ROYAL INSTITUTE
OF TECHNOLOGY

Simulation based evaluation of flexible transit

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Licentiate Thesis
Stockholm, Sweden 2019

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TRITA-ABE-DLT-1919
ISBN 978-91-7873-232-6

Akademisk avhandling som med tillstånd av Kungliga Tekniska högskolan framläges till offentlig granskning för avläggande av teknologie licentiatexamen i transportvetenskap torsdagen den 13 Juni 2019 klockan 13:00 i Sal B1, Brinellvägen 23, Kungliga Tekniska högskolan, Stockholm.

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Tryck: Universitetsservice US AB

Abstract

Transport authorities are faced with the challenge of making effective use of existing transportation infrastructure under increasing needs of transport accessibility, sustainability, and safety. The ongoing growth and adoption of shared mobility options, the anticipation of automated vehicles, and the increased availability of real-time data brought on with the developments of Intelligent Transport Systems, have all inspired many innovations in public transit design. The integration of these technologies in existing public transit holds great potential for operational planning and control, but is also notoriously difficult to evaluate. In the included papers, flexible operational policies that make use of real-time data and connected vehicles are developed and assessed through the extension of an existing public transit simulation framework, BusMezzo.

Paper I explores the incorporation of flexibility in fixed urban transit via real-time short-turning, a fleet management strategy not often studied in a real-time context. In this paper, a decision rule for when and where a short-turn should occur based on predicted passenger costs is developed and evaluated in a case study of a bidirectional urban bus line in Stockholm, Sweden.

Paper II focuses on the design and analysis of an automated feeder service. In this paper an extension of BusMezzo with a module for simulating a variety of flexible transit operations is presented. Estimated reductions in on-board crew costs with vehicle automation motivate a case study of two vehicle fleets where a fully demand-responsive operational policy is compared against fixed route and schedule operations.

Sammanfattning

Transportmyndigheter står inför utmaningen att effektivt utnyttja befintlig transportinfrastruktur under växande behov av tillgänglighet, hållbarhet och säkerhet. Den pågående tillväxten och anammandet av delad mobilitet, förväntningarna på automatiserade fordon, samt den ökade tillgången till realtidsdata tack vare utvecklingen av Intelligenta Transportsystem, har inspirerat många innovationer inom kollektivtrafikdesign. Att integrera dessa tekniker inom befintliga kollektivtrafiksystem innebär en stor potential för operativ planering och styrning, men effekterna av dessa satsningar är notoriskt svåra att utvärdera. De inkluderade uppsatserna utvecklar flexibla operativa strategier som utnyttjar realtidsdata och uppkopplade fordon, och utvärderar dessa genom en utvidgning av ett existerande simuleringsramverk för kollektivtrafik, BusMezzo.

Uppsats I utforskar en utökning av flexibilitet inom kollektivtrafik i tätort med fasta rutter och tidtabeller genom realtids-kortvändning, en strategi för att samordna fordon som inte ofta studeras inom en realtidskontext. I artikeln utvecklas en beslutsregel för när och var en kortvändning ska ske baserad på förväntade passagerarkostnader. Beslutsregeln utvärderas i en fallstudie av en befintlig busslinje i Stockholm.

Uppsats II fokuserar på design och analys av en automatiserad matartjänst. I artikeln presenteras en utvidgning av BusMezzo i form av en modul för att simulera olika varianter av flexibel operativ styrning. Förväntade sänkningar av bemanningskostnader genom automatisering av fordon motiverar en fallstudie av två fordonsflottor, där en fullt efterfrågestyrd operativ strategi jämförs med drift enligt fast rutt och tidtabell.

Acknowledgements

I would like to thank my supervisors Erik Jenelius, Wilco Burghout and Oded Cats for their guidance into the world of transport research and modeling. Thank you for the opportunity to work on this project, for our discussions, both research related and not, and for all your ideas and support over these past years. I am also grateful to my advanced reviewer Mikael Nybacka for the feedback and comments on how to improve this thesis. Furthermore, I would like to thank the Swedish Transport Administration Trafikverket, as well as Sweden's innovation agency Vinnova for financing this project.

A warm thanks to all colleagues and office mates, past and present, for their company, advice and encouragement in tougher periods. Finally, I am always grateful to friends and family for their endless support, and to Gabriella, for your support and patience with me when I disappear into my bubble and for reminding me to also get out of it sometimes.

Contents

1 Introduction **1**
- 1.1 Outline . . . 4
- 1.2 Included papers . . . 4

2 Research objectives **7**

3 Research methodology **11**
- 3.1 Traffic modeling . . . 12
- 3.2 Fleet operations . . . 13
- 3.3 Traveler behavior . . . 15
- 3.4 Level-of-service measurement . . . 16

4 Scientific contributions **19**
- 4.1 Paper I - Real-time short-turning in high frequency bus services based on passenger cost . . . 19
- 4.2 Paper II - Simulation of fixed versus on-demand station-based feeder operations . . . 20

5 Discussion and future directions **23**

Bibliography **25**

Chapter 1

Introduction

Urbanization, population growth and limited road transport infrastructure capacity constitute strong motivations for promoting high degrees of resource sharing in transportation. Public transit is often considered to be a critical component in sustainable urban development (Caragliu et al., 2011). Operating and planning a public transit system is a complex task, however, and systems can struggle to provide a high level-of-service (LoS) to passengers at an affordable cost to providers and users. Recent developments in Intelligent Transportation Systems (ITS) and automated vehicles (AVs) have inspired the developments of many new transit designs characterized by flexible routing and scheduling. From the perspective of a public transit operator, this is due to the operating costs of underutilized fixed-service transport (in particular for areas with low or dispersed population density, such as suburban or exurban areas). From a user perspective, flexible transit can offer a higher LoS that is more personalized relative to fixed public transit. From a public service perspective achieving a high degree of resource sharing with a higher LoS can help alleviate trends of increased congestion by providing competitive shared trip alternatives to private vehicles.

Figure 1.1 displays two dimensions that can be used to characterize different types of public transit systems. The degree of flexibility in schedule and routing on the horizontal axis ranges from systems characterized by a highly predefined schedule and route that does not change once operations have begun, to fully demand-responsive operations where both schedule and route is completely determined by the individual needs of travelers. The vertical axis displays the degree of resource sharing that the system can achieve in terms of number of passengers per trip. Research in flexible transit systems has been developing since the 1960s (Koffman, 2004). As displayed in Figure 1.1, flexible transit encompasses a wide range of service types but, in general, can be put on a spectrum ranging from fixed-route, fixed-schedule systems with real-time demand-responsive fleet management to almost fully demand-responsive routing and scheduling.

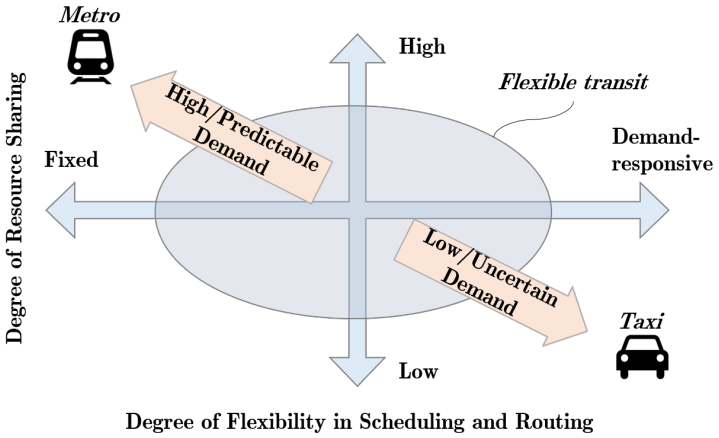

Figure 1.1: Two dimensions of public transit solutions.

The degree of flexibility and resource sharing within a public transit system depends in part on fleet composition in terms of vehicle types as well as demand pattern. In higher demand-density urban settings, fixed transit (e.g., metros or high-frequency urban bus lines) can offer a high degree of resource sharing at high-frequency schedules. Due to the stochastic nature of travel times and passenger demand, however, strictly fixed services can still quickly deteriorate due to the positive feedback loop between imbalances in transit vehicle loads and the variance of headways. A traditional preventative strategy is to introduce a degree of slack in planned service schedules and fleet capacity (Newell, 1971). Increasing the real-time flexibility of the system can also prevent under-utilization of the transit fleet as well as reduce the impact of unforeseen service disruptions on passengers (Ibarra-Rojas et al., 2015).

In contrast, where transport demand-density is lower or less consistent, the potential for resource sharing drops drastically and it is more difficult to make efficient use of a fixed service. Solutions characterized by a high degree of flexibility in routing and scheduling (e.g., taxis) are often targeted at serving lower levels of demand with higher requirements on trip personalization. Dial-A-Ride (DAR) systems (Cordeau and Laporte, 2007) were originally designed with the purpose of serving passengers with reduced mobility, also known as paratransit. Often such services are fully demand-responsive, where vehicle routes and schedules are completely determined by pre-booked or real-time travel requests. DAR services were later expanded to serve the general public in an attempt to offer a more personalized collective service and improve accessibility to public transit for passengers in lower demand-density areas. Although such services have shown potential to offer a higher LoS, spreading the cost of a given trip over a greater number of passengers

is still difficult (Ferreira et al., 2007).

Increasing the flexibility of service operations increases reliance on the ability to effectively match vehicles to passenger trip requests in real-time. Moreover, since neither operator or passenger knows of the exact route and schedule ex-ante, the reliability of the service is more difficult to estimate. Variations in the perceived reliability of a service can heavily influence the mode and route choices of passengers (Carrel et al., 2013), which in turn contributes to the uncertainty of real-time demand predictions in the operational planning of a flexible service fleet. Consequently, transport authorities have attempted to develop hybrid systems that maintain some of the reliability of traditional fixed services but combine this with demand-adaptive scheduling and routing (Koffman, 2004; Potts et al., 2010). The key difference in planning compared to strictly fixed, or strictly demand-responsive transit is in the operational planning phase as well as dynamic demand-dependent adjustments to vehicle routes and schedule.

Emerging technologies have often inspired research in the design and operational control of novel flexible transit solutions. Over the last decades new ITS technologies have been developed with the aim of providing transport authorities with information that is useful to them for planning and operating public transit services (Mageean and Nelson, 2003). Systems for Automated Fare Collection (AFC), Automatic Vehicle Location (AVL), and Automatic Passenger Counters (APC), to name a few, provide high-frequency monitoring of the behavior of a transit network in real-time (Furth et al., 2006). In general, there are two types of real-time public transport performance disruptions: deviations from schedule, and an imbalance between supply and demand (Ceder, 2007). The choice of what control intervention to apply also depends on the objectives of different stakeholders (e.g. individual passengers, the operator or the transport system). Higher degrees of uncertainty can be accounted for with increasing access to real-time data. Network connected systems facilitate the implementation of cooperative real-time control strategies to coordinate connected transit vehicles in adaptation to prevailing traffic and demand conditions (Koutsopoulos et al., 2019). With more formal modeling, different control strategies are easier to evaluate and compare from the perspectives of different stakeholder groups.

There is also great interest in the automation of the public transport system. The introduction of automated vehicles is predicted to reduce the cost, and the convenience of door-to-door transport, as well as in flexible transit services Bösch et al. (2018). Advancements in the ability to match shared vehicles with their customers in real-time, together with the developments of AVs have motivated research in automated shared mobility solutions. Several simulation studies of shared AVs (e.g., Fagnant and Kockelman (2014)) indicate that to achieve many of the promising positive effects that the introduction of AVs can bring, a high degree of resource sharing must be maintained. A defining characteristic of high-level AVs with respect

to public transit is the ability for the vehicle to operate without a driver. As much as 50-70% of the operational costs of bus transit in developed countries consist of on-board crew costs. With a reduction in on-board crew costs, AVs enable provision of innovative flexible public transit solutions at a lower operational cost per vehicle. A second characterizing feature of AVs is their ability to drive continuously without rostering constraints, as well as their ability to both collect and share information regarding current and predicted traffic and demand conditions. Motivated by these prospects, the number of automated shuttle pilots has rapidly increased over recent years. Objectives of the pilots vary. In Europe, automated shuttle pilots focus on integration with existing public transit infrastructure. In Switzerland, automated shuttles have been integrated into fixed-schedule transit. Outside Europe, pilots are motivated mainly by testing the technology under different degrees of uncertainty as well as collecting data on public-opinion and user adoption (Ainsalu et al., 2018).

A question that naturally arises is how to quantify the actual effects of implementing a novel flexible transit solution under alternative technological settings. To explore new flexible transit designs prior to implementation there is a need for modeling tools and metrics to evaluate them. A flexible transit system may for example be specified in terms of analytical equations that exhibit desirable formal properties and ideally enables demonstration of interrelations and bounds for important service design parameters (e.g., Daganzo (1984); Chandra and Quadrifoglio (2013)). To achieve this, however, simplifications of the studied system are often introduced to maintain tractability. As the complexity of the system to be evaluated increases, so does the difficulty in formulating the problem in this way. Methods for evaluating advanced real-time transit management strategies requires dynamic representation of the feedback loop between passenger behavior and transit operations. Multiagent simulation models, with real-time adaptive behavioral representation of individual entities and their interactions, are well suited to model flexible transit systems for this purpose (Ronald et al., 2015).

1.1 Outline

This thesis includes two papers with introductory text organized by the following chapters. Chapter 2 introduces underlying research objectives and research questions followed by research methodology in Chapter 3. In Chapter 4, scientific contributions are discussed in relation to the formulated research objectives. Finally, a discussion and highlighted avenues of future research are given in Chapter 5.

1.2 Included papers

I. Leffler, D., Cats, O., Jenelius, E. and Burghout, W. (2017) Real-time short-turning in high frequency bus services based on passenger cost. 5th IEEE

International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS), pp. 861-866.

II. Leffler, D., Jenelius, E., Cats, O. and Burghout, W. (2019) Simulation of fixed versus on-demand station-based feeder operations To be submitted.

Declaration of Contribution

The idea for Paper I was initiated by Oded Cats and further developed through joint discussion between all co-authors. I was the main contributor in research design, methodology development and implementation, computational experiments, analysis of results and writing. Oded Cats and Erik Jenelius helped greatly with methodology development. All co-authors contributed to the interpretation of results as well as paper revision.

The idea for Paper II was initiated from joint discussion between all co-authors. I was the main contributor in research design, methodology development and implementation, computational experiments, analysis of results and writing. All co-authors helped greatly in discussions of methodology development. Wilco Burghout and Oded Cats also helped greatly in supporting methodology implementation. All co-authors contributed to the interpretation of results and paper revision.

Chapter 2

Research objectives

In this thesis, the objective is to design and analyze novel flexible transit systems as well as improve on existing modeling tools that can be used to evaluate their feasibility. More specifically the research objectives (RO) of this thesis are the following:

RO1 Develop simulation models for the evaluation of flexible transit operations.

The evaluation of flexible transit operations requires a model that enables dynamic representation of travelers and their interactions with the transit system. While many simulation models have been developed to evaluate the performance of flexible transit systems, often these are adjustments of traffic simulation models that do not represent transit-specific supply and demand interactions, or are scenario-specific enhancements of existing fixed transit simulation models. A great deal of progress has been made in recent years but, to the best of our knowledge, there is to date no established model or method for the evaluation of flexible transit. The availability of real-time AFC, APC and AVL data sources offer the opportunity to monitor and develop metrics to measure passenger experiences (e.g., service reliability, crowding at stations or in vehicles, and excess waiting time due to limited service capacity). With connected vehicles and advancements in methods for real-time information dissemination to transit riders, a rapidly growing body of research is to make use of such metrics in the objectives of passenger-oriented operational control strategies. Detailed representation of passenger dynamics, in particular, is thus required to evaluate the performance of novel flexible transit operations and the resulting LoS provided. As there is a high degree of uncertainty in both the technological and behavioral aspects of future transit systems, the model should ideally also enable consistent comparisons between different levels of flexibility within public transit systems for a variety of demand scenarios.

RO2 Improve on existing methods for real-time operational control.

For high-frequency urban transit lines, real-time control strategies have typically focused on improving headway regularity, used as a proxy for expected passenger waiting times. Research in novel real-time control strategies making use of ITS technologies within urban transit tend to focus on interventions that do not require deviations from the scheduled route (such as holding, speed regulation or signal control strategies). A common objective is to use new real-time data sources to e.g., improve transfer synchronization between lines. Short-turning is a strategy that consists of removing a transit vehicle from its currently scheduled route and returning this vehicle to serve the opposite direction. Figure 2.1 displays a conceptual figure of short-turning applied to increase service frequency for a subset of stops along a bi-directional transit line. Start- and end-stops in Figure 2.1 refer to the beginning and end of a short-turn.

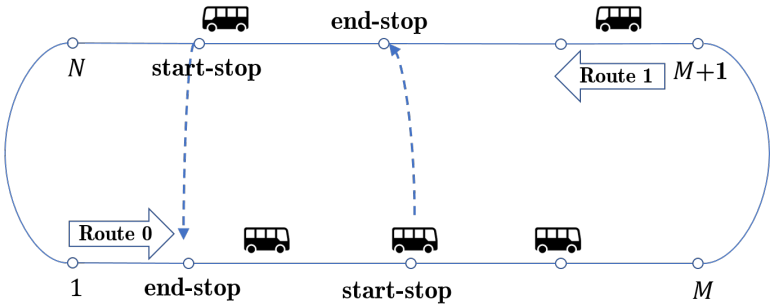

Figure 2.1: Short-turning on a bi-directional line.

Due to the adverse effect this intervention can have on on-board passengers that wish to alight downstream the starting location of the short-turn, this type of strategy is often sparsely applied relative e.g., holding strategies. Research on when short-turning is constructively implemented has thus typically been focused on the use of short-turning at a tactical planning level, i.e., before operations have begun, or to recover from severe service disruptions. Far fewer studies have focused on the potential of utilizing short-turning as a real-time control strategy to improve the LoS for passengers. This motivates the following research question (RQ):

- RQ1: What are the effects of utilizing short-turning as a passenger-oriented, real-time operational control strategy for a high-frequency urban transit line?

RO3 Examine the effects of alternative operational policies in emerging public transit systems.

Space efficient transit in urban areas is heavily dependent on high capacity mass transit. As trunk lines are not directly accessible by the whole population, ad-

ditional, often more flexible first and last-mile solutions are required. A use case that has inspired multiple real-world pilot studies is the application of smaller automated shuttles within an automated demand-responsive feeder/last-mile solution. Figure 2.2 displays examples of introducing different levels of flexibility in scheduling and routing in a feeder to mass transit scenario.

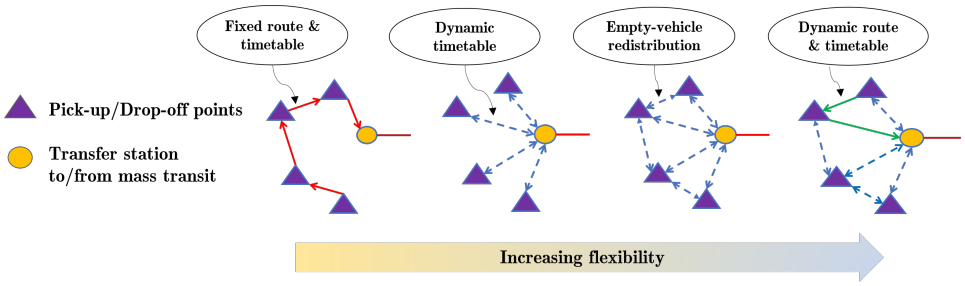

Figure 2.2: Different levels of flexibility in a feeder to mass transit service.

Research on automated public transit in recent years has typically been dedicated to simulation-based evaluation of AVs used as a shared-trip replacement for private door-to-door or ride-hailing trips, or as a demand-responsive replacement of fixed public transit on a city-wide scale. While there are claims that utilizing AVs in feeder/last-mile transit can provide a higher LoS to passengers at a lower operational cost relative fixed service operations, few studies evaluating the effects of such services have been found. This raises the following RQ:

- RQ2: Should automated vehicles follow a fixed-, or on-demand operational policy within an automated feeder service?

Chapter 3

Research methodology

This chapter describes the methodology used to address the research objectives of chapter 2. Through the work of the included papers a modeling framework for the representation of flexible transit systems was developed and integrated within the dynamic, agent-based public transit simulation model, BusMezzo (see Cats et al. (2010) for a detailed description of the structure of BusMezzo and its implementation details). BusMezzo is embedded within the event-based, mesoscopic traffic simulation model, Mezzo (described in greater detail in Burghout (2004)). Modeling a public transit system can be said to consist of the following components (1) road traffic flow, (2) traveler behavior, and (3) operations that define interactions between transit vehicles and travelers (Meignan et al., 2007). In this chapter how these components are represented in BusMezzo and extensions to model flexible transit operations are discussed in relation to the included papers. A high-level overview of the simulation framework is displayed in Figure 3.1.

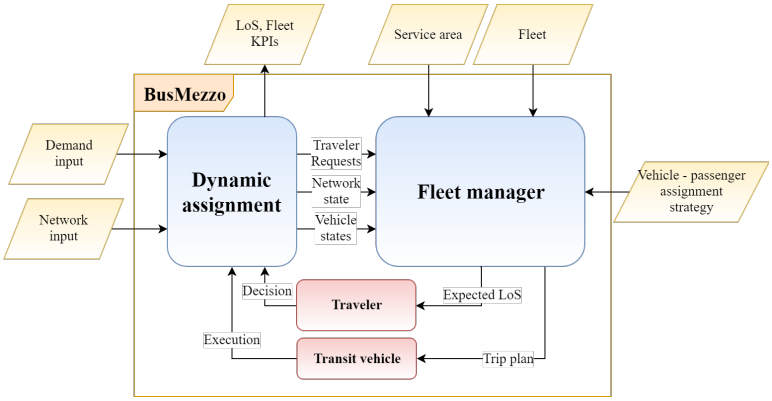

Figure 3.1: High-level overview of the simulation framework for modeling flexible transit.

3.1 Traffic modeling

Simulation of traffic flow is commonly categorized as *macroscopic*, *microscopic* or *mesoscopic*, each representing a different level of modeling detail. The level of modeling detail chosen to evaluate a transport system typically depends on the size of the network to be modeled, what computational resources are available, what input data is available, and what phenomena or performance measures the modeler wishes to isolate. *Macroscopic* models tend to represent traffic as a continuous flow (e.g., the number of vehicles per hour passing a specific point). Often these are inspired by hydrodynamic- or gas-kinetic flow equations and do not explicitly consider the dynamics of individual vehicles. On the other end of the spectrum, *microscopic* models represent traffic flow in much more detail, including longitudinal and lateral interactions between individual vehicles and may sometimes also represent variations in individual driver behaviors. Generally, a more fine-grained level of detail allows for specifying particularities of individual classes of vehicles and their movements and in doing so modeling the effects of heterogeneity in the studied system. While higher degrees of detail can provide more accurate representation, the input data and parameters used in the model need to be equally detailed if the performance of a transit system is to be reproduced faithfully. The *mesoscopic* definition is broad and refers to essentially anything that combines both macroscopic and microscopic levels of representation. In general, however, mesoscopic models will, like microscopic models, still model individual vehicles, but describe their behavior in a more simplified manner.

The flexible transit simulation framework is embedded within the mesoscopic traffic simulation model Mezzo, where the average speed of a vehicle is calculated based on the density of traffic ahead of the vehicle. In Mezzo, a link is divided into two sections, a running section governed by speed-density relations and a queuing section where the shockwave effect of queue propagation and dissipation is represented. At the downstream end of a traffic link, vehicles join a queue of vehicles waiting to enter the next link of their route. Queue servers process these vehicles and pass them into the next link if it is not full.

In both Paper I and Paper II, public transit solutions are modeled in isolation of other traffic, to isolate the effects of alternative operational policies independent of surrounding traffic conditions. Furthermore, this representation does not require input of OD demand matrices, vehicle mix, route choice and preferences of non-transit traffic. Hence, in this case, queues at intersections and the propagation of traffic congestion are not considered. However, the public transit phenomenon of bus-bunching (see for example Schmöcker et al. (2016); Cats et al. (2010) for studies on this topic) is still important to represent in evaluating a real-time strategy for a high-frequency bus line, as in Paper I. Bus-bunching results from variability in travel-time and passenger demand. In Paper I, the variability of vehicles running times is thus represented by a log-normal distribution with mean equal to scheduled

running times. In Paper II, bus-bunching is of less interest for the research interests of the paper, where instead the differences in performance of alternative operational policies are studied with respect to static service design variables (i.e., fleet compositions with and without AVs and feeder transit network configuration) and in handling potential variations in demand intensity. Furthermore, there is a high degree of uncertainty in both traffic dynamics and passenger behaviour with AVs versus non-AVs which is an active research topic in itself. Thus, for Paper II, constant operational speeds of transit vehicles are used. The representation of traffic flow in the included papers can hence be viewed as theoretical isolations that allow us to focus on the operational policies of the flexible transit system by idealizing the potential effects of other phenomena. The surrounding framework, however, still allows for potential de-idealizations of traffic flow conditions and congestion propagation.

3.2 Fleet operations

Relative to fixed route and schedule transit, the core difference in modeling a flexible transit system lies in the modeling of fleet operations. Representation of fixed public transit operations at its core requires the following input:

- *transit network* - a set of transit lines consisting of a fixed sequence of stops and an ordered set of links connecting them,
- *transit vehicles* - a definition of individual vehicle characteristics (e.g., passenger capacity, number of doors for boarding and alighting) that make up the transit fleet,
- *transit trip* - an assignment of a transit vehicle to serve a sequence of stops along a transit line with a desired time for arrival to each stop,
- *transit schedules* - a set of trips to be performed along a transit line at scheduled times by a fleet of transit vehicles.

Vehicles in fixed transit are thus assigned to serve specific trips along specific transit routes as defined on input. BusMezzo explicitly models delay propagation in scheduled trip-chains and provides an interface to model dynamic adjustments to transit schedules (for e.g., real-time holding strategies where transit schedules are dynamically adjusted by delaying a vehicle's departure from stops). For both Paper I and Paper II the modeling of dynamic routing requires an extension of the model. Figure 3.2 displays an overview of BusMezzo components where the focus of extensions to model flexible transit operations are circled in red. The main focus of additions with respect to fleet operations is on capabilities for real-time control adjustments to predefined routes and schedules (Paper I) and dynamic routing and scheduling (Paper II).

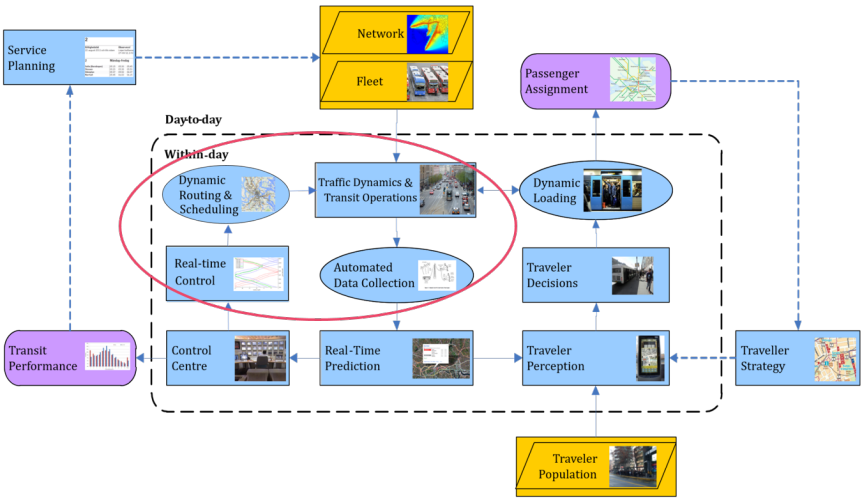

Figure 3.2: Modified BusMezzo framework to model flexible transit operations. Focus of model extensions through the work of Paper I and Paper II is circled in red. Figure adapted from Cats (2013), Figure 1.

In Paper I, additions to BusMezzo are less extensive, as transit vehicles in the studied scenarios will still serve a pre-determined set of trips and transit lines in a fixed sequence. Stop pairs for when a short-turn can potentially occur are defined on input, defined as the beginning and end of the short-turn, and a decision to short-turn between them is made via a real-time decision rule (more details on the methodology used for this purpose are found in Paper I). In a sense, a short-turn is modeled as skipping all downstream stops of the current trip starting from the beginning of the short-turn, and skipping all upstream stops of the next scheduled trip behind the end of the short-turn. An estimated travel time between the stop pair defining the beginning and end of the short-turn is then calculated for the redirected transit vehicle.

In Paper II, a fully on-demand service is modeled, requiring more significant changes. In this case the trips to be performed for any transit route are not known on input, as well as when transit vehicles are available to serve them. A framework for modeling on-demand operations was developed, described in more detail in Paper II. As seen in Figure 3.1, BusMezzo was extended with a "fleet manager" functionality, requiring its own set of inputs. Rather than being assigned to a fixed set of transit lines, a fleet of on-demand transit vehicles are assigned a *service area* defined by a fixed set of stops. Trips between stops of the service area and the routes connecting them are then either dynamically generated or defined as input to the model depending on the type of service that is represented. In contrast to a fixed service, travelers have direct influence over the routing and scheduling

of the on-demand fleet. This influence is defined by the operational policy of the on-demand service, defined by the chosen vehicle-to-passenger assignment strategy required as input to the fleet manager. In accessing an on-demand service without pre-scheduled trips, a traveler must broadcast their intention to use this service. In the on-demand framework this intention is formulated as what is referred to as a travel *request*. Attributes of a request are at minimum a timestamp for when the request was broadcasted, a desired time of departure and locations for pick-up and drop-off. A request may otherwise include additional specifications, such as a desired time of arrival or a request for a specific vehicle type.

3.3 Traveler behavior

In modeling dynamic decision-making of individual users of public transit, a traveler's trip between an origin and a destination can be represented as a path of an acyclic subgraph of the available transit network. The path of a traveler in this case consists of a sequence of access links, transit links, transfer links, and egress links that connect their initial origin and final destination. To model the adaptive behavior of travelers in response to prevailing supply and demand conditions, link traversal is time-dependent and conditionally available and a choice must potentially be made at each node of a path between downstream path alternatives that depend on the current context of the traveler. Based on microeconomic theories of utility maximization, random-utility models are one of the most commonly used analysis tools used to represent choice probabilities between available alternatives (Liu et al., 2010).

In BusMezzo, all passenger decisions are represented with multinomial logit models. Passenger path choices are a result of a sequence of boarding, alighting and walking actions. Available actions are dependent on the passengers context. For example when boarding a vehicle, waiting passengers follow a first-in-first-out rule. Passengers unable to board must wait for the next available vehicle. BusMezzo includes models to study dynamic effects on passenger decisions and LoS (Cats et al., 2016), which is an important feature in evaluating the effects of real-time operational control policies. This is especially true if these are based on real-time information, which is relevant for both Paper I and Paper II.

In Paper I, to represent the case where a passenger that has already boarded a short-turning vehicle and wishes to alight downstream of the short-turn, BusMezzo was extended with the ability to dynamically force passengers to alight at a transit stop. In response to forced alighting a passenger is modeled to consider the stop at which they were forced to alight as their new origin, and a re-evaluation of available path alternatives is made from this context. For Paper II, as a first step to integrate the on-demand framework with the passenger decision model of BusMezzo, a traveler submits a request whenever a decision is made to stay at a stop within the

service area of an on-demand solution.

As displayed in Figure 3.2, the extensions of BusMezzo thus focuses mainly on changes in the modeling of supply side operations with only minor adjustments to passenger decision modeling. Extensions of the modeling framework allow for studying within-day dynamics of flexible transit systems through single-shot simulation runs. Passengers cannot, in other words, learn from past experiences of their choices and adapt their future decision making within the developed framework. As mentioned in Chapter 1, however, the perceived reliability of a transit service can significantly effect transit mode choice, and the reliability of fixed and flexible services is intuitively very different. Although BusMezzo includes features for modeling transit user adaptation and learning over iterative simulation runs (labeled as 'day-to-day' in the outer loop of Figure 3.2), integration of flexible transit framework with these components is not within the scope of this thesis. For both Paper I and Paper II the alternative fixed and flexible operational policies are simulated separately and how the passenger decision model of BusMezzo is used in decision making is less relevant in their respective case studies. For Paper II this is again an isolation from the uncertainty in passenger mode choice between fixed and on-demand transit service alternatives to focus on other research objectives.

3.4 Level-of-service measurement

A passenger's experienced LoS, used as an indicator of transit system performance, is somewhat vague and might be interpreted in several different ways. An underlying assumption in the majority of transport research, however, is that the monetary cost of a trip, as well as the time required to complete a trip from origin to destination, are indicators of experienced LoS. In general it is assumed that an average traveler wishes to reduce both the time and cost of a trip. Even if it is easy to construct examples where this is not actually the case, the assumption still provides an indicator of aggregate LoS provided. Rather than use nominal travel times as an indicator of LoS, the experienced LoS in public transport is sometimes operationalized by observing the amount of time a passenger spends in different segments of their trip (e.g. walking time, waiting time, in-vehicle time, transfer time) and converting this to a monetary cost based on value-of-time estimates for each segment. For example, a passenger that needed to walk a great distance to access public transport may be considered to experience a lower LoS than a passenger that was required to walk less, even if the total trip time from origin to destination is the same between them. In a simulation where individual travelers can make decisions dynamically, a simulated traveler must be able to keep track of variables that influence their choice of mode and route. Which variables to include depend on what is considered to have a significant, and systematic effect on passenger behavior.

In BusMezzo, the observable attributes used in the representative utility cal-

culations for all downstream path alternatives available to the passenger are the anticipated waiting time, in-vehicle time, walking time, and number of transfers of each path. The resulting travel times in each segment of a chosen path is used as a measure of LoS in simulation output. In Paper I nominal travel times are used to evaluate LoS performance and in Paper II both nominal travel times and weighted travel costs are used.

Chapter 4

Scientific contributions

In this chapter the main contributions and results of the included papers are described in relation to the stated research objectives. Table 4.1 gives an overview of their relations.

Table 4.1: Relationship between research objectives and included papers.

		Papers	
	Research objective	I	II
RO1	Develop simulation models for evaluation of flexible transit systems	✓	✓
RO2	Improve methods for real-time operational control	✓	
RO3	Evaluate operational policies in emerging public transit systems	✓	✓

4.1 Paper I - Real-time short-turning in high frequency bus services based on passenger cost

In this paper, introducing higher degrees of flexibility within a fixed route and schedule urban public transit system through the use of AVL and APC data is explored. The main contributions of this paper are (1) the formulation of a passenger-oriented, real-time short-turning decision rule and (2) the extension of a public transit simulation framework for evaluation of similar real-time short-turning strategies under various conditions.

In addressing RO2, a decision rule for determining when and where short-turning should be applied in real-time was developed based on on-board passenger counts and vehicle time-headways. Intuitively the control strategy attempts to balance the negative and positive influences of short-turning on affected passenger groups while improving headway regularity. Relating to RO1, to allow for the simulation of a real-time short-turning decision BusMezzo was extended to allow for dynamic re-routing of buses between associated transit lines (i.e., a transit line and its opposing direction) as well as the ability to force on-board passengers to alight and

remake their choice of how to reach their final destination. The extension of this model allows for testing and refinement of similar real-time short-turning strategies independently or in combination with other operational control interventions.

In addressing RO3 and RQ1 the short-turning decision rule was applied in a case study of a single bidirectional transit line in Stockholm, Sweden, for peak-hour demand, and evaluated relative strictly fixed-service operations. Results indicate that aggressive use of real-time short-turning can improve headway regularity at the expense of passenger waiting times and conservative application of short-turning has the potential to benefit passengers while still improving headway regularity.

4.2 Paper II - Simulation of fixed versus on-demand station-based feeder operations

This paper focuses on the evaluation of fixed versus on-demand operational policies for an automated station-based feeder solution. The main contributions of this paper are: (1) a simulation framework for modeling demand-responsive operational policies relative to fixed route and schedule operations and (2) the design and analysis of an automated station-based feeder solution.

To address RO1, a simulation framework for modeling on-demand operations is proposed. The problem of matching travel requests received in real-time with demand-responsive transit vehicles is partitioned into subproblems that are sequentially solved. The extension of BusMezzo with this functionality allows for consistent comparison of a wide variety of on-demand policies with fixed service operations. A modular implementation structure also allows a simulated on-demand service to switch between operational policies dynamically depending on resulting measures of performance.

In addressing RO3, the simulation framework is applied in a case study of an automated feeder to mass transit solution, a use case for high-level AVs that has grown in popularity over recent years. Two fleet compositions, motivated by estimated reductions in operational costs with vehicle automation are evaluated. In studying RQ2, a set of test scenarios for a simplified test network and demand pattern is developed to isolate differences in fixed versus on-demand operational policies. To model on-demand operations as well as demonstrate a potential sequencing of the simulation framework, a greedy vehicle-to-passenger assignment heuristic is implemented. Results indicate that despite reductions in average total passenger travel times provided by an on-demand service, a fixed operational policy most often results in a higher and more reliable LoS provided regardless of fleet composition. The on-demand service provides shorter in-vehicle times with more direct routes, but without achieving a competitive reduction in waiting times, results in a lower LoS overall relative fixed operations for most demand levels. With an expanded fleet

size, on-demand operations result in lower VKT per passenger. With estimated reductions in distance-based costs, the system cost (sum of operational and passenger costs) of the on-demand service is lower relative to fixed for the lowest demand levels tested. When available fixed transit supply is exceeded, it is found that the on-demand policy results in a more equitable distribution of waiting times relative to fixed operations. While these results are specific to the assumptions made in the simulated scenarios, the study highlights important tradeoffs between LoS and operational cost estimates and potential performance indicators (e.g., cutoff points for when competitive average waiting times are achieved relative to average in-vehicle times) to inform the design of future feeder solutions for similar networks and demand patterns.

Chapter 5

Discussion and future directions

There is always a trade-off between the simplicity of a model and the similarity to what it aims to represent. The precision of the simulated scenario must also be balanced with how generalizable the results could be. The ideal might be to represent a very complex phenomenon with a very simple model. Transport systems are complex and a result of numerous interactions between several different elements (e.g. transport infrastructure, travelers, vehicles, information and communication technologies, weather, etc.). In attempting to model and analyze a transport system we often only have partial access to these interactions and are thus faced with a great deal of uncertainty. This uncertainty only grows when attempting to model a non-existent system, where one cannot validate against realized outcomes but must instead validate against expectations. To address these issues, we must consider trade-offs between computational tractability, transparency, simplicity, precision, and robustness with respect to different levels of detail in modeling traffic flow, transit operations, and passenger behavior. Balancing between these is a choice of which factors and uncertainties to idealize as theoretical isolations (or de-isolations) to target specific research objectives. The main limitations of the methodology and potential future research directions are discussed in Paper I and Paper II. Two potential directions of future work are highlighted here.

The current integration of the flexible transit modeling framework with BusMezzo allows evaluation of fixed and flexible operational policies as separate transit systems. Another interesting research direction is to model and evaluate the performance of co-existing, cooperative or competing fixed and flexible transit services. User perceptions and acceptance of AVs, as well as travel behavior under flexible transit operations are likely to differ from conventional public transit. Methods and technology for providing real-time transit information to passengers is also rapidly developing. With access to this information, passengers can make more informed decisions, and better evaluate the perceived reliability of transit alternatives. The incorporation of a dynamic mode and route choice model that takes into account

LoS and in particular differences in the perceived reliability of flexible transit services is an interesting line of future research. Finally, the case study of Paper II utilizes a simple on-demand operational policy. The current modeling framework provides an interface for the implementation of additional heuristics for matching on-demand vehicles with travel requests. The real-time short-turning policy of Paper I may also be integrated within this framework for future development. Extended implementations and comparisons of alternative flexible transit policies that utilize additional attributes of travel requests and other real-time data sources is thus another interesting future research direction.

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