a queuing model to describe the effect of shared corridors on bunching and tested several operational scenarios, concluding that cooperation and overtaking between lines can assist in reducing bunching along the shared section.

2.3 Driver Advisory Systems

Connected vehicle technology can contribute to reduce the energy consumption, and in the same time improve operational efficiency of bus systems, especially near signalized intersections. In particular, the communication of Signal Phase and Timing (SPaT) information obtained from traffic signal controllers allows to switch from signal-centric strategies (for instance, resorting to TSP requests) towards vehicle-centric (Seredynski et al., 2015). The two SPaT-based controls that are researched in literature are the Green Light Optimal Speed Advisory (GLOSA) (Seredynski et al., 2013; Stebbins et al., 2017) and the Green Light Optimal Dwell Time Advisory (GLODTA) (Seredynski and Khadraoui, 2014). Both solutions have been conceived to mitigate stop-and-go driving. GLOSA does so by providing vehicles with speed guidance, while GLODTA reaches the goal by optimizing dwell time of PT vehicles (i.e. by occasionally holding the buses longer at bus stops). Consequently, performance of the buses is improved without the need of changing traffic signal timings. As up to 20% more fuel is used to accelerate from a full stop to a speed of 8 kilometres per hour (in case of a passenger car), there are significant benefits of moving to stop-and-go or slow-and-go patterns.

GLOSA has been studied in several projects and field operational tests for both cars and buses, e.g. PREDRIVE C2X (Katsaros et al., 2011), DRIVEC2X (Krajzewicz et al., 2012), simTD (Ress and Wiecker, 2016), MobiTraff (Seredynski et al., 2015), Compass4D (18) Extensions of GLOSA have been found in the literature in combination with adaptive signal control strategies (Bodenheimer et al., 2014), with vehicle platooning (Stebbins et al., 2017), and to generate fuel-efficiency speed profiles (Wan et al., 2016). Very limited works combine GLOSA with e-vehicles (Wu et al., 2015). GLODTA advises a prolonged dwell time at bus stops in order to avoid arriving at the next signalized intersection during a red phase (Seredynski et al., 2015).

Both GLOSA and GLODTA strategies rely on Signal Phase and Timing (SPaT) data continuously communicated from controllers placed along the route. Furthermore, real-time positions of buses in the network are accessed through Automated Vehicle Location (AVL) systems to estimate the speed and the additional dwell times. Recently, the work of Giorgione et al. (Giorgione et al., 2017) extended the GLOSA for electrical buses by including information on energy consumption and battery status to instruct the driver to maintain a specific speed so that the bus traverses the next signalized intersection without stopping and affecting signal timings while considering the energy consumption. The introduced eGLODTA determines whether additional dwell time should be advised, considering both schedule adherence criteria and on-route battery charging needs.

2.4. Synthesis

Regularity of transit lines has been analyzed mostly for single lines. The coordination of multiple lines via control has been addressed mainly at the tactical planning phase. A valid research question is how shared transit corridors can be controlled in real-time so that passengers' waiting times – along separate line branches as well as the trunk - are minimized. This question seems not to be properly addressed when looking at the reported literature. Moreover, only few works accounted for coordination between lines with

overlapping routes sharing more than one consecutive common stop, and only few quantified the benefits of cooperative schemes on passengers' journey times. To fill this gap, in this thesis we develop a novel rule-based control strategy for real-time corridor management focusing on branch and trunk networks. The proposed formulation considers the impact of the holding control measure on all relevant passenger groups and accounts for the demand distribution on the lines at the branches and within the common section. The performance of the cooperative control will be compared to the case of independent single-line control and the advantages and disadvantages are quantified from both passenger and operator perspectives, at the line as well as at the network level.

Transit Signal Priority as a strategy can be seen as cost-efficient, since it overall reduces the number of stops at signals, hence avoiding additional stop-and-go operations. On the other hand, such control measures may have some negative impact on the general performance of the whole urban transport system: excessive use of TSP may reduce the capacity of competing traffic streams. Driver Advisory Systems fully utilize V2I and V2V technologies in order to maintain the priority for public transport without changing signal timings and phases and reduce travel times. However, DASs' objective neglects the effects of transit operation, and they may favor bunching between vehicles. On the other hand, holding as a strategy maintains regularity at the cost of excessive travel time. In this dissertation, the two strategies are combined in order to meet both the objectives of regularity and reduced stops at signalized intersections, while the side effects are counterbalanced. Two hybrid controllers will be introduced and evaluated using simulation for a high frequency line. The results will be compared to the independent application of DASs and holding and to different levels of TSP at signalized intersections.

PART I

Multiline Holding Control for Trunk and Branch Networks

3

Methodology

In this chapter, the methodology formulated to control multiple lines for branch and trunk networks is presented. A holding based control criterion is formulated using as decision variable the travel time for the passengers. Firstly, an introduction to branch and trunk networks is given, together with the classification and the characterization of their elements. Then, the actual holding criterion is formulated and the applicability to different parts of branch and trunk networks is demonstrated. Finally, a holding criterion for transfer synchronization, applied at the common stops, is given together with conditions to be chosen based on passenger cost comparison.

3.1. Network Structure

3.1.1. Branch and Trunk Networks

The structure of the public transport network of a city depends of its morphology and the distribution of the demand. The backbone of the public transport networks is usually its urban rail system but it can also be a bus rapid transit system. All public transport modes follow similar structures that can be summarized in the following network structures (Roselló et al., 2016):

- Diametrical/Branch and Trunk;
- X-System;
- Radial/cross system;
- Circle-radial system; and
- Air-bladder system

The first category comprises of networks that connect lower density areas through central areas where and majority of the demand is concentrated around central corridors A typical example of this network structure is given in Figure 3.1. The bus network of the city of Luxembourg consists of a main corridor between the central station to the central business district via the city center providing high frequency. The suburbs of the city are connected with diametrical lines that traverse this corridor.

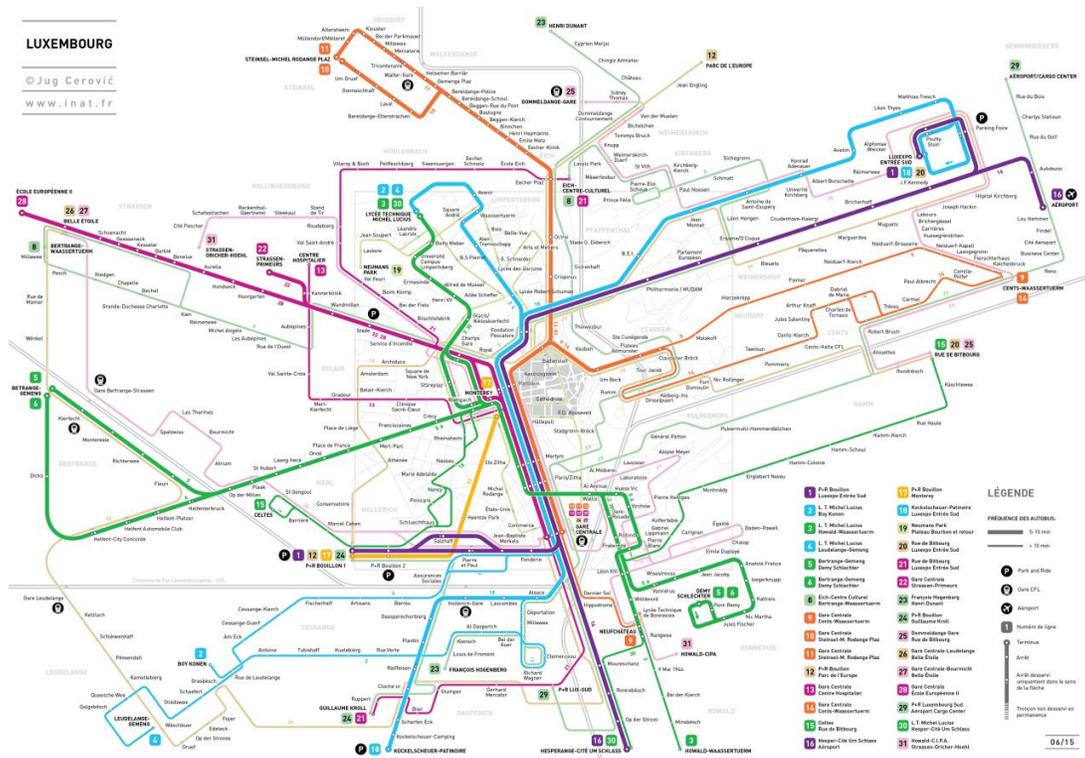


Figure 3-1 Luxembourg city bus network

At the stops on the central corridors, passengers can benefit from the joint frequency at the common part. At the same time, the number of direct services increases with transfers to be needed only for passengers that initiate and finish their trips at the branches of the network. Since the same stops serve multiple lines the system allows direct transfers without walking to another stop. Based on the position of the corridor

and the branches, considering only one direction and the passenger groups in the network, branch and trunk networks can be classified into three main categories depicted in Figure 2.

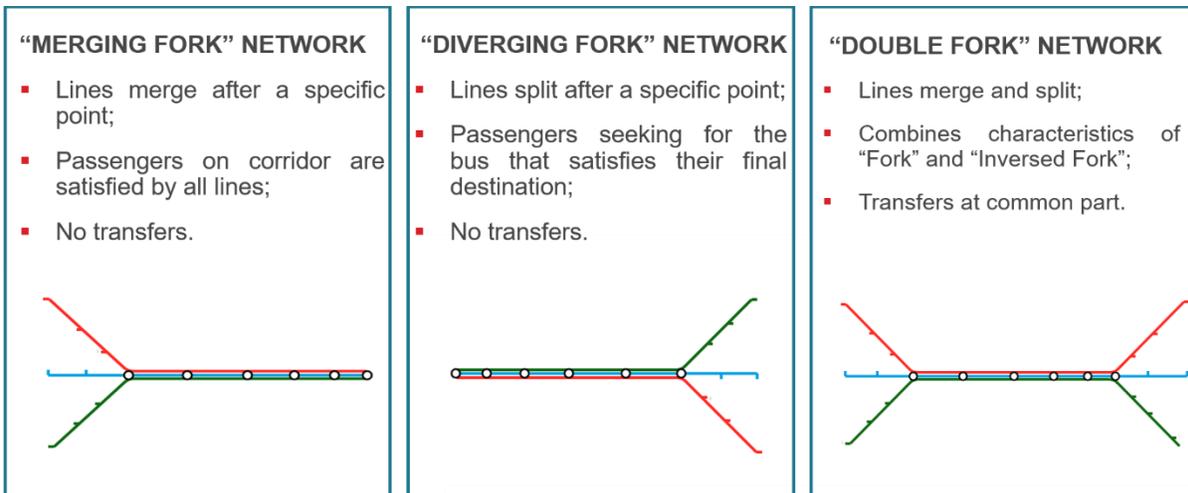


Figure 3-2 Different network configurations with a shared transit corridor

A “merging fork” is the simplest configuration of branch and trunk networks, where lines initiate their trip from different terminals and operate independently at the beginning on separate branches until they merge and serve the same stops on a shared transit corridor. The main characteristic of this network is that at every stop all passengers are satisfied by every bus serving each stop. Because of this characteristic, transfers are not necessary on this network. The main issue on this network configuration is the transition from the branches to the corridor. Any delay caused either from disruptions or control decision on the branches should not propagate as delay at the beginning of the shared transit corridor. Vehicles should arrive at the common part and begin joint operation with the least possible variability in terms of headway. At the common part, lines can be treated as a single line with a joint frequency.

Lines operating on the opposite direction, on a “diverging fork” network start from a common terminal and after operating jointly, they bifurcate to serve their final individual leg of the route. As with the merging fork, at the shared transit corridor the lines operate as a single line. However, at this network configuration at the shared transit corridor, apart from the passengers travelling within the corridor at the common part, there is an additional passenger group travelling from the corridor to the branches that waits for a trip from a specific line that serves their final destination. Additionally, the transition from the joint operation to the individual operation should be regulated. Again, no transfers are considered in this network configuration because at the common part passengers wait to board directly to the bus that satisfies their final destination.

By combining the two aforementioned networks, a general network can be configured, combining the characteristics of both. from now one named “double fork”. From the branches at the beginning of the network, passengers may travel within the branch, from branch to the shared transit corridor and from branches to either the final branch of the same line or one of the other lines. In case of travelling to the branch stops of the other lines, passengers should transfer at the common part. From the shared transit corridor, passengers can travel either within the corridor or from the corridor to the branches and wait for the corresponding line. Finally, at the last leg of the route, when lines do not interact anymore, lines operate as single line again. More complex networks with more lines that interact, merging and diverging at

different stops and with multiple shared segments with different number of lines on each can be defined with all the combinations of these networks.

Accounting for the aforementioned described characteristics, a holding criterion is formulated to control lines operating in such networks. In the following sections the holding criterion's formulation and applicability for each part and network configuration is described analytically.

3.1.2. Network Elements

We define as *Switching Stops*, the stops for which the number of lines operating upstream and downstream changes. The first and the last stop, devised as terminals, are excluded from the analysis. Based on the difference between the number of lines prior and after a switching stop, two categories of switching stops can be defined.

A switching stop where the number of transit lines operating upstream is lower than the number of lines operating between the current and downstream one can be characterized as a *merging stop*, denoted by m . On the other hand, the switching stops where the number of transit lines that operates upstream is greater than the number of lines operating downstream are characterized as *diverging stops*, denoted by s .

There can be stops that serve both as merging and diverging stops (denoted as m/s). For shake of simplicity, these stops are treated as a special case and therefore excluded from the analysis.

For a transit network with n lines, there can be $(n-1)^2$ combinations of merging and splitting stops while the number of critical stops is subject the following constraints:

$$0 \leq m \leq n-1$$

$$0 \leq s \leq n-1$$

$$M+S \leq n$$

Where M and S the total number of merging and splitting stops, respectively.

Between switching stops, the sets of stops can be characterized as branches and shared transit corridors (or, for simplicity, corridors).

As *branch*, we characterize a set of stops that is served exclusively by one line. A branch stop set can start with a diverging stop and/or end to a merging stop. Along this stop set, single line control is recommended, as there is no interaction between lines. Coordination or synchronization control can initiate to branches prior to a shared transit corridor to assist to the corresponding action by the arrival to the common section.

We denominate by *Shared Transit Corridor* a set of consecutive stops that is served by at least two lines. It is important to set a minimum number of consecutive stops, served by multiple lines that can be characterized as a corridor. A shared transit corridor should also be determined based on the relative size of the overlapping part of the network compared to the overall size of the network and the branch stop sets. Additionally, a corridor can be defined based on the distribution of the demand on the network. If there is a subset of the network where the majority of the demand is generated or attracted, that stop set can be considered a corridor.

3.2. Decision Variable

The holding criterion is formulated by including all the terms composing the total passenger travel time for the passengers t_{ijk}^{travel} (t_{ijk}^{hold}), which is a function of holding time t_{ijk}^{hold} , and by explicitly considering the influence of common downstream stops. The travel time consists of the additional waiting time t^{wait} passengers experience when a vehicle is instructed to remain at a stop due to a control decision, and the in-vehicle delay t^{inveh} expresses the additional travel time that passengers experience on board while a vehicle is held due to a control decision. The effect of each time component to travel time is expressed by corresponding weights β^{wait} and β^{inveh} . Travel time t_{ijk}^{travel} is thus expressed by the following formula:

$$t_{ijk}^{travel} = \beta^{wait} t_{ijk}^{wait} + \beta^{inveh} t_{ijk}^{inveh} \quad (3.1)$$

3.3. Passenger Groups

There are seven passenger groups in total to be taken into consideration in these network types:

- Passengers travelling within the initial branch;
- Passengers travelling from branch to shared transit corridor;
- Passengers travelling from initial branch to final branch;
- Passengers travelling within the shared transit corridor;
- Passengers travelling from shared transit corridor to branch;
- Passengers travelling within the final branch;
- Passengers transferring between lines.

The total demand of each line can be expressed as the sum of arrival rates of the different passenger groups:

$$\begin{aligned} \sum_{m=j}^N \sum_{n=m+1}^N \lambda_{m,n} = & \sum_{m=j}^{N^{b1}} \sum_{n=m+1}^{N^{b1}} \lambda_{m,n}^{b1} + \sum_{m=j}^{N^b} \sum_{n=m+1}^{N^c} \lambda_{m,n}^{bc} + \sum_{m=j}^{N^{b1}} \sum_{n=m+1}^{N^{b2}} \lambda_{m,n}^{bb} + \sum_{m=j}^{N^c} \sum_{n=m+1}^{N^c} \lambda_{m,n}^c \\ & + \sum_{m=j}^{N^c} \sum_{n=m+1}^{N^b} \lambda_{m,n}^{cb} + \sum_{m=j}^N \sum_{n=m+1}^{N^b} \lambda_{m,n}^{b2} + \sum_{m=j}^{N_1^{b1}} \sum_{n=m+1}^{N_2^{b2}} \lambda_{m,n}^{transfer} \end{aligned} \quad (3.2)$$

For the sake of simplicity, the sum of arrival rates can be expressed as Λx , where x the index of the corresponding passenger group. Then Equation 3.2 can be written as follows:

$$\Lambda = \Lambda^{b1} + \Lambda^{bc} + \Lambda^{bb} + \Lambda^c + \Lambda^{cb} + \Lambda^{b2} + \Lambda^{transfer} \quad (3.3)$$

All passenger groups have conflicting objectives that coexist in the same stop set and a control decision targeting a specific group affects the remaining. The first six groups are affected by decisions taken to regulate the operation (single or multiline), while the last relies on synchronization between lines. The regularity affected groups will be addressed by the holding criterion formulated in the next section (Section 3.4) while the last in Section 3.5.

3.4. Formulation of the holding criterion for regularity

In this section, a rule based multiline holding criterion is formulated for branch and trunk networks. In the following sections the criterion is formulated in its general form, which can be applied at the shared transit corridor of a double fork network. The adaptability of the criterion at different stop sets is explained in respective sections.

3.4.1. Waiting time expressed as a function of holding time

The number of passengers waiting at a given stop is estimated through the sum of the arrival rates generated at the stop multiplied by the actual headway. Passenger waiting time is assumed to be half the actual headway multiplied by the number of passengers at the stop. The passengers at stop are expressed as the product of the sum of the arrival rates originating at the stop and the actual headway. Therefore, passenger waiting time is expressed by the following formula:

$$t^{\text{wait}} = \frac{h}{2} B = \frac{h}{2} \left(h \sum_{d=j}^N \lambda_d \right) = \frac{h^2}{2} \sum_{d=j}^N \lambda_d \quad (3.4)$$

When a control action is triggered, passenger waiting time differs from the corresponding uncontrolled case. We calculate the passenger waiting time due to holding as the difference between waiting time with (denoted with superscript H) and without holding applied (denoted with superscript 0):

$$t_{ijk}^{\text{wait}} = t_{ijk}^{\text{wait}_H} - t_{ijk}^{\text{wait}_0} \quad (3.5)$$

Each waiting time term comprises the waiting time from the preceding vehicle p and the succeeding vehicle s :

$$t_{ijk}^{\text{wait}_x} = t_{ijk}^{\text{wait}_{px}} + t_{ijk}^{\text{wait}_{sx}} \quad (3.6)$$

$$x = \{0, H\}$$

The waiting time from the succeeding and the preceding vehicle when no holding is applied are shown in the following formulas:

$$t_{ijk}^{\text{wait}_{p0}} = \frac{(t_{ijk}^{\text{exit}} - t_{ijk-1}^{\text{exit}})^2}{2} \Lambda_j \quad (3.7)$$

$$t_{ijk}^{\text{wait}_{s0}} = \frac{(t_{ijk+1}^{\text{exit}} - t_{ijk}^{\text{exit}})^2}{2} \Lambda_j \quad (3.8)$$

Additionally, when a vehicle is instructed to hold, then the waiting time from the preceding and the succeeding vehicles are expressed by Equation 3.9 and Equation 3.10:

$$t_{ijk}^{\text{wait}_{pH}} = \frac{\left((t_{ijk}^{\text{exit}} + t_{ijk}^{\text{hold}}) - t_{ijk-1}^{\text{exit}} \right)^2}{2} \Lambda_j \quad (3.9)$$

$$t_{ijk}^{\text{wait_sH}} = \frac{\left(t_{ijk+1}^{\text{exit}} - (t_{ijk}^{\text{exit}} + t_{ijk}^{\text{hold}})\right)^2}{2} \Lambda_j \quad (3.10)$$

After substituting the corresponding waiting times on Equation 3.5, then Equation 3.5 can be expressed as a function of holding time.

$$\begin{aligned}
& t_{ijk}^{\text{wait}}(t_{ijk}^{\text{hold}}) = \\
& = t_{ijk}^{\text{wait_H}}(t_{ijk}^{\text{hold}}) - t_{ijk}^{\text{wait_0}}(t_{ijk}^{\text{hold}}) = \\
& = (t_{ijk}^{\text{wait_pH}} + t_{ijk}^{\text{wait_sH}}) - (t_{ijk}^{\text{wait_p0}} + t_{ijk}^{\text{wait_s0}}) = \\
& = \left[\frac{\left(t_{ijk}^{\text{exit}} + t_{ijk}^{\text{hold}} - t_{ijk-1}^{\text{exit}}\right)^2}{2} \Lambda_j + \frac{\left(t_{ijk+1}^{\text{exit}} - (t_{ijk}^{\text{exit}} + t_{ijk}^{\text{hold}})\right)^2}{2} \Lambda_j \right] - \left[\frac{\left(t_{ijk}^{\text{exit}} - t_{ijk-1}^{\text{exit}}\right)^2}{2} \Lambda_j + \frac{\left(t_{ijk+1}^{\text{exit}} - t_{ijk}^{\text{exit}}\right)^2}{2} \Lambda_j \right] = \\
& = \Lambda_j \left\{ \frac{\left(t_{ijk}^{\text{exit}} + t_{ijk}^{\text{hold}} - t_{ijk-1}^{\text{exit}}\right)^2}{2} + \frac{\left(t_{ijk+1}^{\text{exit}} - (t_{ijk}^{\text{exit}} + t_{ijk}^{\text{hold}})\right)^2}{2} + \frac{\left(t_{ijk}^{\text{exit}} - t_{ijk-1}^{\text{exit}}\right)^2}{2} + \frac{\left(t_{ijk+1}^{\text{exit}} - t_{ijk}^{\text{exit}}\right)^2}{2} \right\} = \\
& = \Lambda_j \left\{ \frac{\left(t_{ijk}^{\text{exit}} + t_{ijk}^{\text{hold}}\right)^2 + \left(t_{ijk-1}^{\text{exit}}\right)^2 - 2\left(t_{ijk-1}^{\text{exit}}\right)\left(t_{ijk}^{\text{exit}} + t_{ijk}^{\text{hold}}\right) + \left(t_{ijk+1}^{\text{exit}}\right)^2 + \left(t_{ijk}^{\text{exit}} + t_{ijk}^{\text{hold}}\right)^2 - 2\left(t_{ijk+1}^{\text{exit}}\right)\left(t_{ijk}^{\text{exit}} + t_{ijk}^{\text{hold}}\right)}{2} - \frac{\left(t_{ijk}^{\text{exit}}\right)^2 + \left(t_{ijk-1}^{\text{exit}}\right)^2 - 2\left(t_{ijk-1}^{\text{exit}}\right)\left(t_{ijk}^{\text{exit}}\right) + \left(t_{ijk}^{\text{exit}}\right)^2 + \left(t_{ijk+1}^{\text{exit}}\right)^2 - 2\left(t_{ijk+1}^{\text{exit}}\right)\left(t_{ijk}^{\text{exit}}\right)}{2} \right\} = \\
& = \Lambda_j \left\{ \frac{\left(t_{ijk}^{\text{exit}} + t_{ijk}^{\text{hold}}\right)^2 + \left(t_{ijk-1}^{\text{exit}}\right)^2 - 2\left(t_{ijk-1}^{\text{exit}}\right)\left(t_{ijk}^{\text{exit}}\right) - 2\left(t_{ijk-1}^{\text{exit}}\right)\left(t_{ijk}^{\text{hold}}\right) + \left(t_{ijk+1}^{\text{exit}}\right)^2 + \left(t_{ijk}^{\text{exit}} + t_{ijk}^{\text{hold}}\right)^2 - 2\left(t_{ijk+1}^{\text{exit}}\right)\left(t_{ijk}^{\text{exit}}\right) - 2\left(t_{ijk+1}^{\text{exit}}\right)\left(t_{ijk}^{\text{hold}}\right)}{2} - \frac{\left(t_{ijk}^{\text{exit}}\right)^2 + \left(t_{ijk-1}^{\text{exit}}\right)^2 - 2\left(t_{ijk-1}^{\text{exit}}\right)\left(t_{ijk}^{\text{exit}}\right) + \left(t_{ijk}^{\text{exit}}\right)^2 + \left(t_{ijk+1}^{\text{exit}}\right)^2 - 2\left(t_{ijk+1}^{\text{exit}}\right)\left(t_{ijk}^{\text{exit}}\right)}{2} \right\} = \\
& = \Lambda_j \left\{ \frac{2\left(t_{ijk}^{\text{exit}} + t_{ijk}^{\text{hold}}\right)^2 - 2\left(t_{ijk-1}^{\text{exit}}\right)\left(t_{ijk}^{\text{hold}}\right) - 2\left(t_{ijk+1}^{\text{exit}}\right)\left(t_{ijk}^{\text{hold}}\right) - 2\left(t_{ijk}^{\text{exit}}\right)^2}{2} \right\} = \\
& = \Lambda_j \left\{ \left(t_{ijk}^{\text{exit}} + t_{ijk}^{\text{hold}}\right)^2 - \left(t_{ijk-1}^{\text{exit}}\right)\left(t_{ijk}^{\text{hold}}\right) - \left(t_{ijk+1}^{\text{exit}}\right)\left(t_{ijk}^{\text{hold}}\right) - \left(t_{ijk}^{\text{exit}}\right)^2 \right\} = \\
& = \Lambda_j \left[\left(t_{ijk}^{\text{exit}}\right)^2 + \left(t_{ijk}^{\text{hold}}\right)^2 + 2\left(t_{ijk}^{\text{exit}}\right)\left(t_{ijk}^{\text{hold}}\right) - \left(t_{ijk-1}^{\text{exit}}\right)\left(t_{ijk}^{\text{hold}}\right) - \left(t_{ijk+1}^{\text{exit}}\right)\left(t_{ijk}^{\text{hold}}\right) - \left(t_{ijk}^{\text{exit}}\right)^2 \right] = \\
& = \Lambda_j \left[\left(t_{ijk}^{\text{hold}}\right)^2 + \left(t_{ijk}^{\text{hold}}\right)\left(2\left(t_{ijk}^{\text{exit}}\right) - \left(t_{ijk-1}^{\text{exit}}\right) - \left(t_{ijk+1}^{\text{exit}}\right)\right) \right] = \\
& = \Lambda_j \left(t_{ijk}^{\text{hold}}\right)^2 + \left\{ \Lambda_j \left[\left(t_{ijk}^{\text{exit}} - t_{ijk-1}^{\text{exit}}\right) - \left(t_{ijk+1}^{\text{exit}} - t_{ijk}^{\text{exit}}\right) \right] \right\} t_{ijk}^{\text{hold}}
\end{aligned} \quad (3.11)$$

We consider two different waiting time terms at each stop of the shared transit corridor. The first term takes into account all vehicles that serve the current stop and the second only of the vehicles of the same line with the current vehicle. On the shared transit corridor, two passenger groups coexist and have different objectives: passengers travelling within the corridor can be satisfied by all lines and passengers travelling to the branches waiting for a vehicle from the line that serves their final destination. Thus, the first group is affected by regularizing the joint headway on the corridor while the second by the headway of the desired line. For that reason, we introduce two terms derived from the waiting time term of Equation 3.11, each depending on the aforementioned respective headway. The first term calculates the passenger waiting time regardless of the line, while the second is subject to vehicles from the same line i with the current vehicle. The two terms are given in Equation 3.12 and Equation 3.13 respectively:

$$t_{ijk}^{\text{wait}}(t_{ijk}^{\text{hold}}) = \Lambda_j (t_{ijk}^{\text{hold}})^2 + \left\{ \Lambda_j \left[(t_{ijk}^{\text{exit}} - t_{ijk-1}^{\text{exit}}) - (t_{ijk+1}^{\text{exit}} - t_{ijk}^{\text{exit}}) \right] \right\} t_{ijk}^{\text{hold}} \quad (3.12)$$

$$t_{ijk}^{\text{wait}}(t_{ijk}^{\text{hold}}) = \Lambda_j^{\text{cb}} (t_{ijk}^{\text{hold}})^2 + \left\{ \Lambda_j^{\text{cb}} \left[(t_{ijk}^{\text{exit}} - t_{ijk-1}^{\text{exit}}) - (t_{ijk+1}^{\text{exit}} - t_{ijk}^{\text{exit}}) \right] \right\} t_{ijk}^{\text{hold}} \quad (3.13)$$

3.4.2. Projection to the switching stop

Apart from the regularization of the headways of consecutive vehicles, the transition from the branches to the shared transit corridor and vice versa needs to be considered to ensure that any potential control decision at branch stops will not propagate as delay to the next stop set. For this reason, a term related to the expected headway at the upcoming switching stop (merging or diverging) is added. From a merging branch to a shared transit corridor the term accounts for all vehicles that will share the same stops downstream, while from shared transit corridor to branches only vehicles of the same line are taken into account.

Let vehicle k from line i arrive at branch stop j at arrival time t_{ijk}^{arrival} . After the completion of dwell time t_{ijk}^{dwell} , the sum of the actual arrival time and dwell time will be the expected departure (exit) time t_{ijk}^{exit} . Between stops, there are $n-1$ scheduled riding times ($\tau_{j,j-1}^{\text{riding}}$) for example estimated from historical data. The projected departure time from the next switching stop will be estimated by the sum of the scheduled riding times between the current stop j and the switching stop j^{switch} :

$$\tilde{t}_{i,j^{\text{switch}},k}^{\text{exit}} = t_{ijk}^{\text{arrival}} + t_{ijk}^{\text{dwell}} + \sum_{s=j}^{j^{\text{switch}}} \tau_{i,s,s+1,k}^{\text{riding}} \quad (3.14)$$

In the case of the merging stop, in order to estimate the sequence of vehicles irrespective of the line they serve, we need to project the expected departure time of the preceding vehicle and the succeeding vehicle of the same line as well as the expected and actual departure times from the vehicles of the other line. For each vehicle, the actual departure time from the last visited stop is retrieved and the expected departure time from the first common stop is estimated. The expected departure time of the current vehicle needs to be regulated in the case of uneven headways between consecutive vehicles regardless of the line. In case of a diverging stop, the same procedure is followed only for vehicles from the same line.

Then the expected headway between vehicles to the next switching stop is calculated based on the potential waiting time, which is expressed as the difference between the waiting times the passengers at the switching stop will experience with and without holding time:

$$\begin{aligned} \tilde{t}_{i,j^{\text{switch}},k}^{\text{wait}} &= \tilde{t}_{i,j^{\text{switch}},k}^{\text{wait}_H} - \tilde{t}_{i,j^{\text{switch}},k}^{\text{wait}_0} = \\ & \Lambda_j^c (t_{i,j,k}^{\text{hold}})^2 + \\ & \Lambda_j^c \left[\left(\tilde{t}_{i,j^{\text{switch}},k}^{\text{exit}} - \tilde{t}_{i,j^{\text{switch}},k-1}^{\text{exit}} \right) - \left(\tilde{t}_{i,j^{\text{switch}},k}^{\text{exit}} - \tilde{t}_{i,j^{\text{switch}},k+1}^{\text{exit}} \right) \right] t_{i,j,k}^{\text{hold}} \end{aligned} \quad (3.15)$$

3.4.3. In vehicle time

At a stop, passengers on board experience by default waiting time equal to duration of passenger transference. When a vehicle is held, passengers experience this time as additional delay to their travel time. In-vehicle time due to holding is the product of holding time and the number of passengers on board:

$$t_{ijk}^{inveh} = q_{ijk} t_{ijk}^{hold} \quad (3.16)$$

3.4.4. Total travel time

Total travel time t_{ijk}^{travel} consists of all three components of waiting time for the different passenger groups and the in-vehicle time. The total travel time for shared transit corridor for a shared transit corridor of a diverging or a double fork network is the following:

$$\begin{aligned} t_{ijk}^{travel}(t^{hold}) &= \beta^{wait} t_{ijk}^{wait}(t^{hold}) + \beta^{inveh} t_{ijk}^{inveh}(t^{hold}) = \\ &= \beta^{wait} \Lambda_j (t_{ijk}^{hold})^2 + \\ & t_{ijk}^{hold} \beta^{wait} \left\{ \Lambda_j^c \left[(t_{ijk}^{exit} - t_{jk-1}^{exit}) - (t_{jk+1}^{exit} - t_{ijk}^{exit}) \right] + \Lambda_j^{cb} \left[(t_{ijk}^{exit} - t_{jk-1}^{exit}) - (t_{jk+1}^{exit} - t_{ijk}^{exit}) \right] + \right. \\ & \left. \Lambda_j^b \left[(\tilde{t}_{i,j^{split},k}^{exit} - \tilde{t}_{i,j^{split},k-1}^{exit}) - (\tilde{t}_{i,j^{split},k+1}^{exit} - \tilde{t}_{i,j^{split},k}^{exit}) \right] \right\} + \beta^{inveh} q_{ijk} t_{ijk}^{hold} \end{aligned} \quad (3.17)$$

The optimal holding time is then calculated by taking the first derivative subject to holding time and setting it equal to zero, and solving the resulting equation with respect to holding time t_{ijk}^{hold} with the constraint that $t_{ijk}^{hold} \geq 0$:

$$\begin{aligned} \frac{\partial (t_{ijk}^{travel}(t^{hold}))}{\partial (t^{hold})} &= 0 \rightarrow \\ \rightarrow 2\beta^{wait} \Lambda_j (t_{ijk}^{hold}) + \beta^{wait} \left\{ \Lambda_j^c \left[(t_{ijk}^{exit} - t_{jk-1}^{exit}) - (t_{jk+1}^{exit} - t_{ijk}^{exit}) \right] + \Lambda_j^{cb} \left[(t_{ijk}^{exit} - t_{jk-1}^{exit}) - (t_{jk+1}^{exit} - t_{ijk}^{exit}) \right] + \right. \\ & \left. \Lambda_j^b \left[(\tilde{t}_{i,j^{split},k}^{exit} - \tilde{t}_{i,j^{split},k-1}^{exit}) - (\tilde{t}_{i,j^{split},k+1}^{exit} - \tilde{t}_{i,j^{split},k}^{exit}) \right] \right\} + \beta^{inveh} q_{ijk} = 0 \rightarrow \\ \rightarrow 2\beta^{wait} \Lambda_j (t_{ijk}^{hold}) &= \beta^{wait} \left\{ \Lambda_j^c \left[(t_{jk+1}^{exit} - t_{ijk}^{exit}) - (t_{ijk}^{exit} - t_{jk-1}^{exit}) \right] + \Lambda_j^{cb} \left[(t_{jk+1}^{exit} - t_{ijk}^{exit}) - (t_{ijk}^{exit} - t_{jk-1}^{exit}) \right] + \Lambda_j^b \left[(\tilde{t}_{i,j^{split},k+1}^{exit} - \tilde{t}_{i,j^{split},k}^{exit}) - (\tilde{t}_{i,j^{split},k}^{exit} - \tilde{t}_{i,j^{split},k-1}^{exit}) \right] \right\} - \beta^{inveh} q_{ijk} \rightarrow \\ \rightarrow t_{ijk}^{hold} &= \frac{\beta^{wait} \left\{ \Lambda_j^c \left[(t_{jk+1}^{exit} - t_{ijk}^{exit}) - (t_{ijk}^{exit} - t_{jk-1}^{exit}) \right] + \Lambda_j^{cb} \left[(t_{jk+1}^{exit} - t_{ijk}^{exit}) - (t_{ijk}^{exit} - t_{jk-1}^{exit}) \right] + \Lambda_j^b \left[(\tilde{t}_{i,j^{split},k+1}^{exit} - \tilde{t}_{i,j^{split},k}^{exit}) - (\tilde{t}_{i,j^{split},k}^{exit} - \tilde{t}_{i,j^{split},k-1}^{exit}) \right] \right\}}{2\beta^{wait} \Lambda_j} \quad (3.18) \\ \frac{\beta^{inveh} q_{ijk}}{2\beta^{wait} \Lambda_j} &\rightarrow \\ \rightarrow t_{ijk}^{hold} &= \frac{\Lambda_j^c \left[(t_{jk+1}^{exit} - t_{ijk}^{exit}) - (t_{ijk}^{exit} - t_{jk-1}^{exit}) \right]}{\Lambda_j} + \frac{\Lambda_j^{cb} \left[(t_{jk+1}^{exit} - t_{ijk}^{exit}) - (t_{ijk}^{exit} - t_{jk-1}^{exit}) \right]}{\Lambda_j} + \\ & + \frac{\Lambda_j^b \left[(\tilde{t}_{i,j^{split},k+1}^{exit} - \tilde{t}_{i,j^{split},k}^{exit}) - (\tilde{t}_{i,j^{split},k}^{exit} - \tilde{t}_{i,j^{split},k-1}^{exit}) \right]}{\Lambda_j} - \frac{\beta^{inveh} q_{ijk}}{2\beta^{wait} \Lambda_j} \end{aligned}$$

The first two terms regulate the departure from the current stop: the first one considers all vehicles that interact in the shared transit corridor, regardless of the line they serve, while the second regulates the departure subject to departures of consecutive vehicles of the same line i with the current vehicle. The third term regulates the expected departures at line level from the diverging stop, to ensure that the lines will continue to their branch stops with low headway variability. For the third term, the expected departure time from the diverging stop j^{split} is estimated by summing the scheduled riding times between the current stop of each vehicle and the diverging stop. Finally, the holding time calculated is adjusted to the ratio of the passengers on board and the remaining passengers downstream expressed by the corresponding arrival rates.

3.4.5. Weights

As shown in Equation 3.18, the contribution of each term is weighted based on the demand. A weighting factor is also introduced based on the distance to ensure a smoother transition from joint operation to single line operation. The distance term is based on the current stop's distance from the last common stop, j^{split} . The first two weights regulate the headways of vehicles within the corridor, therefore they share the same distance weight multiplied by a parameter $\alpha=0.5$, ensuring that the two terms are equally important when calculating holding time. The first term affects the passengers travelling within the corridor that are indifferent towards the different lines; the second affects the passengers travelling from the shared transit corridor to a specific branch and therefore wait for a specific line that serves their final destination. Finally, the passengers after the shared transit corridor waiting only for a specific line are included.

$$\begin{aligned}\theta_1 &= \frac{\Lambda_j^c}{\Lambda_j} + (\alpha) \left(1 - \frac{1}{j^{\text{split}} - j} \right) \\ \theta_2 &= \frac{\Lambda_j^{\text{cb}}}{\Lambda_j} + (1-\alpha) \left(1 - \frac{1}{j^{\text{split}} - j} \right) \\ \theta_3 &= \frac{\Lambda_j^b}{\Lambda_j} + \left(\frac{1}{j^{\text{split}} - j} \right)\end{aligned}\quad (3.19)$$

3.4.6. Final Holding Criterion

The final holding criterion for the shared corridor of diverging and double fork networks is given in Equation 3.20:

$$\begin{aligned}t_{ijk}^{\text{hold}} = \max \left\{ \theta_1 \frac{\left[(t_{jk+1}^{\text{exit}} - t_{ijk}^{\text{exit}}) - (t_{ijk}^{\text{exit}} - t_{jk-1}^{\text{exit}}) \right]}{2} + \theta_2 \frac{\left[(t_{ijk+1}^{\text{exit}} - t_{ijk}^{\text{exit}}) - (t_{ijk}^{\text{exit}} - t_{ijk-1}^{\text{exit}}) \right]}{2} \right. \\ \left. + \theta_3 \frac{\left[(\tilde{t}_{i,j^{\text{split}},k}^{\text{exit}} - \tilde{t}_{i,j^{\text{split}},k-1}^{\text{exit}}) - (\tilde{t}_{i,j^{\text{split}},k+1}^{\text{exit}} - \tilde{t}_{i,j^{\text{split}},k}^{\text{exit}}) \right]}{2} - \frac{\beta^{\text{inveh}} q_{ijk}}{2\beta^{\text{wait}} \Lambda_j}, 0 \right\}\end{aligned}\quad (3.20)$$

3.4.7. Holding criterion adaptability

Branches prior to shared transit corridor

As a vehicle approaches the shared transit corridor, the control gradually shifts from single line to multiline control, based on the passenger groups that are affected by each control action. The holding criterion takes therefore into account (i) the regularization of the consecutive headways at the current stop, (ii) the regularization of the expected headways at the first common stop between lines and (iii) an adjustment that accounts for the demand on board and the remaining demand downstream. The demand of all subgroups beyond the merging stop are treated as a single subgroup that is addressed by the projection term. There is only one line operating and the demand that can be satisfied by more than one lines is beyond the merging stop, therefore the term of regulating the joint operation is omitted. The final holding criterion for the branch stops prior to a shared transit corridor is given in Equation 3.21.

$$t_{ijk}^{\text{hold}} = \max \left\{ \begin{array}{l} \theta_1 \frac{\left[(t_{ijk}^{\text{exit}} - t_{ijk-1}^{\text{exit}}) - (t_{ijk+1}^{\text{exit}} - t_{ijk}^{\text{exit}}) \right]}{2} + \\ + \theta_2 \frac{\left[(\tilde{t}_{i,j}^{\text{merg},k} - \tilde{t}_{i,j}^{\text{merg},k-1}) - (\tilde{t}_{i,j}^{\text{merg},k} - \tilde{t}_{i,j}^{\text{merg},k+1}) \right]}{2} \\ - \frac{\beta^{\text{inveh}} q_{ijk}}{2\beta^{\text{wait}} \Lambda_j}, 0 \end{array} \right\} \quad (3.21)$$

Shared transit corridor for merging fork networks

For the shared transit corridor of merging fork networks, we assume that all traversing lines are treated as a single line. Instead of regulating the headway subject to consecutive vehicles of the same line, all vehicles that interact with one another are taken into account. Waiting time with and without holding applied is calculated subject to the vehicle that departed prior to the current bus and the next one expected to arrive. Passengers at stops of overlapping routes board on the bus that arrives first to the stop, given that it minimizes their travel time (Chriqui and Robillard, 1975; Marguier and Ceder, 1984). When considering networks that have a shared transit corridor and no line that diverts from it, lines bear identical characteristics on the overlapping segment without alternation on their routes that may result to differences in the utility of choosing one line over another. Under such conditions, the holding criterion for the shared transit corridor is shown in Equation 3.22. The current vehicle from line i is regulating its departure based on the preceding vehicle $k-1$ and succeeding $k+1$ without considering the line these vehicles belong to according to the following holding criterion:

$$t_{ijk}^{\text{hold}} = \max \left\{ \frac{(t_{jk+1}^{\text{exit}} - t_{ijk}^{\text{exit}}) - (t_{ijk}^{\text{exit}} - t_{jk-1}^{\text{exit}})}{2} - \frac{\beta^{\text{inveh}} q_{ijk}}{2\beta^{\text{wait}} \Lambda_j}, 0 \right\} \quad (3.22)$$

Hence, the control along the shared corridor is analogous to a single line passenger cost minimization, except that t^{exit} of the preceding and succeeding vehicles in the common section can be from either line.

Branches after shared transit corridor and single line application

After exiting the shared transit corridor, a single line criterion is used to maintain control on each branch, derived from the shared corridor holding criterion in Equation 3.22 considering neither the remaining demand downstream nor the existence of a further downstream splitting stop. The single line criterion accounts for every stop j which belongs to the branch ($j > j^{\text{split}}$) is given by Equation 3.23:

$$t_{ijk}^{\text{hold}} = \max \left\{ \frac{(t_{ijk+1}^{\text{exit}} - t_{ijk}^{\text{exit}}) - (t_{ijk}^{\text{exit}} - t_{ijk-1}^{\text{exit}})}{2} - \frac{\beta^{\text{inveh}} q_{ijk}}{2\beta^{\text{wait}} \Lambda_j}, 0 \right\} \quad (3.23)$$

3.5. Transferring criterion

We apply a transfer criterion as presented by Gavriilidou and Cats, (2018). The authors applied the following criterion for transferring passengers on a single stop, given different levels of information on the passenger demand. In order to be in line with the formulation of the regularity criterion, we assume that passenger information is based on historical data for boarding, alighting and transferring passengers.

The holding time needed for synchronization is equal to the difference between current time and the expected arrival of the next vehicle of the transferring line and is given by the following formula:

$$t_i^{\text{hold, sync}} = (\tilde{t}_{i+1,j}^{\text{arrival}} - t^{\text{current}}) + \tau^{\text{transfer}} \quad (3.24)$$

where

- $\tilde{t}_{i+1,j}^{\text{arrival}}$ the expected arrival time of the following vehicle of the connecting line $i+1$ at stop j in [time units]
- t^{current} current time in [time units]; and
- τ^{transfer} minimum transferring time between vehicles in [time units].

3.6. Passenger Cost Comparison

At each of the shared transit corridor stops, holding time aims at providing the minimum cost for the passengers. Therefore, the decision to hold for regularity Equation 3.20 or for synchronization Equation 3.24 is based on the minimum passenger cost:

$$\text{Pax_Cost} = \beta_{\text{wait}} c^{\text{wait}} + \beta_{\text{transfer}} c^{\text{transfer}} + \beta_{\text{held}} c^{\text{held}} \quad (3.25)$$

Passenger cost consists of all different components of passenger travel time. Waiting time cost c^{wait} is the product of half of the predicted headway between consecutive arrivals and the arrival rate of the passengers at the current and the downstream stops of the rolling horizon:

$$c^{\text{wait}} = \delta \sum_{m=j}^{\mu} \frac{1}{2} (t_{\text{imk}}^{\text{arr}} + t_{\text{ijk}}^{\text{hold,reg}} - t_{\text{imk}}^{\text{exit}}) \Lambda_{\mu} + (\delta-1) \sum_{m=j}^{\mu} \frac{1}{2} (t_{\text{imk}}^{\text{arr}} + t_{\text{ijk}}^{\text{hold,sync}} - t_{\text{imk}}^{\text{exit}}) \quad (3.26)$$

Where μ is the number of subsequent stops considered for the comparison of passenger cost and δ a dummy variable which is equal to 1 for waiting time cost with holding for regularity and zero when holding for synchronization. Transfer cost c^{transfer} (if the current vehicle will not be held for synchronization) is the time transferring passengers have to wait until the next arrival of the desired downstream line:

$$c^{\text{transfer}} = \delta \left[\tilde{p}^{\text{transfer}} (\tilde{t}_{i+1,j}^{\text{arrival}} - t_{i,j}^{\text{arrival}}) \right] \quad (3.27)$$

The expected number of transferring passengers is estimated as the product between the fraction of alighting passengers a at the transferring stop and the sum of the arrival rates transferring from one line to another:

$$\tilde{p}^{\text{transfer}} = a \sum_{m=1}^j \sum_{n=j}^{N_{i+1}} \lambda_{m,n} \quad (3.28)$$

Finally, the cost of held passengers c^{held} is the product of the passengers on board and the additional time of the control action they experience:

$$c^{\text{held}} = \delta (t^{\text{hold,reg}} q) + (\delta-1) (t^{\text{hold,sync}} q) \quad (3.29)$$

All components are weighted according to results of previous studies (Cats and Loutos, 2016a; Wardman, 2004) for a given comparison horizon. The comparison horizon for the cost of the waiting passengers is set to the number of remaining downstream common stops. Regularity and synchronization criteria can be paired at any stop of the shared transit corridor.

$$t^{\text{hold}} = \begin{cases} t^{\text{hold,reg}} & \text{Pax_Cost}^{\text{reg}} < \text{Pax_Cost}^{\text{sync}} \\ t^{\text{hold,sync}} & \text{Pax_Cost}^{\text{reg}} \geq \text{Pax_Cost}^{\text{sync}} \end{cases} \quad (3.30)$$

4

Applications on Single Line

In the previous chapter, the holding criterion has been formulated and its applicability on different network configurations, among them for single line networks, has been demonstrated.

In this chapter, the performance of the holding criterion as formulated in the previous chapter is assessed for single lines. The criterion is applied and tested using simulation for a high frequency line of the city of Stockholm, Sweden and is compared with a no-control scheme and the currently used headway based strategy. The results indicate that the new decision rule results in relatively minor reductions of passenger cost compared to the currently adopted strategy, and that it allocates the greatest share of holding time at the beginning of the route.

Content of this chapter has been presented in the following work:

Laskaris, Georgios, Oded Cats, Erik Jenelius, and Francesco Viti. "A Real-Time Holding Decision Rule Accounting for Passenger Travel Cost." In Intelligent Transportation Systems (ITSC), 2016 IEEE 19th International Conference On, 2410–2415. IEEE, 2016.

4.1. Case Study

4.1.1. Line Description

The proposed decision rule introduced in Equation 3.23 is tested for a high frequency bus line in Stockholm, Sweden. The bus system in the city center of Stockholm is mainly served by four trunk lines. The case study considers the southbound direction of Line 4, which serves 31 stops. Line 4 has the highest demand and operates between *Radiohuset* and *Gullmarsplan* (Figure 4-1).

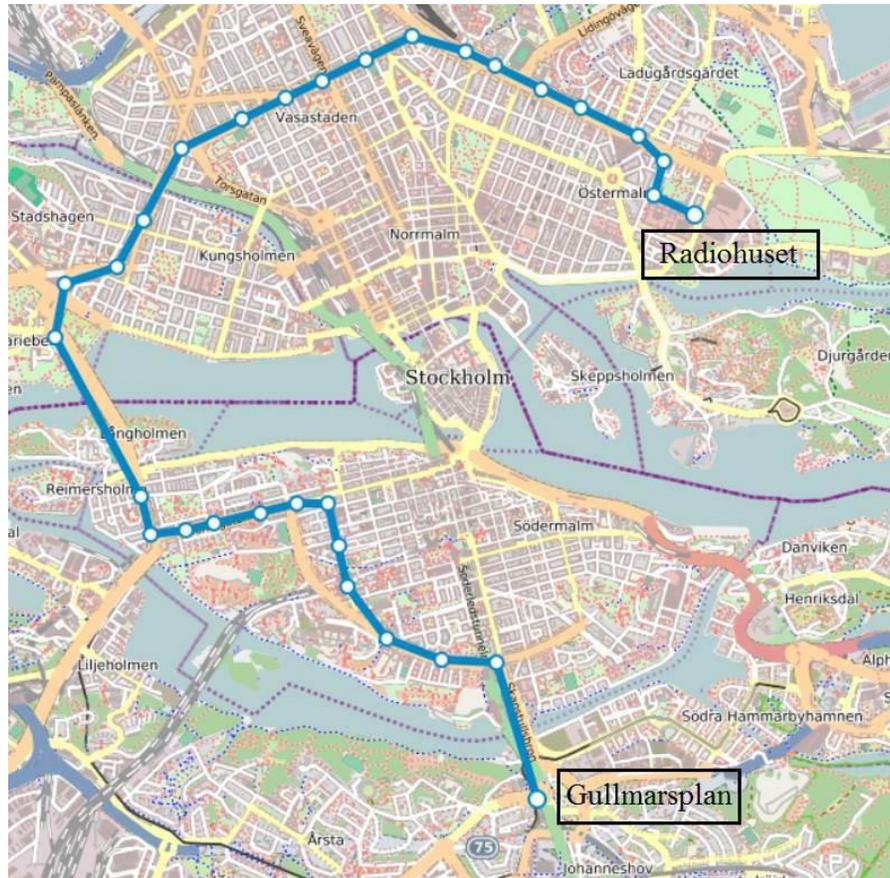


Figure 4-1 Route of line 4 in Stockholm, Sweden

Along the line there are connections with several subway, light rail and commuter train stations as well as bus terminals. During the peak hour approximately 500 passengers are boarding the line and the headway between successive departures is 5 minutes. In order to attain smooth operations and satisfy the demand, articulated buses are used and designated lanes and signal priority are provided along the route. Real time data concerning vehicle locations and aggregated passenger demand data were available for this study. Figure 4-2 illustrates the demand profile of the southbound direction of bus line 4 for the afternoon period (15:00-18:00). The stops with the highest numbers of boarding and alighting passengers are those that allow transfers to other modes. These stops are also used as time point stops for relieving drivers and for service regulation.

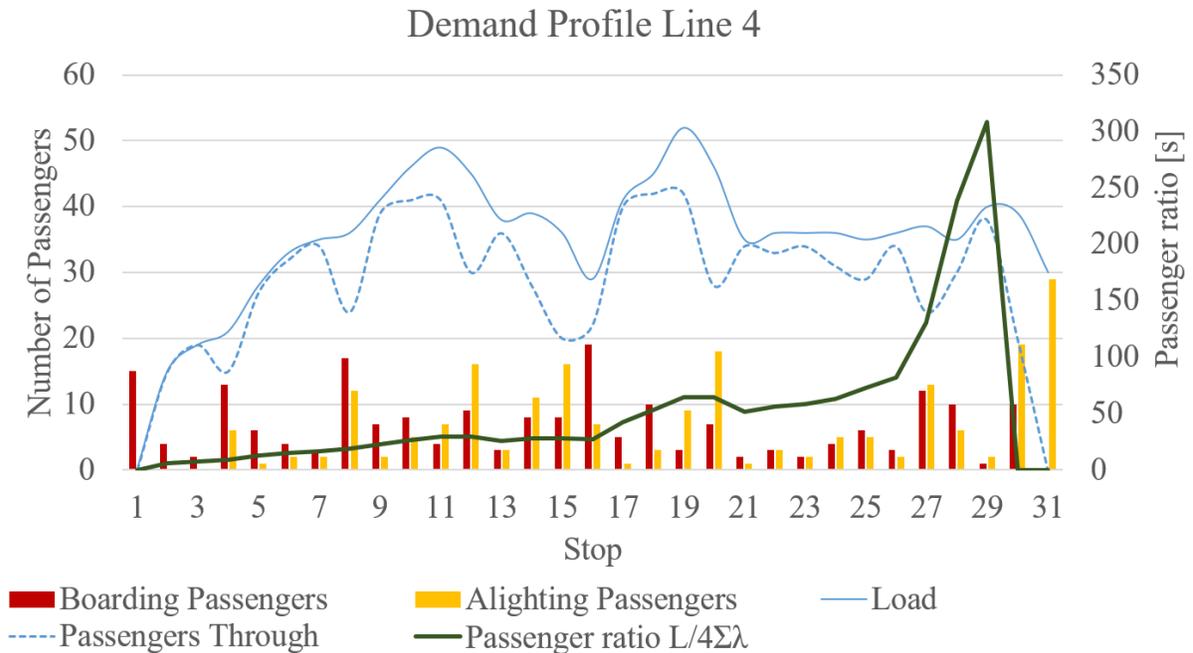


Figure 4-2 Demand Profile of Line 4

4.1.2. Scenario Design

The passenger cost strategy (IPC) is compared with a do-nothing scenario and the even headway strategy. The even headway strategy is currently used for the trunk lines in Stockholm. This strategy is implemented following a series of simulation and field experiment studies (Cats et al., 2011). An empirical analysis of the performance of this strategy demonstrated that it resulted in passenger travel time savings when compared with the previous schedule-based holding control.

Passenger demand data are retrieved for three hours of afternoon operations of the line. Based on the data three different levels of demand were determined to test the two strategies: i) low passenger demand ii) normal (base) passenger demand and iii) high passenger demand. Base passenger demand corresponds to the observed demand level while low and high demand corresponds to 50% and 200% of the base level, respectively.

In the literature there are different approaches concerning the number and the allocation of the control points. Theoretically, all stops can serve as time control points. A common strategy is to allocate time control points prior to stops with high demand (Turnquist and Blume, 1980; Abkowitz and Engelstein, 1984; Liu and Wirasinghe, 2001; Cats et al., 2014). As aforementioned, the new strategy is expected to be triggered more frequently and intensely at the beginning of the route while opting for even headway at the stops where headway variance will be high. In this study all stops can potentially be used for control. This allows identifying where and how frequently the new strategy assigns holding time considering the actual headway and the passenger cost and if it meets the initial assumptions. Table 4.1 summarizes the nine scenarios that were tested.

Table 4.1 Scenarios Tested

	No Control (NC)	Even Headway Strategy (EH)	Passenger Cost Strategy (PC)
Low demand (50)	NC_50	EH_50	PC_50
Base demand (100)	NC_100	EH_100	PC_100
High demand (200)	NC_200	EH_200	PC_200

The scenarios were implemented and tested using the public transport simulation model BusMezzo, which is built on the mesoscopic traffic simulator Mezzo (Toledo et al., 2010). BusMezzo has a wide range of applications and has been previously used to analyze and evaluate real time control strategies (Cats et al., 2011, 2012, 2014). Each scenario was analyzed based on the results of 20 simulation replications. Across the 20 replications the standard error of the headway standard deviation is 5%.

All the parameters of the case study are summarized in Table 4.2 below:

Table 4.2 Case Study Parameters

Number of Lines	1
Frequency of the Line	3-5' min
Number of Stops	31
Network Type	Single line
Simulation tool	BusMezzo
Holding Criterion form	$t_{ijk}^{hold} = \max \left\{ \frac{(t_{ijk+1}^{exit} - t_{ijk}^{exit}) - (t_{ijk}^{exit} - t_{ijk-1}^{exit})}{2} - \frac{\beta^{inveh} q_{ijk}}{2\beta^{wait} \Lambda_j}, 0 \right\}$

4.2. Results

The strategies were evaluated using key measurements of performance of the line, shown in Table 4.3. The coefficient of variation of headways represents the average variability of headways at all stops along the line. It is clear from the results that when a control strategy is applied, the headway variability decreases significantly. Both strategies result in considerable improvements for peak demand, but in general even headway outperforms passenger cost.

Table 4.3 Key measurements of performance of the line

	Average CV of line headway	Bunching %	Average bus trip time (sec)	Average holding time per bus trip (sec)	Average waiting time per passenger (sec)	Average in vehicle time per passenger (sec)	Average weighted travel time per passenger (sec)
NC_50	0.57	40%	3092	0	189.3	99.8	478.4
EH_50	0.32	8%	3291	6.78	156.7	106.2	420.4
PC_50	0.35	12%	3253	4.72	155.9	104.9	416.7
NC_100	0.76	54%	3473	0	230.5	112.4	573.4

EH_100	0.48	16%	3765	10.43	174.0	121.6	469.6
PC_100	0.53	27%	3717	8.15	179.8	119.9	479.5
NC_200	0.79	55%	4291	0	214.2	138.6	567
EH_200	0.57	24%	4484	7.28	177.8	145.8	501.4
PC_200	0.57	29%	4430	4.82	174.7	144.1	493.5

The second measure of performance is bunching. The share of buses that are bunched is the ratio of trips that arrive within a headway 50% lower or 50% greater than the planned headway and the total number of trips (*Transit capacity and quality of service manual*, 2003; Cats, 2014). Again, the even headway strategy yields the best results. However, the passenger cost strategy also reduces bunching significantly compared to when no control is applied. Although the results of the passenger cost strategy cannot be characterized as poor, the dominance of the even headway strategy for these two measures can be explained by the fact that they are consistent with the main objective of the strategy, which is to regulate headways between consecutive vehicles.

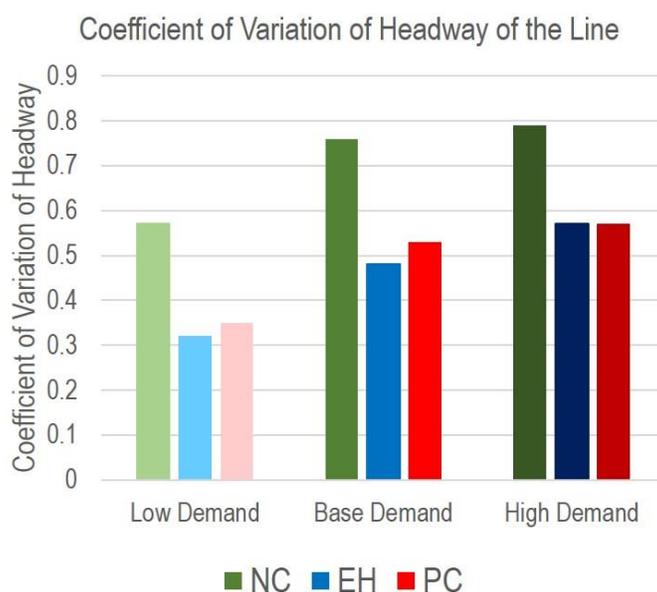


Figure 4-3 Coefficient of Variation of headway of the line for the different scenarios

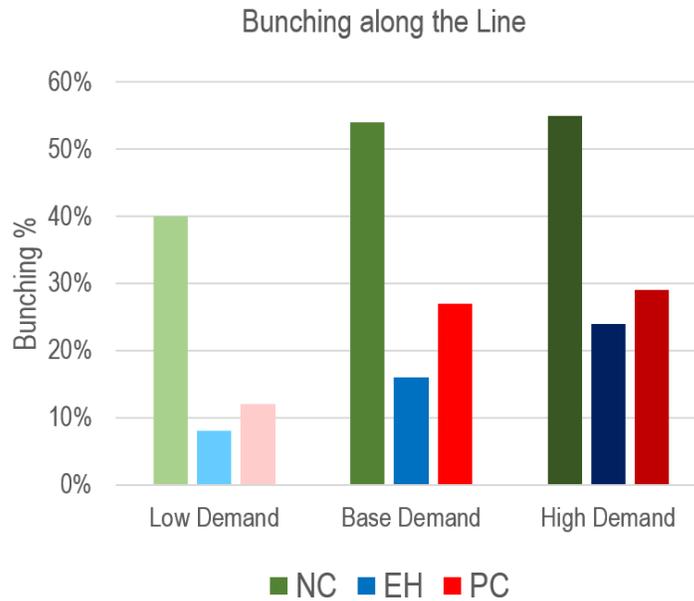


Figure 4-4 Bunching of the line for all different scenarios

When a control strategy is applied, the average trip time is longer due to the additional holding time. Indeed, for all three demand levels the average trip time becomes longer when a control strategy is applied. The new strategy slightly decreases the average average trip time due to the reduction of holding times caused by the passenger ratio.

Furthermore, the effects of the introduced passenger ratio can be observed by the reduced holding time by 20% to 30% when the passenger cost strategy is applied compared to the even headway strategy.

There are no significant differences between the control schemes in terms of waiting times. While both control strategies significantly reduce waiting times compared to the no control scenarios, there are marginal differences between them. At low and peak demand levels, the waiting time is slightly lower for the passenger cost strategy than the even headway strategy. However, the even headway strategy outperforms the passenger cost strategy for the base demand level.

When a control strategy is applied, passengers are experiencing longer in-vehicle delay because of holding time. Due to the reduction in holding time yielded by the passenger cost holding strategy, the in-vehicle delay is reduced. In all three demand scenarios the mitigation of in-vehicle delay is at a similar level, on average 1.2%.

The sum of waiting time and in-vehicle delay is the corresponding travel time of each passenger. For all three demand levels, the no control scheme is outperformed by the schemes with a control strategy and for low and peak demand, the passenger cost strategy is the most effective thanks to slightly shorter in-vehicle times as well as waiting times.

Table 4.4 Travel time at the two halves of the route

	First half of the route			Second half of the route		
	Average waiting time per passenger (sec)	Average in vehicle delay per passenger (sec)	Average weighted time per passenger (sec)	Average waiting time per passenger (sec)	Average in vehicle delay per passenger (sec)	Average weighted time per passenger (sec)
NC_50	174.5	101.6	450.6	213.1	97.9	524.0
EH_50	155.1	107.2	417.5	159.8	105.0	424.7
PC_50	153.5	106.7	413.7	159.4	103.1	421.8
NC_100	189.6	115.6	494.8	296.6	108.9	702.1
EH_100	164.1	122.4	450.5	189.1	121.0	499.3
PC_100	167.4	122.1	456.8	198.7	117.6	514.9
NC_200	189.7	146.2	525.5	259.1	131.3	649.5
EH_200	174.2	150.9	499.3	184.6	139.5	508.6
PC_200	170.2	150.1	490.4	182.7	137.6	503.1

The results suggest that there is no significant gain from implementing the new strategy at system level since there are minor reductions in travel time cost while attaining less regular service compared with the even headway strategy. With the new strategy, more holding time is assigned at the beginning of the route and less after the middle of the route, because of the increasing magnitude of the passenger ratio as shown in Figure 4-2 . This can be also seen in Table 4.4 where the travel time results are split into the first and second halves of the route. On the first part of the route the two control strategies have the same performance. Conversely, on the second half of the route, where the passenger cost strategy instructs vehicles to hold less frequently and for a shorter time, an increasing trend in waiting time is observed simultaneously with a decreasing trend in in-vehicle time, which are also reflected in total travel time.

The overall performance of the passenger-based strategy is also shown by the variability of headways along the route (Figure 4-5). Both strategies are effective in improving regularity but the effect of the new strategy is more pronounced at the beginning of the route. Evidently, both strategies significantly improve headway variability compared to operation without control. Until the middle of the route, both strategies have the same performance. After the 16th stop, the sum of the arrival rates at the downstream stops is not sufficiently high and consequently the magnitude of the passenger ratio is higher. As a result, when the passenger cost strategy is applied, the final holding time assigned is lower. For peak demand the passenger ratio presents a slower increasing trend allowing the passenger cost strategy to perform identically to the even headway strategy.

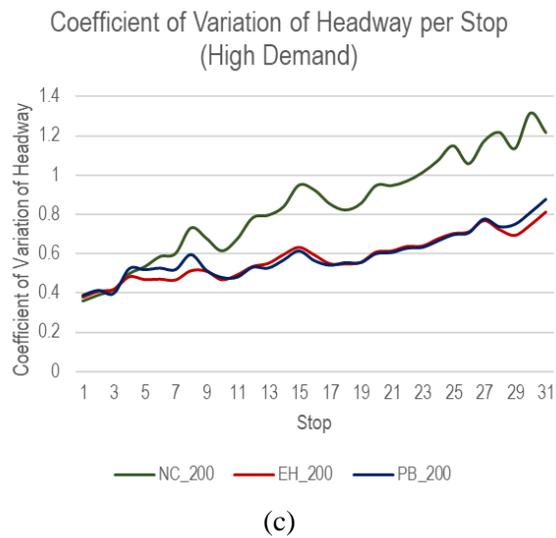
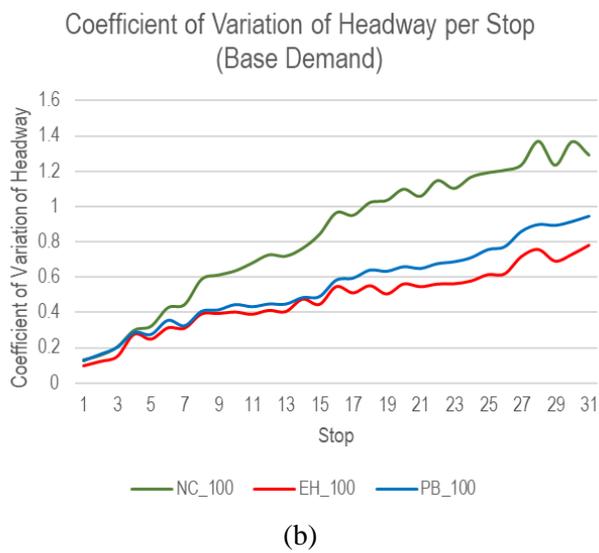
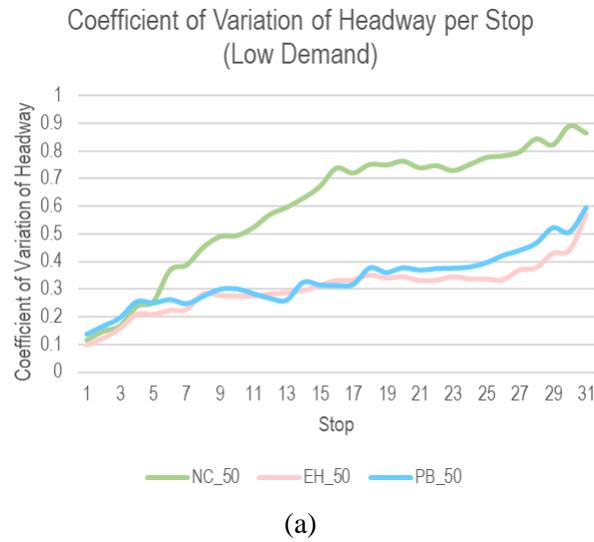


Figure 4-5 Coefficient of variation of headway at each stop

The passenger ratio is a key determinant of the performance of the proposed strategy. By reducing holding time, it also creates a new pattern concerning the stops or route segments where the vehicle can be held. Figure 4-5 shows the average holding time at each stop with even headway strategy and passenger cost strategy and the holding frequency of each strategy. It can be observed how holding time is mitigated due to the effect of the passenger ratio and the larger share of holding time is applied before the middle of the route, where the passenger ratio reduces holding time by less than a minute and then the new strategy allows holding time of several seconds as a vehicle approaches the end of the route.

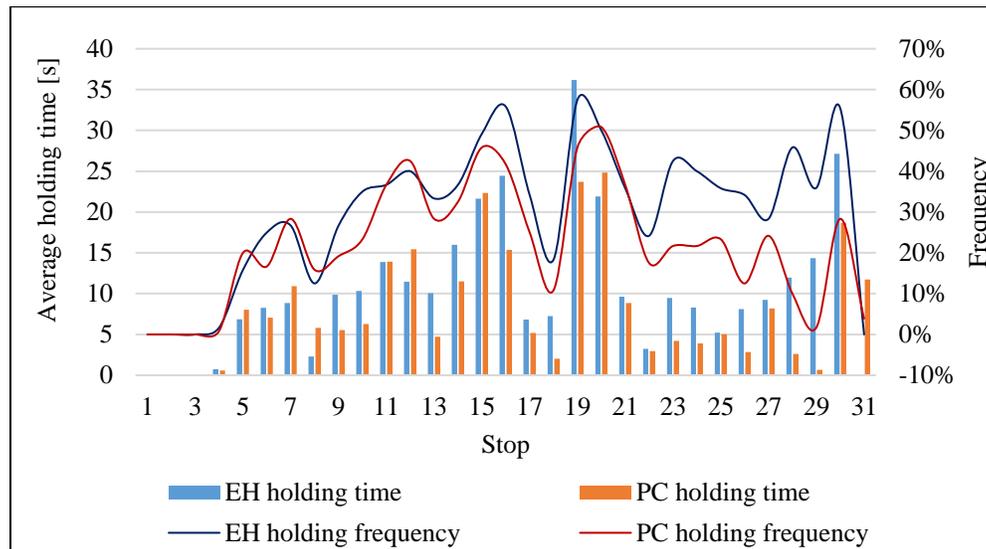


Figure 4-5 Average holding time and holding frequency per stop

At high demand stops, in particular those that provide connections to other modes, the variability in passenger demand is also high. At these stops holding rules should be more frequently applied. This can also be observed in the difference in the frequency with which the vehicles are instructed to hold between the different strategies. When approaching high demand stops, with the passenger cost strategy, vehicles are instructed to hold more frequently in contrast to the general decreasing trend due to the increase in the ratio's magnitude. Although there is a mitigation of holding time at stops, due to the high variability of travel time and demand at these stops more vehicles need to be held and vehicles arriving at these stops with lower occupancy are held longer, affecting the average holding time.

4.3. Discussion

Rule-based holding control strategies aim at regulating the headway between consecutive vehicles and indirectly achieving reductions in passenger travel cost. In this Chapter, the formulated criterion is tested for single line operation and the holding decision is explicitly based on passenger travel cost, which determines holding times at stops. Recommended holding times are calculated based on the headways of consecutive vehicles and the number of passengers that will be affected by the additional travel time. The new holding rule was tested for a high-demand high-frequency bus line in the city of Stockholm using a simulation model, and was compared with the even headway strategy, which is currently used.

The passenger cost strategy performs almost equally well compared with even headway strategy in terms of waiting time and travel time while it yields a minor reduction in in-vehicle time. The two control strategies provide satisfactory results in terms of vehicle-based reliability metrics which are the main

objectives of the even headway strategy. For peak demand the benefits to the passengers from the reduction in in-vehicle delay is sufficient to be reflected in the travel time. Moreover, the passenger cost strategy gives similar results in terms of headway variability and similar or shorter waiting times compared to the even headway strategy while requiring shorter holding times.

With the new strategy holding is more prevalent at the first part of the route with similar performance to the even headway strategy, while the need to control diminishes at the second half of the route. The distribution and the frequency of holding along the line change due to the passenger distribution of the line and the occupancy of buses arriving at these stops.

5

Application on Merging Lines

In this chapter, the first application of the holding criterion for multiline control is presented. The formulated holding criterion is tested for a merging fork network and accounts for coordination at the merging branches and for the joint operation at the shared transit corridor. Results from two different applications (artificial and real world network) show that coordination is achieved as well as consistent network wide travel time benefits.

Content of this chapter has been presented in the following work:

Laskaris, Georgios, Oded Cats, Erik Jenelius, Marco Rinaldi, and Francesco Viti. “Multiline Holding Based Control for Lines Merging to a Shared Transit Corridor.” *Transportmetrica B: Transport Dynamics*, November 26, 2018. <https://www.tandfonline.com/doi/abs/10.1080/21680566.2018.1548312>.

Laskaris, G., Cats, O., Jenelius, E., Rinaldi, M., & Viti, F. (2019). “Principles for setting single line and multiline control based on network characteristics.” In 8th HEART Conference (Presented).

5.1. Experimental and Application Setup

In this Chapter the criterion is tested for a merging fork network. Therefore, for the merging branches the criterion is applied as in Equation 3.21, while at the shared transit corridor as in Equation 3.22. The proposed holding strategy is assessed in two different experimental phases, applying different degrees of freedom in testing parameters. The experimental set-up is summarized in Table 5.1. First, the holding criterion for the branch stops is tested for an artificial network simulated in Mathworks™ MATLAB®; thereafter we proceed to a full network control of a real case study using empirical demand data, and employing the mesoscopic simulation software BusMezzo (Toledo et al., 2010), an agent-based transit operations and assignment simulation model.

Table 5.1 Summary of the key properties of the experimental set-up

Experiment/Application	Platform	Network	Control	Demand
Numerical simulation	MATLAB	Artificial	Branches only	Artificial
Agent-based Transit simulation	BusMezzo	Real	Full Network Control	Actual Data

In the following sections, the experimental set-up, the scenarios tested and the selected performance indicators are described.

5.1.1. Numerical simulation

For the first set of experiments, we consider a transit system including two lines that merge after operating independently, like the one illustrated in Figure 5.1. The two lines consist of 30 stops each, the first 15 of which are single line (branch) stops and the remaining are shared (trunk) stops. Both lines have the same planned headway and trips are dispatched with an offset equal to half of the planned headway, so that vehicles from the two lines are planned to arrive to the first common stop in an alternate fashion. All branch stops of both lines including the first common stop are simulated. All branch stops are considered time control points, i.e. holding can be applied at any of the stops. It is assumed that AVL and historical data are available and no capacity constraints are taken into consideration. In addition, all stops are assumed equidistant (i.e. scheduled riding times are the same between stops) and both lines have the same demand profile.

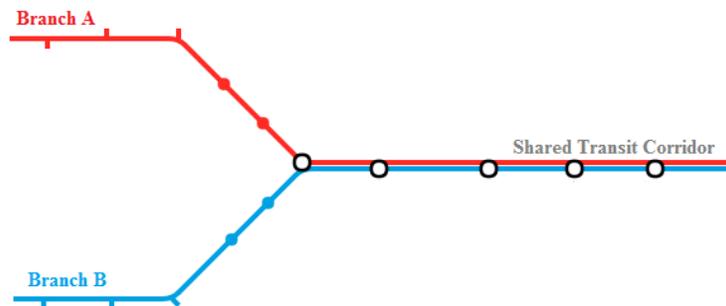


Figure 5-1 Schematic configuration of a merging fork network

The network is implemented in Mathworks™ MATLAB®. As the simulation progresses, vehicles are dispatched from the origin terminal, their running times between stops are sampled and, when vehicles arrive at stops, passengers are generated according to the actual headways. Vehicle dispatching times, actual riding times and passenger arrival rates are sampled from the corresponding distributions summarized in Table 5.2. Dispatching times are sampled by Gamma distribution. By varying the shape a and the scale b of the distribution, perfectly regular to perfectly irregular dispatching times can be replicated. For the current experimental setup, a shape parameter $a=10^6$ and scale parameter $b=10^{-5}$ were chosen, eliminating any disturbance in dispatching times allowing vehicles to depart on schedule. The stochasticity sources are the actual riding time and the passenger demand; trip chaining actions (i.e. the complete daily tours of the buses) are not considered in this experiment.

Riding times are sampled from lognormal distributions with scheduled riding times as the mean and a 20% standard deviation of the mean. The passengers generated are sampled from a Poisson distribution given the average arrival rate λ and the actual headway. The Poisson distribution has been used in the literature to replicate random arrivals of passengers at stops (Fu and Yang, 2002; Toledo et al., 2010). Demand is given in terms of arrival rates per origin-destination pair for each stop. The total number of boarding passengers is the sum of the arrival rates that originate from the given stop given the actual headway between vehicles at the stop. The number of alighting passengers depends on the number of passengers generated at upstream stops with the current stop as their destination. We consider the dwell time function as a linear function of boarding passengers B and alighting passengers A , multiplied by the service time needed per passenger to board and alight as estimated in the study of (Dueker et al., 2004).

$$t^{\text{dwell}} = 3.48B + 1.7A \quad (5.1)$$

where B is the number of boarding passengers and A the number of alighting passengers.

Table 5.2 Summary of distributions specified in the experiment

Dispatching Time	Gamma Distribution	(a, b)
Actual Riding Times	Lognormal Distribution	(μ, σ)
Boarding Passengers	Poisson Distribution	(λ)

After updating vehicle occupancy, depending on the scenario, the assigned controller is triggered. Since overtaking is not allowed, the current vehicle cannot depart if its preceding vehicle is still at the stop, following a strict FIFO priority rule. After serving all branch stops, vehicles are sorted at the first common stop based on their arrival time and passengers are generated according to the actual joint headway between vehicles.

All the parameters of the numerical simulation are summarized in Table 5.3 below:

Table 5.3 Numerical Simulation Parameters

Number of Lines	2
Frequency of the Line	10min (5min joint frequency)
Number of Stops	15 branch stops and a common stop
Network Type	Merging Fork
Simulation tool	Mathworks™ MATLAB®

Holding Criterion form

$$t_{ijk}^{\text{hold}} = \max \left\{ \begin{array}{l} \theta_1 \frac{[(t_{ijk}^{\text{exit}} - t_{ijk-1}^{\text{exit}}) - (t_{ijk+1}^{\text{exit}} - t_{ijk}^{\text{exit}})]}{2} + \\ + \theta_2 \frac{[(\tilde{t}_{i,j}^{\text{merg},k} - \tilde{t}_{i,j}^{\text{merg},k-1}) - (\tilde{t}_{i,j}^{\text{merg},k} - \tilde{t}_{i,j}^{\text{merg},k+1})]}{2} - \\ - \frac{\beta^{\text{inveh}} q_{ijk}}{2\beta^{\text{wait}} \Lambda_j}, 0 \end{array} \right.$$

5.2.2. Agent-based transit simulation BusMezzo

The numerical simulation presented in Section 5.1.1 lacks in monitoring all different passenger groups and their travel times. Therefore, a more sophisticated simulation environment is adopted. BusMezzo is a mesoscopic transit simulator built on the mesoscopic traffic simulator Mezzo (Burghout et al., 2005). BusMezzo has been shown to replicate phenomena of transit operation such as the propagation of headway variability and bunching (Toledo et al., 2010). Furthermore, demand can be given in terms of origin-destination pairs, and passengers are simulated as agents and can choose the optimal path that corresponds to the maximal individual utility (Cats et al., 2016). The user can monitor the travel time and the path of each passenger separately within the network and retrieve passenger cost of each passenger group, an important factor for the assessment of the performance of the criterion. Finally, the transit simulator has been used previously to compare and assess the performance of holding strategies, both schedule based and regularity based (Cats et al., 2011, 2012).

For the application using BusMezzo, lines 176 and 177 of the city of Stockholm are chosen (Figure 5-2). The two lines connect the metro station of Mörby centrum with the Ekerö communities via the densely populated municipality of Solna. As shown in Figure 5-2, the eastbound direction of lines 176 and 177 serve, before the shared transit corridor, 19 and 12 stops respectively. At the shared transit corridor, the two lines provide a tangential connection between the different radial metro lines and commuter trains as well as buses and the light rail connecting the outskirts of the city with the city center. The timetable of the lines is designed so that vehicles of the two lines depart from their terminals in a fashion that allows them to enter the trunk alternately. Overtaking is allowed in any part of the network. The entire fleet is equipped with real-time vehicle positioning data.

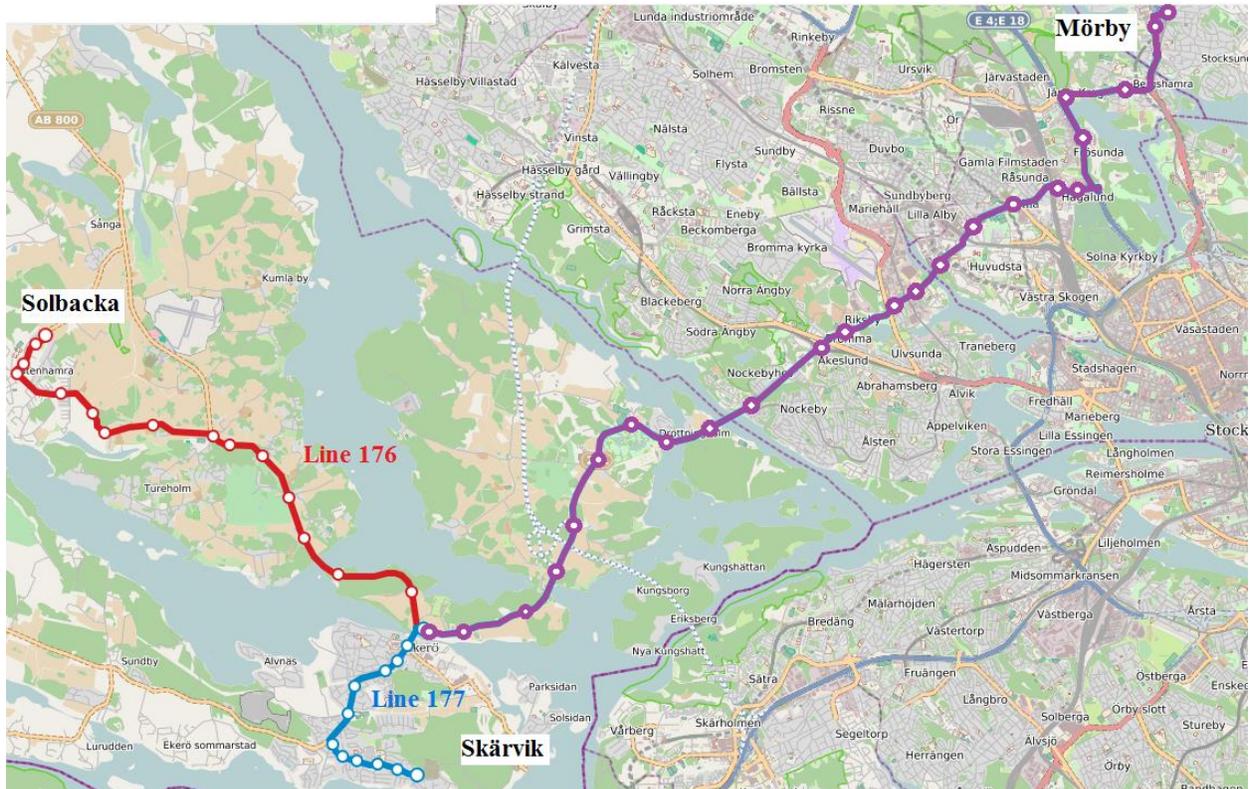
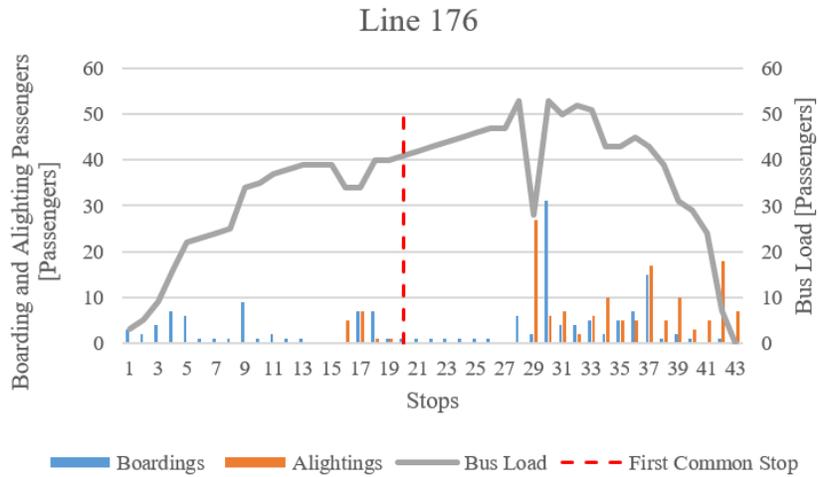


Figure 5-2: Lines 176 and 177 in Stockholm, Sweden

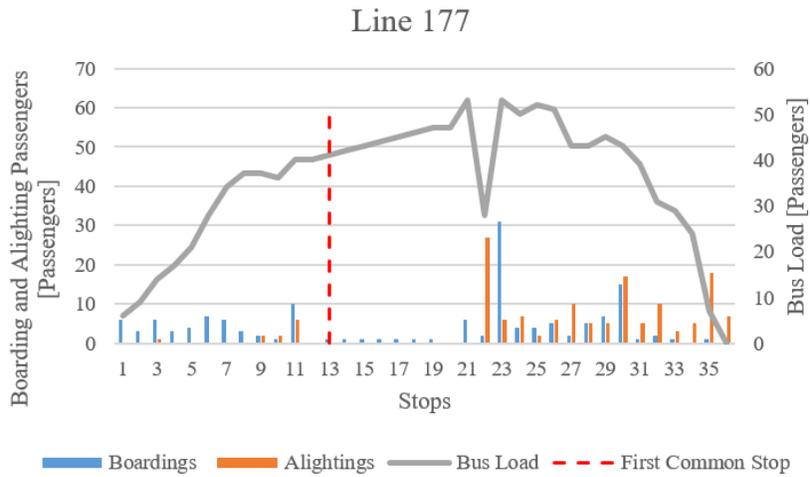
Empirical data for the demand and travel times of the lines was retrieved and specified as input to the simulation model. As can be observed in Figure 3, the two lines have a similar demand profile, with the majority of the passengers travelling from the branch to the trunk or along the trunk. Only a small share of the passengers has stops along the branch as both its origin and destination. In Table 5.4, the demand distribution for each of the lines is summarized.

Table 5.4: Demand Distribution Breakdown for Lines 176 and 177

	Line 176		Line 177	
	Passengers per vehicle trip	Share of Total Demand	Passengers per vehicle trip	Share of Total Demand
Total Demand	147	100%	144	100%
Demand on Branch	14	9.5%	7	4.9%
Demand on Shared Transit Corridor	133	90.5%	137	95.1%
Corridor Demand generated at branch stops	40	27.2%	44	30.6%
Corridor Demand generated at corridor stops	93	63.3%	93	64.5%



(a)



(b)

Figure 5-3: Demand profiles of lines 176 (a) and 177 (b) (Westbound)

5.1.3. Scenarios

Three different schemes are tested: (i) a no control (NC) scheme (vehicles depart immediately after the completion of boarding and alighting operations); (ii) an independent implementation of passenger cost strategy applying the criterion of Equation. (3.23) (IPC), and; (iii) the new cooperative scheme formulated in Eqn. (3.21) (CPC). All scenarios tested using the MATLAB numerical simulation are summarized in Table 5.5.

Table 5.5: Scenario design for experiments using numerical simulation

	No Control (NC)	Independent Passenger Cost (IPC)	Cooperative Passenger Cost (CPC)
Demand Profile 1 (25%-75%)	NC_1	IPC_1	CPC_1
Demand Profile 2 (50%-50%)	NC_2	IPC_2	CPC_2
Demand Profile 3 (75%-25%)	NC_3	IPC_3	CPC_3

For the BusMezzo case study, the first level of comparison concerns differences in tactical planning. Two scenarios with equal headways and unequal headways are tested. For the first scenario, both lines have the same headway of 10 min. For the second scenario, line 177 runs with a headway of 5 min while line 176 has a headway of 10 min. The planned joint headway is calculated as the average headway between the lines. The formulated CPC criteria are compared against a do-nothing scenario (NC) and an Even Headway control strategy (EH), which regulates the departure time based on the headways between consecutive vehicles and, at the same time, limits the maximum allowed holding time to 80% of the planned headway of the line (Cats et al. 2011). The schemes are tested for the actual demand and for a peak demand scenario, which corresponds to a uniform increase of +50% compared to the empirical demand level. The scenario design for the BusMezzo case study are summarized in Table 5.6.

Table 5.6: Scenario design for the application using transit simulation

		No Control (NC)	Even Headway Strategy (EH)	Cooperative Passenger Cost (CPC)
Scenario 1: Equal Headways	Actual Demand	S1_NC_1	S1_EH_1	S1_CPC_1
	Peak Demand	S1_NC_2	S1_EH_2	S1_CPC_2
Scenario 2: Unequal Headways	Actual Demand	S2_NC_1	S2_EH_1	S2_CPC_1
	Peak Demand	S2_NC_2	S2_EH_2	S2_CPC_2

All the parameters of the agent based simulation are summarized in Table 5.7 below:

Table 5.7 Numerical Simulation Parameters

Number of Lines	2
Frequency of the Line	10min (5min joint frequency)
Number of Stops	36-43 (24 common stops)
Network Type	Merging Fork
Simulation tool	BusMezzo

Holding Criterion form

$$t_{ijk}^{\text{hold}} = \max \left\{ \begin{array}{l} \theta_1 \frac{\left[(t_{ijk}^{\text{exit}} - t_{ijk-1}^{\text{exit}}) - (t_{ijk+1}^{\text{exit}} - t_{ijk}^{\text{exit}}) \right]}{2} + \\ + \theta_2 \frac{\left[(\tilde{t}_{i,j}^{\text{merg},k} - \tilde{t}_{i,j}^{\text{merg},k-1}) - (\tilde{t}_{i,j}^{\text{merg},k} - \tilde{t}_{i,j}^{\text{merg},k+1}) \right]}{2} - \\ - \frac{\beta^{\text{inveh}} q_{ijk}}{2\beta^{\text{wait}} \Lambda_j}, 0 \end{array} \right.$$

5.1.4. Performance Indicators

Regularity performance indicators

The *coefficient of variation of headway*, the ratio between the standard deviation and the average headway, reflects the degree of variability of service headway. The coefficient of variation of the joint headway of both lines is also calculated to examine the impact of line coordination on trunk performance. The coefficient of variation of headway is calculated in line level based on departure-based headways. The coefficient of variation of the joint headway at the merging stop is based on arrivals to demonstrate the arrival with less variability at the common section due to coordinating control at the branch stops prior to the shared transit corridor.

The *level of bunching* is calculated for each line as the share of actual headways that are 50% greater or lower than the planned headway (*Transit capacity and quality of service manual*, 2003).

Passenger performance indicators

The *generalized travel time* is reported with its components, waiting time and in-vehicle time. In the numerical experiments, the passenger travel times are given per passenger and per route segment for the branch stops. In the real case study, control is applied in BusMezzo also at the shared transit corridor, considering cooperation between lines. Thus, the travel times are reported at the line level and, in the shared transit corridor, for the joint operation. Furthermore, travel times are also given at the network level and compared per passenger group: the passengers travelling on branches, from branches to the shared transit corridor and within the shared transit corridor.

Vehicle performance indicators

Since holding has consequences for vehicle travel times, the *90th percentile of travel time* of vehicle trips, which is the determinant of fleet size requirements, within the branch for both lines is also reported. For the performance of the controller with BusMezzo, the 90th percentile of the total travel time for both lines is used. Moreover, the *average holding time* at each branch stop is investigated. Finally, the *prediction error* of the vehicle arrival projection scheme used by the controller to estimate the expected departure from the first common stop is examined.

Number of Replications

A certain number of replications is needed so that the results are within a certain confidence interval. The sample size needed for reliable and robust results is calculated using the following formula:

$$N' \geq t_{\frac{\alpha}{2}, N-1}^2 \frac{X_s^2}{X_d^2}$$

where,

N' sample size;

$t_{\frac{\alpha}{2}, N-1}$ student $-t$ value for reliability α and a sample N ;

X_d standard deviation of the chosen indicator for the sample N ;

X_s accepted standard deviation.

The weighted travel time is used as reference measurement, since it lies at the basis of the formulation of the holding criterion. For the numerical experiment, 200 replications are conducted. Setting as a desired standard deviation a time equal to 1.5% of weighted travel time and for a student $-t$ value of 1.971957 for 5% error and a sample of 200 replications, the maximum number of replications needed is 30, so the chosen number of replications is indeed sufficient. Likewise, for BusMezzo using the same reference measurement, 50 replications are conducted. For a student $-t$ value of 1.677 for 10% error, 20 replications are sufficient.

5.2. Results and Analysis

5.2.1. Numerical experiments

Line performance

The performance in terms of regularity and travel time indicators is given in Table 5.8.

Table 5.8: Line level performance indicators

Distribution	Scenario	Line A				Line B					
		CV Head way	Bunching	Waiting Time [sec]	In vehicle time [sec]	Generalized travel time [sec]	CV Head way	Bunching	Waiting Time [sec]	In vehicle time [sec]	Generalized travel time [sec]
25-75	NC	0.50	0.10	138.63	308.66	585.92	0.49	0.09	136.79	308.32	581.90
	IPC	0.45	0.07	136.00	307.76	579.77	0.45	0.07	134.53	309.32	578.38
	CPC	0.41	0.05	133.88	307.82	575.58	0.42	0.05	133.73	308.83	576.30
50-50	NC	0.71	0.17	126.95	318.35	572.26	0.72	0.17	125.43	319.32	570.17
	IPC	0.59	0.10	120.94	320.10	561.99	0.59	0.11	119.17	320.33	558.67
	CPC	0.47	0.06	117.48	320.32	555.27	0.48	0.06	116.63	322.17	555.42

75-25	NC	0.66	0.19	163.99	319.28	647.26	0.67	0.18	163.58	321.65	648.81
	IPC	0.54	0.12	154.82	321.18	630.81	0.54	0.12	154.07	325.52	633.65
	CPC	0.41	0.06	148.69	323.22	620.60	0.41	0.06	148.54	322.49	619.57

As expected, applying control reduces service variability, and control strategies are more effective the higher the demand along the branch (case 75-25), which yields higher potential gains for demand-aware control strategies. Equivalent results are also found in terms of bunching. The control schemes reduce headway variability and this is reflected in the results of waiting times at stops. The waiting time gains due to controlling are greater at the third demand scenario for both lines. Since the control scenarios are based on holding, passengers may experience increased on-board time due to the additional time a vehicle remained at a given stop. In-vehicle time with IPC and CPC increases only marginally compared to the do-nothing scenario. This can be explained by the fact that both holding criteria adjust the holding time calculated to the occupancy and the remaining demand downstream, to limit excessive in vehicle time. The cooperative control yields the lowest travel time in all three scenarios.

Coefficient of Variation of Headway along the branch stop for each scenario

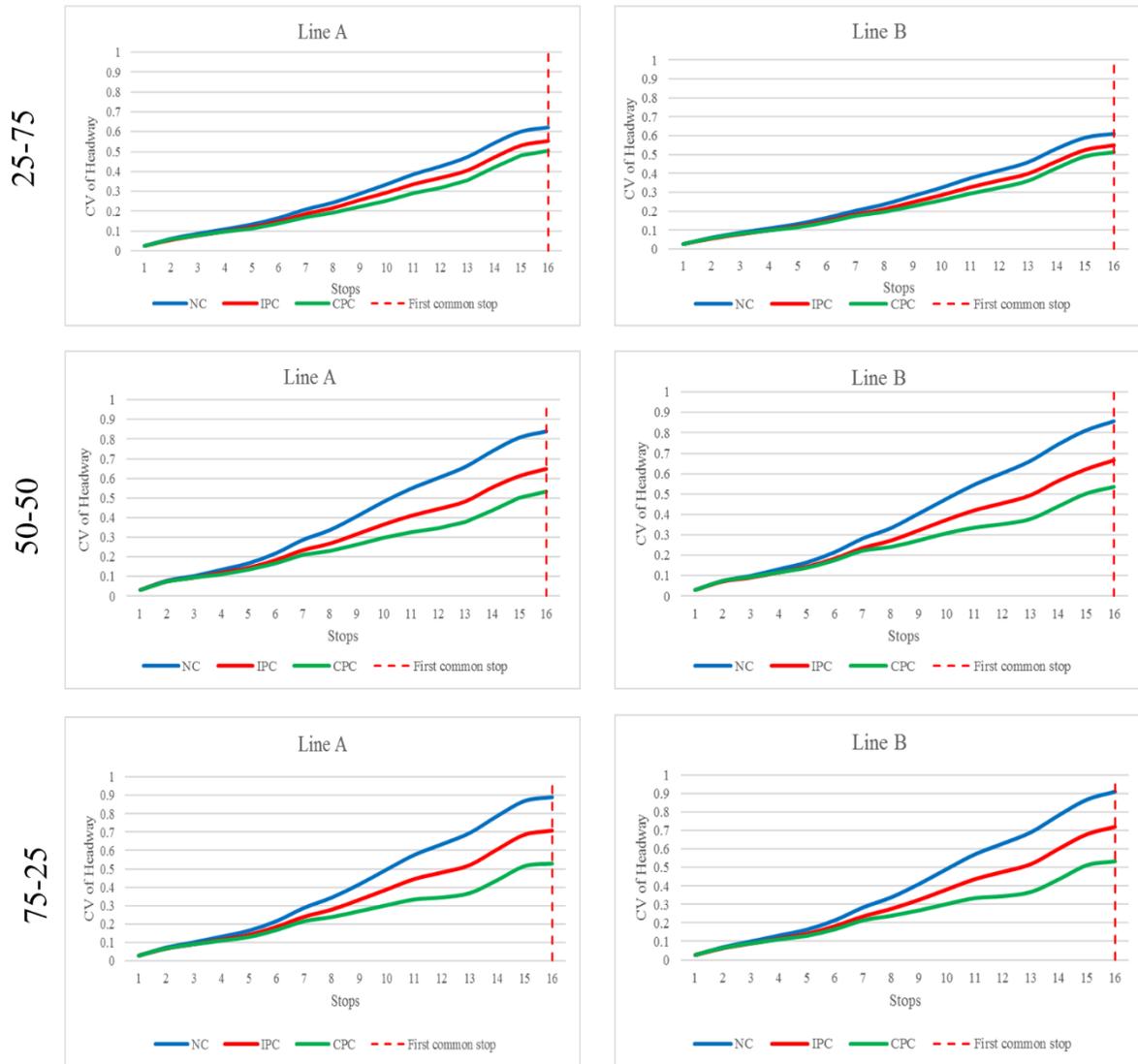


Figure 5-4: Coefficient of variation of headway along branch stops for each scenario

The effectiveness of the new control scheme is investigated by analyzing the progression of the variability of headways along the branch stops (Figure 5.4). Both controllers result in improved headway variability compared to the No Control scenario. For the scenario with low demand on the branch, CPC follows the same behavior as the single line controller, which relies only on the consecutive headways at the current stop corrected by the occupancy and the passengers on board. In contrast, in the third demand scenario, CPC is more effective and maintains low headway variability in the part of route where most of the demand is concentrated. Recall that CPC holding criterion is an extension of the IPC holding criterion with the addition of line coordination and a more appropriate adjustment to the remaining demand, considering also the demand that can be served by both lines via the passenger ratio and the weights added to each term. As a result, the main objective of the controller shifts between the importance of line regularity or line

coordination based on the demand distribution, resulting in more effective control in this network configuration than single line control.

Arrival at the first common stop

One of the most crucial elements in the current network configuration is the transition from the branches to the trunk. The total holding time before the trunk is estimated with respect to the actual line headway at the current branch stop and the expected headway at the first common stop. It is then adjusted considering the distance from the trunk itself and the number of passengers that will experience the additional time the vehicle remains at the stop. Figure 5.5 shows the coefficient of variation of headway at the first common stop, based on the arrivals of vehicles from both lines. While IPC yields some beneficial results at the first common stop, CPC outperforms it with a better performance for all three demand scenarios, yielding a greater level of coordination. The most significant reduction is observed for the third demand profile, resulting from control on all branch stops since the majority of the demand is concentrated in that part of the line.

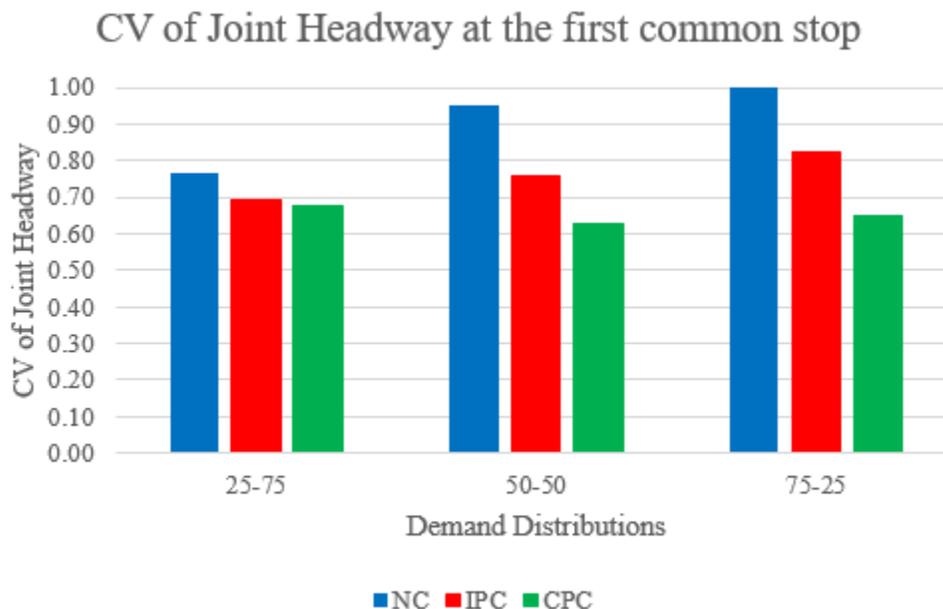


Figure 5-5: CV of Joint Headway at the first common stop

Travel time distribution

Finally, CPC outperforms all other schemes in travel time variability for most of the scenarios, as can be seen from the travel time distributions in Figure 5-6. By reducing the variability in travel time until the first common stop, the adherence to the joint headway can be ensured.

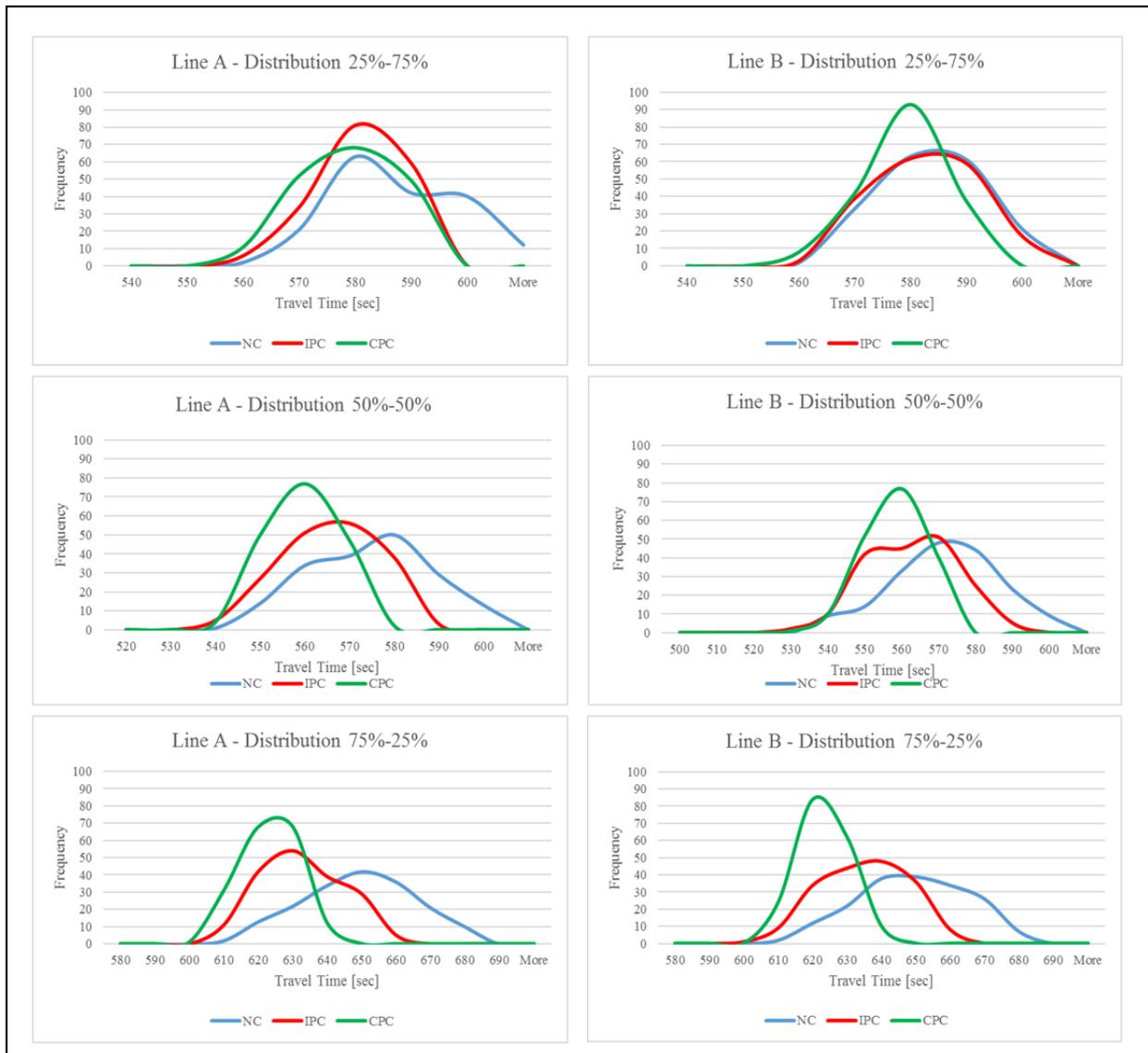


Figure 5-6: Branch Travel Time Distributions for the different scenarios

Interestingly, at the 25%-75% demand distribution scenario, while line B shows satisfactory results, line A shows an increased travel time variability. It seems that for this demand distribution, one line out of the two is in charge of line coordination, applying additional control, while the other continues to aim for line regularity, which gradually weakens towards the end of the individual segment. For branch demand equal or greater than the corridor demand, both lines perform similarly. In addition to higher variability, the no control scenarios also result in longer vehicle travel times than the controlled scenarios. This can be explained by the experimental setup and the assumption that overtaking is not allowed due to the FIFO departure rule.

5.2.2. Transit simulation application

Line Results

In terms of regularity measurements at the line level, EH outperforms the other schemes, as it directly relates to its objective in Scenario 1. Line headways vary less with EH for both lines 176 and 177 (Table 5.9) and almost no bunching occurs under all scenarios. However, travel times at the branches are the lowest with CPC. Compared to EH, CPC estimates the holding time needed at a stop based on the current spacing between vehicles and the expected position current vehicle will have at the first common stop. Therefore, the final holding time with CPC is higher resulting in stronger control compared to EH. However, this comes at the cost of an increased in-vehicle time, especially for the shorter line (Line 177). Overall, CPC is more beneficial in terms of generalized passenger travel time.

For the second scenario, it can be observed that for this specific setup, CPC is contributing less in terms of regularity for the high frequency line (Line 177). The regularity indicators show lower gains in the regularity factors, CV of headway and bunching. Interestingly, CPC performs similarly to EH for line 176 on regularity indicators. With CPC, waiting time and in-vehicle time per passenger are also lower than with single line control for both base and high demand.

Table 5.9: Line performance indicators for Scenario 1

		Line 176			Line 177						
		CV Headway	Bunching	Waiting Time [sec]	In vehicle time [sec]	Generalized travel time [sec]	CV Headway	Bunching	Waiting Time [sec]	In vehicle time [sec]	Generalized travel time [sec]
Base Demand	NC	0.154	0.015	270.47	1605.17	2146.11	0.151	0.024	269.74	1457.96	1997.44
	EH	0.116	0.00	267.85	1585.34	2121.04	0.114	0.000	265.39	1464.32	1995.09
	CPC	0.190	0.055	225.70	1552.46	2003.85	0.11	0.006	196.84	1518.01	1911.68
Peak Demand	NC	0.179	0.029	362.6	1759.3	2484.5	0.177	0.025	376.9	1694.5	2448.4
	EH	0.145	0.006	348.3	1699.5	2396.0	0.155	0.011	362.2	1685.3	2409.7
	CPC	0.231	0.072	304.2	1748.8	2357.2	0.179	0.024	313.0	1737.1	2363.1

Table 5.10 Line performance indicators for Scenario 2

		Line 176					Line 177				
		CV Headway	Bunching	Waiting time [sec]	In vehicle time [sec]	Generalized travel time [sec]	CV Headway	Bunching	Waiting time [sec]	In vehicle time [sec]	Generalized travel time [sec]
Base Demand	NC	0.16	0.02	214.45	1615.98	2044.88	0.38	0.22	161.08	1481.26	1803.42
	EH	0.11	0.00	194.65	1667.62	2056.91	0.19	0.02	133.27	1518.39	1784.93
	CPC	0.11	0.01	182.99	1620.80	1986.77	0.26	0.10	131.30	1487.29	1749.88
Peak Demand	NC	0.19	0.15	335.59	1806.73	2477.91	0.34	0.17	253.98	1655.16	2163.13
	EH	0.15	0.02	352.01	1845.77	2549.78	0.20	0.02	225.76	1701.28	2152.80
	CPC	0.14	0.11	280.05	1811.40	2371.50	0.29	0.10	209.01	1695.26	2113.28

When plotting the coefficient of variation of headway along each of the lines, EH is consistent in keeping headway variation low while two patterns for the CPC are observed (Figure 5-7). Up to the branch stops (prior to the dashed red line), CPC performs similar to EH, maintaining a low coefficient of variation of headway. Close to the first common stop, the control criterion aims mostly for line coordination and vehicles are held to ensure a lower joint headway variability at the first common stop and further downstream. At the shared transit corridor, there is a loss of in-line headway adherence. Line 176 exhibits the highest headway variability with CPC, while for line 177 coefficient of variation of headway increases faster for the peak demand scenario.

The coefficient of variation of headway is plotted against the stops for both lines under scenario 2 in Figure 5-8. According to the results, CPC manages to maintain lower or equal variability compared to the single line strategy prior to the overlapping segment. It can also be observed that line 177 is severely penalized at the shared transit corridor, where the headways of the line are regulated also subject to vehicles of line 176. This leads to a lower performance on the shared transit corridor and, as shown before, lower overall performance of the line in terms of regularity.

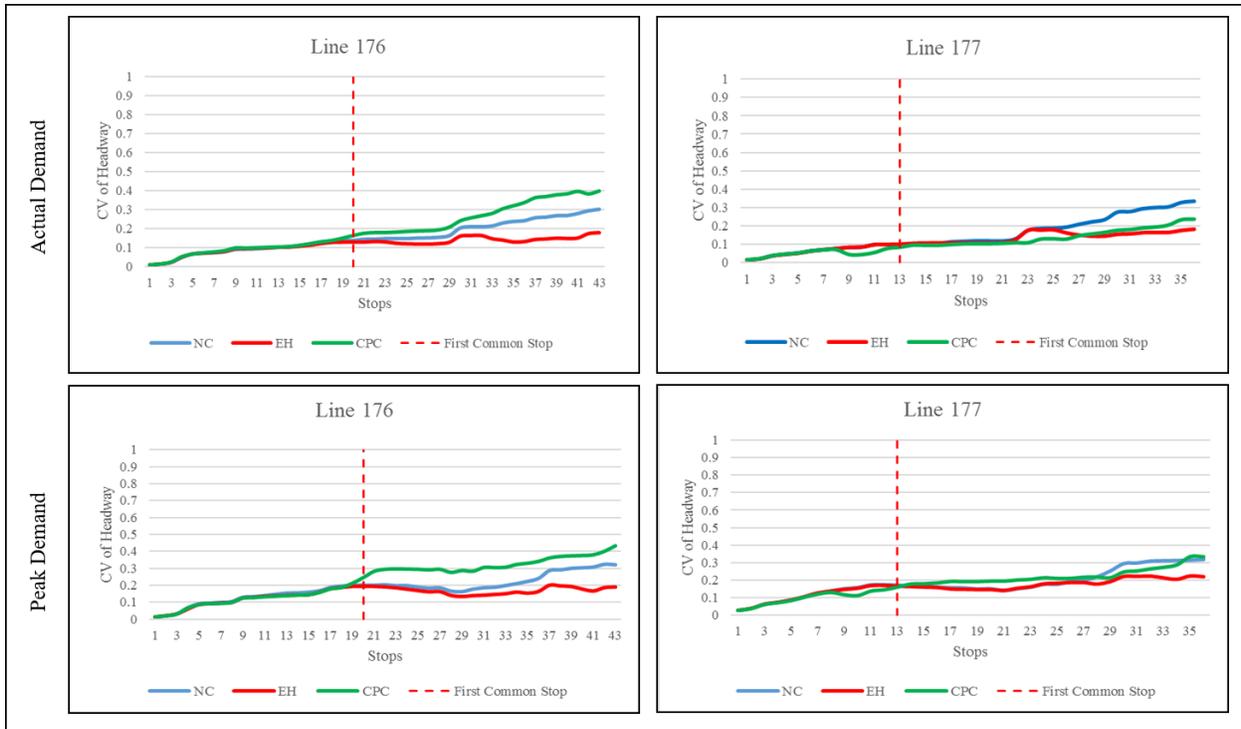


Figure 5-7: CV of Headway of lines 176 and 177 for Scenario 1

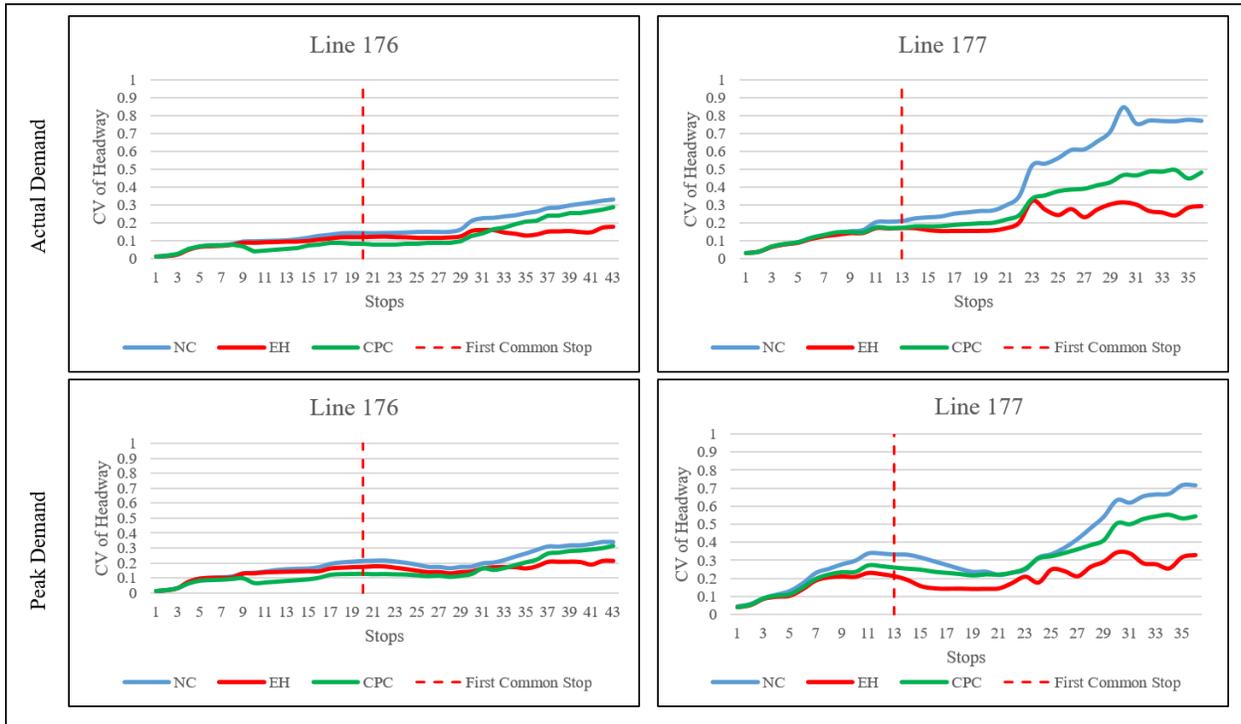


Figure 5-8 CV of Headway of lines 176 and 177 for Scenario 2

Shared Transit Corridor

In this section, the results of the joint performance of the two lines are discussed. Table 5.11 summarizes the performance indicators for the joint operation in the shared part for the first scenario. The proposed cooperative control results in a smoother transition to the common part. As it can be seen by the arrival pattern at the first common stop, the cooperative scheme outperforms all other schemes. The variability of the joint headway remains low compared to EH. This is also reflected by travel times per passenger, where the greater gains are in terms of waiting time.

Table 5.11: Performance Indicators for the joint operation in the shared transit corridor for Scenario 1

Shared Transit Corridor		CV of Headway at the merging stop	CV of the Joint Headway (Corridor)	Waiting Time per passenger [sec]	In vehicle time per passenger [sec]	Generalized Travel Time per passenger [sec]
Actual Demand	NC	0.722	0.833	252.99	1233.06	1739.03
	EH	0.728	0.832	248.04	1227.03	1723.10
	CPC	0.488	0.420	168.77	1215.91	1553.46
Peak Demand	NC	0.735	0.812	397.2	1407.9	2202.2
	EH	0.748	0.823	374.9	1367.1	2116.9
	CPC	0.616	0.490	303.5	1399.1	2006.1

In case of lines with different headways (Scenario 2), with CPC vehicles arrive at the merging stop with significantly lower variability of headway compared to the other schemes. In the case of cooperation between lines, the coefficient of variation of headway is lower too. The benefits of cooperation are also reflected in the travel times per passenger, which is the lowest under CPC. The results are similar for both demand levels. The results for the shared transit corridor in Scenario 2 are shown in Table 5.12.

Table 5.2 Performance Indicators for the joint operation in the shared transit corridor for Scenario 2

Shared Transit Corridor		CV Headway at the merging stop	CV Headway (Corridor)	Waiting time per passenger [sec]	In vehicle time per passenger [sec]	Generalized travel time per passenger [sec]
Base Demand	NC	0.56	0.84	165.36	1252.87	1583.58
	EH	0.54	0.65	125.85	1300.87	1552.58
	CPC	0.44	0.52	122.30	1249.84	1494.44
Peak Demand	NC	0.59	0.70	303.95	1401.31	2009.21
	EH	0.52	0.59	262.76	1462.68	1988.19
	CPC	0.46	0.48	236.54	1443.22	1916.29

Network travel times per passenger group

Table 5.13 summarizes the relative differences in time per passenger when compared against the No Control scenario. There is a significant reduction in waiting time with CPC, with a marginal increase in in-vehicle

time in both Scenario 1 and Scenario 2. Overall, the EH gives a very small improvement in travel time at the network level, whereas passengers receive time saving of more than 10% and even 15% with the CPC.

Table 5.3: Network performance with control compared to NC

	Network		Waiting Time	In Vehicle Time	Net Network Total Gains
Scenario 1	Actual	EH	-1.1%	-0.34%	-1.45%
	Demand	CPC	-18.9%	2.79%	-16.19%
	Peak	EH	-1.16%	0.81%	-0.35%
	Demand	CPC	-15.8%	1.83%	-13.9%
Scenario 2	Actual	EH	-4.6%	2.4%	-2.1%
	Demand	CPC	-17.0%	1.6%	-15.4%
	Peak	EH	-5.1%	1.9%	-3.2%
	Demand	CPC	-18.4%	0.0%	-18.4%

Network users consist of three passenger groups, which have different stakes in the control logic, depending on their travel paths. As illustrated in Figure 5-11, the two strategies impact the passengers travelling within the branch similarly, with marginal differences compared to the uncontrolled scenario. The passengers traversing the merging point are exposed to line coordination control at the branch, and line or corridor regularity control depending on their final destination. This penalizes their travel time by increasing the in-vehicle time. On the other hand, passengers travelling within the shared transit corridor, which constitute most of the total demand, are favored by the better coordination between lines through reductions in waiting time.

In scenario 2, the results are similar to the equal headway setting. Passengers travelling from the branch to the corridor experience longer in-vehicle times, because of holding time to regulate the transition to the common route segment. On the shared transit corridor, CPC manages to reduce the waiting time per passenger in both cases, with an additional decrease of 20 sec for the peak demand scenarios.

Travel times

Holding strategies trade off an increase the travel time of the vehicles against a reduction of variability. When comparing the 90th percentile of vehicle travel times, it can be observed that CPC leads to different results for the lines under the first scenario setup (Figure 5-9). Under CPC, Line 176 has a lower average travel time than with EH and NC but greater variability, while the travel time of line 177 is prolonged by almost 5 min with lower variability compared to the other schemes. Hence, there is no conclusive relation between the introduction of CPC and vehicle travel time variability. As can be expected, variability for both lines increases with the demand. When applying CPC, vehicles regulate their departures at the majority of stops of both lines (the shared transit corridor stops) subject to parameters that are exogenous with respect to their own line to achieve coordination in a corridor level. It is therefore expectable to encounter a loss in line performance to achieve higher benefits at the network level.

However, when regulating lines with different headways as in Scenario 2 (Figure 5-10), CPC shows results that are more robust. More specifically, line 176 has a higher average travel time but lower variability than in Scenario 1. Furthermore, the average travel time of line 177 is shorter with CPC compared to EH with the same level of variability. In Scenario 2, EH again outperforms all other schemes but the results with CPC also allow the operator to better administer the available fleet resources.

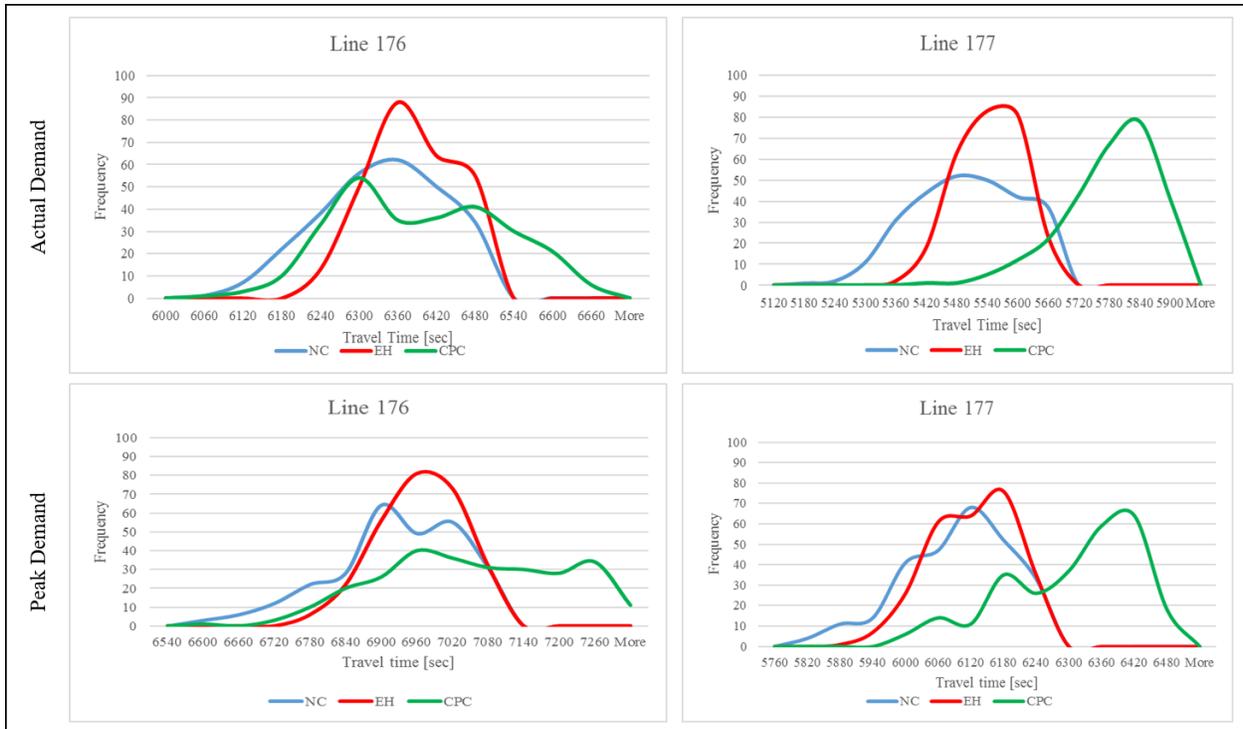


Figure 5-9: Travel time distribution for lines 176 and 177 for Scenario 1

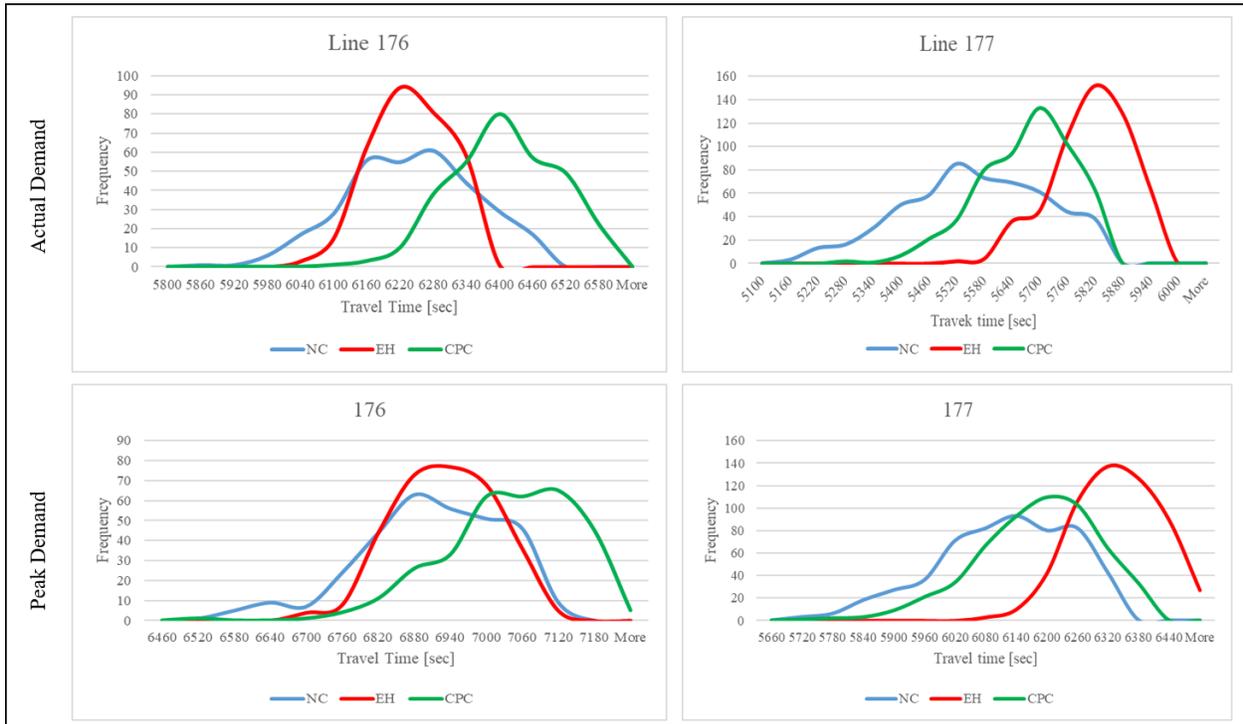


Figure 5-10 Travel time distribution for lines 176 and 177 for Scenario 2

Holding times and frequency of holding

In this specific case study, the shorter line (line 177) is consistently charged with extra holding time, the greatest share of which is aimed at line coordination.

One feature of the cooperative control scheme is that the control objective on the branches gradually shifts from single line regularity towards line coordination. The transition and the main source of holding time depends on the remaining downstream demand and the distance from the merging stop. Figure 5-13 shows the average holding time at each branch stop of line 176 and 177, respectively, and the contribution of each of the holding criterion terms. Aiming for line coordination adds significantly more holding time with respect to the average holding times of the line, especially towards the end of the branch. It is worth noting that at the beginning of the route, where branch regularity is more important, control is rarely necessary since variability has not propagated to undesired levels and the demand on the branch is low, and hence it does not lead to service disturbances. When line coordination becomes the most crucial factor for control on the branches, vehicles are held for significantly longer times. Holding time for line coordination is introduced at the last stops of the branch. This additional time penalizes the passengers travelling from the branch to the shared transit corridor. If this passenger group is the majority of the demand, the control can yield to longer travel times due to control, reducing the overall net gains achieved by CPC.



Figure 5-11: Travel time difference between NC and EH, CPC for the different passenger groups for Scenario 1

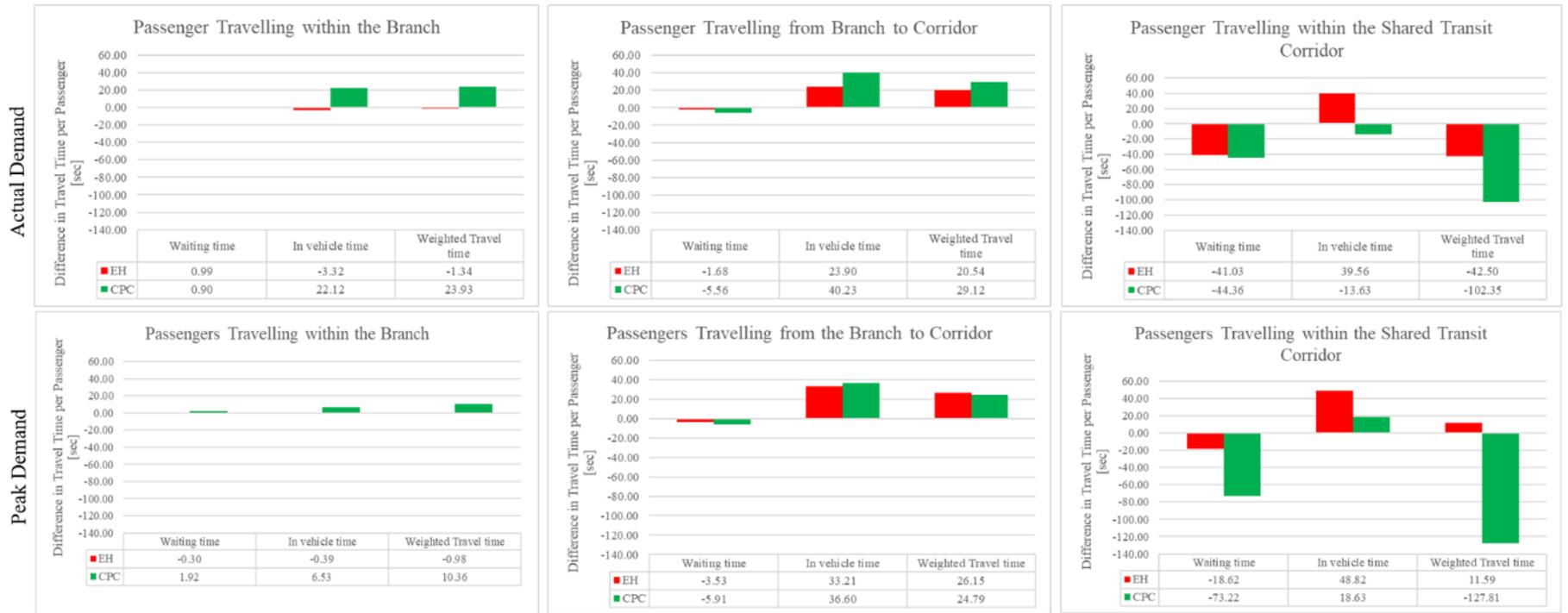


Figure 5-12 Travel time difference between NC and EH, CPC for the different passenger groups for Scenario 2

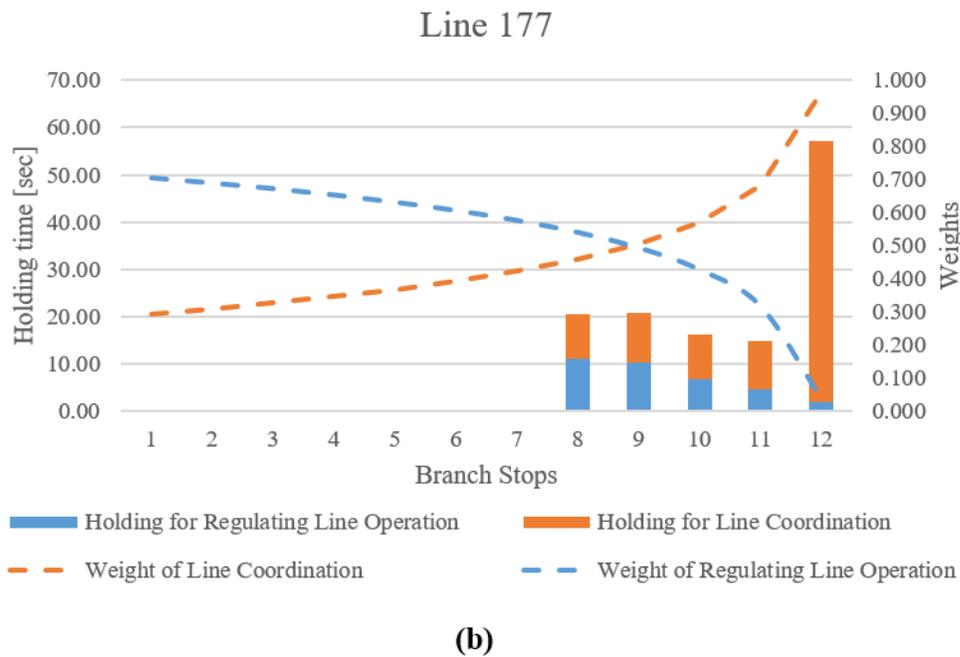
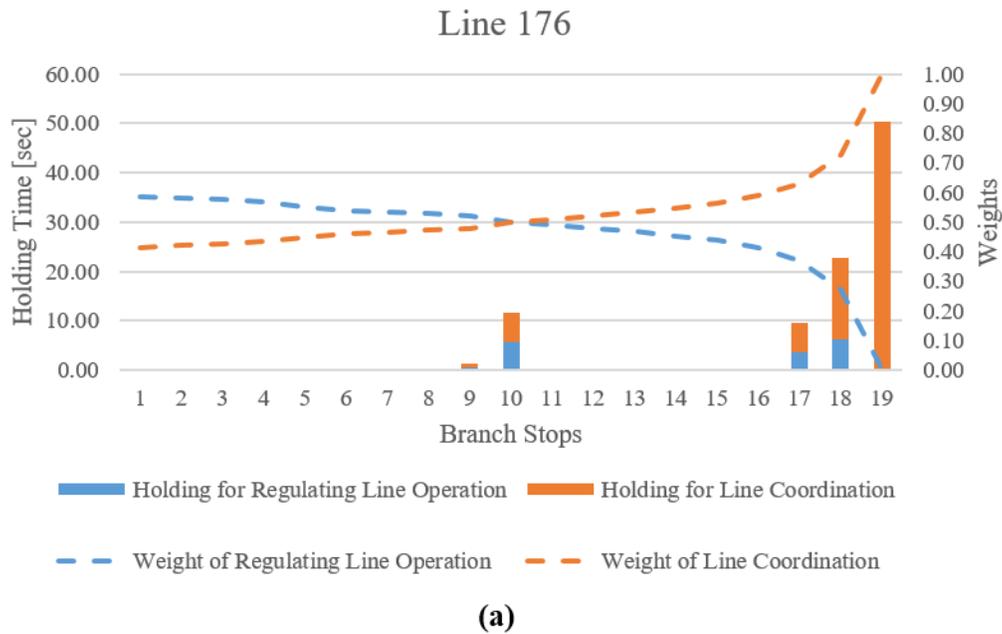
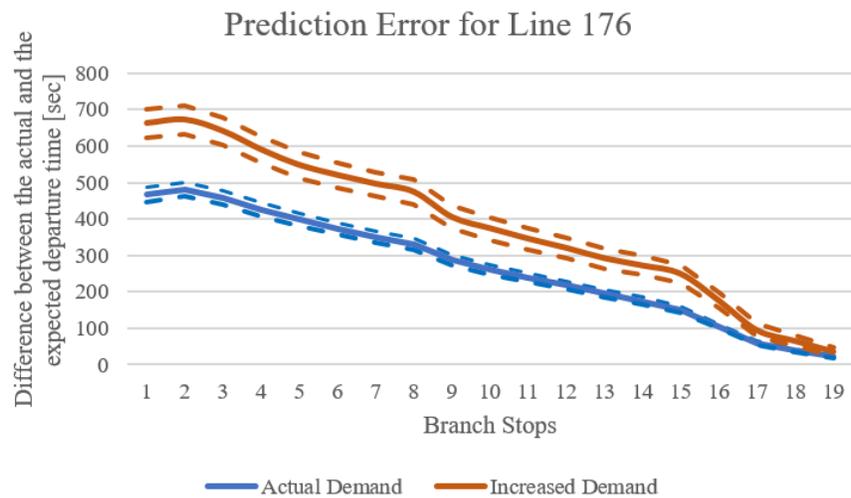


Figure 5-13: Average holding time at the branch stops of line 176 (a) and 177 (b)

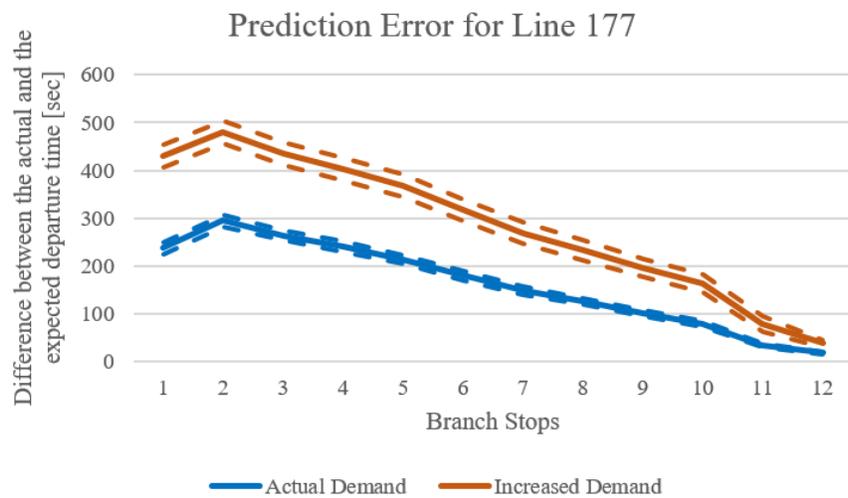
Projection accuracy

The new cooperative control scheme on the branches includes a term for line coordination that incorporates predictions of vehicle departure times for both lines from the first common stop. The expected departure time is calculated by summing the scheduled riding times between the current branch stop and the merging stop. The estimation error increases for increased prediction horizons, i.e. the further upstream the stop is,

and hence further away from the first common stop (Cats and Loutos, 2016b). Figure 5-14 depicts the average difference between the projected time to departure as calculated at each stop and the corresponding actual departure time from the merging stop for lines 176 and 177. The average difference and its deviation decrease as vehicles approach the first common stop and, for the longer branch, line coordination is exposed to more inaccurate estimations at the beginning of the route. These results are consistent with the empirical analysis of the same prediction scheme reported in Cats and Loutos (2016). The prediction error also increases for higher demand.



(a)



(b)

Figure 5-14: Prediction Error on every branch stop of Line 176 (a) and Line 177 (b)

The weights introduced in the holding criterion for the branch stop include a distance correction term that amplifies the impact of the line coordination term as vehicles approach the common segment. However, the holding criterion still includes holding time from the line coordination term, the calculation of which

can be based on projected departure times with high prediction error. Ultimately, the quality of controllers can be improved by improving the quality of the prediction schemes deployed in their application.

5.3. On characterizing a stop set as shared transit corridor

5.3.1. Experimental Setup

In this chapter we focus on understanding how the distribution of length between branches and shared corridors, as well as the demand, affects the performance of real time cooperative control as opposed to single line control. Therefore, we test different network configurations, where both schemes can be applied, under different stop set sizes. Considering regularity indicators and total passenger cost as Key Performance Indicators, we define under which conditions a stop set can be characterized as shared transit corridor and is recommended to be treated as one control wise. We test merging fork networks comprising of different configurations of branch stops and corridor stops. A toy network is used, composed of two lines with 30 stops each. Both lines have the same demand profile. The scenarios tested on the merging fork network are summarized in **Error! Reference source not found.**

Table 5.14 Merging Fork Scenarios

Scenario Number	Number of Stops		Network Stops	Share of Branch Stops (%)	Share of Corridor Stops (%)
	Branch Stops	Corridor Stops			
1	27	3	30	90	10
2	24	6	30	80	20
3	21	9	30	70	30
4	18	12	30	60	40
5	15	15	30	50	50
6	12	18	30	40	60
7	9	21	30	30	70
8	6	24	30	20	80
9	3	27	30	10	90

5.3.2. Merging Fork application for different numbers of stops results

Regularity Index

The scenario set concerning different distributions for the two stop sets is conducted considering the toy network of Figure 8-1(a). Table 5.15 summarizes the results of the CV of headway for each of the lines and of the joint headway for the shared transit corridor. It is clear from the results that single line control outperforms multiline in regulating line headways. Indeed, the variability of individual line headways with multiline control almost doubles and, similarly to the findings reported in the previous sections, one line is more penalized due to the coordination actions taken prior to the shared transit corridor.

Table 5.15 CV of Headway of merging fork scenarios

Scenario	CV of Headway					
	Single Line Control			Multiline Control		
	Line 1	Line 2	Shared Transit Corridor	Line 1	Line 2	Shared Transit Corridor
1	0.18	0.18	0.58	0.27	0.27	0.57
2	0.17	0.19	0.61	0.30	0.27	0.51
3	0.17	0.18	0.59	0.28	0.30	0.48
4	0.17	0.18	0.55	0.30	0.29	0.45
5	0.18	0.18	0.62	0.31	0.29	0.44
6	0.17	0.17	0.66	0.33	0.30	0.43
7	0.17	0.17	0.64	0.31	0.30	0.42
8	0.16	0.17	0.64	0.32	0.30	0.42
9	0.17	0.17	0.59	0.30	0.30	0.41

On the other hand, multiline control is superior in regulating the joint headway between lines. As depicted in Figure 5-15, the coefficient of variation of joint headway decreases significantly as the length of shared corridor increases. The overlapping segment can be treated as a shared transit corridor stop set if long enough, so that an operator can aim at regulating the joint headway. In any other case, single line control should be preferred.

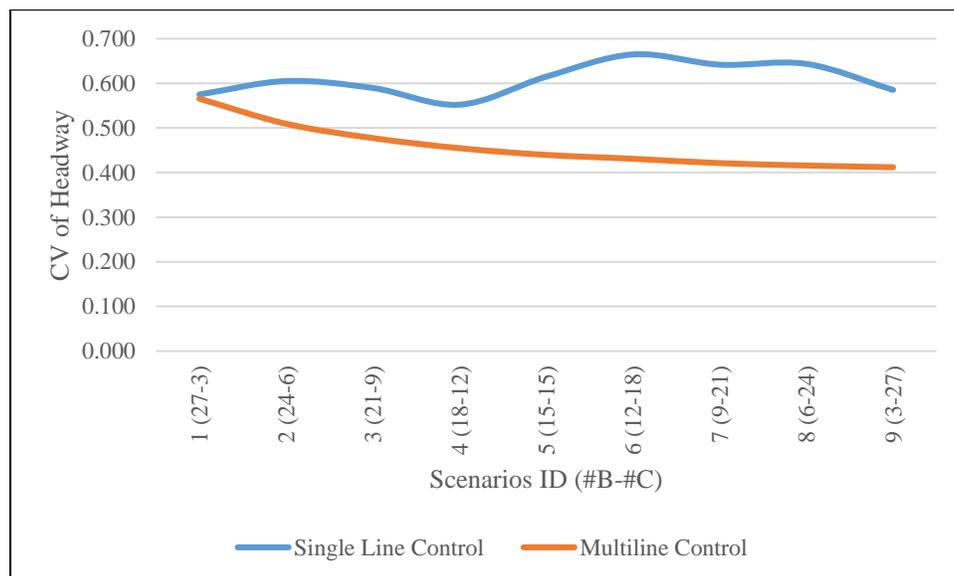


Figure 5-15 CV of Joint Headway for the merging fork scenarios

Passenger Cost

The passenger costs over the different scenarios clarifies what should be the minimum size of the corridor set. Figure 5-16 illustrates the difference in passenger costs, compared to no control, at a network level. Both control regimes exhibit similar performances for the scenarios with longer branch stop sets (Scenarios 1-4).

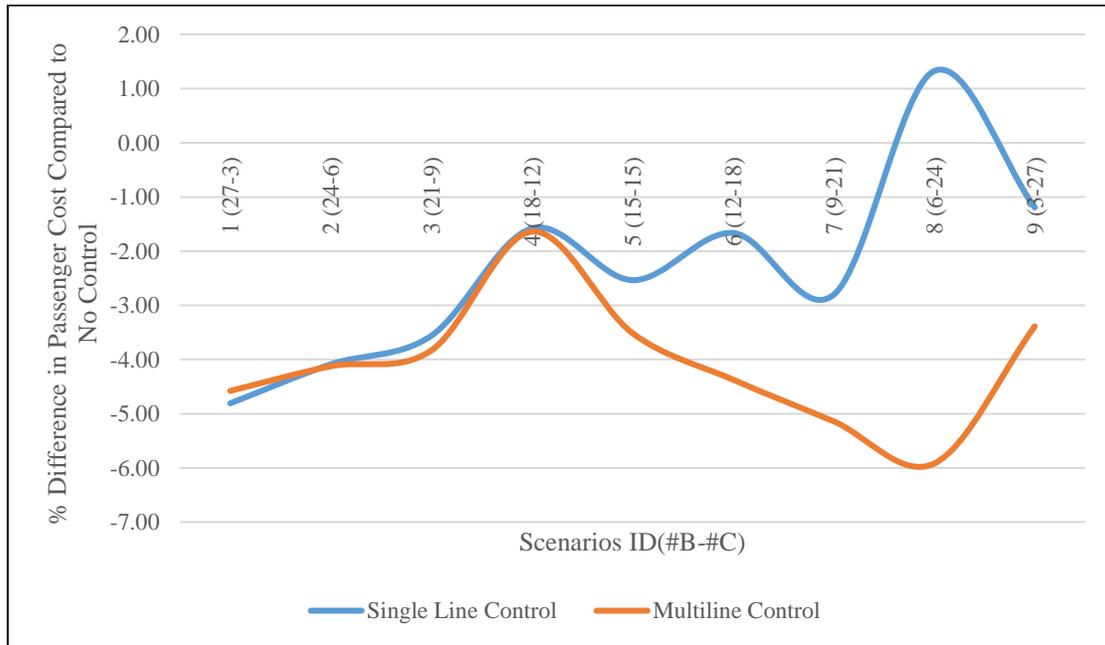


Figure 8-3 Difference between Multiline and Single Line Passenger Cost and No Control Scenario

However, for even sized branch and corridor stop sets (Scenario 5) and longer corridor stop sets (Scenarios 6-9), a significant difference is observed in favor of multiline control.

Combining the results obtained, we can deduce that an overlapping segment should be characterized as shared transit corridor where multiline control can be successfully applied when the number of corridor stops is half or more that of the total stops of the route of each line.

5.4. Discussion

A typical transit network configuration consists of lines that operate initially on individual stops and then merge serving a shared transit corridor. For such network configurations, in this chapter we apply a real-time holding criterion gradually accounting for coordination, which is extended beyond the single line level. Furthermore, the additional benefits of applying control on the joint operation are tested by regulating the departures from the shared stops based on all vehicles that serve the stop. The developed control criteria are tested using an artificial network and a real-world network through simulation.

The addition of a line coordination term in the control strategy reduces the variability of the joint headway when vehicles enter the shared transit corridor. The extent of this reduction depends both on the demand distribution along the line and on the demand level. From the numerical analysis conducted, the holding criterion is proven to adjust to the demand distribution at the branches, by prioritizing the regularization of line headway or the joint headway. In all scenarios, the arrival to the shared transit corridor is achieved with lower variability compared to single line control.

The real-world network was simulated for two different scenarios, one for lines with equal headways and one with different headways. As we showed in the results section, the proposed control approach enacts a tradeoff between network-wide results and single line, passenger group related indicators. While comparing the regularity performance indicators in line level, it is observed that CPC's gains are not in the level of single line control. In addition, due to control decisions to coordinate the lines, passengers travelling from branch to shared transit corridor are penalized with additional in vehicle time. On the other hand, the significant reduction of travel time with coordinated control in the shared transit corridor, where the majority of the demand is, without loses for any passenger group in the remaining parts of the network sum up to higher time savings for passengers in network level.

Overall, the multiline holding criterion is sensitive in two main factors:

- Length of the lines;
- Demand profile.

Both factors have been assessed in the current study as of same and critical importance as they were introduced as weighting factors in the holding criterion. Depending on the size of each stop set (branch-corridor) and their corresponding demand, the results may differ, since the criterion will always prioritize regulating the headway that benefit the majority of the passengers. The flexibility of the criterion demonstrated by numerical experiments at the branches, where the criterion behaves differently depending on the segmentation if the demand. Also, control has different effects for lines with different lengths, with one line losing further in performance for the overall benefit of the system. A full sensitivity analysis based on the demand segmentation can validate when it is more beneficial and for which passenger groups to apply single line or multiline control.

We furthermore compared the operation of single line control and coordinated control for the shared transit corridor. The results demonstrate that cooperation between different lines outperforms single line control at the shared transit corridor, drastically reducing the waiting times of the passenger groups that travel within the common segment. These savings yield an overall reduction in total passenger cost. Hence, cooperation can be a viable solution, depending on the distribution of passengers along the network.

Finally, we tested merging fork networks with different number of branch and corridor stops to define under which conditions we can characterize a set of stops corridor control-wise. Through experimental results, based on both toy networks, we show that a stop set can be treated as a shared transit corridor in terms of control if it has equal or higher number of stops compared to the branches of the network. The results are clearer more evident in terms of passenger cost.

6

Application on Diverging Fork Networks

In this chapter the formulated criterion is applied for a real world network that resembles a diverging fork. The multiline holding criterion is compared with single line control for different demand levels. Results show that gains in overall network performance as well as for specific passenger groups can be achieved under specific demand distributions.

Content of this chapter has been presented in the following work:

Laskaris, Georgios, Oded Cats, Erik Jenelius, Marco Rinaldi, and Francesco Viti. "A Holding Control Strategy for Diverging Bus Lines," In Conference of Advanced Public Transport and Transit Data (CASPT) 23-25 July, 2018, Brisbane, Australia. <http://orbilu.uni.lu/handle/10993/37874>.

Laskaris, G., Cats, O., Jenelius, E., Rinaldi, M., & Viti, F. (2019). "Principles for setting single line and multiline control based on network characteristics." In 8th HEART Conference (Presented).

6.1. Experimental Setup

6.1.1. Case Study

In this chapter, the holding criterion is applied for a diverging fork network. For the shared transit corridor the full corridor criterion is applied (Equation 3.20) and on the branches in its single line form (Equation 3.23). The routes of lines 176 and 177 of the bus network of the metropolitan area of Stockholm, Sweden, are structured in fork network configuration, consisting of a common set of stops and two branches, each one served by one of two lines (6-1). The lines operate between Mörby and the Ekerö community, to Solbacka and Skärvik. There are 24 common stops all located in the municipality of Solna, providing connections with the commuter train, light rail and subway. Line 176 has 19 branch stops and line 177 has 12 branch stops. Because of their layout, they provide an ideal ground for evaluating the proposed holding rule for the westbound direction. The frequency of the lines is set to 10 min with a joint frequency of 5 min at the shared transit corridor and the vehicles depart alternately from the common terminal at Mörby.

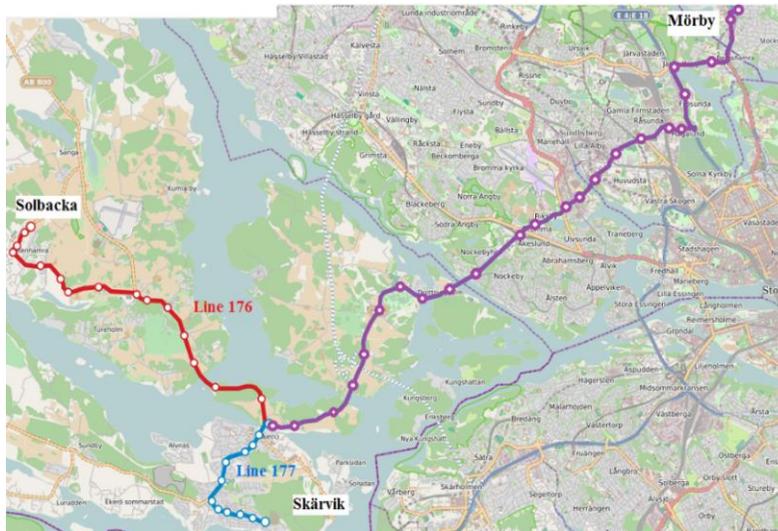


Figure 6-1 Lines 176 and 177 in Stockholm, Sweden

6.1.2. Scenario design

The selected scenarios assess the performance of the network for the actual demand of the lines. The demand of lines 176 and 177 and the segmentation of the demand is given in Table 6.1. It can be observed that the majority of the demand travels within the common part, followed by the passengers that travel from the shared transit corridor to the branch and the smallest share of the demand of each of the lines travels within the branches.

Table 6.1 Demand Segmentation for Lines 176 and 177

	Line 176		Line 177	
	Passengers	% demand	Passengers	% demand
Total Demand	148	100.00	143	100.00
Demand Generated at Corridor	137	92.57	137	95.80
Demand Generated at Branch	11	7.43	6	4.20
Demand within Corridor	108	72.97	108	75.52
Demand Corridor to Branch	29	19.59	29	20.28
Demand within Branch	11	7.43	6	4.20

Apart from the actual demand, the lines are also tested for an increased demand by 50%. A do-nothing scenario is used as a benchmark for both demand levels. Additionally, two control schemes are also applied, to compare their performance for this network type. The first is a single line holding criterion that aims on even headways from the preceding and the succeeding vehicle and at the same time limits the maximum allowed headway to a share of the planned headway. The single line criterion is introduced by Cats et al (2011) and it has outperformed other holding rule based strategies. The second control scheme is based on the multiline holding criterion introduced in this study in Equation 3.20. The aim of the comparison of the two criteria is to assess the strengths and the weaknesses of each scheme with regard to the performance of the lines and the different passengers groups. The scenarios are summarized in Table 6.2. The no control scenario is denoted with NC, the single line control as Even Headway (EH) and the multiline control named Cooperative Passenger Cost (CPC).

Table 6.2 Actual Demand Scenarios

	Actual Demand (100)	Peak Demand (150)
No Control (NC)	NC_100	NC_150
Even Headway (EH)	EH_100	EH_150
Cooperative Passenger Cost (CPC)	CPC_100	CPC_150

All the parameters of the case studies are summarized in Table 6.3 below:

Table 6.3 Numerical Simulation Parameters

Number of Lines	2
Frequency of the Line	10min (5min joint frequency)
Number of Stops	36-43 (24 common stops)
Network Type	Diverging Fork
Simulation tool	BusMezzo

Holding Criterion form

$$t_{ijk}^{\text{hold}} = \max \left\{ \theta_1 \frac{[(t_{jk+1}^{\text{exit}} - t_{ijk}^{\text{exit}}) - (t_{ijk}^{\text{exit}} - t_{jk-1}^{\text{exit}})]}{2} + \theta_2 \frac{[(t_{ijk+1}^{\text{exit}} - t_{ijk}^{\text{exit}}) - (t_{ijk}^{\text{exit}} - t_{ijk-1}^{\text{exit}})]}{2} + \theta_3 \frac{[(\tilde{t}_{i,j}^{\text{split}},k} - \tilde{t}_{i,j}^{\text{split}},k-1)}{2} - (\tilde{t}_{i,j}^{\text{split}},k+1} - \tilde{t}_{i,j}^{\text{split}},k)}{2} - \frac{\beta^{\text{inveh}} q_{ijk}}{2\beta^{\text{wait}} \Lambda_j}, 0 \right\}$$

Demand Distribution

The second set of scenario examines the effect of various demand distributions on the different user groups under the multiline control. This set is comprised of twenty five scenarios which are tested with different demand segmentation. The scenarios are summarized in Table 6.4. Each row correspond to a different share of passengers travelling from the corridor to branch, each column to a different share of passengers travelling within branch and each cell on the passengers travelling within the corridor. The index of each scenario is given in parenthesis. The total demand is the same for all scenarios and the distribution of the passengers at stops follows the pattern of the actual demand as much as possible (subject to integer rounding).

Table 6.4 Diverging Fork Scenarios

		Share of Passengers Travelling within Branch (%B)				
		5	10	15	20	25
Share of Passengers Travelling from Corridor to Branch (%CB)	5	(1) 90	(3) 85	(6) 80	(10) 75	(15) 70
	10	(2) 85	(5) 80	(9) 75	(14) 70	(19) 65
	15	(4) 80	(8) 75	(13) 70	(18) 65	(22) 60
	20	(7) 75	(12) 70	(17) 65	(21) 60	(24) 55
	25	(11) 70	(16) 65	(20) 60	(23) 55	(25) 50

6.2. Results

6.2.1. Shared Transit Corridor performance

The results of the performance of each control scheme at the corridor are summarized in Table .

Table 6.5 Performance Indicators of the Shared Transit Corridor

Shared Transit Corridor	CV of Joint Headway	Level of Bunching	Waiting time per passenger [sec]	In vehicle time per passenger [sec]	Generalized travel time per passenger [sec]

1_100	NC	0.507	0.397	155.4	194.3	505.2
	EH	0.421	0.307	153.6	196.1	503.3
	CPC	0.391	0.283	151.7	194.7	498.2
1_150	NC	0.512	0.378	150.5	214.1	515.1
	EH	0.468	0.341	149.1	215.8	513.9
	CPC	0.424	0.315	148.9	214.4	512.1

The trips of both lines serve first the corridor stops. Vehicles are dispatched without any disruption and there is no trip chaining; hence the sources of stochasticity are only endogenous from running times and passenger demand along the corridor. The first index for the performance of the lines at the corridor is the coefficient of variation of the joint headway. Joint headway is defined as the difference between consecutive departures of trips at the corridor stops. It is clear from the results that CPC outperforms the benchmark and the single line control, obtaining the lowest variability among the scenarios. For both demand levels, the differences between the control schemes are similar. According to the Transit Capacity and Quality of Service Manual the level of bunching is defined as the share of trips for which the actual headway of deviates by more than 50% from the planned headway (*Transit capacity and quality of service manual*, 2003). For the shared transit corridor this applies to the planned joint headway. Bunching along the corridor decreases significantly with multiline control as all vehicles from different lines are taken into consideration by the criterion. Single line control neglects that bunching may occur between vehicles of the different lines serving the same set of stops. The regularity indices' findings are also reflected in the travel time components. Similarly, both strategies reduce the waiting time at stop for both demand levels, relatively to the reduction of headway variability. In vehicle time is slightly increased with EH compared to the do-nothing scenario, which is expected as holding strategies tend to prolong the time spent at stops to regulate operations. CPC manages to maintain in vehicle time at the same level as NC. The weighted travel time is a sum of waiting time and in vehicle time and for both demand levels the lowest is achieved with CPC strategy.

6.2.2. Line Performance

Applying single line control is expected to be more effective at line level compared to cooperative control. Indeed, the results summarized in *Table* show how for both lines, EH outperforms CPC at every scenario.

Table 6.6 Performance Indicators at line level

		Line 176					Line 177				
Pe Actual Demand		CV of Headway	Bunching	per	per	Time	CV of Headway	Bunching	per	per	Time
				Waiting time passenger [sec]	In vehicle time passenger [sec]				Weighted Travel Time per passenger [sec]	Waiting time passenger [sec]	
Pe Actual Demand	NC	0.27	0.10	314.7	148.0	777.4	0.33	0.14	320.9	157.1	799.0
	EH	0.17	0.01	310.8	148.8	770.4	0.17	0.01	312.5	158.6	783.6
	CPC	0.21	0.03	311.1	148.3	770.5	0.21	0.03	314.4	158.0	786.7
	NC	0.38	0.21	320.5	160.6	801.5	0.40	0.25	333.3	172.0	838.6

EH	0.20	0.03	314.2	161.5	789.8	0.24	0.07	321.3	173.4	816.0
CPC	0.25	0.07	314.9	160.8	790.6	0.34	0.16	326.5	173.5	826.6

Recall that with EH the same criterion is applied throughout the entire line, while with CPC the criterion adjusts to the stop set, from multiline (Equation 3.20) to single line criterion (Equation 3.23) moving from corridor to branch. When looking at line level, single line is the most recommended choice as it results in the lowest values in regularity indices and passenger travel times. Multiline control performs better than no control with satisfactory results in terms of bunching mitigation. The case study network consists of two lines of different length. It can be observed from the results that the longest line (Line 176) with CPC results in better performance compared to Line 177, which is seven stops shorter. The gains of CPC over NC are lower as demand increases. This can be explained by the nature of the multiline criterion. At each stop the final holding time depends on the share of the demand at the remaining downstream stops. At the last stops of the corridor until the first stops of the branch, the criterion handles the transition from joint to single line operation. During this transition, a loss of performance is observed which is recovered gradually as vehicles progress along the branch. Furthermore, similar to the merging fork application one of the lines faces losses in performance in order to regulate the joint operation (Chapter 5). As shown in Figure , the level of variability with CPC for line 176 shows an upward trend compared to EH until the 35th stop where CPC starts to regulate the line’s headway strongly. On the other hand, for line 177 there are not enough stops in order to restore the variability of the headway. Especially at the peak demand scenario, the performance of line 177 is severely affected by regularization of joint operation and the transition to individual operation and it presents an extremely poor performance in headway variability. Although there is a tendency to recover, buses of one line do not manage to fully recover from the loss of regularity during the transition due to the length of the line in terms of branch stops.

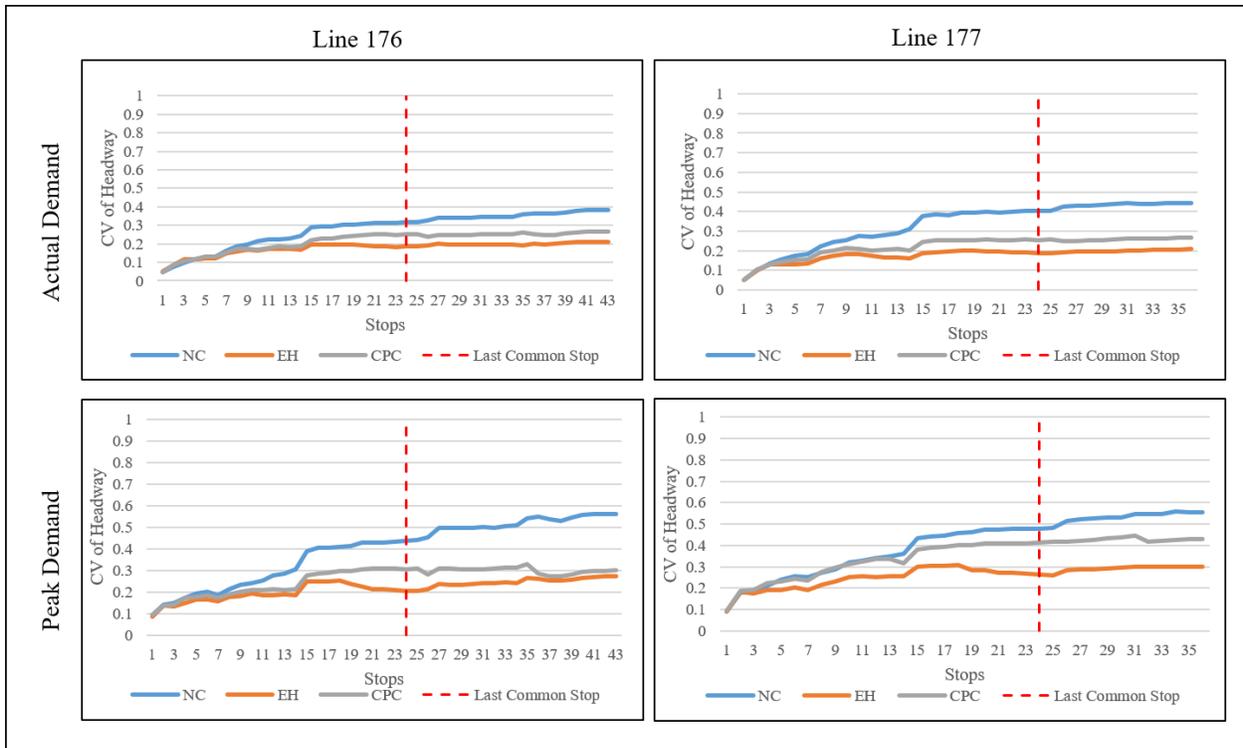


Figure 6-2 CV of Headway per stop

Travel Times

The 90th percentile of travel times and its variability is used as a measure of performance of the controller. The histograms of travel times for the actual demand and the peak demand for all passenger segmentations are depicted in Figure 6-3. It is noted from the results that CPC has less variable travel times for the actual demand profile and it yields better performances for the longer line (line 176). With CPC, travel times of line 176, in the actual demand scenario provide a less variable travel time distribution with also shorter travel time on average. Under standard demand conditions (100), CPC outperforms EH. When demand increases (scenario 150), variability affects all control scenarios (NC, EH, CPC), and EH becomes the better alternative. Based on the results, vehicle scheduling with CPC has no high fleet requirements at demand level 100 due to low variability in travel time. However, this is not the case for the scenario set with demand level 150, where variability increases especially for line 177 and may require additional vehicles to be dispatched in order to operate the line.

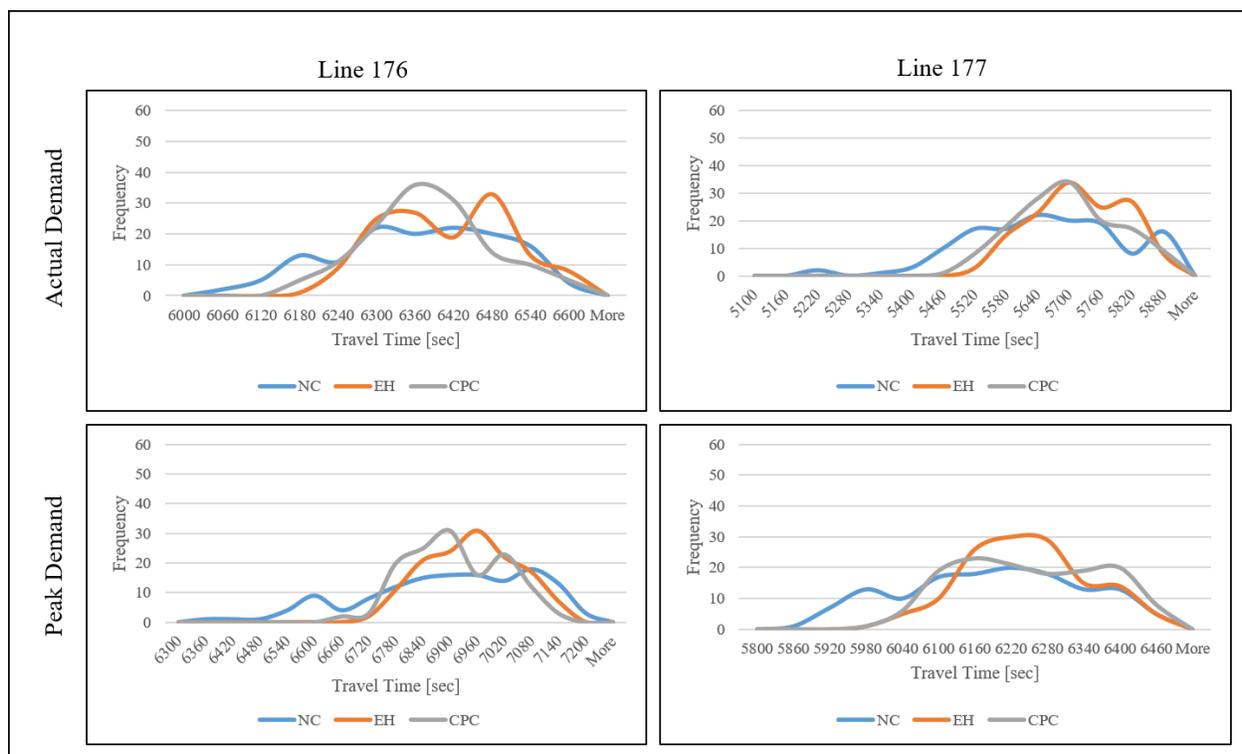


Figure 6-3 Travel Time Distribution

Passenger Travel Times

Figure shows the differences in passenger travel time compared to no control with each strategy for the two components of the passenger cost and as a sum of the weighted travel time. With EH, reductions are achieved in waiting times in both scenarios. While the two schemes perform similarly in terms of waiting time savings for the actual demand, the reduction of waiting time with even headway strategy is double compared to CPC at the peak demand scenario. CPC shows the same behavior for in-vehicle delay. The gains in in-vehicle delay are even higher in peak demand scenario, where EH shows an increasing trend in in-vehicle delay. Because of this great reduction in in-vehicle time, CPC outperforms EH at travel time per passenger for both demand levels.

We also explore the direct effect of each control scheme on each passenger group for the two demand levels. The % difference in performance per passenger group compared to the benchmark scenario for the two lines is shown in Table 6.7 and Table for Line 176 and 177 respectively.

For the actual demand scenario, CPC manages to have greater reductions in travel time for the passengers travelling within the corridor and for the passengers travelling from the corridor to the branch for both lines. For passengers travelling within the branch, the performance in terms of travel time is better with single line control. However, looking at both terms of travel time, multiline control achieves higher savings in in-vehicle delay for line 176 while it outperforms single line control in waiting time for line 177 for the passengers travelling within the branch. For peak demand, EH outperforms in waiting time reduction for all passenger groups for both lines. CPC performs better in terms of in-vehicle time and maintains the best performance for the passengers travelling within the shared transit corridor. There is a minor difference between strategies in travel time for passengers travelling from corridor to branch, mainly thanks to results of CPC in in-vehicle time. Finally, there is a sharp difference in performance at travel time for the branch passengers for Line 177, which does not manage to recover from the transition from corridor to branch.

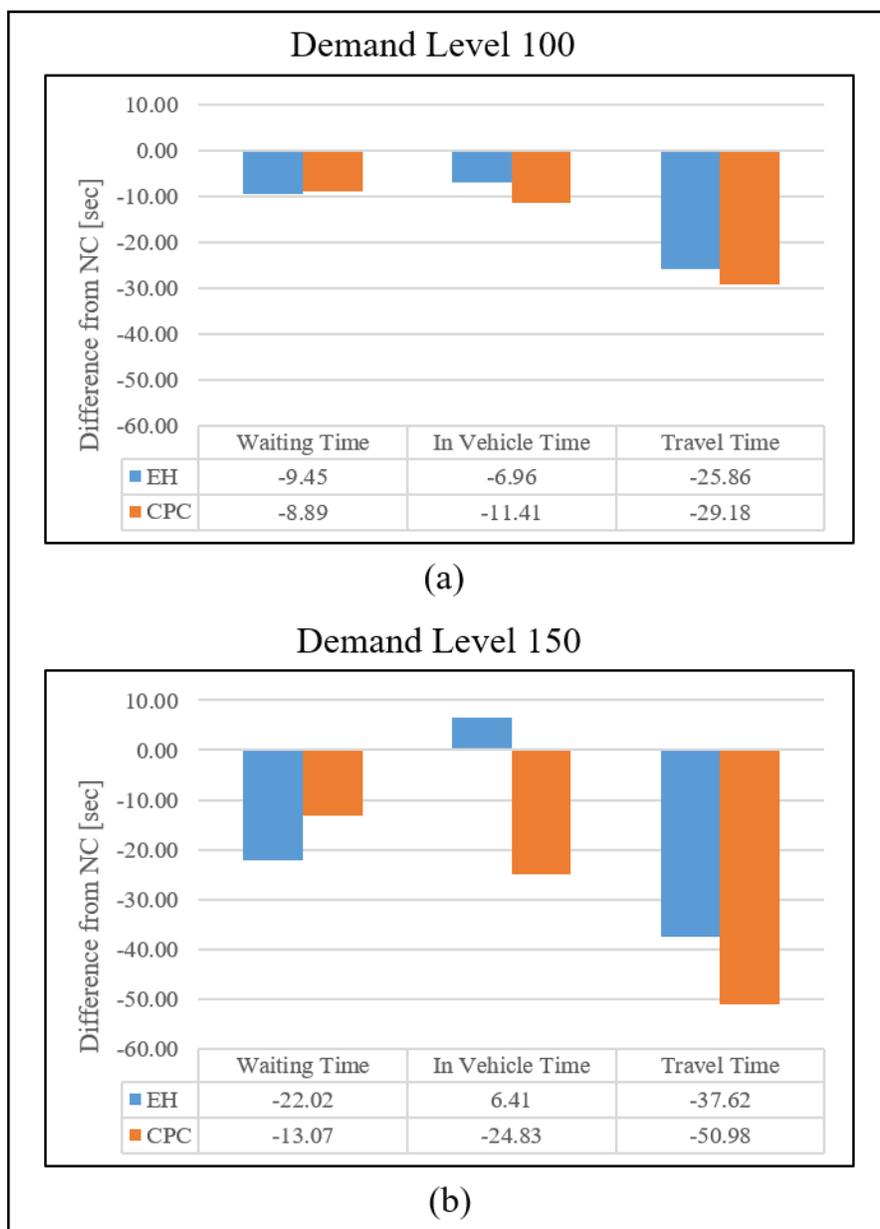


Figure 6-4 Passenger cost differences compared to NC for (a) actual demand and (b) peak demand

Table 6.7 % Performance difference between NC and EH, CPC for the different passenger groups for Line 176

Line 176									
	Branch			Corridor to Branch			Corridor		
	Waiting Time	In vehicle time	Travel Time	Waiting Time	In vehicle time	Travel Time	Waiting Time	In vehicle time	Travel Time
	Demand Level 100								
EH	-7.4	0.1	-3.4	-5	1.0	-0.5	-4.8	0.8	-0.3
CPC	-3.0	-1.5	-2.2	-2.8	-0.1	-0.8	-3.5	0.1	-0.6
	Demand Level 150								
EH	-13.3	-0.3	-6.6	-12.5	0.0	-3.3	-5.7	1.1	-0.6
CPC	-10.9	-0.9	-5.7	-8.9	-0.5	-2.7	-3.0	0.3	-0.6

Table 6.8 % Performance difference between NC and EH, CPC for the different passenger groups for Line 177

Line 177									
	Branch			Corridor to Branch			Corridor		
	Waiting Time	In vehicle time	Travel Time	Waiting Time	In vehicle time	Travel Time	Waiting Time	In vehicle time	Travel Time
	Demand Level 100								
EH	-8.4	1.5	-5.2	-7.8	0.1	-2.4	-0.4	0.8	0.5
CPC	-9.2	4.3	-4.8	-8.0	-1.5	-3.5	-1.5	-0.5	-0.7
	Demand Level 150								
EH	-15.8	1.0	-10.4	-9.8	0.5	-2.7	-3.4	0.3	-0.7
CPC	-7.0	2.5	-4.0	-8.0	-1.0	-3.2	-2.9	-0.5	-1.1

6.2.3. Demand Distribution Scenarios

The second scenario set deals with different demand shares between the three passenger groups of a diverging fork network. The three passenger groups to be distinguished in this network configuration are i) the passengers travelling within the shared transit corridor, ii) passengers travelling from the shared transit corridor to a branch and iii) passengers travelling within a branch. The scenarios are tested on a real world Diverging Fork network from the city of Stockholm, Sweden. Lines 176 and 177 consist of 43 and 36 stops respectively. The common stops between lines are 24, and there are 19 remaining branch stops for line 176 and 12 branch stops for line 177. Twenty-five different demand scenarios are tested, as detailed in **Error! Reference source not found.** Each row corresponds to a different share of passengers travelling within the branch while each column to different share of passengers travelling from corridor to branch; each cell contains the share of the total demand that travels within the corridor with the scenario ID in parenthesis. Both lines have the same demand segmentation for all scenarios.

Table 6.9 Diverging Fork Scenarios

		Share of Passengers Travelling within Branch (%B)				
		5	10	15	20	25
Share of Passengers Travelling from Corridor to Branch (%CB)	5	(1) 90	(3) 85	(6) 80	(10) 75	(15) 70
	10	(2) 85	(5) 80	(9) 75	(14) 70	(19) 65
	15	(4) 80	(8) 75	(13) 70	(18) 65	(22) 60
	20	(7) 75	(12) 70	(17) 65	(21) 60	(24) 55
	25	(11) 70	(16) 65	(20) 60	(23) 55	(25) 50

Regularity Index

The demand scenario results for the coefficient of variation are shown in Table 6.10. The coefficient of variation of joint headway with single line control and multiline control for all different scenarios

Table 6.10 CV of Headway of diverging fork scenarios

Scenario ID (%B-%CB)	CV of Headway					
	Single Line Control			Multiline Control		
	Line 176	Line 177	Shared Transit Corridor	Line 176	Line 177	Shared Transit Corridor
1 (5%-5%)	0.162	0.194	0.457	0.180	0.214	0.362
2 (5%-10%)	0.171	0.172	0.427	0.192	0.219	0.360
3 (10%-10%)	0.171	0.169	0.446	0.185	0.194	0.340
4 (5%-15%)	0.168	0.178	0.436	0.212	0.229	0.389
5 (10%-10%)	0.167	0.182	0.437	0.183	0.203	0.345
6 (15%-5%)	0.176	0.176	0.439	0.185	0.184	0.341
7 (5%-20%)	0.173	0.186	0.435	0.230	0.241	0.398
8 (10%-15%)	0.172	0.169	0.427	0.198	0.215	0.343
9 (15%-10%)	0.170	0.177	0.430	0.184	0.197	0.334
10 (20%-5%)	0.190	0.161	0.390	0.186	0.188	0.318
11 (5%-25%)	0.163	0.168	0.453	0.221	0.257	0.443
12 (10%-20%)	0.162	0.172	0.393	0.216	0.220	0.400
13 (15%-15%)	0.160	0.183	0.429	0.208	0.217	0.378
14 (20%-10%)	0.164	0.176	0.455	0.189	0.174	0.357
15 (25%-5%)	0.159	0.172	0.412	0.170	0.168	0.314
16 (10%-25%)	0.165	0.168	0.411	0.216	0.235	0.397
17 (15%-20%)	0.168	0.176	0.379	0.215	0.210	0.356
18 (20%-15%)	0.163	0.177	0.384	0.191	0.193	0.336
19 (25%-10%)	0.170	0.167	0.362	0.185	0.163	0.304
20 (15%-25%)	0.179	0.167	0.368	0.229	0.230	0.403
21 (20%-20%)	0.161	0.165	0.356	0.206	0.201	0.346
22 (25%-15%)	0.164	0.172	0.386	0.204	0.185	0.328

23 (20%-25%)	0.156	0.165	0.361	0.225	0.216	0.366
24 (25%-20%)	0.164	0.159	0.361	0.191	0.182	0.320
25 (25%-25%)	0.158	0.160	0.323	0.207	0.216	0.377

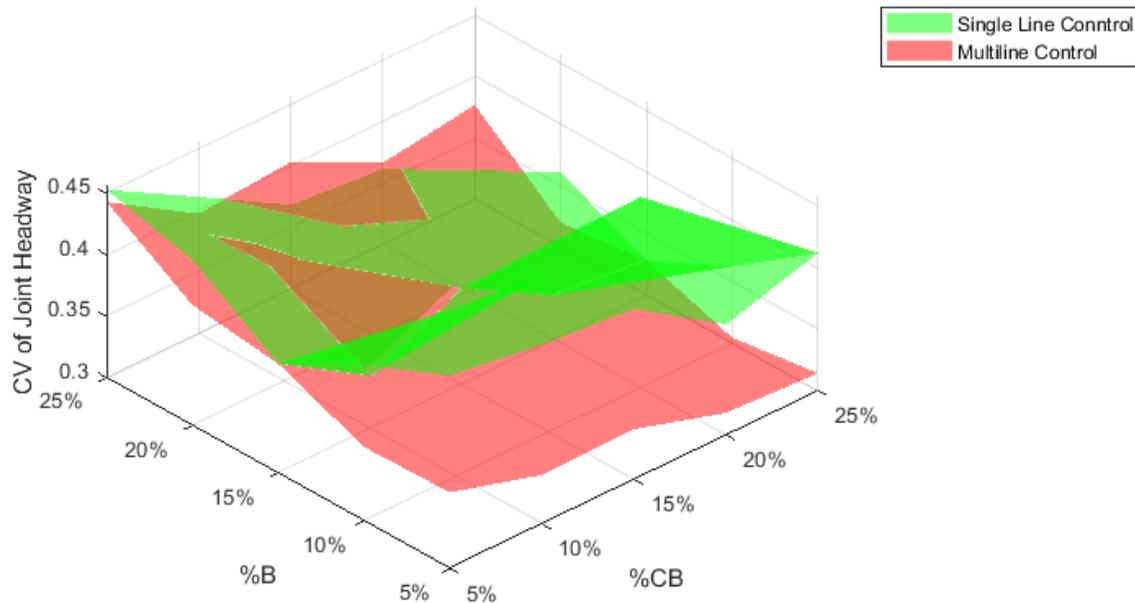


Figure 6-5 Difference between Multiline and Single Line Passenger Cost and No Control Scenario

Unlike the Merging Fork scenarios, for these variable demand scenarios on the real world network from Stockholm line and joint performance do vary substantially among different demand segmentations. In scenarios exhibiting low share of passengers travelling from corridor to branch (1, 3, 6, 10 and 15), both strategies show similar performance in line level and multiline control performs better in terms of variability of joint headway at the overlapping segment. In contrast, for scenarios where traversing passengers comprise one fourth of the total demand (11, 16, 20, 23 and 25), multiline control performs poorly compared to single line control.

Passenger Cost

At the second set of scenarios we investigate the effect of the demand segmentation on the different passenger groups. By comparing the travel time of each passenger group between single line and multiline control we analyze the effect of each control scheme on their travel cost. In the following tables (Tables 6.11-6.13), the difference in passenger cost between CPC and EH is given for each passenger group and for the network in total (**Error! Reference source not found.**). A color scale from green to red is used to characterize the performance of the multiline control compared to single line control and given for each table scaled based on the range between the highest and the lowest difference between passenger cost with each control scheme. Green color corresponds to greater gains from multiline control while red from single line control.

Shared Transit Corridor

Error! Reference source not found.6.11 shows the differences in passenger cost for the passengers travelling within the shared transit corridor. Since the demand on this part of the network can be satisfied by more than one line, multiline control results in lower passenger cost at the majority of the scenarios. Obviously, CPC is more effective when the majority of the demand is concentrated at the shared transit corridor. Specifically, when the shared transit corridor passenger share is more than 70% of the total demand, the gains are higher. The results are sensitive to the increase of demand from the corridor to branch, due to fact that these passengers have conflicting objectives in terms of controlling within the same route segment. This can be observed at the scenarios with high share of passengers traversing from corridor to branch where EH performs marginally better then CPC. Holding time with CPC is a sum of holding times weighted by the corresponding demand share. Passengers travelling within the corridor benefit from regulating the joint operation while passenger travelling beyond the corridor from line regularization, therefore the size of the group impacts the control decision. The size of the branch passenger group does not affect the performance of CPC for the corridor passengers.

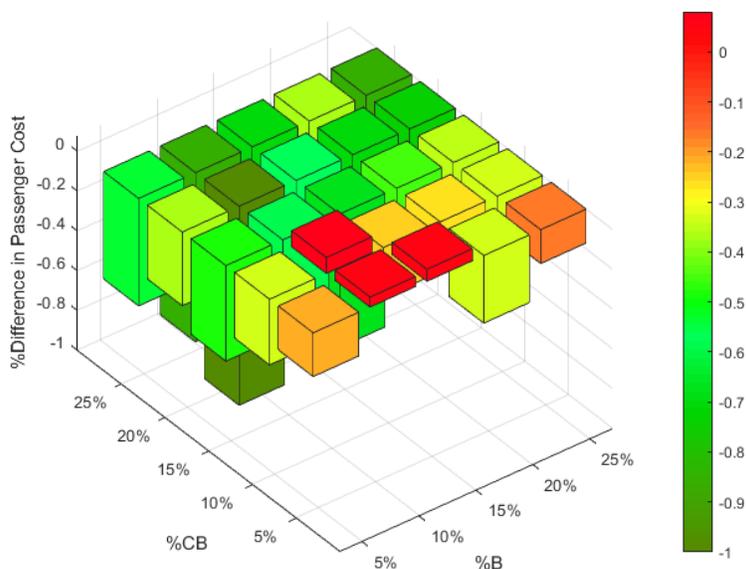


Figure 6-6 Difference between EH and CPC passenger cost for passengers travelling within the corridor

Table 6.11 % Difference between EH and CPC passenger cost for passengers travelling within the corridor

		Share of passengers travelling within the Branch %B				
		5	10	15	20	25
Share of passengers travelling from Corridor to Branch %CB	5	-0.54	-0.85	-0.71	-0.36	-0.85
	10	-0.37	-1.00	-0.57	-0.71	-0.74
	15	-0.48	-0.59	-0.67	-0.46	-0.35
	20	-0.33	0.08	-0.25	-0.26	-0.34
	25	-0.22	0.05	0.06	-0.34	-0.17

Corridor to Branch

The group of passengers that travels from corridor to branch generally benefits by single line operation. The cost comparison of this passenger group is shown in **Error! Reference source not found.** Single line control results in lower passenger cost compared to multiline control, with the latter having marginal differences from the passenger cost of EH at the few scenarios where it manages to achieve better results. This can be explained by the fact that they experience the control actions for the transition of the line from corridor to branch and a prolonged travel time due to holding to regulate the joint operation. CPC has the best performance in the scenarios with 10% demand for both branch and corridor to branch.

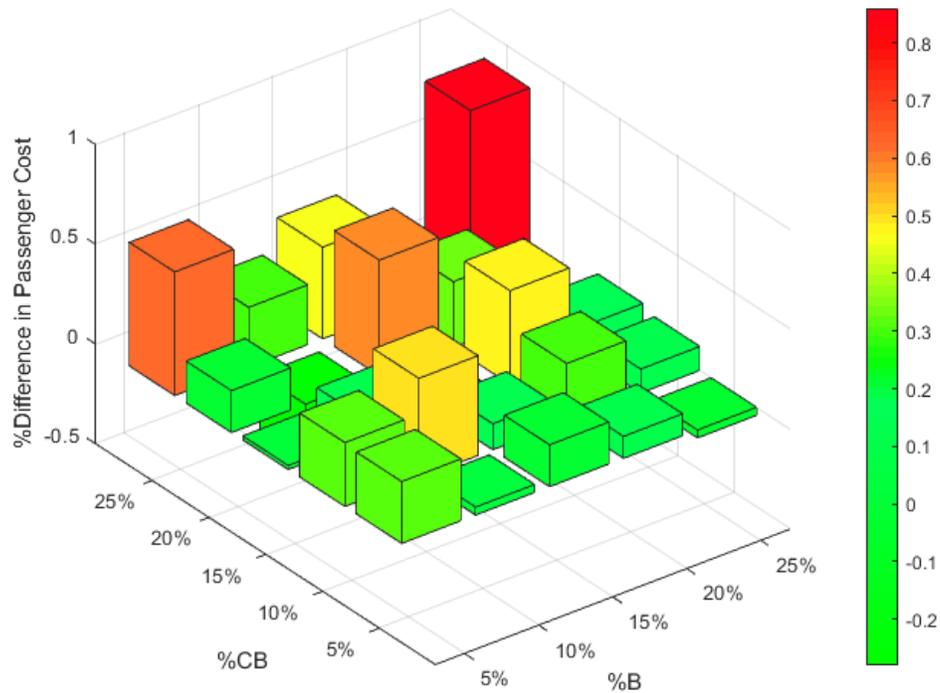


Figure 6-7 Difference between EH and CPC passenger cost for passengers travelling from corridor to branch

Table 6.12 % Difference between EH and CPC passenger cost for passengers travelling from corridor to branch

		Share of passengers travelling within the Branch				
		%B				
		5	10	15	20	25
Share of passengers travelling from Corridor to Branch	5	0.62	0.30	0.46	0.16	0.86
	10	0.21	-0.28	0.58	0.33	-0.05
	15	0.02	0.12	-0.17	0.47	0.15
	20	0.32	0.50	0.13	0.29	0.12
	25	0.31	0.04	0.21	0.11	-0.04

Branch

The results of passenger cost for the branch demand follow the same pattern with the corridor group. As shown in **Error! Reference source not found.**, CPC performs better for low share of traversing passengers, regardless of the size of branch group. Although control schemes on this part of the network focus only on line regularization, CPC starts to regulate the line headway for the transition to their individual operation via the projection term to the diverging stop. The importance of the projection term is relative to the share of branch demand beyond the diverging stop. A low share of passengers groups travelling from corridor to branch keeps the objectives of regulating the corridor and the branch distinctive, resulting in substantial benefits for CPC. When the corridor demand is half of the total demand then single line control is clearly outperforming multiline control.

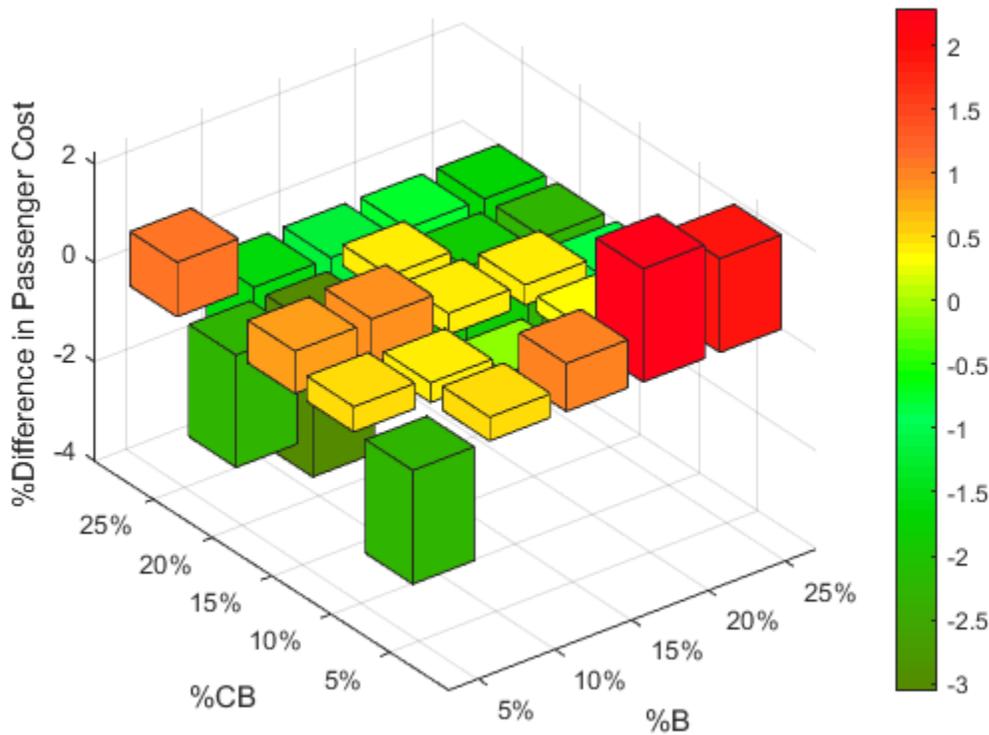


Figure 6-8 Difference between EH and CPC passenger cost for passengers travelling from corridor to branch

Table 6.13 % Difference between EH and CPC passenger cost for passengers travelling within the branch

		Share of passengers travelling within the Branch				
		%B				
		5	10	15	20	25
Share of passengers travelling from Corridor to Branch	5	1.10	-1.57	-1.22	-0.72	-1.64
	10	-2.27	-3.06	0.42	-1.84	-2.26
	15	0.86	0.91	0.43	0.41	-0.88
	20	0.51	0.40	-0.08	0.33	-0.30
	25	-2.30	0.48	0.97	2.29	1.90



Total Demand

The summarized results for the cost of the total demand show the effectiveness of each control scheme under each demand scenario. As observed in **Error! Reference source not found.** there is a clear pattern based on the demand segmentation. Multiline control is found most effective for scenarios where more than 60% of the demand is concentrated at the shared transit corridor regardless of the share of the group of passengers travelling within the branch. The performance is mostly affected by the passengers travelling between stops sets, as they influence the magnitude of joint and single line control at the corridor. When this group comprises 25% of the total demand, CPC is steered away from regulating joint operation into single line, reducing its performance on this network part and making the single line control strategy more efficient, since it does not switch objectives along the route.

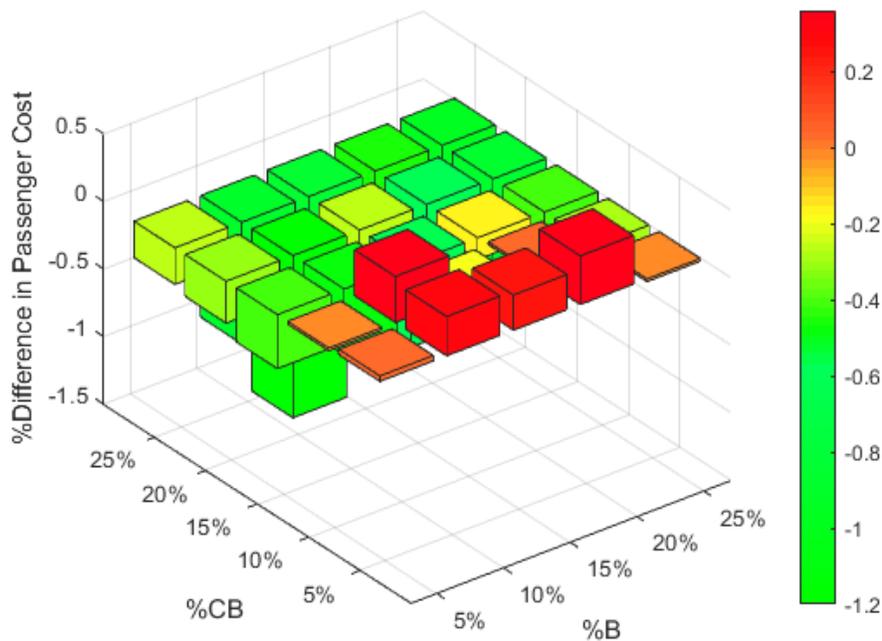


Figure 6-9 Difference between EH and CPC passenger cost for passengers travelling from corridor to branch

Table 6.14 % Difference between EH and CPC passenger cost for passengers for the total demand

		Share of passengers travelling within the Branch %B				
		5	10	15	20	25
Share of passengers travelling from Corridor to Branch %CB	5	-0.27	-0.90	-0.54	-0.45	-0.98
	10	-0.31	-1.20	-0.25	-0.61	-0.86
	15	-0.40	-0.49	-0.62	-0.16	-0.41
	20	-0.02	0.34	-0.18	0.02	-0.29
	25	0.04	0.29	0.26	0.36	-0.02



6.3 Conclusions

In this chapter, we apply the multiline holding criterion for diverging fork networks based on the minimization of the additional passenger travel times due to holding. The criterion regularises the joint headway and the line headway at the shared transit corridor, while also regulates the expected departure from the last common stop accounting for all different passenger groups and adjusting holding time to the number of passengers that experience the control action. We evaluated the criterion using simulation on a case study of two lines of city of Stockholm, Sweden under different demand levels.

The proposed holding criterion can regulate the operation of the network and result to higher gains than single line control. When the majority of the demand is on the passengers groups that do not interact CPC can have marginal gains or outperform single line holding. On the other hand, a high number of traversing passengers reduces the effectiveness of the criterion, in which case single line control is recommended.

Furthermore, a transition period for the criterion to shift from joint control and single line control which yields a loss of performance around the last common stop. If the line does not have a considerably long branch there is no time to mitigate the effect and ends up with poorer performance.

Demand segmentation has a significant effect on the holding criterion. When the majority of the demand is on the passengers groups that do not interact (corridor and branch) CPC outperforms single line control. Conversely, a high number of traversing passengers reduces the effectiveness of the criterion, in which case single line control is recommended.

7

Application on Double Fork Networks

After the applications in merging and diverging fork networks, the full application is presented for a double fork network. Synchronization is also included on the shared transit corridor. The criterion is applied on an artificial network and assessed using scenarios with different shares of transferring passengers and configuration of the synchronization criterion. Multiline control results to a lower overall cost for the network, while synchronization depends on the stop that synchronization is applied and the comparison horizon chosen between regularity and synchronization.

The Content of this chapter has been partially presented at the following conferences and its content is unpublished to date:

Laskaris, G., Cats, O., Jenelius, E., Rinaldi, M., & Viti, F. (2018). Real time multiline holding control for networks with shared transit corridor. *In 7th HEART Conference*.

7.1. Case Study

7.1.1. Description of the Network

The full criterion presented in Chapter 3 is tested for a generic artificial network consisting of two lines operating in one direction as depicted in Figure 7-1. Each line consists of 30 stops, and have the same stop sets. The first ten stops of each line serve the passengers within the initial branch, followed by ten successive stops within the shared transit corridor, which is the set of common stops between lines, and finally the last ten stops of each line compose the final branch of the lines. The lines have the same frequency of 10min. The vehicles from each line are dispatched so that an ideal joint frequency of 5min is offered at the common part and vehicles arrive alternately at the merging stop. Vehicles operate in one direction and there is no trip chaining, meaning vehicles complete one trip in one direction only, without being assigned for another trip to the opposite direction.

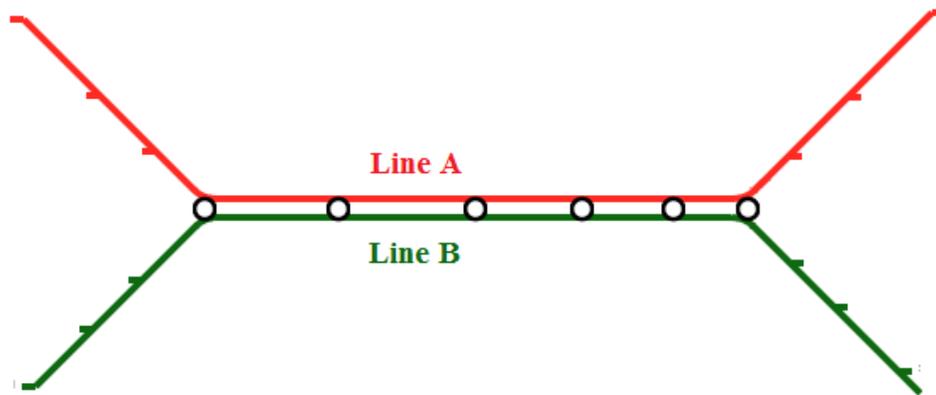


Figure 7-1 Schematic representation of double fork network

The demand profiles of the lines are given in Figure 7-2. The demand segmentation is given in Table 7.1. The majority of the demand is concentrated at the shared transit corridor while the two branches and the traversing passenger groups have similar demand shares.

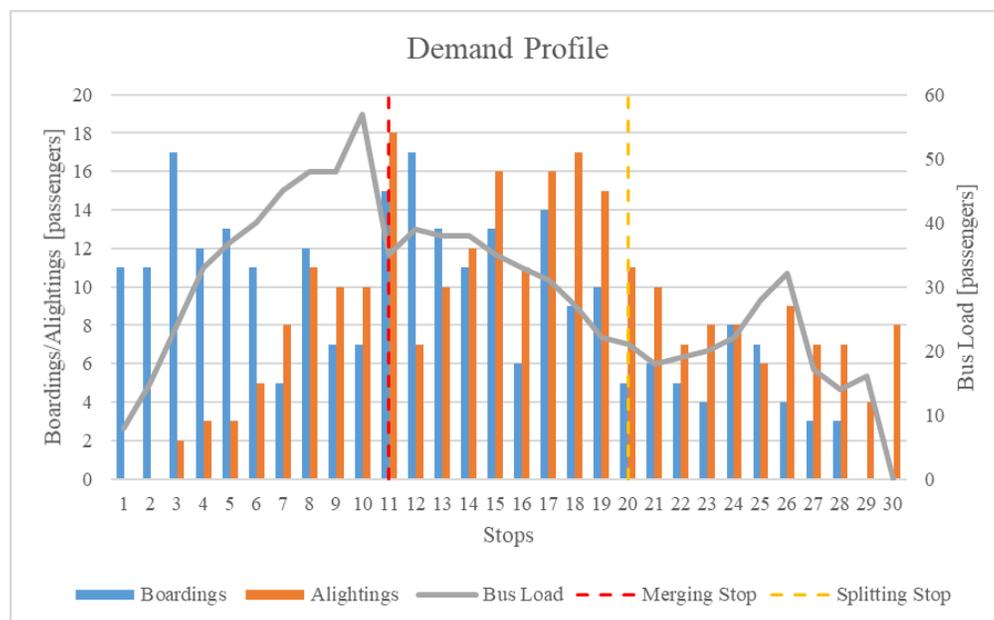


Figure 7-2 Demand Profile of line 1 and 2

Table 7.1 Demand Segmentation

Passenger Group	Passengers	Demand Share
Within Initial Branch	52	20.08%
Branch to Corridor	41	15.83%
Branch to Branch	13	5.02%
Within Corridor	92	35.52%
Corridor to Branch	21	8.11%
Within Final Branch	40	15.44%
Total Demand	259	100.00%

At the shared transit corridor, all stops can be considered shared transfer stops. For this experimental setup, one common stop is chosen as control point for both regularity and synchronization.

7.1.2. Scenarios

The first division of the scenarios is based on the two general passenger groups that are benefited by either the regularity criterion or the transferring criterion. In order to assess the effect of synchronization on the network three scenarios with different share of transferring passengers are tested corresponding to 5%, 10% and 15% of the total demand. Passengers are transferring only from line 1 to line 2. The size of passenger group affected by the regularity criterion remains unchanged through the different scenarios. The dynamics of the subgroups of passengers travelling to different parts of the network and affected by regularity are assessed in the results for the different parts of the network.

An important factor is the stop where the choice between the regularity and transferring criterion is made. Two different scenarios are tested: in the first transferring criterion is enabled at the merging stop and in the second at the diverging and last stop of the corridor. For the first two scenarios three different horizons

for passenger cost comparison are tested. The cost comparison for the current stop only, for the full and half the length of the downstream stop set.

Three different control schemes are compared, a do-nothing scenario (NC), a single line rule based holding control strategy (EH) and the cooperative passenger cost (CPC) criterion for the different cost comparison horizons.

In summary, the scenarios are divided in two categories based on the stop that both synchronization and regularity criterion is applied, in three based on the control scheme chosen (NC-EH-CPC) and a final subdivision in CPC scenarios based on the horizon chosen for comparison. All the different attributes of the scenarios are summarized in Table 7.2.

Table 7.2 Scenarios

Share of Transferring Passengers	Stop	Control Scheme	Horizon
5%	Merging Stop	NC	NA
		EH	NA
		CPC	Current Stop
10%	Merging Stop	NC	Half Stop Set
		EH	Full Stop Set
		CPC	Full Stop Set
15%	Diverging Stop	NC	NA
		EH	NA
		CPC	Current Stop
			Half Stop Set
			Full Stop Set

All the parameters of the case studies are summarized in Table 7.3 below:

Table 7.3 Numerical Simulation Parameters

Number of Lines	2
Frequency of the Line	10min (5min joint frequency)
Number of Stops	30-30 (10 common stops)
Network Type	Double Fork
Simulation tool	BusMezzo
Holding Criterion form	$t_{ijk}^{\text{hold}} = \max \left\{ \theta_1 \frac{[(t_{jk+1}^{\text{exit}} - t_{ijk}^{\text{exit}}) - (t_{ijk}^{\text{exit}} - t_{jk-1}^{\text{exit}})]}{2} + \theta_2 \frac{[(t_{ijk+1}^{\text{exit}} - t_{ijk}^{\text{exit}}) - (t_{ijk}^{\text{exit}} - t_{ijk-1}^{\text{exit}})]}{2} \right.$ $\left. + \theta_3 \frac{[(\tilde{t}_{i,j^{\text{split}},k}^{\text{exit}} - \tilde{t}_{i,j^{\text{split}},k-1}^{\text{exit}}) - (\tilde{t}_{i,j^{\text{split}},k+1}^{\text{exit}} - \tilde{t}_{i,j^{\text{split}},k}^{\text{exit}})]}{2} - \frac{\beta^{\text{inveh}} q_{ijk}}{2\beta^{\text{wait}} \Lambda_j}, 0 \right\}$

7.2. Results

7.2.1. Corridor Results

The shared transit corridor is the most important stop set of this network since the majority of the demand is generated or travels into this part of the network and a higher frequency is provided by the joint operation. Passengers on this part of the network are benefited by the joint frequency between vehicles of different lines. Table 7.4 shows the coefficient of variation of the joint headway at the shared transit corridor for all different scenarios. Undeniably, CPC manages to have the lowest variability by accounting for all lines that interact. The only exception is the scenario that allows synchronization at the last stop and the cost comparison accounts for only the diverging stop. This trend is a result of the number of synchronization events that take place at the last stop.

Table 7.4 Coefficient of Variation of Joint Headway

	Joint Headway	Merging Stop	Diverging Stop
Scen1	NC	0.504	0.491
	EH	0.412	0.401
	CPC	0.388	0.392
	CPC_ALL	0.389	0.393
	CPC_ONE	0.398	0.403
Scen2	NC	0.521	0.490
	EH	0.406	0.381
	CPC	0.409	0.388
	CPC_ALL	0.403	0.387
	CPC_ONE	0.393	0.419
Scen3	NC	0.518	0.515
	EH	0.435	0.427
	CPC	0.399	0.423
	CPC_ALL	0.399	0.401
	CPC_ONE	0.401	0.460

Two representative examples of scenario 3 and with synchronization allowed at the merging and the diverging stop respectively are illustrated in Figure 7-3. It is reminded that scenario 3 has the highest share of transferring passengers. The coefficient of variation of joint headway is given per stop and the evolution along the shared transit corridor. With CPC, coordination between lines initiates at the branches and vehicles enter to the shared transit corridor with a lower coefficient of variation. CPC manages to maintain it for the majority of the corridor stops until the point that a transition to single line operation starts. The most notable difference between the two scenarios is at the behavior at the stop where synchronization is allowed. While at the merging stop scenario rarely occurs, at the diverging stop scenario is the most frequent control decision. Vehicles are held for synchronization, waiting for a time equal to the joint headway increasing the level of variability by almost the same amount of time. Since this happens to the last common stop, it does not affect the joint operation.

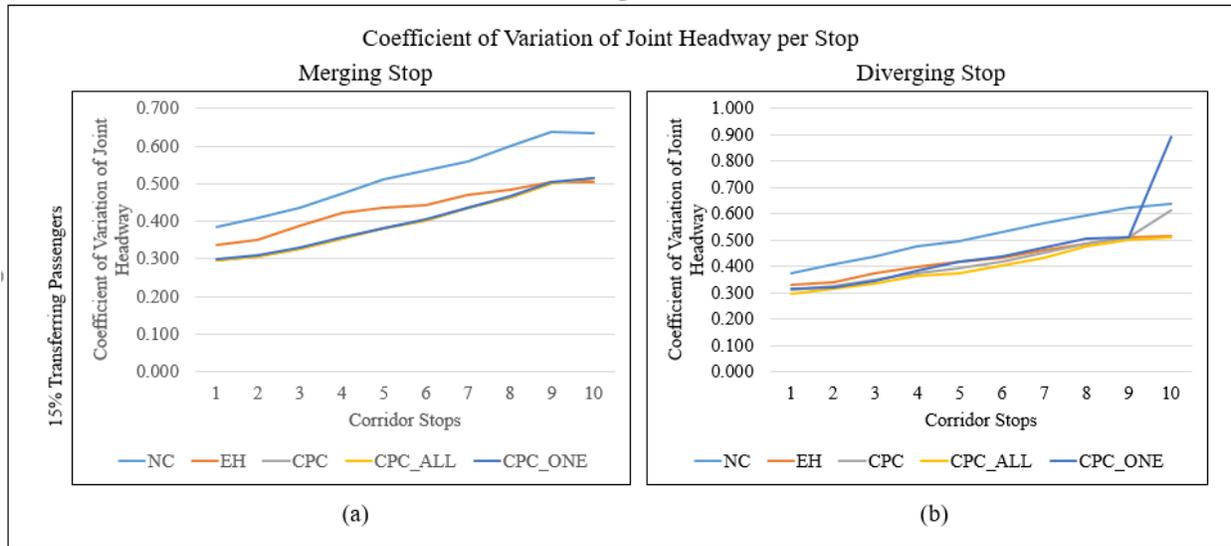


Figure 7-3 Coefficient of Variation of Joint Headway per Stop

The same results are reflected in the passenger cost for the shared transit corridor. The results are summarized in Table 7.5. CPC outperforms NC and EH in terms of waiting time in all scenarios. NC results to the lowest in-vehicle time among scenarios due to the fact that the control scenarios rely on holding. The reduction of waiting time comes with the cost of an increased in-vehicle time. Between the scenarios where control is applied CPC is approximately at the same level with the no control scenario. Again, when synchronization is chosen more frequently, it requires longer holding time and this is noticed at the CPC scenario with cost comparison only at the diverging stop. The in-vehicle delay is significantly higher compared to the scenarios with different horizons and control schemes.

Table 7.5 Passenger cost at the shared transit corridor

		Scenario 1			Scenario 2			Scenario 3		
		Waiting Time [sec]	In vehicle time [sec]	Travel Time [sec]	Waiting Time [sec]	In vehicle time [sec]	Travel Time [sec]	Waiting Time [sec]	In vehicle time [sec]	Travel Time [sec]
Merging Stop	NC	169.7	151.4	490.9	167.6	152.2	487.4	176.1	152.2	504.5
	EH	163.3	154.0	480.6	161.5	155.0	477.9	166.8	155.1	488.8
	CPC	161.2	152.1	474.5	161.2	154.2	476.7	164.1	152.9	481.1
	CPC_ALL	162.0	152.7	476.7	161.5	153.9	476.8	164.1	152.9	481.1
	CPC_ONE	161.6	152.5	475.6	161.2	153.9	476.4	164.3	153.0	481.5
Diverging Stop	NC	173.3	150.8	497.4	172.9	151.3	497.0	173.6	152.3	499.4
	EH	165.9	153.0	484.8	164.1	154.1	482.4	164.8	154.8	484.4
	CPC	163.9	152.8	480.7	163.6	153.5	480.6	159.8	156.8	476.3
	CPC_ALL	163.9	152.9	480.6	164.4	153.2	482.1	160.9	154.2	476.0
	CPC_ONE	164.1	154.8	482.9	154.0	161.2	469.2	149.9	163.5	463.4

7.2.2. Line level Results

The coefficient of variation of headway per stop is shown in Figure 7-4 for line 1 and in Figure 7-5 for line 2. The performance improves significantly compared to NC and as expected EH is the most effective in regulating the line operation. With CPC, the evolution of the variability index follows similar behavior with the lines in merging and diverging fork networks. For both lines, at the branches prior to the shared transit corridor, the variability of the line headway starts increasing when the coordination is prioritized and the regularity of the joint operation becomes more important. At the end of the corridor, the criterion shifts again from joint operation to single line operation and the loss of performance cannot be recovered until the end of the line. An interesting trend is shown on the line held for synchronization at the diverging stop. At the scenarios with high share of transferring passengers, the CPC_ALL scenario shows a significant decrease at the coefficient of variation at the diverging stop compared to the scenarios with the other cost comparison horizon. This scenario has the lowest share of holding for synchronization. There are no similar effects at the connecting line (Line 2).

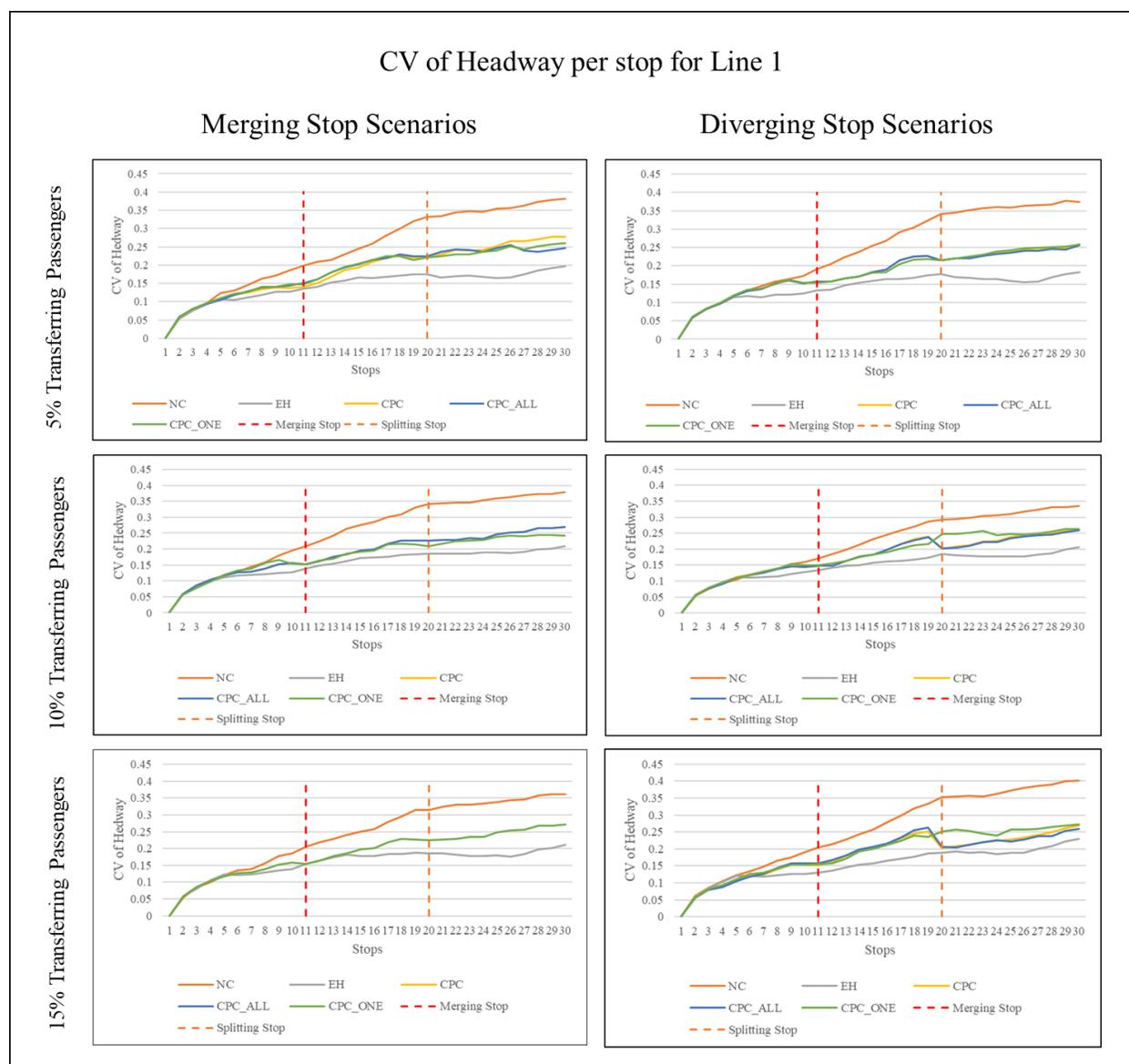


Figure 7-4 Coefficient of Variation of Headway per Stop of Line 1

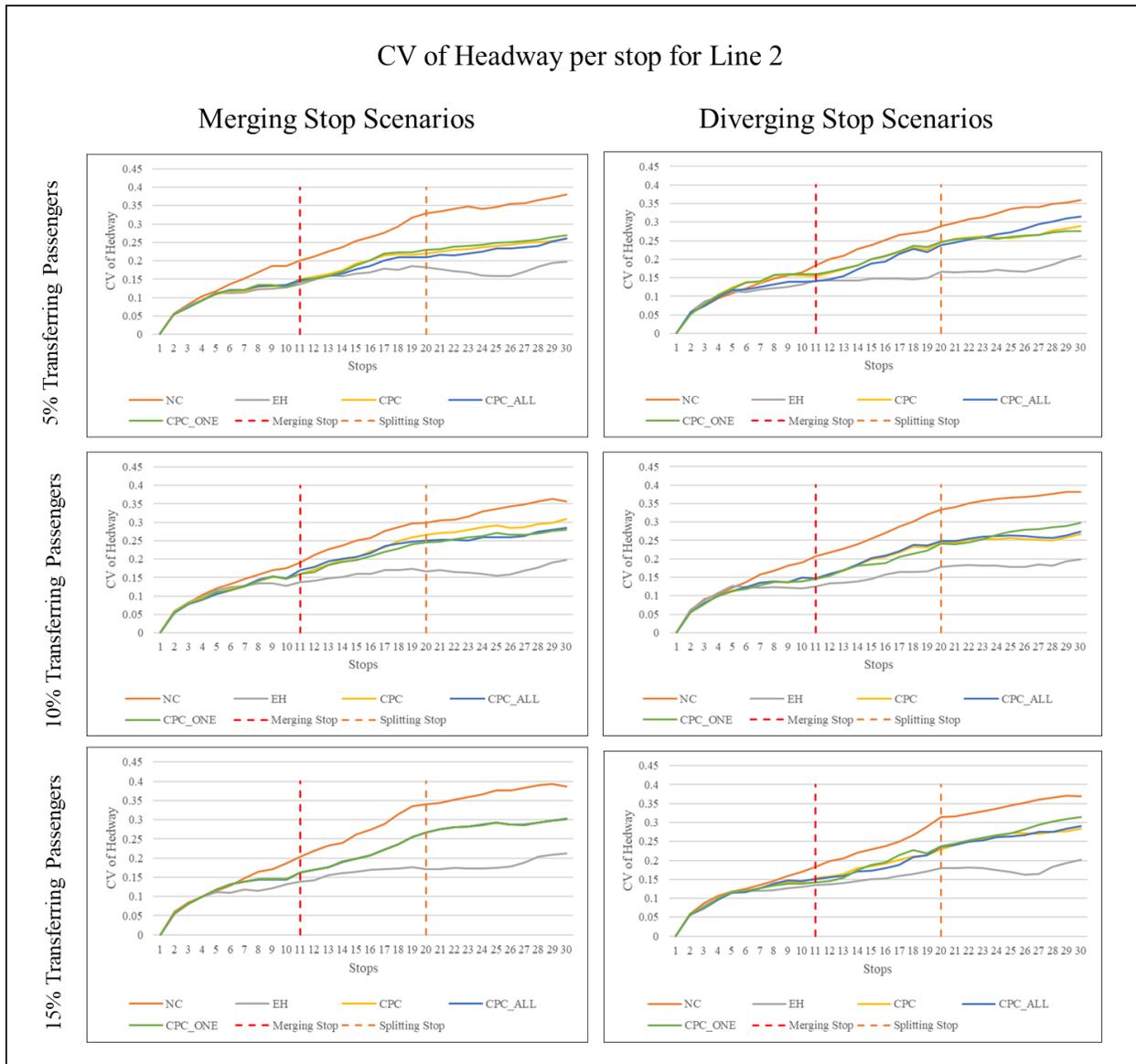


Figure 7-5 Coefficient of Variation of Headway per Stop of Line 2

Table 7.6 and Table 7.7 show the passenger cost results for line 1 and line 2 respectively. As expected and complementing the aforementioned results, EH outperforms CPC in line regularity for both lines, meeting its objective. Compared to NC, CPC achieves better results in waiting time with a lower cost for the passengers on board. In vehicle time with CPC slightly increases or remains at the same level with NC. Again the only exception is Scenario 3 with synchronization at the last common stop. Due to the high number of synchronization events, passengers of line 1 that are favored by the regularity of the line are penalized with additional time waiting for line 2.

Table 7.6 Passenger cost of Line 1

		Scenario 1			Scenario 2			Scenario 3		
	Line 1	Waiting Time	In vehicle time	Travel Time	Waiting Time	In vehicle time	Travel Time	Waiting Time	In vehicle time	Travel Time
		[sec]	[sec]	[sec]	[sec]	[sec]	[sec]	[sec]	[sec]	[sec]
Merging Stop	NC	314.0	144.2	772.2	315.2	144.4	774.9	314.0	144.4	772.3
	EH	304.2	146.0	754.4	308.3	147.4	764.0	304.4	147.1	755.9
	CPC	307.3	145.0	759.5	310.5	146.0	767.1	310.2	145.2	765.6
	CPC_ALL	309.0	145.6	763.5	310.0	146.2	766.3	310.2	145.2	765.6
	CPC_ONE	308.6	145.4	762.5	310.2	145.9	766.3	310.2	145.3	765.7
Diverging Stop	NC	314.1	143.9	772.2	313.4	144.3	771.1	314.4	144.7	773.4
	EH	304.3	145.7	754.2	308.3	146.3	762.9	305.2	147.1	757.6
	CPC	308.9	145.7	763.5	306.7	145.0	758.5	309.4	147.5	766.4
	CPC_ALL	308.9	145.7	763.5	306.7	144.8	758.3	308.6	146.0	763.2
	CPC_ONE	308.6	146.7	764.0	309.1	151.2	769.3	310.4	153.2	774.0

Table 7.7 Passenger cost of Line 2

		Scenario 1			Scenario 2			Scenario 3		
	Line 2	Waiting Time	In vehicle time	Travel Time	Waiting Time	In vehicle time	Travel Time	Waiting Time	In vehicle time	Travel Time
		[sec]	[sec]	[sec]	[sec]	[sec]	[sec]	[sec]	[sec]	[sec]
Merging Stop	NC	310.2	143.7	764.1	310.7	144.1	765.5	315.4	144.7	775.4
	EH	305.4	146.7	757.4	304.7	146.6	756.0	304.9	146.7	756.5
	CPC	308.4	144.9	761.6	308.1	145.6	761.7	309.9	145.0	764.8
	CPC_ALL	309.3	145.2	763.8	308.6	145.5	762.8	309.9	145.0	764.8
	CPC_ONE	308.4	145.0	761.7	308.1	145.9	762.1	310.1	144.9	765.1
Diverging Stop	NC	311.8	143.8	767.3	316.6	144.3	777.4	312.2	144.6	769.0
	EH	305.8	145.9	757.5	307.0	146.1	760.1	303.5	146.5	753.4
	CPC	309.1	145.5	763.7	312.4	145.6	770.3	308.6	145.9	763.1
	CPC_ALL	309.1	145.6	763.7	312.4	145.7	770.4	307.1	145.4	759.7
	CPC_ONE	310.4	145.5	766.4	309.5	145.1	764.1	308.1	145.3	761.4

7.2.3. Passenger Costs

The control decisions taken have different effect on each of the six passenger groups in a double fork network. Figure 7-6 illustrates the percent difference of passenger cost compared to NC for all scenarios at network level. It is clear from the results that the biggest gaining for CPC is achieved prior and at the shared transit corridor. The greatest reductions for CPC are reported for the passengers travelling within the corridor followed by the initial branch. The passengers traversing between stops sets are most crucial passenger groups for CPC since they experience the control action for regulating the operation of each stop

set and the transition between stop sets. This is more evident for the groups that travel between branches and from corridor to branch. The reduction in passenger cost is lower with CPC than with EH. For the diverging stop scenarios with addition of actions for synchronization, a significant increase in passenger cost is reported for a cost comparison only at current stop. Apart from the cost increase for passengers travelling from the initial branch to final branch, the cost increases also for the passengers travelling from corridor to branch in contrast with CPC for different cost horizons. EH is dominant at the final branch in all scenarios



7.2.4. Travel Times

A robust travel time helps the operator to create a robust timetable and manage the available fleet and driving roster. Figure 7-7 and Figure 7-8 depict the travel time distribution for line 1 and line 2 respectively. Overall, single line control yields to a less variable travel time for both lines. CPC shows the same trends in terms of average travel time and variability especially when synchronization happens at the first commons stop. Synchronization results to a longer travel time but at the same level of variability as EH. While for line 1, increased travel time is observed in scenario 2 and 3 for line 1, Line 2 shows a similar trend only for scenario 3, the scenario with the highest number of transferring passengers.

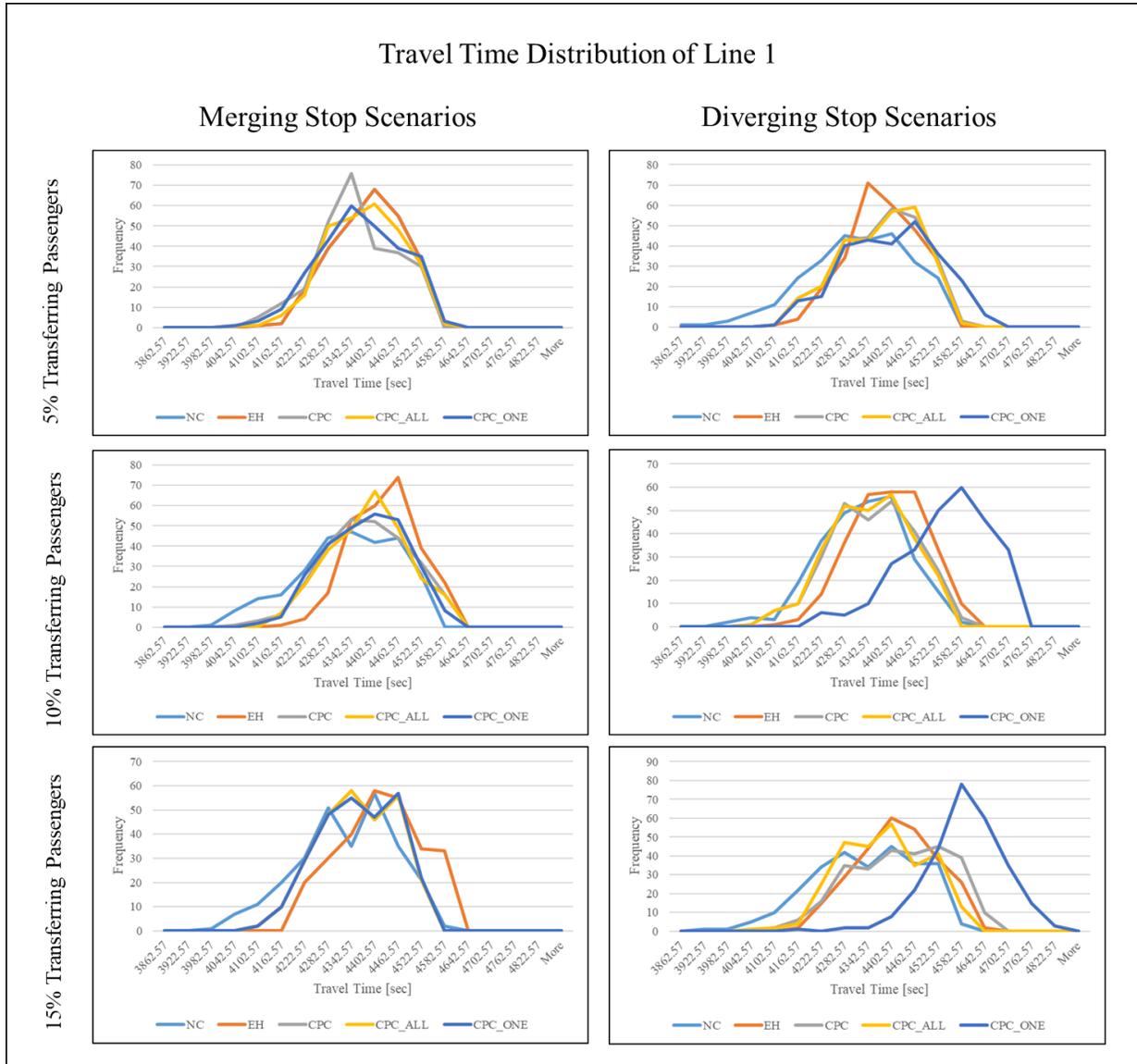


Figure 7-7 Travel Time Distribution of Line 1

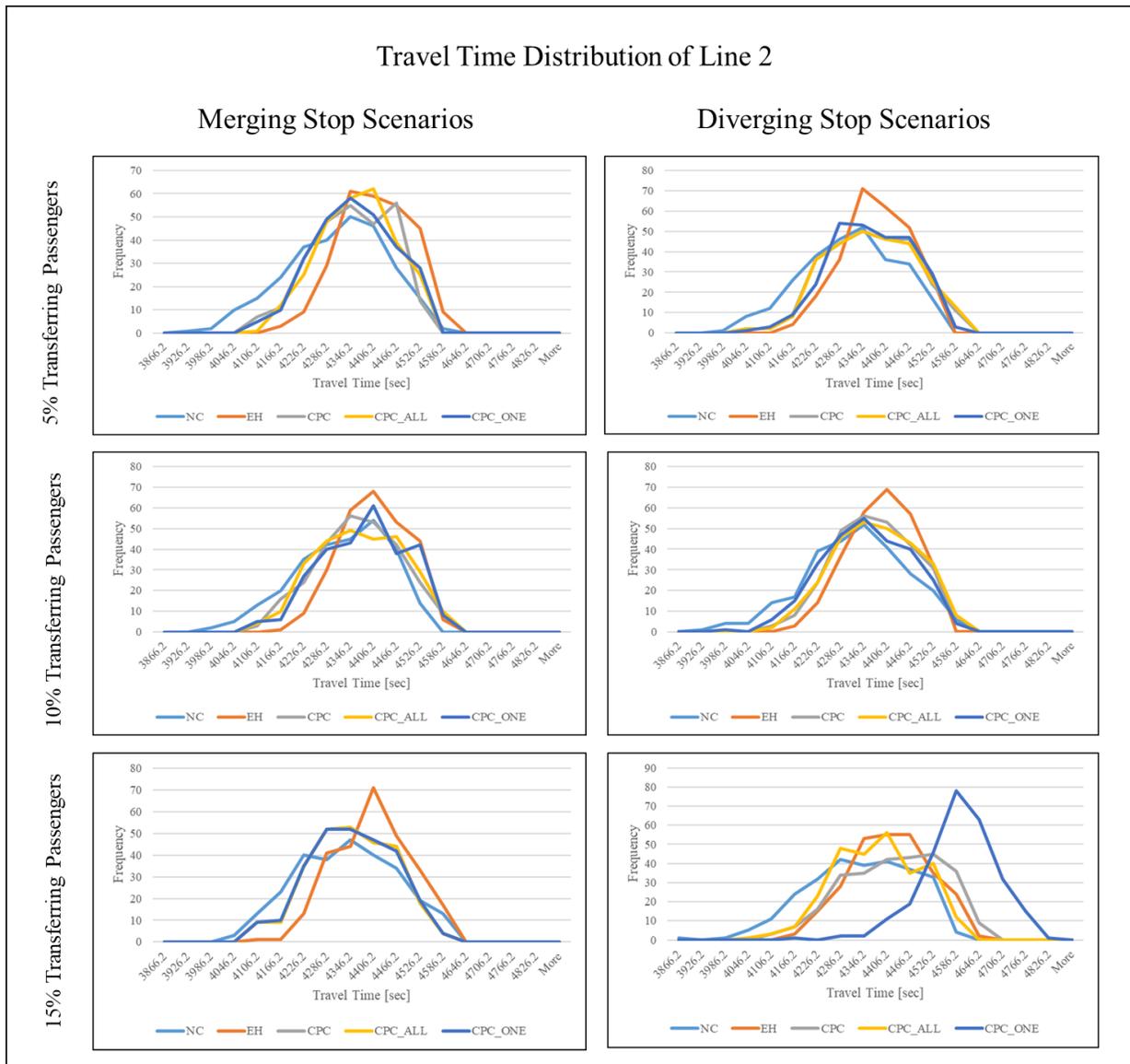


Figure 7-8 Travel Time Distribution of Line 1

7.2.5. Transfer Waiting Time

It is reminded that the simulation is built on the assumption that tactical planning ensures the alternately arrival of the vehicles of different lines at the common part, offering a shorter joint headway at the common segment. A scenario that would have allowed only synchronization decisions could have resulted to extreme delays that can propagate and reduce further the level of service.

Table 7.8 summarizes the average transfer time for each scenario and its deviation. No Control and Even Headway Strategy in all scenarios do not account for the interaction with other lines. At these scenarios the lowest average transfer time is reported. At the shared transit corridor, CPC aims to maintain or restore regularity based on the joint frequency of the common stop set. Therefore, in the majority of the scenarios the average transfer time corresponds to the joint frequency of the corridor. In all scenarios, CPC has shown the lowest variability of transfer time. The distribution of transfer time among all different scenarios is depicted in Figure 7-9. It can also be observed that the longer the cost comparison horizon, the lower

standard deviation of transfer time. In general, in the current network configuration and with a tactical planning that ensures denser frequencies on the corridor, transferring time should be equal to the joint headway between lines. Synchronization decisions may reduce the transferring time but will penalize the regularity of the system and the corresponding passenger groups.

Table 7.8 Average Transfer Time and Standard Deviation

		NC		EH		CPC		CPC_ALL		CPC_ONE	
		Average Transfer Time [sec]	St Deviation								
Merging Stop	Scenar io 1	287.8	39.7	303.2	42.3	295.7	29.1	289.1	30.2	288.6	34.5
	Scenar io 2	288.5	37.3	291.0	34.7	293.2	26.5	307.3	28.2	303.6	30.8
	Scenar io 3	295.5	42.6	285.3	43.2	297.0	26.6	299.1	25.4	299.0	25.4
Diverging Stop	Scenar io 1	291.3	34.5	308.0	43.2	318.1	24.7	310.8	26.6	304.5	28.8
	Scenar io 2	287.1	38.2	286.9	34.7	297.5	24.8	301.5	30.0	299.0	30.0
	Scenar io 3	294.7	38.8	282.6	41.3	293.6	26.6	288.9	24.5	295.9	27.9

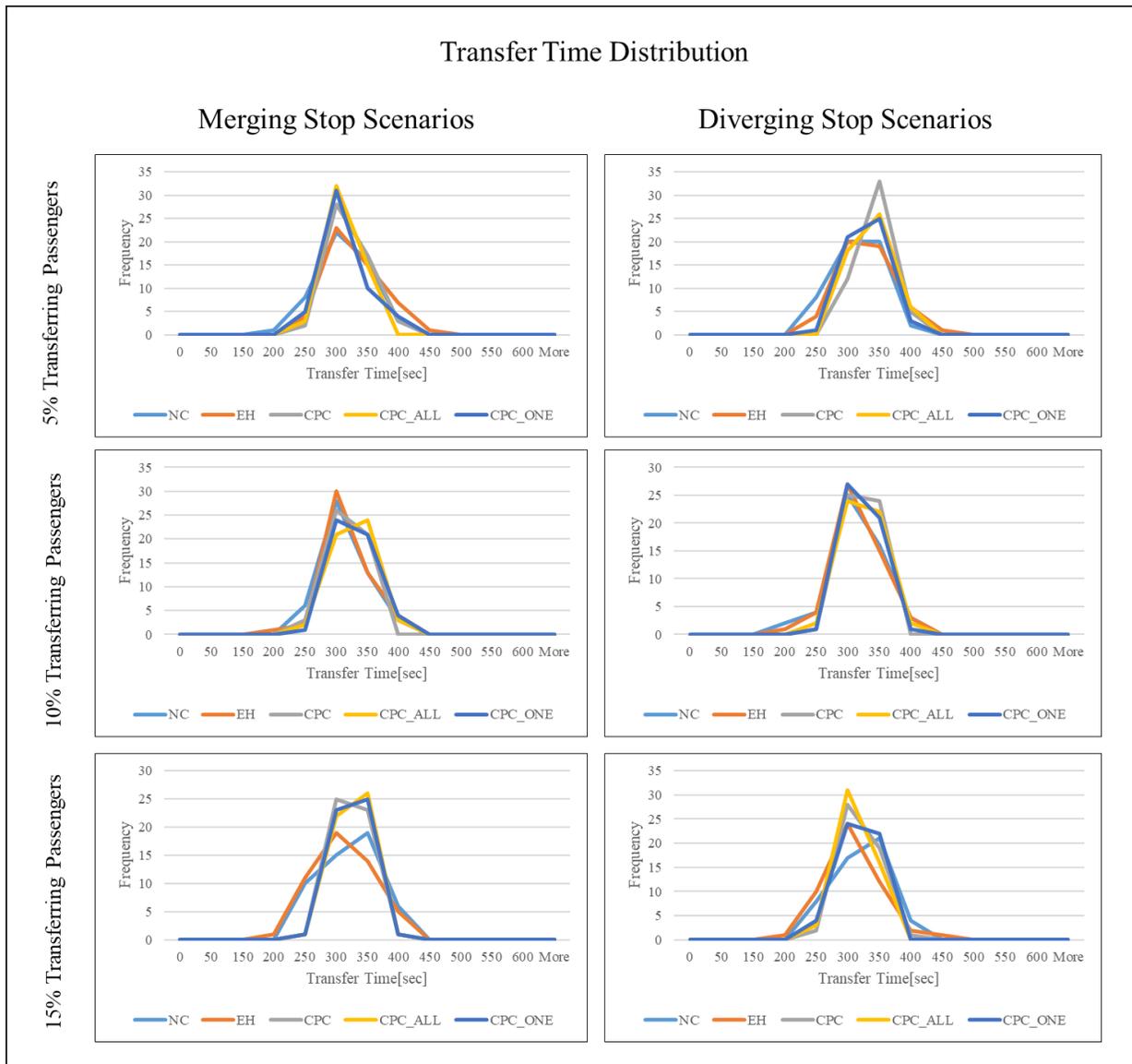


Figure 7-9 Transfer Time Distribution

7.2.6. Controller Decision

The decision between holding for regularity or for synchronization is taken based on the comparison of the passenger cost for three different comparison horizons. In the first set of scenarios, the synchronization criterion is applied at the merging stop while at the second at the diverging stop. The frequency of each decision per scenario is summarized in Table 7.9.

Table 7.9 Controller Decisions

Comparison Horizon		All		One		Middle	
		Regularity	Synchronization	Regularity	Synchronization	Regularity	Synchronization
		Merging Stop					
Merging Stop	Scen1	100%	0%	100.0%	0.0%	100%	0%
	Scen2	100%	0%	99.0%	1.0%	100%	0%
	Scen3	100%	0%	99.5%	0.5%	100%	0%
		Diverging Stop					
Diverging Stop	Scen1	95.4%	4.6%	66.4%	33.6%	94.6%	5.4%
	Scen2	92.4%	7.6%	10.1%	89.9%	85.2%	14.8%
	Scen3	87.1%	12.9%	1.1%	98.9%	47.2%	52.8%

Controlling for regularity at the beginning of the shared transit corridor is dominant. Regardless the length of the horizon, the majority of the passengers are downstream at the shared transit corridor and they are benefited by the regularization of the system. A synchronization decision at the merging stop can cause extremely long waiting time at the passengers along the shared transit corridor. Therefore, when the comparison of passenger cost extends beyond the current stop the system focuses exclusively on maintaining regularity. When comparing the cost only at the current stop, it can be observed that control for synchronization occurs but again comprises only 1% of the control decisions.

When synchronization is allowed at the diverging stop, the results are significantly different from the merging stop. The comparison horizon extends to the branch stop set. At a branch stop set, the demand is lower compared to the demand of the shared transit corridor making synchronization a feasible option. Similar to the merging stop, vehicles are held mostly to restore regularity, but even in Scenario 1 with a low share of transferring passengers, the controller chooses to hold for synchronization. The share of synchronization decisions increases with the share of transferring passengers and with the shortening of the comparison horizon. At the most myopic scenario (current stop cost comparison), at scenarios 2 and 3, synchronization is the most frequent choice.

7.3. Discussion

In this chapter, the full criterion for regularity as formulated in Chapter 3 is tested for an artificial double fork network with two lines. In addition, synchronization is allowed either at the merging or at the diverging stop and the criterion for choosing between synchronization and regularity is the passenger cost of each control action.

Overall the results shown that multiline control is more beneficial for the network, resulting to a lower overall passenger cost for the system. This result is based on the substantial gains at the shared transit corridor. As in merging fork network, coordination helps to achieve a joint headway with lower variability prior to the common stop set and this is maintained along the corridor. Although the performance of CPC at line level is not as effective as single line control, significant reduction as achieved compared to no control and with lower in vehicle delay for the lines, a usual shortcoming of holding control strategies.

Due to the high concentration of the demand at the shared transit corridor, from control perspective it is not recommended to favor synchronization over regularity at the merging stop since the expected synchronization cost is very high for the system. At the diverging stop, synchronization becomes feasible and for shorter cost comparison horizon is the dominant choice. However, at the diverging stop and after regulating the joint operation, transferring passengers are benefited mostly by the low variability of the joint headway and their average transfer time corresponds to the headway of the shared transit corridor.

PART II

Enhancing Holding Strategy with Cooperative-ITS

Enhancing Holding Strategy with Cooperative-ITS

In this chapter, the holding strategy introduced in the first part of this dissertation is combined with Cooperative Intelligent Transport Systems in order to combine the objectives of maintaining regularity and reduce the number of stops at traffic signals. A holding criterion has been combined with two Driver Advisory Systems (GLODTA and GLOSA) and in this chapter both methodologies are presented.

The Content of this chapter has been presented in the following works:

Laskaris, Georgios, Marcin Seredynski, and Francesco Viti. 2019 Enhancing Bus Holding Control Using Cooperative ITS *Submitted to IEEE Transactions on Intelligent Transport Systems (Under Review)*

Laskaris, Georgios, Marcin Seredynski, and Francesco Viti. 2019 A real time hybrid controller for regulating bus operations and reducing stops at signals *6th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS) (Prese)*

8.1. Driver Advisory Systems

8.1.1. Introduction

In the previous part of this dissertation, holding has been extended to account for multiple lines and the passengers experiencing the control action and restore regularity to branch and trunk networks. Similarly to other holding strategies, control actions require additional time that correspond to longer travel times.

One category of ITS integrated and used in Public Transport applications is Cooperative ITS (C-ITS). Cooperative ITS consist of technologies that allow vehicles to communicate among each other (Vehicle to Vehicle (V2V) Communication) and with infrastructure (Vehicle to infrastructure (V2I) Communication). Thanks to these technologies, information can be transmitted in real time to the vehicles allowing the driver to react, reducing the dependence from a centralized control center. The existing C-ITS based applications on public transport focus on providing priority at traffic signals. Given that the next signal head is in communication range, information for signal time and phasing can be transmitted to the vehicles. There are two C-ITS-based applications, known as Driver Advisory Systems (DASs) that can reduce the number of traffic signal priority requests and its impact on the rest of the traffic. Based on the received information the driver is advised to either extend the dwell time at a stop (Green Light Optimal Dwell Time Advisory (GLODTA)) or modify the vehicle's speed in order to ensure traversing green (Green Light Optimal Speed Advisory (GLOSA)). Until now, DASs exclusively focus on providing priority, neglecting the sequence of vehicles increasing the occurrence of bunching and reducing the regularity of the line.

The aforementioned solutions have been developed to seek different objectives (regularity for the first and minimization of stops at traffic lights for the other two). Holding and GLODTA are based on the same principle of delaying a vehicle by remaining for an additional time at a stop and speed advisory has been used in order to compensate for the holding times. We explore a potential synergy of holding strategy and the DASs both by computing analytically, when a vehicle completes its dwell time, the holding time depending on its headway from the preceding and the succeeding vehicles together with the time and the speed needed to traverse the next green phase. The combined controllers are presented in the following sections.

8.1.2. Green Light Optimal Dwell Time Adaptation

Similar to holding strategies, Green Light Optimal Dwell Time Advisory (GLODTA) introduces additional dwell times at bus stops when the vehicle is ready for departure. Given that a bus stop is within the Dynamic Short Range Communication (DSRC) distance from the next signalized intersection downstream, the driver can be instructed to hold an additional amount of time if the average speed to reach the signal will allow the bus to traverse the next green phase. This means that eventual delays incurred at the signal are instead transferred to the upstream stop and overall trip time is not extended. The additional advantage is that the total number of stops for a trip is reduced, and hence less energy is consumed and emissions are expected to be reduced. Details on how GLODTA can be implemented in practice is given in (Seredynski et al., 2013) and the application of GLODTA is depicted in Figure 9-1.

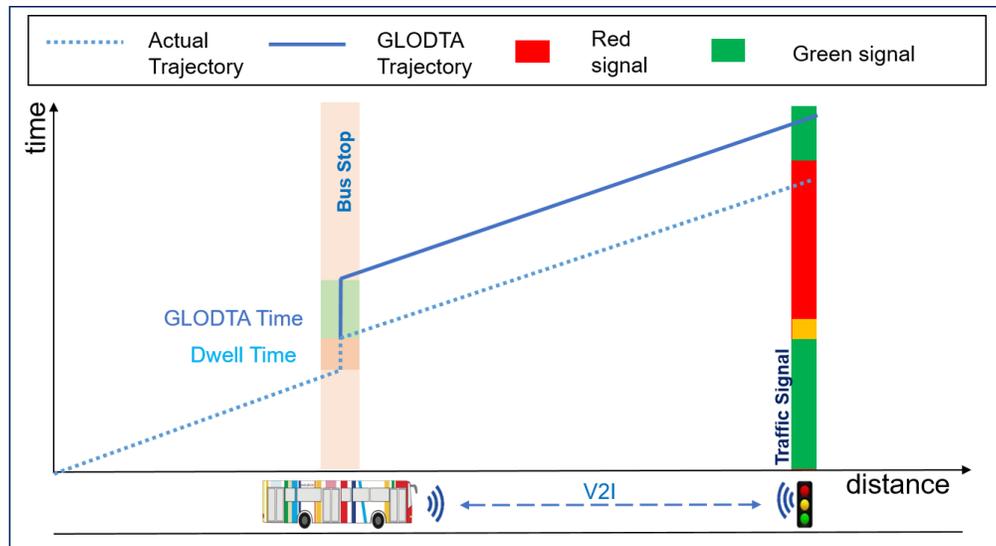


Figure 9-1 GLODTA

8.1.3. Green Light Optimal Speed Adaptation

With Green Light Optimal Speed Advisory (GLOSA), vehicles within the communication range of a downstream traffic light receive information of the cycle and the current indication. Based on the vehicle's current speed and with respect to the speed limit, the driver is instructed to modify the bus speed and stay within a certain range in order to traverse the upcoming signalized intersection during the green phase. GLOSA has been proven to be effective when stops are placed far away from the signal, as no reliable communication can be transmitted to apply GLODTA. Compared to Transit Signal Priority (TSP), where traffic light timings are adapted to provide a certain level of priority to the buses (see Section 9.1.3), GLOSA is not causing any delays to the rest of the traffic, instead the bus adjusts its trajectory to the cycle of the traffic light, therefore it can be preferred over TSP. Application of GLOSA is also described in the following pseudocode:

START

Departure from stop

IF (vehicle within communication range)

Estimate $t^{arr,tl}$

IF (indication=Green during $t^{arr,tl}$)

Keep current speed V

ELSE

Estimate V' so that $t^{wait,tl} = 0$

$V = V'$

END IF

END IF

END

Traditionally, GLOSA is applied between stops. When a vehicle enters within the communication range of a downstream signal head, Signal Phase and Time (SPaT) information is transmitted. Given the position of the vehicle and the estimated arrival time at the intersection, GLOSA instructs the driver to adjust the bus speed in order to arrive at the signalized intersection during green. The speed advised by GLOSA should

always be within the speed limits and the within vehicle and operational specifications to avoid passenger discomfort. A graphical representation of GLOSA is given in Figure 9-2. A vehicle travels towards the next signalized intersection. When it enters within the communication range of the signal head, it receives information for the current indication and cycle of the traffic light. Given that with its actual speed is expected to arrive during red, it is instructed to accelerate to arrive during green phase.

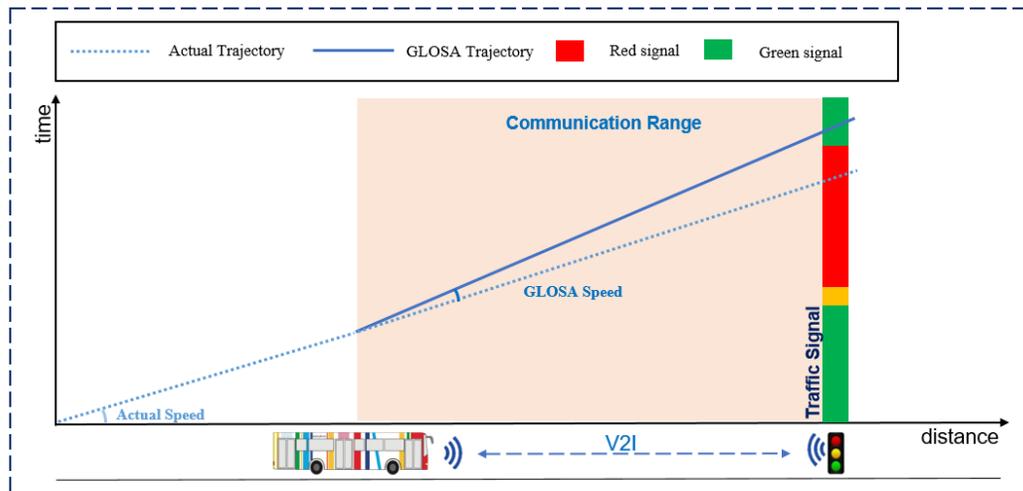


Figure 9-2 GLOSA

8.1.4. Transit Signal Priority

TSP can be adopted at traffic lights to avoid buses to stop and in the same time provide some additional priority to the general traffic stream. This is obtained by detecting bus arrivals (via detectors or via C-ITS communication) and modifying green and red times. Green times can be anticipated (or extended) such that vehicles pass without modifying their planned trajectory. In our approach, before requesting a priority at traffic signals a bus attempts to traverse the signalized intersection using DASs. That is, first a bus attempts to avoid stopping at signals from the stop. If this fails, priority request can be sent to the traffic controller. If the vehicle arrives close to end of the red phase then a green recall can be triggered and the green phase will start earlier by the assigned TSP time set by the operator t^{TSP} . If the vehicle is expected to arrive at the beginning of red and has to wait for the whole duration of red, green can be extended from the previous phase. The green extension and the green recall are shown also in the following pseudocode:

START

Departure from stop

IF $(t^{wait,tl} \leq t^{TSP})$

$$t^{Green} = t^{Green} + t^{TSP}$$

OR

$$t^{Red} = t^{Red} - t^{TSP}$$

END IF

END

8.2. R-GLODTA

8.2.1. Assumptions and limitations

Our modelling approach consists of three main components:

- the bus system;
- the infrastructure;
- the communication layer.

The bus system refers to the lines that constitute the bus network. It also involves the transit routes, the vehicles, the bus stops as well as the passengers. We assume that vehicles are dispatched based on a predefined schedule. Automatic vehicle location (AVL) technology is assumed to be available in real time and the location of all vehicles is considered known network wide. The location of the vehicles is also monitored by a centralized control center, which also administers the information and reacts dynamically with corrective actions to any disturbance. It is also assumed that buses are moving on dedicated lanes and do not interfere with the rest of the traffic apart from eventually obtaining priority at the signalized intersections. For this study, the bus system consists of a single line serving one transit route. Since fleet management is not under the scope of this study, all vehicles dispatched are assumed to conduct a single trip and operate in one direction.

The second element is the infrastructure. Traffic lights are assumed to be pre-phased, with a-priori stages, cycle times and green/red timings. Priority to public transport can be given upon request. For the sake of simplicity, between stops only one signalized intersection is considered and the distance bus stop and traffic light may vary.

The third and final element corresponds to the cooperative communication environment composed of interconnected vehicles communicating positions and priority levels. We assume that all signals are equipped with Dynamic Short-Range Communications technology (DSRC), which allows infrastructure-to-vehicle communication and provides SPaT information to all vehicles within signals proximity. The goal of our approach is to manage efficiently three interacting components: the in-vehicle control managed by a Driver Assistance System (DAS) dashboard supporting the bus drivers and a signal control system regulating traffic and eventually providing priority to the buses. The methodology can be adopted in fully automated systems.

8.2.2. Problem Formulation

We present a hybrid control strategy which not only considers explicitly the actual time headway between consecutive vehicles, in order to arrive as evenly spaced as possible at stops, hence reducing the level of bunching and overall improving line regularity, but also, when a vehicle obtains SPaT information, assists to traverse the next intersection during the green phase.

In particular, at stops selected to apply control (Time Control Points), candidate holding times to restore regularity of the service are determined by a simple rule subject to the forward and backward headways, following the rule developed in Cats et al., (2011). In order to ensure that vehicles, by the time of their departure, will also traverse the downstream signalized intersection without stopping, the candidate holding time should also be within a specific time interval estimated via GLODTA. In case of an on time or late arrival, only GLODTA time is checked and triggered only if it results in time savings for the line.

In addition, the controller is further enhanced by signaling and speed advisory. Requests for green time extension and green recall are considered, expecting to be in line with the findings of previous studies for

need of weak TSP instead of strong TSP (Seredynski and Khadraoui, 2014) . When in communication range, speed advisory can be given via GLOSA to adjust the vehicle's speed to further increase the probability of traversing during green.

We assume a bus line i , the route of which consists of $J = \{j_1, j_2, \dots, j_n\}$ stops and there are $K = \{k_1, k_2, \dots, k_n\}$ trips conducted. Between stops, there are $J - 1$ links that connect the stops with different lengths. Links may contain a signalized intersection, the distance of which from the upstream bus stop is known. The average cruising speed of each vehicle with the minimum and maximum speed are also known and within the speed limits.

Holding criterion

As primary objective, bus regularity should be sought in order to guarantee high quality of service for the passengers. A well-established control strategy to regularize bus headways is holding, in which buses are instructed to hold on a bus stop for an additional time such that headway with the preceding and the succeeding vehicles is modified.

The holding criterion chosen for this study is, as in other chapters, the criterion used by Cats et al. (2011) Cats et al., 2011. The criterion has been compared with other holding strategies using simulation for frequency-based services and has proven to be superior (Cats et al., 2012, 2011). The criterion is based on the actual headway of the vehicle subject to its preceding and succeeding buses. Additionally, the maximum allowed holding time is limited to a specific share of the planned headway. The formula to calculate departure (exit) time t_{ijk}^{exit} is given as Equation 9.1:

$$t_{ijk}^{exit} = \max \left\{ \min [term1, term2], t_{ijk}^{arr} + t_{ijk}^{dwell} \right\} \quad (9.1)$$

Where $term1$ and $term2$ are given by Equation 9.2 and Equation 9.3 respectively:

$$term1 = t_{ijk}^{arr} + \frac{t_{imk+1}^{arr} + SRT - t_{ijk-1}^{arr}}{2} \quad (9.2)$$

$$term2 = t_{ijk-1}^{arr} + \alpha PH \quad (9.3)$$

In the equations, t_{ijk}^{arr} and t_{ijk}^{dwell} are the arrival time and the dwell time of bus k at stop j and for line i , respectively. $term1$ is estimated as the average between the arrival time of the previous vehicle t_{ijk-1}^{arr} and the arrival time t_{imk+1}^{arr} of the following vehicle $k + 1$. We estimate the arrival time of the succeeding vehicle from the last visited stop m to the current stop j by summing the scheduled riding time SRT between the last visited stop m and the current stop j to the arrival time at the last visited stop m t_{imk+1}^{arr} . For simplicity's sake, we will consider a single line control from now on leaving the extension of the work to multiple lines to future research. PH is the planned headway, while α is the threshold ratio parameter that limits the maximum allowed holding. Threshold ratio parameter ranges between 0.6-0.8 (Fu and Yang, 2002; Cats et al., 2011).

After the completion of dwell time t_{ijk}^{dwell} , information of the current signal indication of the downstream traffic light is transmitted. Given that the vehicle departs from stop after dwell time and will cruise with its average speed V_k , the arrival time at traffic light is estimated using Equation 9.4:

$$t_{ijk}^{arr,tl} = t_{ijk}^{exit} + \frac{d}{V_k} \quad (9.4)$$

Where $t_{ijk}^{arr,tl}$ is the estimated arrival time at traffic light, t_{ijk}^{exit} the departure time of vehicle k from stop j , d the distance between stop and the downstream signalized intersection and V_k the average speed of the vehicle.

If by the expected arrival at the traffic light, if the indication is green then the vehicle is expected to traverse the intersection without stopping. On the other hand, if the indication is red, the waiting time at traffic light $t_{ijk}^{wait,tl}$ is calculated by subtracting the current red time $t^{Red,c}$ from the red time t^{Red} as in Equation 9.5:

$$t_{ijk}^{wait,tl} = t^{Red} - t^{Red,c} \quad (9.5)$$

The waiting time at traffic light is also the GLODTA time t^{GLODTA} . If vehicle departs after t^{GLODTA} , it will arrive by the time green starts. Practically, the expected waiting time at traffic light which translates as delay is transferred at the bus stop, where it can be utilized as additional dwell time serving additional passengers. The additional time to remain at stop t^{GLODTA} with the duration of green constitute a time interval, within which if the vehicle departs, will traverse the downstream signalized intersection without stopping (Equation 9.6). If a vehicle departs at a time within this interval, it is expected to traverse the next signalized intersection during green:

$$\left[t^{GLODTA}, t^{GLODTA} + t^{Green} \right] \quad (9.6)$$

After defining the interval within which if the vehicle departs can traverse the next signalized intersection without stop, then its departure should be regulated based on the headways between consecutive vehicles. The headway of the current, the preceding, and the succeeding vehicle are compared. If the headway from the preceding vehicle is shorter than the headway from the succeeding one then the vehicle has arrived early. In case of an early arrival, the vehicle should remain at the stop in order to restore regularity. From Equation 9.1 both terms for actual holding time needed and the maximum holding are estimated. Firstly, the expected arrival time at the traffic light with the optimal holding time as calculated by *term1* by Equation 9.4. If vehicle arrives during green phase at traffic light, then it will depart from stop after holding time t_1^{hold} , which satisfies both criteria. If vehicle does not arrive during green time, the condition is tested for the maximum holding time.

If with either of the two candidate holding times both regularity and green light criteria are met, holding time is selected and counts as a combined controller. If with both holding times the bus arrives at the stop during the red phase then the holding time with the less estimated remaining time at the traffic light is selected and the controller counts simply as a regularity controller:

$$t^{hold} = \min \left(t_{ijk}^{exit} + t_{ijk,1}^{hold} + \frac{d}{V_k}, t_{ijk}^{exit} + t_{ijk,2}^{hold} + \frac{d}{V_k} \right) \quad (9.7)$$

In case of on time or late arrival, the vehicle will depart after t^{GLODTA} in order to recover by saving time at traffic light, again if needed. This joint strategy, which we name R-GLODTA, is shown with the following Figure 9-3.

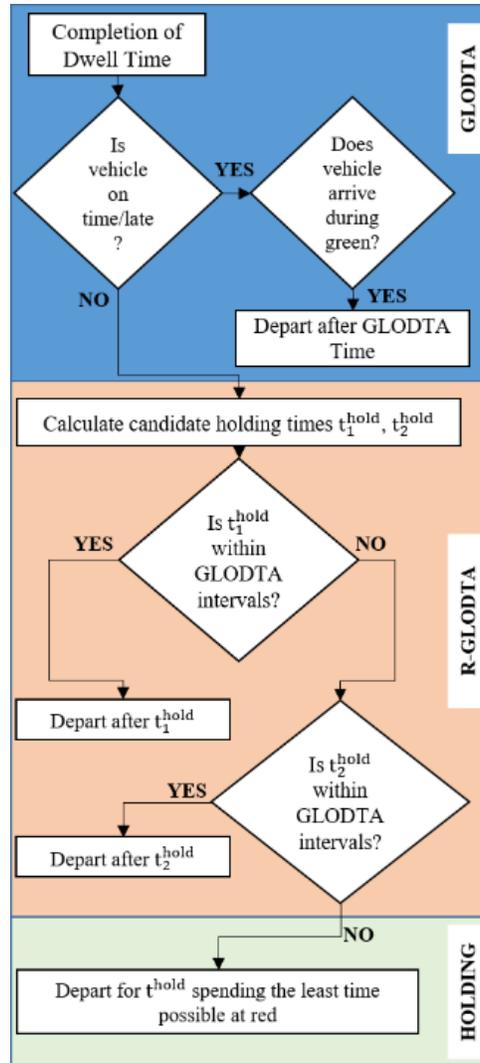


Figure 9-3 R-GLODTA flow chart

8.3. R-GLOSA

In this section, we combine the aforementioned holding strategy with speed recommendation from the corresponding DAS, named from now on as R-GLOSA. A vehicle arrives at a stop and the passenger's transference starts. By the completion of dwell time, information of the cycle and the current indication of the downstream signal head have been transmitted. Firstly, using Equation 9.1 the estimated departure time t_{ijk}^{exit} is calculated to maintain regularity prolonged by holding time, if needed. Using the departure time obtained by Equation 9.8, the expected arrival at traffic light is projected by adding the running time to the traffic light.

$$t_{ijk}^{arr,tl} = t_{ijk}^{exit} + \frac{d_{j,tl}}{V_k} \quad (9.8)$$

Where $t_{ijk}^{arr,tl}$ the expected arrival time at the first signalized intersection downstream, $d_{j,tl}$ the distance between current bus stop j and the signalized intersection tl and V_k the average speed of vehicle k at the link downstream of stop j .

Given the indication of the traffic light and the cycle length by the time vehicle k is at the stop, the expected indication is estimated by the expected arrival time. If the current indication is red then the remaining time for red $t^{Red,remain}$ is estimated and added to the expected arrival time $t_{ijk}^{arr,tl}$. Then the recommended speed is calculated using Equation 9.9:

$$V_k^{RGLOSA} = \frac{d_{j,tl}}{(t_{ijk}^{arr,tl} - t_{ijk}^{exit} + t^{Red,remain})} \quad (9.9)$$

In case of green, the vehicle should either accelerate to catch the current phase or wait for the next green phase. Therefore, two candidate speeds can be recommended, one for the estimated arrival time $t_{ijk}^{arr,tl}$ and one for the expected arrival at the next green phase, given by Equation 9.10 and Equation 9.11 respectively.

$$V_1^{RGLOSA} = \frac{d_{j,tl}}{(t_{ijk}^{arr,tl} - t_{ijk}^{exit})} \quad (9.10)$$

$$V_k^{RGLOSA} = \frac{d_{j,tl}}{(t_{ijk}^{arr,tl} - t_{ijk}^{exit} + t^{Green,remain} + t^{Red})} \quad (9.11)$$

Where t^{Red} the red time of the cycle of the current traffic light. All candidate speeds should respect the speed limits. In cases that both speeds are within the speed limits, V_1^{RGLOSA} is selected as the vehicle is instructed to accelerate and arrive during current green phase, while with V_2^{RGLOSA} the vehicle will try to arrive during green phase of the next cycle. All speeds outside the predefined range of speeds are excluded. If no holding time is assigned to the vehicle and only the speed advisory part is used, the controller is treated as GLOSA. On the other hand, if all candidate speeds do not respect the speed limits then the controller is treated as a holding strategy. A pseudocode of R-GLOSA is given below.

START R-GLOSA

Calculate t^{hold}

IF ($t^{hold} > 0$)

 Calculate $t^{arr,tl}$

IF (*Indication = RED*)

Calculate V^{GLOSA}

$$V^{GLOSA} \leftarrow \left[d / \left(t^{arr,tl} - t^{exit} + t^{Red,remain} \right) \right]$$

ELSE

Calculate V_1^{GLOSA}, V_2^{GLOSA}

$$V_1^{GLOSA} \leftarrow \left[d / \left(t^{arr,tl} - t^{exit} \right) \right]$$

$$V_2^{GLOSA} \leftarrow \left[d / \left(t^{arr,tl} - t^{exit} + t^{Green,remain} + t^{Red} \right) \right] \text{ **ENDIF**}$$

IF ($V_{\min} \leq V_1^{GLOSA} \leq V_{\max}$)

RETURN t^{hold}, V_1^{GLOSA}

ELSEIF ($V_{\min} \leq V_2^{GLOSA} \leq V_{\max}$)

RETURN t^{hold}, V_2^{GLOSA}

ELSE

RETURN t^{hold}

ENDIF

ELSE

Calculate $t^{arr,tl}$

IF (*Indication = RED*)

Calculate V^{GLOSA}

$$V^{GLOSA} \leftarrow \left[d / \left(t^{arr,tl} - t^{exit} + t^{Red,remain} \right) \right]$$

ELSE

Calculate V_1^{GLOSA}, V_2^{GLOSA}

$$V_1^{GLOSA} \leftarrow \left[d / \left(t^{arr,tl} - t^{exit} \right) \right]$$

$$V_2^{GLOSA} \leftarrow \left[d / \left(t^{arr,tl} - t^{exit} + t^{Green,remain} + t^{Red} \right) \right]$$

ENDIF

```

IF ( $V_{\min} \leq V_1^{GLOSA} \leq V_{\max}$ )
    RETURN  $V_1^{GLOSA}$ 

ELSIF ( $V_{\min} \leq V_2^{GLOSA} \leq V_{\max}$ )
    RETURN  $V_2^{GLOSA}$ 

ELSE
    RETURN Depart after completion of dwell time

ENDIF
ENDIF
END

```

8.4. Synthesis

In this chapter, two Driver Advisory Systems were introduced and combined with a rule based holding criterion into a hybrid controller that combines the objectives of both. Holding is the main actor in maintaining regularity for the system and either it result within a specific time interval for R-GLODTA or paired with speed advisory (R-GLOSA) in order to traverse to the first downstream signalized intersection during green. The combined objectives should minimize the toll holding time has on travel time, account for the sequence of the vehicles and reduce platooning while providing priority at signals and finally reduce the number of transit signal priority requests. The two hybrid controllers are tested using simulation in the following chapters for a real world case study of the city of Luxembourg. The controllers are compared to the individual applications of DAS and holding and different level of TSP and the results are assessed for both regularity and link indicators.

R-GLODTA

In this chapter, the performance of the hybrid controller R-GLODTA is evaluated using simulation of a realistic scenario of a major line in Luxembourg City. The results show that buses are efficiently operated without necessarily providing additional priority to public transport via TSP, hence without negatively affecting the capacity of the private vehicles system. The new controller improves further the performance in terms of regularity and reduces sufficiently the number of stops at traffic lights.

The Content of this chapter has been presented in the following works:

Laskaris, Georgios, Marcin Seredynski, and Francesco Viti. 2019 "Towards Optimised Deployment of Electric Bus Systems with On-Route Charging using Cooperative ITS." *Proceedings of the 98th Annual Meeting of the Transportation Research Board, January 2016, Washington, D.C.*

Laskaris, Georgios, Marcin Seredynski, and Francesco Viti. 2019 Enhancing Bus Holding Control Using Cooperative ITS Submitted to *IEEE Transactions on Intelligent Transport Systems (Major Revision)*

9.1. Experimental Setup

9.1.1 Case study}

The proposed control scheme is tested and evaluated by simulating a high frequency line. We compare the new control criteria with independent application of holding and Driver Advisory Systems at the selected time control points and a no-control case is used as a benchmark. We tested the simulated controls for one of the busiest lines of the city of Luxembourg, line number 16. The route of the line is depicted in Figure 9-1. The line consists of 19 stops in the eastbound direction and connects the new activity zone at the south part of the city with the city center, the central business district of Kirchberg and finally the airport of Findel. This line provides also connection with the other major transport hubs of the city (central railway station, Kirchberg multimodal transport hub). During peak hour, the frequency of the line is 10 minutes and articulated buses are used for the trip. The demand profile of the line is displayed in Figure 9-2. All intersections have been assumed equipped with TSP technology, and all bus stops have been set as time control points. We assume that all traffic lights have the same signal program with cycle of 120 seconds (80 green and 40 red) with the red indication first at the simulation environment. No coordination has been considered between signals.



Figure 9-1 Line 16 Luxembourg City

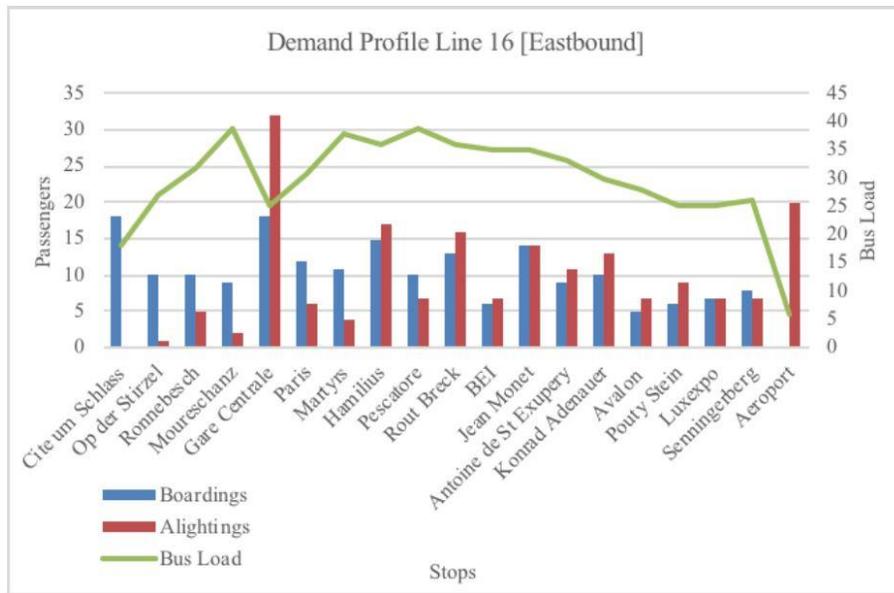


Figure 9-2 Demand Profile of Line 16

9.1.2. Simulation Environment

We developed a simulation environment in Mathworks MATLAB. The basic elements of the code are the physical network and the passenger demand. The simulation environment was built in order to capture the dynamics of transit operation. The simulator mimics the basic actions at and between stops but there are some limitations and assumptions that should be taken into consideration. For the sake of simplicity, the first is that vehicles cannot overtake. This is a common assumption taken in literature (Chen et al., 2013; Xuan et al., 2011; Gkiotsalitis and Cats, 2019b). When vehicles are overtaking, in simulation, they are reordering and the same rules apply in terms of simulating the remaining parts of operation. The communication layer is assumed to be functional continuously without disruptions once the vehicle is within the communication layer. Finally, all acceleration and deceleration actions are not taken into consideration. It is assumed that the vehicle reaches instantly its speed by the departure time from stop.

During simulation, there are two dimensions that are logged: Time and Passengers. Passengers enter and exit to the network via the stops along the line. The time passengers spend in the network is the time spent waiting for the next vehicle to board at stops and the in-vehicle time (the time between the origin stop and the destination stop including all intermediate stops).

In terms of time, the following information is recorded:

- Dispatching time from terminal;
- Actual riding time between stops;
- Time spent at signalized intersection (if any);
- Arrival time at each stop;
- Dwell time at each stop;
- Departure time at each stop;

for passengers:

- The number of boarding passengers;
- The number of alighting passengers;
- The number of passengers on board.

The main sources of stochasticity are the dispatching time, the riding time between stops and the number of passengers at stops. Dispatching times are drawn by a Gamma distribution given the planned headway between departures and the user can increase the variability by changing the shape and the size of the distribution. For the current setup, we assume that vehicles are dispatched with a perfectly regular frequency.

The calculation of actual riding times on the links between stops depends on the existence of a signalized intersection. If there is no signalized intersection, the riding time is sampled by a lognormal distribution with given inputs being the scheduled riding time and the desired standard deviation.

Lognormal distribution is recommended in literature due to its fitting and simplicity as concluded by the works of Clark and Watling (Clark and Watling, 2005), Hollander and Liu (Hollander and Liu, 2008) and Sumalee et al. (Sumalee et al., 2006). A lognormal distribution is characterized by its location parameter μ and its scale parameter σ . The location parameter and the scale parameter are calculated using the scheduled riding time SRT and due to the lack of historical data, the standard deviation of riding times is set to 20% in order to capture the variability of travel time during a normal day of operation. The location and the scale parameter are calculated using the following formulas:

$$\mu = \ln \left(\frac{SRT}{1 + \frac{SRT_{dev}}{SRT^2}} \right)$$

$$\sigma = \sqrt{\left(1 + \frac{SRT_{dev}}{SRT^2} \right)}$$

After calculating the parameters of the distribution, the actual riding time for each link is sampled. In case of a link with a signalized intersection, instead of the travel time, speed is sampled. Speed limit as well as the speed range due to vehicle technical specifications are given as an input. Once the vehicle departs from a stop, a speed is sampled from the vehicle speed range. We assume that the decision for the speed follows a normal distribution with average speed to be the average cruising speed of the vehicle. If the vehicle stops at a traffic light then once the traffic light is green, speed is resampled and the vehicle cruises until the next stop with new speed. When GLOSA is available, speed is resampled once the vehicle enters within the communication range of the traffic light (given as input by the user). With GLOSA, a speed is suggested in order to traverse during green. To replicate the speed transition, GLOSA speed is resampled again from normal distribution with average the recommended speed and lower variability compared to normal speed. Based on the speed profile of the bus along the link, once it reaches the next stop, the travel time is calculated.

In case of a stop while red, the waiting time is registered and the vehicle continues after resampling a new speed. The actual riding time is the sum of the running times prior and after the intersection and the waiting time at the traffic light. Based on the speed profile of the bus along the link, once it reaches the next stop, the travel time is calculated.

Since we study a frequency-based system, where the frequency of the line is sufficiently high (less than 12min), we consider that passengers arrive randomly at the stops. Therefore, we assume that passengers arrival at stops follow Poisson distribution in line with the literature. At each stop, passengers are grouped by destination and they are represented by their arrival rate λ . During dwell time, the number of passengers per origin destination pair is sampled from Poisson distribution using the corresponding arrival rate and the actual headway of the current vehicle from the preceding. The sum of boarding passengers per origin destination constitutes the boarding passengers from the visiting stop. Since the boarding passengers are given per origin destination pair, the sum of passengers on board with destination the current stop correspond to the alighting passengers. Occupancy is updated by adding the boarding passengers and subtracting the alighting passengers from the number of passengers on board.

During simulation each trip is generated and a vehicle arrives at the first stop at its dispatching time. At each stop, the arrival time of the vehicle is registered and the actual headway is calculated and boarding passengers are estimated. Dwell time is calculated as the sum of the product of the boarding and alighting passengers with the corresponding rate with a constant that captures additional delays occurring at stop. After the completion of dwell time, if no control is applied the vehicle departs and the departure time is registered. If control is applied the corresponding controller is triggered and returns the additional time a vehicle is held at the stop. If the controller includes a TSP call, the time the green phase of the next traffic light is also returned to be added to the cycle. Since overtaking is not allowed, in the case of bunched vehicles, the successor cannot depart prior to its preceding vehicle. As a recovery strategy, the following vehicle departs after an additional time to increase the headway between vehicles.

Each replication simulates a three-hour operation of the bus lines. The three hour operation corresponds to the morning peak hour, where the highest variability in travel times and the highest passenger demand are recorded. This time period reflects better the highly stochastic nature of public transport operation. For each replication, the first three and the last three trips are excluded from the analysis as they run deterministically and constitute the warm up and the cool down period of the simulation.

9.1.3. Scenarios

In order to compare the aforementioned control strategies and evaluate the performance of the proposed C-ITS based control strategy six scenarios were tested. As benchmark, a do-nothing scenario is used. Buses run without any C-ITS support and they do not receive any priority at signals. Additionally, at stops no control action takes place (Class 0). The second set of scenarios consists of the individual application of the control strategies: holding strategy, GLODTA and strong TSP at traffic lights with t^{TSP} of 15sec (Class 1). With holding applied, buses seek for regularity when controlled, with GLODTA, the additional dwell time is added to the boarding-alighting time at each stop to avoid arriving during red at the next traffic light and finally with TSP buses remain uncontrolled and instead priority is provided in form of green extension and green recall at signalized intersection to mitigate the number of stops at traffic lights. In the next scenario is the hybrid controller R-GLODTA suggested in this study, which combines the strategies of the previous level of control (Class 2). The final level of control, R-GLODTA is enhanced with GLOSA and weak TSP with t^{TSP} of five seconds (Class 3). All scenarios are summarized in Table 9.1.

Table 4

Scenario Class	Scenarios
Class 0	No Control GLODTA
Class 1	Holding TSP
Class 2	R_GLODTA
Class 3	R_GLODTA+GLOSA R_GLODTA+TSP

9.1.4. Performance Indicators

The main performance indicators used in this study are the adherence of headway of the line as well as the total trip time and its variability. Moreover, we will also analyze the delay at the signalized intersections and the number of times the vehicles managed to pass through a green phase. Finally, for the performance of the joint controller, the number of times requested is given and the share of each sub-controller are recorded. In summary, these are the performance indicators selected for the study:

- Regularity indicators: Coefficient of variation of headways, bunching;
- Passengers' cost indicators: in-vehicle time, waiting time at stops;
- Link performance indicators: stop frequency and delay at traffic light, average speed and running time;
- Controller performance: share of control requests and share of controller choice.

9.2. Results

The first indicator for the performance of the line in terms of regularity is the variability of headway and how it propagates along the line. The coefficient of variation of headway is the ratio of standard deviation over the average value and indicates the level of variability of the headway at each stop. In Figure 9-3, the coefficient of variation (CV) of headway for all simulated scenarios is depicted. It can be observed that there are two different trends based on the main objective of the strategy applied.

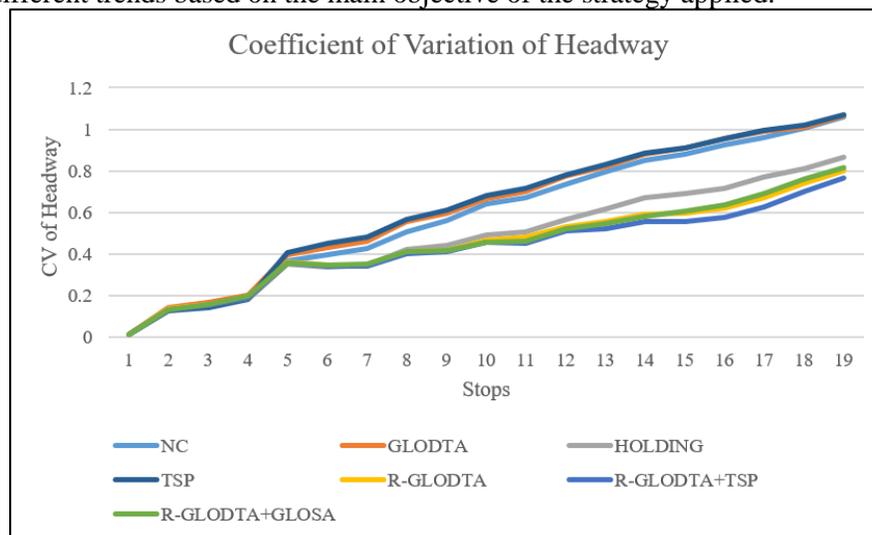


Figure 9-3 Coefficient of Variation of Headway per Stop

Strategies focusing on the provision of signal priority and neglecting the effects of operation and interaction between buses, and strategies that regulate the headway between vehicles. In the first category, the GLODTA or TSP scenarios can be found with minor differences compared to the do nothing scenario and a high level of variability as vehicles progress. On the other hand, holding, R-GLODTA alone and enhanced with weak TSP and GLOSA show significant improvement on maintaining the propagation of headway low. R-GLODTA outperforms holding and its performance improves further with weak TSP. Although R-GLODTA with GLOSA performs better than GLODTA and TSP, the combination is not the most effective compared to R-GLODTA and TSP.

Regularity performance indicators at line level are summarized in Table 9.2. Similarly to the coefficient of variation per stop, R-GLODTA outperforms the other strategies with minor differences from holding and R-GLODTA with TSP. GLOSA has a significant impact on the regularity of the line. This can be explained by the fact that GLOSA adjusts the speed in order to traverse green. Acceleration and deceleration can shorten the headway between consecutive vehicles and cause platoons. The index of bunching used in the share of buses that arrived at a stop with headway 50% longer or 50% shorter than the planned headway, as in Transit Service and Quality Manual. Again, R-GLODTA has the lowest level of bunching between all scenarios. Passenger indicators are also recorded during simulation. It is noted that none of the two strategies is designed to reduce travel times, but they manage to reduce headway irregularity, the number of stops at traffic lights and the number of TSP requests without significantly increase the total travel time. The benefits from both strategies to passenger travel times are indirect as a result of the regularization of headways. As expected, differences between strategies can be observed in in-vehicle times. The additional time added due to control actions increases the time passengers spend on board. The higher in-vehicle time can be compensated with a more robust travel time and the overall improved performance of the line.

Table 5 Regularity Performance Indicators

	CV of Headway	Bunching	Waiting time [sec]	In vehicle time [sec]
NC	0.59	0.37	300.03	204.87
GLODTA	0.62	0.37	300.98	211.2
HOLDING	0.48	0.27	300.08	212.71
R-GLODTA	0.44	0.20	299.96	215.00
R-GLODTA+TSP	0.42	0.19	301.9	212.36
R-GLODTA+GLOSA	0.43	0.21	301.64	226.26
TSP	0.62	0.38	302.75	202.77

One of the objectives of the proposed scheme is the mitigation of stop and go at signalized intersections, therefore the performance of each scenario at a link level is assessed. The results are summarized in Table 9.3. Unquestionably, providing unconditional signal priority to public transport can reduce dramatically the number of stops at signals and the corresponding delay at signalized intersections. However, this reduction will potentially penalize the rest of the traffic. R-GLODTA shows slightly increased number of stops compared to GLODTA alone. This can be explained by the fact that the combined controller prioritizes regularity over stopping at signals. Therefore, it will not exchange holding for regularity to secure passing during green. Weak TSP improves substantially the performance of R-GLODTA in terms of frequency of stops and delay at intersections. Speed adjustment with GLOSA transfers waiting time at traffic lights to running times to the links. A GLOSA advice to decelerate in order to arrive at the intersection during green, prolongs the running time between stops. All R-GLODTA scenarios result in lower total running time compared to an independent application of GLODTA or holding but higher than TSP, but they compensate

with their regularity indicators, especially bunching. Among scenarios the differences of the speed is marginal.

A final comparison is the number of TSP requests between the TSP and the R-GLODTA with TSP scenarios. The number of TSP requests is halved with R-GLODTA and with the combination of weak TSP can achieve comparable results with TSP in reducing stop and go actions at traffic lights while it contributes to the regularity of the line.

Table 6 Performance Indicators

	Stop at traffic light frequency per segment	Total waiting time at traffic light per segment [sec]	Total Running time [sec]	Average Speed [km/h]	Times GLOSA triggered per segment	Number of TSP requests per segment
NC	5.6	113.9	2160.3	18.8	0.0	0.0
GLODTA	4.3	60.7	2135.7	19.0	0.0	0.0
HOLDIN G	5.4	109.2	2154.2	18.8	0.0	0.0
TSP	1.3	26.1	2084.6	19.7	0.0	4.1
R- GLODTA	4.7	69.4	2132.4	19.0	0.0	0.0
R- GLODTA +TSP	2.9	52.7	2115.9	19.3	0.0	1.7
R- GLODTA +GLOSA	4.7	49.6	2172.1	18.7	2.1	0.0

Less variable travel times help the operator to administer the available resources with efficiency. As aforementioned, holding based control strategies tend to increase the travel time but at the same time limit the variability. Figure 9-4 shows the travel time distribution for each scenario and the average travel time and standard deviation is given in Table 9.4. It is clear from the results that the lowest average travel time can be achieved at the scenario with TSP, while holding based strategy provide a more robust travel time. With strong TSP, average travel time is the same with slightly higher variability. R-GLODTA's performance is characterized by an increased travel time compared to other scenarios but with the same level of variability as holding strategy alone. The combination with weak TSP decreases further the variability of travel time. By meeting both objectives of regularity and reduction of stop and go actions, R-GLODTA can counterbalance the increased travel time. In addition, the more robust travel time help the operators in tactical planning and in administering the available resources (vehicles and driver roster) more efficiently.

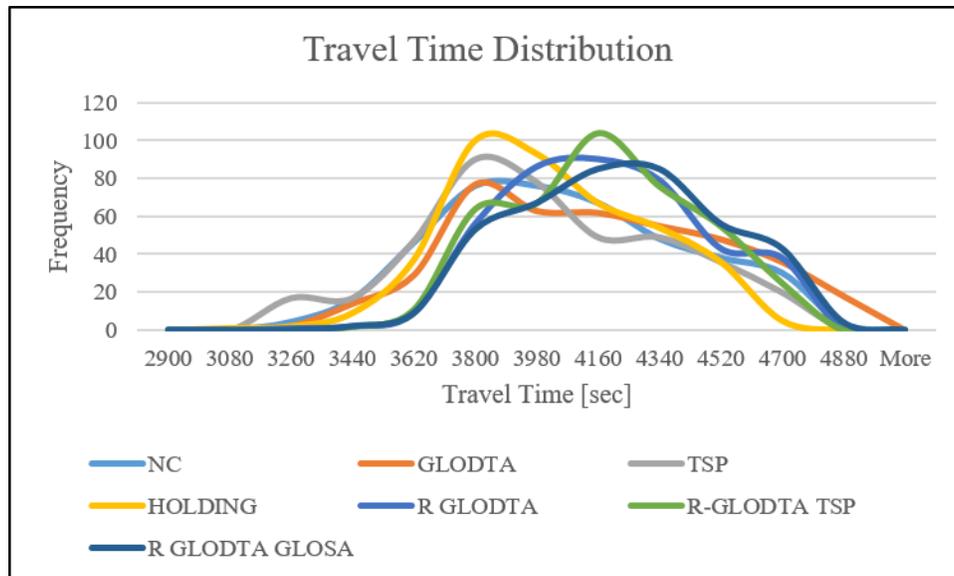


Figure 9-4 Travel Time Distribution

Table 9.4 Average Travel Time and St. Deviation

	Average Travel Time [sec]	St. Deviation [sec]
NC	3972.6	351.1
GLODTA	4055.2	371.3
TSP	3907.1	361.3
HOLDING	3930.1	290.5
R-GLODTA	4089.1	293.2
R-GLODTA+TSP	4081.7	283.3
R-GLODTA+GLOSA	4130.7	292.1

A final analysis is performed to check how many times the different strategies are adopted in the simulated scenarios. Table 9.5 shows the share of each control decision, i.e. when each control was needed.

Table 9.5 Controller Frequency

	Control Request	Controller Choice		
		GLODTA	Holding	R-GLODTA
R-GLODTA	61%	38%	42%	19%
R-GLODTA + TSP	58%	37%	49%	14%
R-GLODTA + GLOSA	62%	37%	51%	13%

Fixing regularity is prioritized over reducing stops at traffic lights. Controlling actions are reduced when R-GLODTA is combined with TSP. R-GLODTA aims on addressing both objectives and the number of independent application of holding or GLODTA. On the other hand, the combination with TSP or GLOSA reinforce the objective of GLODTA. The need of holding alone intensifies in these scenarios to restore

regularity. It is observed that with GLOSA, holding is triggered more than half of the times a controller was requested. If the changes of speed do not account for the sequence of vehicles, undesired phenomena as formation of platoons are more likely to occur and impact the performance of a bus line.

9.3. Discussion

In this chapter the results of a hybrid control strategy that combines a C-ITS-based driving assistance system, namely Green Light Optimal Speed Adaptation (GLODTA) with bus holding control at bus stops. The logic behind this integrated method is that bus holding can effectively broaden its objectives beyond bus regularity to reduce the number of stops at traffic lights. The combined controller is assessed with a simulation study and compared with independent application of the strategies but also with enhanced versions of the strategy with TSP and GLOSA. This is the first study that shows the performance of GLODTA and its combination with GLOSA and TSP at line level and in particular in terms of line regularity.

R-GLODTA validates the synergy between the two holding based strategies. R-GLODTA outperforms holding in regularity indicators providing also shorter in vehicle time compared to other holding strategies. GLODTA alone or strong TSP cannot achieve the same significant gains in terms of regularity in a line level. Moreover, regularity indices with R-GLODTA can further improved by the introduction of weak TSP.

As far as frequency of stopping at traffic signal is concerned, the results shown that although strong TSP is dominant in reducing the number of stops at traffic lights, with R-GLODTA comparable results can be obtained without affecting the regularity of the line. The additional waiting time at stop to meet both objectives reduces drastically the number of TSP requests and can reduce the impacts of prioritising public transport at signalized intersections to the rest of the traffic. Overall, R-GLODTA is a simple but effective extension of GLODTA that improves both service regularity and reduces the number of stops at traffic signals.

In addition, the performance of GLOSA and TSP as enhancements to R-GLODTA is also evaluated in terms of regularity. TSP can be limited in terms of time and requests when combined with R-GLODTA by increasing the gains in regularity and maintaining a satisfactory level at the link performance. On the other hand, speed advisory when GLODTA is reinforcing R-GLODTA should also account for the position of vehicles as it severely impacts the regularity of the line.

10

R-GLOSA

In this chapter the controller is tested using simulation for a bus line of the city of Luxembourg and compared to a benchmark scenario, the single application of bus holding, two variants of a Cooperative ITS-based speed advisory system and different levels of transit signal priority. Results show that there are additional benefits compared to traditional holding in terms of regularity while similar performance to strong transit signal priority is achieved in terms of time spent at traffic lights.

The Content of this chapter has been presented in the following works:

Laskaris, Georgios, Marcin Seredynski, and Francesco Viti. 2019 A real time hybrid controller for regulating bus operations and reducing stops at signals *6th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS) (Presented)*

10.1. Case Study

Line 16 of the city of Luxembourg is used as a case study to assess the performance of the controller. Line 16 operates between the new business district at the south of the city of Luxembourg and the airport via the city center. The route of line 16 is depicted in Figure 10-1. This line is considered the backbone of the bus network of the city as it connects all major transport hubs (Central station, Kirchberg transport hub, Airport) and the city center with the business districts of the city and the European Union institutions. The greatest part of the route consists of major urban streets and signalized intersections. In the city center, buses operate on a dedicated bus lane, isolated from the rest of the traffic and transit signal priority is provided. During peak hours, the line has frequency of 10min and high capacity buses are used (articulated and double articulated). The trajectory of the vehicles can be monitored using AVL and both vehicles and infrastructure are equipped with V2I communication technology to transmit and receive SPaT information. Passenger count data at line level are openly available provided by Luxembourg data portal (“Luxembourg Open Data,” n.d.). All intersections have been assumed equipped with TSP technology, and all bus stops have been set as time control points (TCP). We assume that all traffic lights have the same signal program with cycle of 120 seconds (80 green and 40 red) with the red indication first at the simulation environment. No coordination has been considered between signals.

10.2. Scenarios

Scenarios with different control schemes are tested. Initially, a no control (NC) scenario is used as benchmark to compare different control schemes. The two driver advisory systems, GLOSA and GLODTA, are applied independently. Additionally, holding is applied as strategy and the new hybrid control strategy R-GLOSA. With GLODTA, the vehicle is held it stop in order to arrive at the next signalized intersection during green. Lastly, different levels of TSP. The first level, referred as weak TSP, the scenario in which both green extend and green recall are up to 5sec. With strong TSP, green phase can be modified by 15sec. Finally, there is an intermediate scenario with 10sec of green recalls and extents. All scenarios are summarized in Table 10.1.

Table 10.1 Scenarios

Scenarios	
NC	No Control
H	Holding
GLDT	GLODTA
GLS	GLOSA
TSP5	Weak TSP
TSP10	Intermediate TSP
TSP15	Strong TSP
R-GLS	R-GLOSA

10.3 Results

All regularity indicators are summarized in Table 10.2. It is clear from the results that the control schemes, the objective of which is to regulate the operation, dominate the regularity indicators. The coefficient of variation of headway and the level of bunching are chosen as regularity indicators. The first index is the ratio of standard deviation of headway over the average headway. Following the definition of Transit

Capacity and Quality of Service Manual (*Transit capacity and quality of service manual*, 2003), level of bunching corresponds to the share of trips with actual headway 50% higher or lower than the planned headway. Specifically, holding and R-GLOSA result to the lowest variability of headway and less vehicles arriving in platoons. It should be noted that R-GLOSA has a minor difference from holding control since it is based on the same criterion to calculate holding time. The additional gaining comes from the speed recommendation given by the GLOSA part of the controller. Among strategies there are no significant differences in waiting time of passengers at stops. The independent application of the two DASs has no effect on system's regularity. Both have the same performance with the benchmark scenario. However, GLOSA is more effective than GLODTA in reducing the cycle time, a finding in line with (Seredynski and Khadraoui, 2014). The same results are obtained when different levels of TSP are applied. Transit signal priority outperforms the rest in terms of travel time and as a consequence reduces the in-vehicle time for passengers. The stronger the TSP, the greater the reduction in travel time. However, the reduction in travel time is not connected to the regularity. The regularity indicators remain unchanged regardless the TSP strength and similar to the do-nothing scenario. R-GLOSA manages to integrate the performance of holding strategy in terms of regularity and GLOSA in terms of cycle time. The cycle time with R-GLOSA is better than weak TSP and results to the least variable cycle time among all strategies, giving the operator the opportunity to administer more efficiently the available resources and construct a more robust schedule.

Table 10.2 Regularity performance indicators

	CV Line	Bunchin g	Waiting time [sec]	In vehicle time [sec]	Cycle time [sec]	Cycle time deviation [sec]
NC	0.599	0.372	302.98	204.74	4096.91	415.61
HOLDIN G	0.486	0.269	302.38	211.90	4042.55	415.61
GLODT A	0.628	0.382	302.40	212.49	4166.16	505.49
GLOSA	0.597	0.351	302.63	200.66	4050.49	480.16
RGLOSA	0.466	0.254	302.30	212.73	4042.09	394.56
TSP5	0.607	0.378	303.14	204.00	4060.26	472.07
TSP10	0.590	0.358	302.22	203.25	4013.18	472.07
TSP15	0.613	0.370	301.45	198.51	4012.75	490.94

The performance indicators for the links are documented in Table 10.3. Interestingly, the frequency of stops at traffic lights with R-GLOSA is the highest among all control strategies. This can be explained by the stochasticity of the simulator on sampling the speed and time between stop and traffic light chosen, which is subject to the starting time of the green phase. Additional slack time can be added to ensure that vehicle arrive at the middle of the green phase. On the other hand, the total average delay at traffic lights is comparable to strong TSP, which has the best performance in these two indicators. Contrary to regularity performance indicators, DASs perform better than holding in reducing the number of stops and the delay at traffic signals. The running time on the signalized links is also lower, meeting the objectives of both GLODTA and GLOSA. R-GLOSA reduces the running time at signalized links at the same level of weak TSP. The average speed of the vehicles remains unchanged among scenarios with holding, DAS or the combination of both and increases using stronger TSP. The stronger the TSP, the higher the performance. It should be noted, that the delay at the intersection for the rest of the traffic streams should be taken into account to compensate the priority to PT.

Table 10.3 Link Performance Indicators

	Frequency of Stop at Traffic Lights	Total Average Delay at Traffic Lights [sec]	Running Time	Average Speed [km/h]
NC	0.309	1778.8	2821.0	18.8
HOLDING	0.302	1751.0	2817.0	18.8
GLODTA	0.237	947.6	2790.6	19.1
GLOSA	0.305	942.3	2808.3	19.0
RGLOSA	0.374	465.2	2828.7	18.6
TSP5	0.223	1265.9	2781.0	19.2
TSP10	0.152	876.5	2757.2	19.4
TSP15	0.076	435.5	2738.2	19.7

In practice, the operator is interested in maintaining a smooth operation and prioritize PT. When holding is applied, the travel time increases and the additional delay at signalized intersections is not taken into account. TSP heavily prioritizes PT neglecting the impact on regularity by increasing bunching. Figure 10-1 shows the tradeoff between the average delay at traffic lights and the additional time due to control. Obviously, the application of TSP or GLOSA alone do not extend the time spent at stop. It can be seen that GLODTA and GLOSA, can achieve the same level of performance as with intermediate TSP. As expected holding extend significantly the travel time of vehicles because of the additional time added due to control and has no effect on delay at traffic signals. R-GLOSA delays the vehicles as much as holding but at the same time the property of reducing delay at traffic signals is similar to strong TSP. Therefore, the gaining obtained in running time can compensate the extended time at stops. Again, it is worth mentioning, the results may differ on the holding criterion chosen.

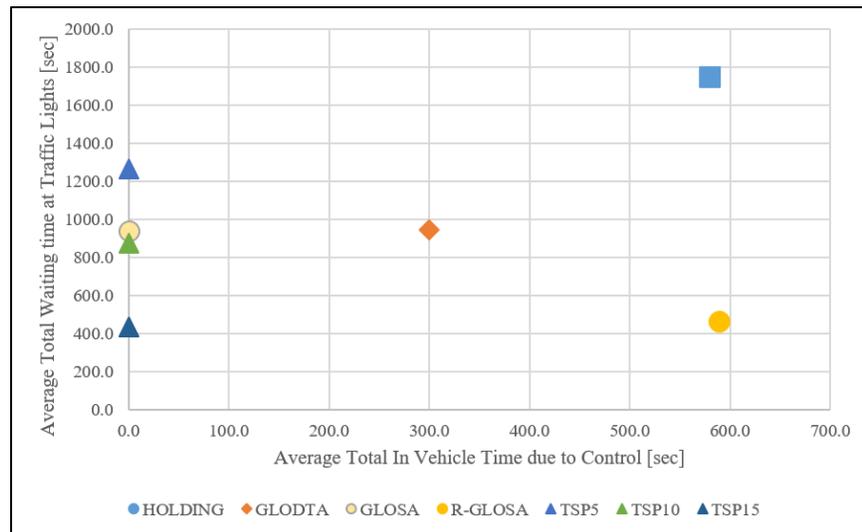


Figure 10-1: Trade off between waiting time at traffic light and holding time at stop

10.4. Discussion

We introduced a combined controller based on holding and speed adjustment to regulate the headway of a bus line and mitigate the number of stops at traffic lights. The proposed control strategy is tested of a high frequency bus line of the city of Luxembourg and its performance is compared to other control schemes and different levels of TSP.

R-GLOSA perfectly integrates the objectives of regulating the operation of the line and minimize the delay at traffic lights. Furthermore, it contributes to a less variable travel time giving the operator the opportunity to administer more efficiently the available resources and construct a more robust schedule. Strong TSP still remains the most effective solution in reducing the number of stops at traffic signals and the corresponding delay. R-GLOSA manages to perform as well as strong TSP, while at the same time regulates the departures of the vehicles from stops. The time saved at signalized intersections compensates the extended travel time obtained by holding control actions.

Conclusions

In this chapter of the thesis, the conclusions of the dissertation are drawn. All the findings are summarized based on these the main research questions are answered, followed by recommendations for future research.

11.1. Research Questions

This dissertation focused on real time public transport control. Specifically, the focus was on holding strategy extended towards two directions: Multiline holding control and the integration of cooperative ITS based Driver Advisory Systems. The methodologies formulated for both directions and their performance was assessed and the results and their analysis are documented in the previous chapters. Based on the obtained results and in order to address the objective of this dissertation, the research questions stated in the first chapter are answered below:

- *R.Q.1: How single line rule based criteria can be extended to account for multiple lines?*

Current rule based criteria are limited to regulate single line operation. The only interaction between lines that has been taken into consideration is transfer synchronization at a single transfer hub. In order to apply multiline control, all the interactions between lines at the current and the downstream parts of the network must be taken into account. Given the stop set the current control point belongs to (branch or corridor), a multiline control should account for both the headway of the line and the joint headway between consecutive vehicles. An additional element that should be addressed is the transition between stop sets, otherwise control actions of the upstream stop set can propagate as delay to the downstream. Synchronization should be also available as an option with the least possible impact on the regularity of the system. Finally, passengers waiting at stops and on board are affected by a decision to hold, which can lead to either a longer waiting time or on-board time. Holding by definition increases the travel time, but the impact on the passenger travel time can be limited. In Chapter 3, a holding criterion is formulated addressing all the aforementioned points. In the following chapters (Chapters 4-7) the new criterion was tested for all different type of branch and trunk networks, proving its applicability and managed to achieve considerable gaining in terms of passenger cost.

- *R.Q.2: Which are the interactions between passenger groups in a transit network?*

Based on their travelling pattern in a network, passengers can be divided into two main categories: Passengers travelling on a specific line and passengers transferring from a line to another. The first group is benefited by maintaining the regularity of the system and the second by the synchronization between services. The two different holding strategies may have conflicting interests in a network, since the decision taken to favor one may penalize the other. In chapter 7, both holding for regularity and for synchronization on the common part was allowed and the two criteria were both available at the merging and the diverging stop. On a set of consecutive common stops, maintaining regularity is more important and a decision to synchronize increases dramatically the cost for the non-transferring passengers. Transferring passengers are benefited mostly by a stable joint headway as a result of control for regularity which yields an overall higher network performance.

Furthermore, the first group can be further divided into subgroups based on their origin and destination. There are passengers that travel within a given stop set or traverse between stops sets. Passengers travelling within a stop set, depending on the stop set, rely on the line or the joint headway and the regulation of them. As a result, they rarely interact with the remaining group sets. On the other hand, traversing passenger groups have proven to be the most influential for a transit network. Specifically, these groups are affected the most by the actions for coordination at the initial branches or for the transition to single line operation. For instance, traversing passengers

from corridor to branch can initiate transition earlier in the shared transit corridor reducing the performance of the criterion in regulating the joint operation. Also, at the same group set, due to the fact that they seek for a specific line instead of all the available lines, they increase the overall cost of the shared transit corridor. Finally, between lines, one of the two usually is taking the toll of coordination which yields to a more unstable operation of the line in terms of travel times as a trade off for the system. The aforementioned conclusions are drawn from the results from all different applications in Chapters 5, 6 and 7.

- *R.Q.3: When is it beneficial to apply single and when it is advised the use of multiline control?*
There are two main factors that should be taken into account to decide between single and multiline control. The first and most important factor is the distribution of the demand in the network. As shown by the results in Chapter 8, different results can be obtained under different demand segmentations. For multiline control, it is important that a significant share of the total demand should be concentrated at the common stops of the shared transit corridor. As aforementioned, traversing passengers tend to experience longer travel times as they are affected by control decisions on multiple stop sets. Therefore, when traversing passengers in a network exceed a specific share of demand, neglecting coordination and prioritizing single line control can contribute more to the network. The second factor is the size of each stop set of the network. According to the results, a shared transit corridor should constitute at least half of the network stops to justify control actions for the joint operation. Additionally, a sufficiently long enough final branch to recover from the loss of performance observed during transition from corridor to branch.

Synchronization between lines is also a category of multiline control. In this dissertation, synchronization was applied together with regularity at the merging and the diverging stop of the network. According to the results, it is recommended that synchronization on branch and trunk networks is applied at the last common stop. Following this rule, the costs between regularity and synchronization become comparable and transfer synchronization results in smaller losses for the system.

- *R.Q.4: To which extent C-ITS can enhance holding as a strategy?*

Cooperative ITS allow to broaden the range of control strategies. So far, through Driver Advisory Systems they have proven to be effective in mitigating the number of TSP requests by remaining for additional time at stops or adjusting speed. In chapter 9, a rule based holding strategy has been combined with two DASs in order to account for the regularity of the system and also reduce the number of stops at traffic signals, utilizing the potential delay at signal as holding time to regulate operation or saving travel time by adjusting the speed. The results of the two hybrid controller are reported in Chapters 10 and 11 and they validate the initial hypothesis that the utilization of C-ITS can improve the performance of a holding strategy and extend its objectives.

In the next sub-sections, we recapitulate these points, highlighting the main findings and the contributions of this dissertation.

11.2. Main Findings

In this section, the main findings of this research are summarized and presented based on the contributions on multiline holding control and the integration of C-ITS.

Multiline Holding Control:

Concerning multiline control, this thesis contributes to the domain of real time control in the following aspects:

- a) A new rule based holding criterion is formulated, which accounts for all different lines that interact within a branch and trunk network.
- b) The cost for passengers experiencing the control decision is introduced in a rule based holding strategy. After the calculation of holding time, it is adjusted to the number of passengers on board and the remaining passengers waiting at the current and the remaining downstream stops. This resulted to a lower in-vehicle delay for the passengers compared to conventional rule based holding strategies.
- c) For single line application, the magnitude of control relies on the affected passengers. The controller tends to be stronger and more frequent prior to stops or group of stops with high demand compared to traditional recommendations for controlling at these stops.
- d) When coordination starts prior to shared transit corridor, vehicles manage to initiate joint operation with less variability.
- e) One of the lines is charged with additional time for control in order to contribute not only to its regularity but also to the coordination between lines.
- f) Cooperation between lines and in extend controlling jointly lines at a shared transit corridor can result to higher gains in passenger cost for the network in total.
- g) Attention should be given to the transition from joint operation to single line operation. The transition period results to a loss of performance, which can be recovered given a sufficiently long final branch.
- h) Transfer synchronization can be applied but due to its high cost to the passengers benefited by the regularity of the system it can be rarely applied at a merging stop. Synchronization is more feasible at the diverging stop and for a short cost comparison horizon. Due to the regulation of joint operation the average transfer time is equal the joint headway and less variable compared to other strategies.
- i) In order to apply multiline holding control, a shared transit corridor should be well defined in terms of topology and demand. In addition, the group of traversing passengers should not constitute more than 25% of the total demand of the network.

Integration of Cooperative ITS with Holding Strategies:

- a) The time a vehicle is held at a stop to restore regularity is decided in conjunction with the time by Driver Advisory System GLODTA in order to reduce the number of stops at traffic signals and the number of TSP requests, resulting to a new hybrid controller R-GLODTA.
- b) Holding has also been combined with speed advisory to avoid stopping at traffic lights provided by GLOSA (R-GLOSA). After being held at a stop, the bus is instructed to develop speed which ensures will traverse the downstream intersection during green.
- c) Both hybrid controllers managed to outperform the individual application of holding or DAS. The regularity indices were improved compared to holding and the frequency of stop and go actions is reduced.
- d) With R-GLOSA, a reduction in travel time and in vehicle delay as a result of the speed advisory.
- e) TSP requests can be limited and together its impact to the rest of the traffic by continuously prioritizing public transport.
- f) R-GLOSA leads to the same increase in additional time at stop with holding, but as a trade off the delay of the vehicle at traffic lights is at the same level with strong TSP.

Limitations and Implementation Aspects

The aforementioned findings are bound to limitations based on the assumptions and the properties of the simulation models used. To begin with, concerning multilane control and the transition between stop sets the expected headway at the next switching stop depends on the quality of the prediction of the arrival time at the corresponding stop. The projection relies on historical data which do not guarantee high accuracy in predictions. As shown in Chapter 5, the quality of the prediction and the accuracy is drastically reduced with distance (with a difference of a full headway from actual arrival). Same applies for the second part of the thesis for the estimation of the expected arrival at the next signalized intersection. In order to increase the accuracy and as a consequence the effectiveness of the criterion and multilane control real time data should be utilized and integrated in the projection procedure. Apart from the estimation of the arrival time, real time data can be utilized for the actual number of passengers in the network. Passenger data that can be acquired in real time can benefit the criterion by distributing properly the holding time needed per passenger group and the number of passengers that are experiencing the control action. Furthermore, in the case of pairing with synchronization criteria, the knowledge of actual number of transferring passengers instead of an estimation based on historical data will substantially improve the choice between controlling for regularity and synchronization in real time.

The simulation models and their properties have an effect also on the assessment of the methodologies presented in the current dissertation. BusMezzo is a mesoscopic transit simulator capable of simulating effectively operation and application of holding based control strategies. However, due to the mesoscopic approach of the model, the interaction between vehicles on links is not simulated and bunching occurring on the links is only captured at stops. Therefore, performance indicators such as delay at signalized intersection and average speed which are main components of travel times cannot be measured. As a result travel times can be systematically over- or underestimated based only on the selected distribution for travel time and its parameters.

The bus simulator built with Mathworks MATLAB has also some limitations to be reported and affect the results. First of all, similarly to BusMezzo, vehicles are also simulated in a mesoscopic fashion both for the stop and the link based activities. For the link based activities, the simulator should be extended in a microscopic fashion in order to fully capture the acceleration and the deceleration of the vehicles and the interaction between vehicles when they are on the same link. Furthermore, the simulator is not allowing overtaking neither at links nor at stops, a feature that automatically increases travel time of the succeeding vehicles as the delay of their leader increases. Finally, the model can simulate the operation of one line and due to the way it is coded it cannot replicate transfers or the simultaneous operation of multiple lines, which limits the number of applications.

11.3. Future Research

This dissertation addressed the research questions stated in the first chapter. The answers and findings of this work can be the foundation for future work on the topic and further research questions that were out of the scope of this dissertation.

First and foremost, the integration of real time passenger data for crowding and waiting passengers. Current regularity criterion is based on historical data for passengers, expressed as arrival rates per origin destination pair. Based on this, the expected number of waiting passengers at the current and the downstream stops and the expected occupancy is estimated and used as an input to the criterion to represent the passengers that are expected to experience the control decision and adjust it accordingly. The evolution of APTS in collection of passenger data, apart from the abundance of historical data increases the availability of real time passenger data via different sources. Real time data can be integrated, replacing the historical data

providing the actual passenger costs and increase the accuracy of each control decision. In addition, the criterion can be tested in a real world network in agreement with the operator of a PT network with this structure and assess its performance and document any shortcomings that can occur during operation.

Secondly, the generalization of the holding criterion in its general form with transfers for more than two lines. The holding criterion in terms of regularity as formulated in Chapter 3 can be applied in different branch and trunk networks with multiple merging and diverging stops due to its myopic nature. The difficulty arise when there is the need of synchronization. In the shared transit corridor, controlling for regularity and for synchronization are two conflicting objectives satisfying different passenger groups. As shown in Chapters 7 and 8, due to the comparison of passenger costs regularity is most of the times dominant at the case of two lines and transferring passengers only from one line to the other. In the case of multiple lines and multiple transferring passenger groups seeking for different connecting lines. The location for applying the synchronization criterion has proven to be critical together with the size of the transferring group the horizon chosen for comparison. Given that regularity is more important for the system and in order to get the highest benefit possible for the transferring passengers, all the aforementioned factors must be assessed via a sensitivity analysis.

An important factor that affects the performance of the system is passenger behavior in branch and trunk networks. The assumptions made in this dissertation for the passengers decisions are based on previous work of Marguier and Ceder, (1984), according to which passengers choose the line on an overlapping route that minimizes their generalized travel cost. In such networks, there are many passenger subgroups that co-exist and interact and make decisions based on their trip purpose but and the current condition of the network. Empirical data from different branch and trunk networks can be collected and processed to derive behavioral patterns in such networks in terms of line choice in corridor and transfer stop selection. The data can be used to formulate the utility and the perceived costs in this networks. The updated utility functions can be then used to assess the behavior of passengers in these networks under different control strategies, single and multi-line, but also in disruption scenarios.

Finally, in this dissertation Driver Advisory Systems decisions are combined with holding strategy to account for regularity in extend to the reduction of TSP requests. As shown by the results in Chapter 10 and 11, both hybrid controllers, R-GLODTA and R-GLOSA, have proven to be more effective than the individual application of holding and the DASs. Further research can focus on the comparison between the two controllers and show under which conditions each one is more effective given the stop configuration in a link, the proximity to signalized intersections, the speed limits, and the frequency of the lines and in combination with different holding strategies. Additionally, in the current application the control decision is taken subject to the first downstream signalized intersection. The controllers presented can be extended to define the full trajectory of a bus between stops and accounting for all signalized intersections in between and the expected trajectory of its leader and follower.

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