Attractiveness of public transport systems in a metropolitan setting

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ATTRACTIVENESS OF PUBLIC TRANSPORT SYSTEMS IN A METROPOLITAN SETTING

PhD Dissertation

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PREFACE

This PhD thesis entitled *Attractiveness of public transport systems in a metropolitan setting* is submitted to meet the requirements for obtaining a PhD degree at the Department of Management Engineering, Technical University of Denmark. The PhD project was supervised by Otto Anker Nielsen, Professor at DTU Management Engineering, and co-supervised by Sigal Kaplan, Associate Professor at DTU Management Engineering and The Department of Geography, Hebrew University of Jerusalem. The thesis is paper-based and consists of the chapters listed in the tables of content, which include the papers listed below.

Paper 1: Ingvardson, J. B., Jensen, J. K., Nielsen, O. A., 2017, Analysing improvements to on-street public transport systems: a mesoscopic model approach. Published in *Public Transport*, 9 (1), 385-409.

Based on conference paper:

Ingvardson, J. B., Jensen, J. K., Nielsen, O. A., 2015, Mesoscopic modelling of on-street public transport. *Proceedings of the Conference on Advanced Systems in Public Transport* (*CASPT 2015*), Rotterdam, Netherlands, July 19-23, 2015.

Paper 2: Ingvardson, J. B., Nielsen, O. A., Raveau, S., Nielsen, B. F., 2017, Passenger arrival and waiting time distributions dependent on train service frequency and station characteristics: A smart card data analysis. Re-submitted after first round of review to *Transportation Research Part C: Emerging technologies*.

Paper 3: Ingvardson, J. B., Nielsen, O. A., 2017, Effects of new bus and rail transit systems – an international review. Published in *Transport Reviews*, 38 (1), 96-116.

Paper 4: Ingvardson, J. B., Nielsen, O. A., 2017, How urban density and network topology influence public transport ridership: Empirical evidence from 48 European metropolitan areas. Submitted to *Journal of Transport Geography*.

Paper 5: Ingvardson, J. B., Nielsen, O. A., 2017, Satisfaction and public transport use: A comparison across six European cities using structural equation modelling. Submitted to *Transportation Research Part A: Policy and practice*.

Paper 6: Ingvardson, J. B., Kaplan, S., Nielsen, O. A., Di Ciommo, F., de Abreu e Silva, J., Shiftan, Y., 2017, The Role of Satisfying Existence, Relatedness and Growth Needs in Commuter Modal Use Frequency. Re-submitted after first round of review to *Transportation*.

Based on conference paper:

Ingvardson, J. B., Kaplan, S., Nielsen, O. A., Di Ciommo, F., de Abreu e Silva, J., Shiftan, Y., 2017, The Commuting Habit Loop: The Role of Satisfying Existence, Relatedness and Growth Needs in Modal Choice. *Proceedings of the Transportation Research Board (TRB) 96th Annual Meeting*, Washington D.C., USA, January 8-12, 2017.

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I am very grateful for my main supervisor Professor Otto Anker Nielsen and co-supervisor Associate Professor Sigal Kaplan. During the entire project they have provided help and feedback on small and larger things related to the PhD. Without your help and guidance this project would not have been possible. I am deeply thankful for this.

In May 2016, I visited Floridea Di Ciommo in Barcelona to collaborate on a satisfaction survey. To Floridea, thank you very much for hosting me and for the good collaboration on the project and the paper. I would also like to thank João de Abreu e Silva and Yoram Shiftan for their help in finishing the paper. I am already looking forward to continue working with you on other projects starting in January 2018.

During the Danish Winter 2016-17, I spent four months in the Chilean Summer visiting Professor Juan Carlos Muñoz and Assistant Professor Sebastián Raveau at the Pontificia Universidad Católica de Chile. To JuanCa, I am thankful for kindly hosting me during those four months, showing great hospitality and for discussions on my project. To Sebastián, thank you for the great collaboration and feedback on my project throughout my stay, and afterwards. Also a big thanks to the big group of students for making me feel welcome at the department. I hope to come back to visit soon!

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Jesper Bláfoss Ingvardson, December, 2017

SUMMARY

Attractive public transport systems are essential for ensuring mobility in metropolitan areas as urbanisation continues to put pressure on the increasingly congested transport networks. It is therefore important to design attractive public transport systems which appeal to not only captive, but also choice users if public transport is to accomplish its share of transport growth. This requires a system that meets the expectations of the travellers in terms of providing a competitive and attractive service, which is traditionally associated with expensive metro systems. However, cost-effective systems such as Bus Rapid Transit (BRT) and Light Rail Transit (LRT) have become increasingly popular alternatives for relieving congestion and creating attractive public transport in medium-sized cities or corridors where metro networks are financially infeasible.

The objective of this PhD study is to create a better understanding of the determinants of attractiveness of public transport systems in an urban setting. Due to the width of the topic, this thesis includes six individual contributions, which seek to analyse public transport from different perspectives. However, all studies focus on how to ensure attractive public transport systems as perceived by both passengers at the individual level and for society at an overall level. This includes comparisons across the main public transport modes, namely BRT, LRT and metro or heavy rail systems, to contribute with insights on possible differences, which is especially important when considering the large differences in construction costs. The analyses performed as part of this thesis can be divided into three research areas within the overall theme, namely i) public transport operations, ii) effects of implementing the systems on a larger scale, and iii) the main determinants of travel satisfaction.

The first part contains a two-fold analysis of specific aspects related to public transport operations. The first study analyses on-street public transport systems, i.e. BRT and LRT, with the objective of evaluating design elements and implementation. These systems comprise many design elements ranging from infrastructure elements, e.g. partly segregated bus lanes or fully segregated busways, to Advanced Public Transport Systems (APTS) elements, e.g. pre-board fare collection, signal prioritisation, and holding strategies. Due to the large flexibility in implementing these systems effects can vary widely across systems. This thesis proposes to evaluate such systems using a combined mesoscopic simulation model and large-scale public transport assignment model. This allows for analysing in detail the effects of individual service elements while similarly evaluating the effects in the entire transport network. The results from a case study suggest synergy effects when implementing BRT and LRT as coherent systems including both segregated infrastructure and APTS elements, hence highlighting the importance of thorough planning.

Another important part of public transport operations is to minimise waiting times for passengers which is the topic of the second study. While much research has focused on

minimising waiting times at transfers this study proposes a general framework for modelling and evaluating passengers' first waiting time when accessing the public transport system. In these cases passengers have the possibility to time their arrival at the station based on the timetable, hence passengers will either arrive randomly or non-randomly. This study proposes to model this arrival behaviour explicitly by a mixture distribution consisting of two components, namely a uniform distribution and a beta distribution. The framework is validated using a large-scale Automated Fare Collection (AFC) system from the Greater Copenhagen Area, which showed that a large share of passengers arrive timely even at short headways, i.e. 5 minutes. These results highlight the importance of providing accurate and updated timetables to passengers allowing them to minimise their waiting time, which is perceived as more onerous than other time components. The importance of this finding is further emphasised when considering that public transport operators are using frequency-based timetables, which can be seen as less attractive for passengers if headway times are longer than 5 minutes. The general framework can be easily adopted in transport models, thereby ensuring more accurate estimations of passenger effects when evaluating changes to operations.

The second part focus on aggregate effects of public transport systems in terms of traffic impacts, strategic effects and ridership attraction with specific focus on the differences between public transport modes. The findings of a literature review of 86 systems showed that less expensive BRT systems can obtain large effects in terms of travel time reductions resulting in significant changes to mode choice as car users move to public transport. However, the effects vary notably due to differences in system design and dependent on local conditions, e.g. the relative attractiveness of the systems as compared to the rest of the transport system. In terms of strategic effects the review observed similarly large increases to property values after implementing BRT systems as after implementing its rail-based counterparts, LRT and metro. However, effects varied notably across systems, hence highlighting the influence of local conditions. In summary, the attractiveness and effects of new public transport systems were independent of mode as effects were more related to the general improvement. However, for high-capacity BRT systems it is a larger challenge to avoid negative externalities while still ensuring attractive station environments within dense urban areas.

In terms of ridership attraction, a regression analysis estimating public transport network ridership across 48 European cities found significant influence from service coverage and urban density. The analysis specifically revealed four underlying factors in the dataset. Ridership was positively associated with the coverage of metro, suburban, and light rail networks, employment and population density, and network connectivity including transfer possibilities. On the other hand, ridership was negatively associated with economic inequality in terms of unemployment, GDP per capita, car ownership and GINI coefficient.

The third part includes two studies on travel satisfaction with specific focus on the influence of psychological beliefs rather than solely focusing on service characteristics. This thesis contributes to extending previous research by analysing the psychological factors such as attitudes and norms, and specifically, whether the travel mode contribute to satisfying the needs of the travellers. This was analysed through two analyses using structural equation modelling of satisfaction survey data.

The first study deployed a large-scale passenger satisfaction survey from six participating European cities. The results were consistent across all cities in highlighting three important factors influencing travel satisfaction, namely i) accessibility measures, e.g. travel speed, reliability and service frequency; ii) reasonable fares in terms of perceived value of the system, and iii) norms in terms of perceived societal and environmental importance of public transport. Hence, this suggests that passengers not only prioritise traditional travel characteristics, but also consider other aspects when evaluating travel alternatives.

The second study extended previous research by proposing a general framework for representing the relationship between travel satisfaction and mode choice incorporating the Theory of Planned Behaviour and the ERG theory of human needs. This unifying framework allows for measuring and evaluating the sense of well-being rather than solely focusing on service characteristics. This included four sets of factors, namely i) existence needs, i.e. functional needs such as travel time and costs, ii) relatedness needs including social norms, iii) growth needs including attitudes and self-concepts, and iv) travel difficulties related to each transport mode, e.g. too far distance to nearest public transport stop and congestion or parking problems for car users. Using a tailor-made survey distributed in the multimodal Greater Copenhagen Area, the results confirmed that travel mode use frequency was related to overall travel satisfaction through a cyclical process while being subject to satisfaction of needs and travel difficulties. Specifically, the results suggested the importance of higher-order growth needs of self-efficacy and positive self-concepts in addition to functional needs. For public transport travel satisfaction and travel use frequency was mainly motivated by functional difficulties with other modes.

In summary, this PhD study has contributed to research within public transport planning covering topics related to public transport operations, impacts of implementation, and determinants of travel satisfaction. This includes important implications for policy and practice as findings suggest the importance of ensuring coherent planning of public transport systems in order to obtain optimal results for passengers and society. Specifically, the results from this thesis show that significant improvements can be created with less expensive BRT systems if ensuring thorough planning and implementation. Finally, while the findings of this thesis confirm previous studies in highlighting the importance of traditional service characteristics, it also suggests a strong link between travel satisfaction, travel use frequency and psychological beliefs in terms

of attitudes and social norms. Hence, it could be relevant for public transport to focus on addressing other needs of the travellers than pure transport, e.g. focusing on the environmental and social aspects as findings suggest are important for many travellers.

RESUMÉ (DANISH)

Attraktiv kollektiv trafik er afgørende i bestræbelserne på at sikre mobilitet i storbyområder, hvor urbaniseringen medfører store udfordringer i form af stadigt stigende trængsel i transportnetværket. Det er derfor vigtigt at gøre kollektiv trafik så attraktivt, at det appellerer til både tvangsbrugere og frivillige brugere for at kollektiv trafik skal kunne løfte sin del af den generelle trafikvækst. Det kræver, at systemet opfylder de rejsendes forventninger om et konkurrencedygtigt og attraktivt serviceniveau, hvilket ofte forbindes med dyre metrosystemer. Dog er de alternative og billigere løsninger Bus Rapid Transit (BRT) og letbaner i stigende omfang populære løsninger, der kan bidrage til at gøre den kollektive trafik mere attraktiv og dermed nedbringe trængslen, specielt i mellemstore byer eller i områder, hvor metroer ikke er samfundsøkonomisk rentable.

Formålet med denne ph.d.-afhandling er at skabe øget viden og en bedre forståelse af de bagvedliggende faktorer, der bidrager til at gøre kollektiv trafik i storbyområder attraktivt. Grundet det brede emne vil denne afhandling indeholde seks individuelle bidrag, der hver især belyser emnet fra forskellige vinkler. De vil dog alle fokusere på, hvad der gør kollektiv trafik attraktivt set både fra passagerernes individuelle og samfundets overordnede perspektiv. Studiet bidrager specifikt med ny viden ved at sammenligne dette på tværs af de kollektive transportformer BRT, letbaner og metro- og S-togssystemer, hvilket er særdeles vigtigt taget de store forskelle i anlægsomkostninger i betragtning. De seks analyser relaterer sig til tre områder inden for det overordnede tema; i) drift af kollektiv trafik, ii) overordnede effekter af kollektiv trafik, og iii) passagertilfredshed.

Den første del indeholder to analyser af specifikke elementer relateret til driften af kollektiv trafik. Først analyserer kollektiv trafik i gadeniveau, dvs. BRT og letbaner. Disse systemer er opbygget af en række forskellige designelementer spændende fra infrastrukturelementer, f.eks. delvist afskærmede busbaner og helt afskærmede busveje, til avancerede intelligente trafiksystemer (ITS), herunder automatisk billettering før påstigning, signalprioritering og strategier til at forebygge *bunching* (klumpning) af køretøjerne. Da systemerne kan tilpasses fleksibelt til en given kontekst ved at indeholde fra ét til mange designelementer, der hver især forbedrer driften, vil effekterne variere betydeligt afhængig af den endelige implementering. Dette studie foreslår at vurdere disse systemer baseret på en kombineret mesoskopisk simuleringsmodel af selve driften samt en makroskopisk kollektiv trafikmodel af hele netværket. Dette gør det muligt både at analysere effekterne af individuelle designelementer i detaljer og samtidig vurdere effekterne i hele netværket. Resultaterne fra et casestudie indikerer markante synergieffekter, når der implementeres BRT- og letbanesystemer indeholdende både infrastruktur- og ITS-elementer, hvilket understreger vigtigheden af grundig kollektiv trafikplanlægning med fokus på hele løsninger.

Dernæst undersøges, hvorledes passagerventetider kan nedbringes. Mens meget forskning har fokuseret på at nedbringe ventetider ved skift foreslår dette studie i stedet en generel metode til at modellere og vurdere den første ventetid som passagerer oplever når de ankommer til stationer. Her har passagererne mulighed for aktivt at planlægge deres ankomsttidspunkt afhængig af køreplanen, og de vil således ankomme enten tilfældigt eller ikke-tilfældigt. Dette studie foreslår at modellere denne specifikke transportadfærd eksplicit ved at anvende en miksturfordeling bestående af to komponenter; en uniform- og en betafordeling. Metoden, der blev valideret ved at anvende Rejsekortdata for Storkøbenhavn, viste, at en stor del af passagererne aktivt forsøger at planlægge deres ankomst til stationen, selv ved så lav *headway* som fem minutter mellem afgange. Disse resultater understreger vigtigheden af at offentliggøre nøjagtige og opdaterede køreplaner til passagererne, som derved har mulighed for aktivt at nedbringe deres ventetid ved at planlægge deres ankomst til stationen, hvilket er særligt vigtigt når man tager højde for, at ventetid opfattes mere genererende end andre rejsetidskomponenter. Vigtigheden understreges yderligere af, at trafikselskaber i stigende grad benytter frekvensbaserede køreplaner, der således kan opfattes mindre attraktive for passagerer, specielt når *headway* er mere end fem minutter. Metoden kan desuden let implementeres i transportmodeller, og dermed forbedre modellering af ventetider samt give mere nøjagtige vurderinger af passagereffekter ved driftsændringer.

Den anden del fokuserer på overordnede effekter af kollektiv trafik med specifik fokus på forskellen mellem kollektive transportformer. Dette inkluderer analyser af opnåede trafikale og strategiske effekter samt, hvordan transportformerne hver især bidrager til passagermængden i systemet. Et litteraturstudie af 86 kollektive trafiksystemer viste, at BRT-systemer kan opnå markante trafikale effekter i form af rejsetidsbesparelser og deraf følgende ændringer i transportmiddelvalg, hvor bilister skiftede til kollektiv trafik. De trafikale effekter varierede dog meget på tværs af projekterne, typisk grundet varierende grad af implementering af designelementer, men også lokale forskelle, herunder hvor attraktiv den nye kollektive løsning er i forhold til det eksisterende transportnetværk. Analysen af strategiske effekter viste, at der blev opnået tilsvarende stigninger i ejendomspriser efter implementering af BRT-systemer som efter banebaserede systemer som letbaner og metro. Dog varierede effekterne igen markant, hvilket igen understreger betydningen af lokale forhold. Sammenfattende viste litteraturstudiet således, at attraktiviteten og effekterne af nye kollektive trafiksystemer var uafhængige af transportform, og dermed, at effekterne rettere var knyttet til graden af forbedring. Dog indikerede resultaterne også, at såfremt BRT-systemer implementeres med tilsvarende stor kapacitet som metro, vil det være en større udfordring at undgå negative eksternaliteter i form af støj og barriereeffekter og samtidig sikre attraktive stationsområder i tætte byområder.

Det kollektive netværks overordnede betydning for passagermængden blev ligeledes undersøgt via en regressionsanalyse, der specifikt undersøgte sammenhængen mellem passagertal i den kollektive trafik og en række karakteristika for 48 europæiske byer og deres transportnetværk. Analysen identificerede fire bagvedliggende faktorer, der havde signifikant indflydelse på passagermængden. Mere specifikt viste analysen, at den samlede passagermængde i kollektiv trafik er positivt korreleret med dækningsgraden af det kollektive netværk af metro, S-tog og letbaner, arbejds- og befolkningstætheden i byområdet, og netværksindikatorer som netværksforbundethed inklusive antallet af skiftemuligheder i netværket. Modsat var passagermængden negativt korreleret med økonomisk ulighed i form af arbejdsløshed, BNP per indbygger, bilejerskab, og GINI-koefficienten.

Den tredje del indeholder to studier af brugertilfredshed, der i stedet for kun at fokusere på transportformernes servicekarakteristika også medtager de rejsendes psykologiske overbevisninger. Afhandlingen udvider således eksisterende forskning ved at analysere brugertilfredshed med udgangspunkt i psykologiske faktorer såsom holdninger og normer, og specifikt analyserer hvorvidt transportmidlet bidrager til at opfylde de rejsendes behov. Dette blev undersøgt gennem to analyser af tilfredshedsundersøgelser, der begge anvender structural equation modelling.

Det første studie analyserede en traditionel passagertilfredshedsundersøgelse indsamlet fra seks europæiske byer. Resultaterne fremhævede konsistent på tværs af byer tre vigtige faktorer, der påvirker graden af tilfredshed; i) mobilitetsfaktorer som f.eks. rejsehastighed, regularitet og frekvens, ii) rimelige billetpriser i forhold til det oplevede serviceniveau, og iii) normer i form af den oplevede sociale og miljømæssige vigtighed af kollektiv trafik. Dette tyder således på, at passagerer ikke kun prioriterer traditionelle servicekarakteristika, men også tager andre aspekter med i deres vurdering af tilfredshed.

Det andet studie bidrager til eksisterende forskning ved at foreslå en generel model, der beskriver sammenhængen mellem brugertilfredshed og transportmiddelvalg. Modellen forener *Theory of Planned Behaviour* (Ajzen, 1991) og ERG-behovsteorien (*existence*, *relatedness*, *growth*) i en samlet model således, at tilfredshed vurderes ud fra hvorvidt transportmidlet bidrager til en følelse af velvære frem for udelukkende at fokusere på transportmidlets servicekarakteristika. I følge modellen påvirkes tilfredshed af fire faktorer; i) eksistensbehov, dvs. grundbehov som eksempelvis rejsetid og -omkostninger, ii) relationsbehov, herunder sociale normer, iii) vækstbehov, eksempelvis holdninger og éns selvopfattelse, og iv) rejsevanskeligheder knyttet til hvert transportmiddel, eksempelvis for langt til nærmeste stop/station eller trængsels- og parkeringsproblemer ifm. biltrafik. Modellen blev analyseret ved hjælp af en skræddersyet spørgeskemaundersøgelse, der blev distribueret i Storkøbenhavn, og resultaterne viste, som forventet, at transportmiddelvalget er korreleret med den generelle brugertilfredshed gennem en vekselvirkning og samtidig påvirket af behovstilfredsstillelse og rejsevanskeligheder. Specifikt indikerede resultaterne vigtigheden af, at transportmidlet opfylder personlige vækstbehov ved eksempelvis at bidrage til éns selvopfattelse eller tiltro til egne evner, udover at opfylde de rene grundbehov i form af eksempelvis rejsetid. For kollektiv trafik var tilfredshed og transportmiddelvalg dog primært motiveret af vanskeligheder ved at benytte andre transportformer.

Sammenfattende har denne afhandling bidraget med ny forskning indenfor kollektiv trafikplanlægning omhandlende emner relateret til selve driften af systemet, hvilke effekter, der kan opnås ved implementering samt de betydende faktorer for passagertilfredshed. Resultaterne antyder vigtige praktiske konsekvenser idet de påviser vigtigheden af sammenhængende planlægning for derved at opnå optimale effekter til gavn for passagerer og for samfundet. Specifikt viser resultaterne eksempelvis, at der kan opnås store effekter ved at implementere den billigere løsning BRT hvis man samtidig sikrer grundig planlægning og implementering. Derudover bekræfter resultaterne af passagertilfredshed og transportmiddelvalg vigtigheden af traditionelle servicekarakteristika, men de viser også, at psykologiske faktorer som eksempelvis personlige holdninger og sociale normer har markant betydning. Der kunne således med fordel også fokuseres på miljømæssige og sociale aspekter, hvilket resultaterne af studierne viser også er vigtige for mange rejsende.

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1 INTRODUCTION

Metropolitan areas around the world are experiencing increased urbanisation as more than one million people are moving to urban areas every year (Moreno et al., 2016). This global trend poses a challenge because that same mobility which ensures economic agglomeration is threatened by increasing congestion of the transport network. As these dense urban areas with high traffic demands do not have much room for capacity improvements, it is increasingly important to utilise the limited space efficiently. The low capacity of private vehicles makes it important to focus on other transport systems for improving urban mobility. At the same time many cities experience environmental problems with increased air pollution. And as transport accounts for 23 % of global greenhouse gas (GHG) emissions there is also strong incentives for relieving environmental externalities (UN - United Nations, 2016).

To ensure sustainable mobility in dense urban areas public transport systems play an important role. The high capacity enables efficient transport of passengers with low environmental impacts, hence contributing to environmental sustainability. By providing transport for all traveller groups including elderly, disabled, students, low-income and young individuals public transport also contributes to social sustainability. For public transport to also be financially sustainable it is important to ensure sufficient ridership. Consequently, overall sustainability require the system to be an attractive choice which is used by not only captive users, e.g. those without the possibility to use cars, but also choice users who actively chooses public transport due to experiencing satisfactory service. Hence, it needs to meet the expectations of the travellers in terms of providing a fast, reliable and comfortable service, as suggested to be the most important determinants of travel satisfaction by much previous research, e.g. Lierop et al. (2017); Mouwen (2015).

Many cities around the world implement and extend rail and metro systems to meet the requirements of travellers due to their high attractiveness in terms of high-capacity, fast speed and reliable operations. However, the large construction costs of such systems make them difficult to implement as they require sufficiently high urban density to be financially feasible. For medium-sized cities or travel corridors with less demand alternative and less expensive improvements to conventional bus services need to be considered. Light Rail Transit (LRT) is one less expensive alternative which incorporates several of the attractive features of metro and urban rail systems, however at a much lower cost. Since the first modern LRT system was inaugurated in Nantes, France, in 1985, it has been successfully implemented in many medium-sized cities and travel corridors around the world, especially in Europe and North America (Bottoms, 2003). Another even cheaper alternative is Bus Rapid Transit (BRT[1]) which is an upgraded bus system

[1] Also known as Buses with High Level of Service (BHLS), an often used abbreviation in Europe.

incorporating design elements from rail-based systems in order to ensure faster and more reliable service than conventional buses. This includes segregated infrastructure, improved stations, traffic signal prioritisation, pre-board fare-collection, and other Intelligent Transport Systems (ITS[2]) (Wright and Hook, 2007). Following the success of the first BRT system implemented in Curitiba, Brazil, in 1974, other systems have been implemented at an increasing rate, especially in Latin American cities, thereby ensuring improved public transport at a much lower cost than its rail-based counterparts (Hidalgo and Muñoz, 2014). Also in a Danish context these systems are being implemented to improve public transport where metro networks would be economically infeasible. In Aarhus, the first modern LRT system in Denmark opened in December 2017 with two other systems currently being constructed in Odense and Copenhagen. And, in Copenhagen a short BRT section was inaugurated in 2014 while a dedicated BRT line is planned to open in 2020 in Aalborg.

While less expensive than metro and heavy rail systems, BRT and LRT systems are still very costly, hence emphasising the importance of ensuring informed decisions during the planning stage. This requires knowledge on the anticipated effects that can be obtained by various system alternatives. Notably, whether the system is perceived to be attractive by the passengers is highly important to ensure satisfaction, sufficient ridership and financial sustainability of the system. Much previous research has focused on the determinants of creating an attractive public transport system in terms of ensuring high level of travel satisfaction (e.g. Cao et al. (2015); de Oña et al. (2013); de Oña and de Oña (2015)), and generating high ridership numbers (e.g. Chen et al. (2010); Taylor and Fink (2013)). Within public transport research many efforts have been devoted to analysing passenger satisfaction, and most operators or agencies perform this on a regular basis. Most studies have analysed passenger satisfaction by evaluating the importance and ranking of traditional service characteristics, see a review in Lierop et al. (2017). From such studies the importance of network accessibility, travel speed, service frequency and reliability has been highlighted (Lierop et al., 2017; Mouwen, 2015). While the importance of these service characteristics in ensuring satisfied passengers should not be neglected, new insights from the research area of social psychology have emerged highlighting the importance of attitudes, lifestyle and habits on travel behaviour (De Vos et al., 2016; Van Acker et al., 2010). Findings suggest that the choice of, and satisfaction with, car use can be attributed also to symbolic and affective values including travel socialisation (Haustein et al., 2009; Steg, 2005), and bicycling is related to positive cycling experiences (Sigurdardottir et al., 2013). However, only few studies have analysed this specifically for public transport satisfaction and use frequency.

[2] Also known as Advanced Public Transport Systems (APTS) when used within public transport systems.

Other studies have argued whether the choice of system in itself is an important characteristic of public transport systems, however without drawing conclusions. Several sources have previously found evidence of a so-called rail factor where passengers prefer rail-based modes over bus-based modes, all else equal (Axhausen et al., 2001; Fosgerau et al., 2007; Nielsen, 2000). However, studies found quite different behavioural preferences among passengers (Anderson et al., 2014). Also, rail-based systems might lead to larger strategic effects making them more attractive from a socio-economic point of view, e.g. as reflected in changes to property values and increased urban development (Mohammad et al., 2013). However, other sources found no evidence of a rail factor, but suggested that higher attractiveness was caused by increased level-of-service such as higher comfort and increased reliability (Ben-Akiva and Morikawa, 2002; Tørset, 2005). Hence, more research is needed on this topic of ensuring attractive public transport.

1.1 AIM AND MAIN CONTRIBUTIONS

The main purpose of this Ph.D. project is to obtain a better understanding of the determinants of attractiveness of public transport systems in a metropolitan setting. The project aims at contributing with insights by analysing it from different perspectives, however all focusing on how to ensure attractive public transport systems for passengers and for society. This includes comparisons across public transport modes to better understand the reasons for possible differences. The analyses are split into three parts with two studies dedicated to advancing knowledge within each research field, however they do all overlap around the main theme of the study. In particular, this study contributes with the following:

- Analysing the effects of specific improvements to public transport operations.
- Analysing larger scale impacts of implementing public transport systems.
- Analysing the main determinants of travel satisfaction focusing on psychological aspects.

1.1.1 Improvements to public transport operations

This part consists of two studies focusing on the effects of improving public transport operations. The first study (*Analysing improvements to on-street public transport systems: a mesoscopic model approach*, published in *Public Transport*, 2017) is dedicated to on-street public transport systems, i.e. BRT and LRT, which have been implemented at an increasing rate throughout the world to improve public transport systems in medium-sized cities or corridors where demand is not sufficient for metro systems. In Europe, modern LRT systems have been implemented in many cities since the success of the first system in Nantes, France, which opened in 1985 (Bottoms, 2003), while in Latin America the success of the first BRT system implemented in Curitiba, Brazil, in 1974 has given rise to many more systems being implemented around the world. Both systems offer notable improvements to traditional bus systems at a low cost by comprising many individual service elements making implementation flexible, e.g. pre-board fare collection, segregation from other traffic, and signal prioritisation. However, this design flexibility can be a risk for creating non-optimal system designs as important design elements can be excluded easily during the planning and implementation stages. It is therefore important to know how such individual elements contribute to improving service, both individually and as a coherent system. The aim of the first study is to develop a methodology to evaluate on-street public transport systems by modelling the operations in detail. This will make it possible to analyse the effects of individual design elements and the full effects of coherent system designs.

The second study (*Passenger arrival and waiting time distributions dependent on train service frequency and station characteristics: A smart card data analysis*, re-submitted *Transportation Research Part C: Emerging Technologies*, 2017) focuses on passenger waiting times which are perceived by passengers to be more onerous than other time components (Fosgerau et al., 2007; Paulley et al., 2006). It is therefore important to analyse how to reduce passenger waiting times when planning public transport, both in terms of waiting time at the origin and waiting times when transferring mid-way. Much research has studied the latter by optimising timetables to reduce transfer times, e.g. Parbo et al. (2014). However, less research has focused on the initial waiting times when accessing the public transport network. Traditionally, passengers have been able to time their arrival to stations in order to actively minimise their waiting time. This is now easier than ever due to the prevalence of mobile travel planners. However, as more operators are moving towards frequency-based timetables passengers cannot actively arrive timely at stations, hence possibly resulting in increased waiting times. The aim of the second study is to analyse the initial waiting times experienced by passengers including the influence of service characteristics on actual travel behaviour. This includes specifically the differences between timetable types, service frequency and station characteristics. The results can also be used in transport models to increase the accuracy of waiting time prediction when evaluating public transport projects.

1.1.2 Large-scale effects of public transport systems

This part focuses on aggregate effects of implementing public transport systems with specific emphasis on comparisons across public transport modes. As financial sustainability of public transport requires sufficient ridership this is investigated through a two-fold analysis by firstly comparing the impacts from implementing BRT, LRT and metro systems, and secondly analysing the determinants of public transport ridership with specific focus on differences across public transport modes and network topology.

The first study (*Effects of new bus and rail transit systems – an international review*, published in *Transport Reviews*, 2017) is based on the large impacts resulting from metro systems, which have improved public transport attractiveness remarkably due to their high attractiveness. This can lead to increased ridership and satisfied passengers, but also strategic effects in terms of increased property values and urban development. However, only few studies have previously compared the effects of implementing BRT and LRT systems with the strategic effects traditionally associated with metro systems. Hence, the contribution of the first study is to analyse whether such large traffic impacts and strategic effects can be obtained by the less expensive LRT and BRT systems. This is analysed through a literature review comparing both effects on demand, e.g. ridership, travel times and modal shifts, and strategic effects, e.g. changes to property values and increased urban development. The comparison allows for estimating to what extent effects are mode-specific or whether similar effects can be obtained when implementing less expensive systems.

The second study (*How urban density and network topology influence public transport ridership: Empirical evidence from 48 European metropolitan areas*, submitted to *Journal of Transport Geography*, 2017) focuses on the importance of dense coverage to ensure high level of accessibility for passengers. This requires an inter-connected network where passengers can easily navigate from origin to destination. The extent of public transport networks and the number of transfer stations are important for ensuring both robustness and mobility. On the other hand, networks with only single lines and less transfer possibilities can lead to large detours for passengers resulting in increased travel times and decreased attractiveness. Hence, the aim and contribution of the second study is to specifically analyse the influence of various network topologies and public travel modes on public transport ridership while simultaneously taking into account the main determinants of ridership identified by previous literature. This includes comparisons of different types of networks, e.g. LRT, suburban rail, and metro systems, as these systems have different capacity, and possibly attractiveness, thereby making it possible to estimate the importance of dense networks in attracting large ridership numbers as well as analysing potential differences across modes.

1.1.3 Determinants of travel satisfaction

This part focuses on understanding the underlying motivators of travel mode choice as this is essential to design attractive public transport systems. Traditionally the mode choice of travellers is explained by utility theory where the utility function usually takes into account characteristics associated with each mode such as travel time and travel cost (McFadden, 2001). However, previous research has established that travel behaviour is highly influenced by psychological factors such as attitudes, social norms, and travel habits (Haustein et al., 2009; Van Acker et al., 2010). Despite of this, much previous research within travel satisfaction has been dedicated to analysing the importance of various key service characteristics, e.g. Lierop et al. (2017); Mouwen (2015). Only few studies have included the importance of satisfying the needs of travellers. The most adopted evaluation method is the Satisfaction with Travel Scale (STS), which measures satisfaction in terms of subjective well-being consisting of both affective and cognitive components (Ettema et al., 2011). While the measure does take into account feelings and emotions related to the travel experience, it does not directly evaluate how well the travel mode satisfies the needs of the traveller. Hence, a research gap exists in analysing the relationship between psychological aspects, e.g. habits and norms, and satisfaction with service characteristics and travel use frequency. The two studies included in this dissertation focus specifically on this.

The aim of the first study (*Satisfaction and public transport use: A comparison across six European cities using structural equation modelling*, submitted to *Transportation Research Part A: Policy and Practice*, 2017) is to compare the main determinants of travel satisfaction with public transport service characteristics. The analysis also includes specifically the influence of social norms in terms of willingness to recommend public transport to others as well as the inter-relationships with travel use frequency of public transport and private car. The contribution includes a validation of the approach and results by using a large-scale satisfaction survey across six European cities.

The second study (*The role of satisfying existence, relatedness and growth needs in commuter modal use frequency*, re-submitted to *Transportation*, 2017) further investigates the influence of psychological aspects on passenger satisfaction by focusing on how well the travel mode contributes to needs satisfaction as opposed to solely focusing on the overall satisfaction with the various modes. This will be analysed using the ERG theory of human needs (Alderfer, 1969) and the Theory of Planned Behaviour (Ajzen, 1991). The study not only focuses on public transport, but takes a bird eye view by including also car drivers and bicyclists, hence making it possible to compare across the most relevant modes.

1.2 OUTLINE

The remainder of this thesis includes the six papers, each within its own chapter. Hence, chapters 2 and 3 cover the two papers focusing on public transport operations, chapters 4 and 5 include the two papers on impacts from public transport systems, and chapters 6 and 7 cover the papers on travel satisfaction. Finally, chapter 8 concludes this dissertation by summarising the main contributions from each of the six papers, and possible future paths for research.

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2 Analysing improvements to on-street public transport systems: a mesoscopic model approach

Ingvardson, J. B., Jensen, J. K., Nielsen, O. A., 2017, *Analysing improvements to on-street public transport systems: a mesoscopic model approach*. Published in *Public Transport*, 9 (1), 385-409 (2017). Accepted December 29, 2016.

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Based on conference paper:

Ingvardson, J. B., Jensen, J. K., Nielsen, O. A., 2015, *Mesoscopic modelling of on-street public transport*. Proceedings of the Conference on Advanced Systems in Public Transport (CASPT) *2015*, Rotterdam, Netherlands, July 19-23, 2015.

Abstract

Light rail transit and bus rapid transit have shown to be efficient and cost-effective in improving public transport systems of cities around the world. As these systems comprise various elements, which can be tailored to any given setting, e.g. pre-board fare-collection, holding strategies and other Advanced Public Transport Systems (APTS), the attractiveness of such systems depend heavily on their implementation. In the early planning stage it is advantageous to deploy simple and transparent models to evaluate possible ways of implementation. For this purpose, the present study develops a mesoscopic model which makes it possible to evaluate public transport operations in details, including dwell times, intelligent traffic signal timings and holding strategies while modelling impacts from other traffic using statistical distributional data thereby ensuring simplicity in use and fast computational times. This makes it appropriate for analysing the impacts of improvements to public transport operations, individually or in combination, in early planning stages. The paper presents a joint measure of reliability for such evaluations based on passengers' perceived travel time by considering headway time regularity and running time variability, i.e. taking into account waiting time and in-vehicle time. The approach was applied on a case study by assessing the effects of implementing segregated infrastructure and APTS-elements, individually and in combination. The results showed that the reliability of on-street public transport operations mainly depends on APTS-elements, and especially holding strategies, whereas pure infrastructure improvements induced travel time reductions. The results further suggested that synergy effects can be obtained by planning on-street public transport coherently in terms of reduced travel times and increased reliability.

2.1 INTRODUCTION

Bus rapid transit (BRT) and light rail transit (LRT) are being implemented around the world due to the high attractiveness at a relatively low cost compared to underground systems (Hidalgo and Muñoz 2014). In Copenhagen the first BRT segment opened in 2014 and the first LRT line is scheduled to open in 2023. These systems comprise segregated infrastructure, signal priority and other intelligent transport systems (ITS) and advanced public transport systems (APTS) (Hwang et al. 2006). These elements may be implemented individually or in combination, locally or system-wide. The advantages of these systems include reduced travel times, improved comfort and increased reliability which is obtained through optimising the operations, for example by improved dwell time procedures, as compared to conventional bus services. Due to the varying implementation scopes and optimisation procedures, the potential effects will also differ greatly.

On-street public transport systems are complex due to (1) their being affected by car traffic (unlike metro networks), and (2) operations being very much dependent on the service characteristics, e.g. vehicle types, boarding and alighting procedures or holding controls. The effects of implementing BRT or LRT in favour of conventional bus services will vary significantly depending on the actual system design (Hensher and Golob 2008). Considering the complexity of mass public transport systems, which are large-scale, dynamic systems, combining multiple actors and requiring constant management and monitoring, such systems are inherently vulnerable (Cats 2013; Kim et al. 2015; Reggiani et al. 2015). Because of the number of people served by the system, the importance of connectivity and accessibility in daily life and network propagation effects, any disruption can negatively impact the entire system resulting in high societal and economic costs (Cats 2013; Reggiani et al. 2015; Kim et al. 2015). For example, small disruptions affecting single vehicles have significant impacts in terms of congestion leading to crowding, discomfort and lower service reliability (Cats et al. 2016). In order to maintain a high level of reliability, transit operators operate within high inventory levels in terms of vehicle fleet and system buffer times. Because reliability is key to reduce inventory levels, reliability is becoming increasingly important in operation of critical infrastructure and high reliability organizations in the transport sector, with the growing demand by stakeholders for lean operation (Pettersen and Schulman 2016).

The current study proposes new operational reliability indicators adoptable at the early planning stage. The study is motivated by the need to reduce the gap between the high importance of robustness analysis in transport planning and the lack of a systematic evaluation of the consequences of service disruptions in network design processes and assessing the robustness value of new investments (Cats 2016). The proposed approach serves as a coping strategy for the inherently stochastic nature of transit systems due to daily fluctuations in traffic, travel demand and supply availability. For example, sources of travel time uncertainty are congestion in the network and dwell times which constitute up to 50% of the total travel time for buses in Copenhagen, each contributing with 20–25% (Ingvardson and Jensen 2012a; Movia 2014). The contribution of the current study is three-fold.

Firstly, it provides new operational measures of reliability as perceived by passengers and it takes into account the stochasticity related to in-vehicle travel time and waiting time. Evaluating service reliability is important both from the supply side and the demand side perspective. In fact, a recent study from Copenhagen has shown that reliability is valued much higher than actual travel time (Prato et al. 2014).

Secondly, it complements Cats and Jenelius (2014) by applying a corridor-based mesoscopic model for reliability analysis. The proposed model is in line with other newly developed mesoscopic models, such as MATSim and BusMezzo. The model was originally developed as part of the thesis of the authors (Ingvardson and Jensen 2012a, b), but has been enhanced in several ways with the purpose of being able to model individual APTS elements as well as different on-street public transport systems. The model's simplicity, transparency and tractability make it suitable for evaluating reliability of on-street public transport systems in the early planning phases. Notably, the work of Cats and Jenelius (2014) focuses on system vulnerability due to irregularities in operations, while the current analysis focuses on system reliability at the early planning stage by accounting for regular operational fluctuations in travel time variability and headway time regularity.

And *thirdly*, while the implementation of human-centric design and operational measures has been gaining momentum to improve system performance and level of service, a systematic evaluation of their impacts is scarce (Fadaei and Cats 2016). This study fills this knowledge gap by analysing and comparing the effects of individual operational building blocks, e.g. holding strategies and boarding procedures as well as their synergy effects with respect to improving transit operations.

The remainder of this paper is structured as follows. Section 2 introduces the service reliability measure for evaluating the reliability of transport operations. The model approach is introduced in Sect. 3, while Sect. 4 presents the application on a case study corridor including model validation and definition of scenarios. Section 5 reports the results of the case study scenarios while Sect. 6 discusses the applicability of the model and concludes the work.

2.2 THE PROPOSED TRANSIT SERVICE RELIABILITY INDICATORS

Passengers' value of time in the public transport system differs significantly between spending time in the transport vehicles (in-vehicle time) and waiting and transferring between vehicles (out-of-vehicle time) (Nielsen 2000; Balcombe et al. 2004; Fosgerau et al. 2007). The inconvenience of waiting for the next transit vehicle, either at the departure stop or when transferring, makes it important to not only minimise travel times, but even more importantly to minimise the passengers' waiting time (Parbo et al. 2014). Hence, when managing public transport it is crucial to ensure a reliable service. Ultimately, unreliable operations make it necessary for the users to add a buffer to the travel time thus extending the actual travel time (Parbo et al. 2016).

Several definitions of reliability exist, also within public transport. A general formulation defines it as "*continuity of correct service*" (Avizienis et al. 2001). In a public transport context this can be interpreted as maintaining the same service as displayed in the public timetables. From the passengers' point of view this covers a combination of how they experience the anticipated waiting time at the stop, and how they experience the same in-vehicle travel time between stops. For high-frequency public transport operations this implies a low variation of running time while maintaining a homogeneous headway time between vehicles.

In this paper we propose a distribution-based service reliability measure suitable for high and medium-frequency public transport operations in a two-fold manner as sketched in Figure 2.1. It is reasonable to describe reliability in terms of distributions (Ceder 2007), hence measuring reliability in statistical terms. The mean, variation and coefficient of variation are therefore useful measures for the degree of variation of the operation. The lack of reliability can be quantified as the standard deviation multiplied by the corresponding value of time, hence supporting the use of statistical terms (Balcombe et al. 2004). Thus, the effective travel time includes the mean travel time and the standard deviation due to unreliability. This can be adopted for various time elements, e.g. running times, waiting times, etc.

The metrics applied in the evaluation of *service reliability* in this study are: (1) the coefficient of variation of the running time (*running time variability*), and (2) the number of headway times within the threshold of ±50% of the scheduled headway time (*headway time regularity*). By using these measures it is possible to capture the service reliability of public transport operations in terms of the total travel time experienced by passengers, i.e. the continuity of running times (in-vehicle times) and headway times (waiting times).

The proposed measures improve the indicators suggested by Nakanishi (1997) and Kittelson and Associates et al. (2003) by extending them to better represent the actual service. Nakanishi (1997) proposed an on-time performance indicator and a service regularity indicator. The on-time performance indicator is based on the percentage of trips departing from all scheduled time points, not including terminals, between 0 and 5 min after their scheduled departing time. The service regularity is measured as the percentage of headway times that deviate less than 50% from the scheduled headway. This measure also makes it possible to evaluate whether passengers experience a reliable service. Kittelson and Associates et al. (2003) recommend headway adherence which is based on the coefficient of variation of the headway times at a given stop. The improvement in our proposed measures is three-fold.

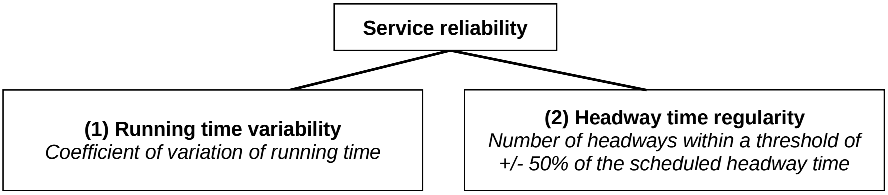

Figure 2.1: Measures of service reliability for high frequency public transport operations as proposed by Ingvardson and Jensen (2012a).

Firstly, the new measures are based on running times instead of departures times in order to account for delay propagation in the system.

Secondly, we calculate the statistical distribution instead of a single value of headway time regularity to account for operational stochasticity in daily service variation and to cope with the inherent uncertainty in the early planning stage.

And *thirdly*, instead of calculating aggregate measures at the zone-level or at every stop, the measures are calculated at important nodes in terms of size and system operation. This approach allows an efficient and transparent identification of connectivity cavities in the system.

2.3 THE PROPOSED MODEL

Recent research efforts have resulted in several mesoscopic simulation models, e.g. BusMezzo (Cats 2011), MISTRANSIT (Cortés et al. 2007), SmartBRT (Werf 2005), MILATRAS (Wahba and Shalaby 2006), DYBUS/DYBUS2/DYBUSRT (Nuzzolo et al. 2001, 2015), and MATSim (Balmer et al. 2008). Focusing on transit operations, Toledo et al. (2010) evaluate the effects of varying passenger demand and travel time uncertainty on on-time performance and headway reliability of transit vehicles. Cats et al. (2012) and Fernandez et al. (2010) investigate the effects of various holding strategies on passengers in terms of headway variability, travel time and waiting times. Cats (2016) evaluates the effects of a network extension on crowding in transit vehicles. And Fernandez et al. (2010) evaluate the effects of station layouts and operational strategies in terms of passenger interchanges, bus operations at stops and stop capacity within busways. Other studies have analysed the applicability of mesoscopic models on large-scale test networks (Nuzzolo et al. 2016) and real networks (Wahba and Shalaby 2011; Neumann et al. 2012).

This paper develops a mesoscopic simulation model in line with existing models for modelling public transit operations in a feedback loop with a macroscopic traffic assignment model. The mesoscopic model simulates the operation of public transit vehicles individually in a detailed manner whereas other traffic is macroscopically determined using the output of the macroscopic model, i.e. traffic volumes determining speed-density relationships, augmented with distributional data representing possible daily traffic fluctuations. The stochasticity of travel time is represented by sampling from link-specific distributions while traffic dynamics are explicitly modelled in the macroscopic model. The feedback loop allows for representing the implications of changes in running time on the number of passengers and traffic volumes, in order to plan for service robustness and reliability. Pedestrian and bicycle traffic at right/left turns in signalised intersections are represented in the current model by time penalties dependent on the signal timing plans of the traffic signals for cyclists and pedestrians.

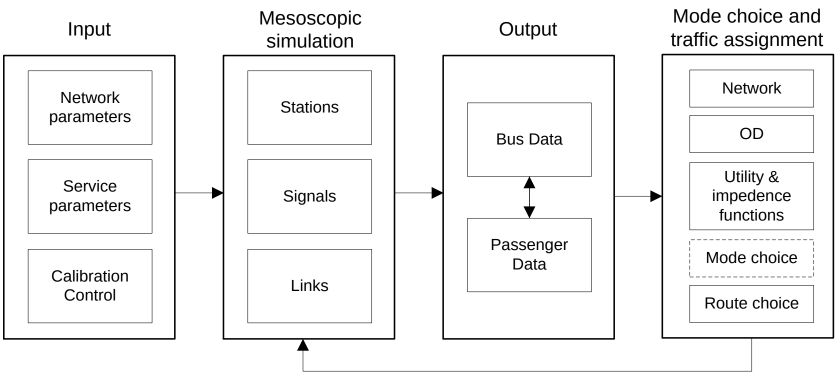

Figure 2.2; Illustration of the model framework, including input, output, and the mode-choice and traffic assignment model feedback loop

The model is event-based, and vehicles and their movements are simulated stepwise based on observations of bus behaviour in Copenhagen and Istanbul conducted as part of Ingvardson and Jensen (2012a) and Ingvardson and Jensen (2012b). This includes observations of different infrastructure designs, i.e. buses running in fully segregated busways, partly segregated bus lanes, and in mixed traffic at different congestion levels. Conventional bus operations are simulated by use of current observations from bus line 5A in Copenhagen, whereas observations from the Metrobús system in Istanbul make it possible to model infrastructure designs containing segregated busways. By utilising this form of data in the model it is possible to simulate the variation in operations without data on exact traffic levels on roads and at intersections. An illustration of the overall work flow of the model is sketched in Figure 2.2.

2.3.1 Input

The input to the model consists of characteristics related to the network, the passengers, and the operations of the public transport line. The input values are based on empirical data collected as part of Ingvardson and Jensen (2012a) and official data from the public transport agency of Copenhagen (Movia). The data is implemented in a stochastic manner as statistical distributions. Hence, it is possible to simulate the variation of operations based on the statistical variation in the input parameters such as passengers boarding a specific vehicle.

2.3.1.1 Network parameters

The network consists of links, signals, and stations. These are associated with a number of parameters, e.g. for links this includes the length and maximum speed, whereas for signals it includes cycle time and green time.

2.3.1.2 Service parameters

Service parameters are related to the level of service and the public transport operation. Hence, it includes the boarding and alighting time per passenger (depending on ticket type), and the vehicle seat capacity for evaluating comfort levels. The dispatching input includes the headway time between departures at the starting node and the level of randomness by which buses are dispatched, i.e. the level of bunching at the departure stop.

2.3.1.3 Calibration controls

To capture minor variations in the operations a number of calibration control parameters have been implemented. These parameters include holding controls and reflect the behaviour of a driver who catches up with a bus and thus holds back to ensure a certain time gap between the vehicles. These parameters are also used when simulating different bunching controls.

2.3.2 Simulation

The simulation of vehicles is based on the characteristics of the operations which suggest that the travel time of an individual vehicle basically consists of three elements: (1) time spent to travel the distance, (2) time spent dwelling at stops, and (3) potential time spent waiting at traffic signals. The time spent on links to travelling the distance depends on the speed and acceleration profile of the vehicle and external factors such as congestion if driving in mixed traffic. Time spent at stops depends on a fixed amount of time for deceleration and acceleration and for opening and closing the doors. Additionally there is a variable amount of time used for passengers to board and alight the vehicle which is dependent on vehicle and service planning characteristics. The same is the case for signals along the route where the vehicle potentially uses a fixed amount of time to decelerate and accelerate and a variable amount of time for waiting at the signal. At each event and for every vehicle the model will calculate the position, time and occupancy, e.g. when arriving at a stop these parameters are calculated based on the input variables, cf. Figure 2.3.

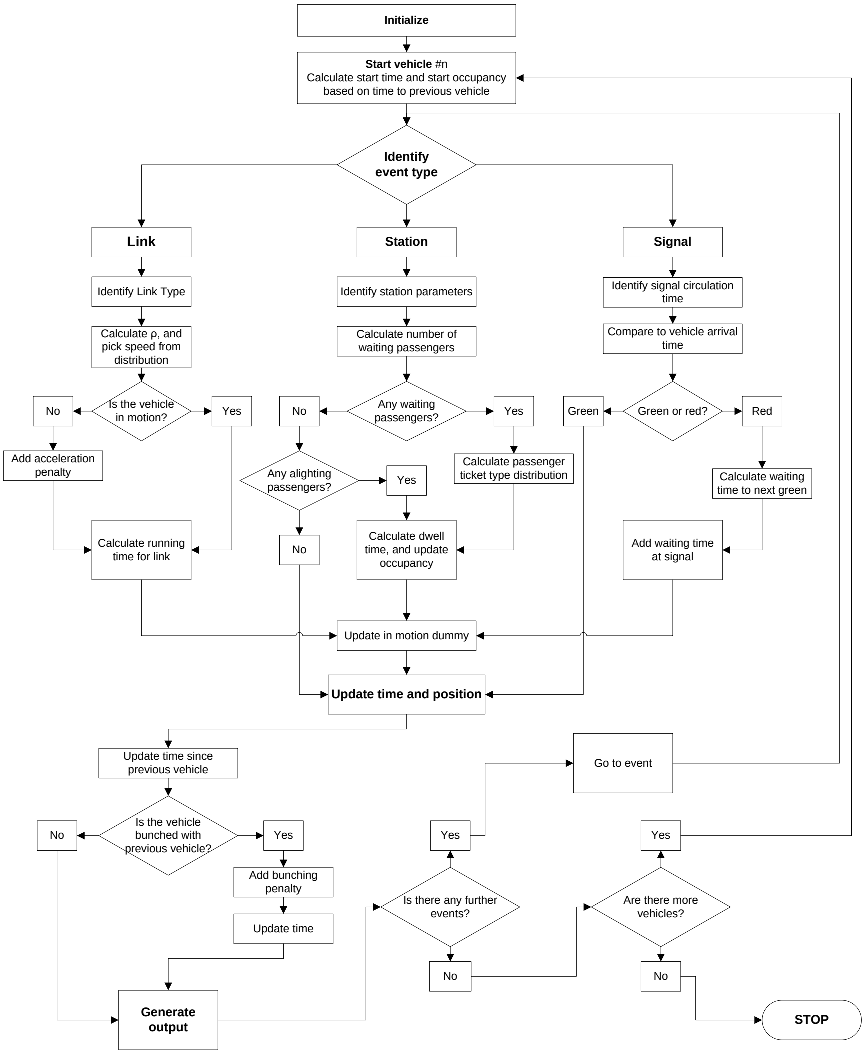

Figure 2.3; Detailed overview of the model simulation framework. More information can be found in Ingvardson and Jensen (2012a)

After initialising the model with relevant input the first vehicle is assigned. The vehicle initially identifies the first event. Then the time, distance travelled, and changes in occupancy at the event are calculated. The output from the event is an update of this information (time, location, and occupancy) which is used as input to the next event. At each event the headway times between vehicles are calculated as this is used to calculate the number of passengers waiting at stops and to control bunching and possible overtakings if such are allowed. Also, a dummy variable denoting whether the vehicle is in motion or not is updated. This dummy is implemented as the travel time on a link is dependent on whether the vehicle is already in motion or if it needs to accelerate. When all vehicles have been through all events, i.e. travelled the entire corridor, it is possible to calculate and evaluate the effects for vehicles and passengers. If a scenario results in significant travel time reductions the output will be used as input to an assignment model making it possible to evaluate the changes to passengers' route choices. This is important to evaluate the effects for the passengers on the public transport line being investigated as well as in the entire public transport network.

2.3.2.1 Links

The time spent travelling on links generally depends on trip time (e.g. hour, day, week, season), number of passengers, and the habits of the individual driver (Ceder 2007). In traditional traffic assignment models the travel time on links can be estimated according to traffic flow theory (Ortúzar and Willumsen 2011). As this mesoscopic simulation model does not model car traffic this approach is not adopted. Instead this model estimates the speed of the public transport vehicle on a given link based on empiric speed data.

Link type	Description	Congestion level
W	No disturbance from other traffic. This includes busways only.	-
N	Low disturbance from other traffic. This includes bus lanes only.	-
M	Medium disturbance from other traffic. This includes mixed use lanes.	0.80-1.00
K	High disturbance from other traffic. This includes road with some congestion.	0.55-0.80
H	Very high disturbance from other traffic. This includes roads with major congestion.	0.00-0.55

Table 2.1; List of link types used in the model

The framework for calculating the speed of public transport vehicles is based on letting the speed be randomly distributed thus simulating that the travel speed both depends on local conditions of the road and on external factors such as the driving behaviour. Hence, when a given vehicle arrives at a given link the speed on that link will be randomly drawn from an appropriate link-specific distribution. In this way it is possible for the model to calculate the time it takes for the vehicle to travel on that link. To include the fact that the characteristics of the road influence the speed of the vehicle, the links in the network have been categorised into different link types, see Table 2.1.

The categorisation of link types is based on the travel speed, the availability of bus lanes or busways, and the traffic congestion level defined by the actual speed, *v*, and the free speed of the link, v_f, as *(1 - v/vf)*. Both measures are included to take into account the variability of travel speed as this to a large extent depends on the congestion level. The actual travel speeds are based on GPS data for a number of cars traveling in the Copenhagen area during 2014. In other contexts where GPS data is not available the actual speeds can also be based on output from the traffic assignment model.

Each link type has been assigned a number of parameters which makes it possible to calculate the travel time for the transit vehicle on a given link. These parameters include the mean and standard deviation of the top speed on the link in addition to a penalty term which takes into account the acceleration of the vehicle to reach that specific maximum speed. The latter is only included if the vehicle has been brought to a stop at the previous event such as at a red signal.

The distributional data of travel speeds of the public transport vehicle for the five different link types are based on empirical data collected as part of Ingvardson and Jensen (2012a). This data was tested using the Shapiro–Wilk test (Shapiro and Wilk 1965) in order to justify the hypothesis of the data being random and normally distributed. This test was chosen due to its higher statistical power as compared to the Kolmogorov–Smirnov, Lilliefors and Anderson–Darling tests (Razali and Wah 2011).

Link type	**Distribution**	**Mean [km/h]**	**Standard deviation [km/h]**	**W**	**Pr < W**
W	Normal	60.5	4.85	0.933	0.2225
N	Normal	37.4	3.60	0.943	0.1562
M	Normal	26.0	3.18	0.977	0.3840
K	Normal	17.9	2.96	0.965	0.3089
H	Normal[3]	9.8	3.06	0.945	0.4527

Table 2.2; Test for normality for the empiric data of travel speeds for the five link types

The test results presented in Table 2.2 show that the hypothesis cannot be rejected at a 95% confidence level. Thus, the normal distribution is accepted as providing a good fit for the data. Due to the nature of the normal distribution which is symmetric around the mean it has been necessary to limit the possible values for links of type H. The speed on these links can only take on values between 5 and 15 km/h. This has been done to avoid very low or even negative speeds in the model.

As the speed of each vehicle is drawn randomly vehicles that are traveling close to each other can travel at quite different speeds. As this is not realistic, dependency between speeds of successive vehicles has been implemented. This dependency is implemented

[3] Can only take on values in the interval [5,15]

by letting the speed of a given vehicle be partly dependent on the speed of the previous vehicle. Both vehicles will have a speed drawn from the appropriate distribution from the given link type. However, if two vehicles travel within 15 s of each other on the same link the second vehicle will adopt the same speed as the first vehicle. If the headway time between successive vehicles on a specific link is more than 180 s the travel speeds will be fully independent. The transition between full dependency and full independency of travel speeds is calculated linearly as (180 - *t*)/165, where *t* is the time between vehicles. This is illustrated by an example: two transit vehicles travelling on the same link (link type M) at a headway time of 60 s results in 0.73. The vehicles draw speeds from the appropriate distribution, cf. Table 2.2, resulting in speeds of e.g. 28.79 km/h for the first vehicle and 22.47 km/h for the second vehicle. In the model the first vehicle will then be assigned a speed of 28.79 km/h (assuming that no other vehicles travelled this link within 180 s prior to the first vehicle). Due to the short headway time the second vehicle will not travel at 22.47 km/h. Instead the speed is adjusted to $0.73 \times 28.79 + (1 - 0.73) \times 22.47 = 27.07$ km/h. By this the model ensures that vehicles travelling at very short headways, i.e. in very similar traffic conditions, do not travel at very different speeds.

2.3.2.2 Signals

Signals are modelled as nodes and are based on the signal timing plans using three input parameters: (1) the cycle time, (2) the start time for the green phase, and (3) the end time for the green phase. The model then calculates the potential waiting time until the next green phase for a given vehicle approaching a given signal. Signals that have priority for public transport vehicles are modelled using extended green times. For traditional bus operations there is no full transit priority in signals, i.e. buses have to yield for pedestrians and bicycles when turning right, and also for car traffic when turning left. Such delays caused by other traffic have been implemented by use of time penalty. Thus, the model can be used to evaluate signal prioritisation measures for public transport vehicles.

2.3.2.3 Stations

Stations are modelled as nodes with two parallel procedures being calculated simultaneously; (1) the number of boarding passengers, and (2) the number of alighting passengers. These are used to calculate the total dwell time.

The dwell time calculations depend on the type of boarding process. When all passengers board and alight through the same door the dwell time can be estimated by a linear model of the form (Ceder 2007):

$$D_{ik} = \begin{cases} b + \delta_B \cdot B_{ik} + \delta_A \cdot A_{ik}, & if \quad B_{ik} > 0 \quad or \quad A_{ik} > 0 \\ 0, & if \quad B_{ik} = A_{ik} = 0 \end{cases}$$

For vehicles with multiple doors where boarding and alighting passengers use different doors the dwell time can be calculated as (Ceder 2007):

$$D_{ik} = \begin{cases} b + \max(\delta_B \cdot B_{ik}, \delta_A \cdot A_{ik}), & if \quad B_{ik} > 0 \quad or \quad A_{ik} > 0 \\ 0, & if \quad B_{ik} = A_{ik} = 0 \end{cases}$$

where, D_{ik} is the dwell time of the vehicle serving trip *i* at stop *k* including the time required for acceleration and deceleration (D_{ik} = 0 if vehicle *i* do not stop at stop *k*); *b* is the dead time portion including acceleration, deceleration, and closing and opening of doors; B_{ik} is the number of passenger boarding the vehicle serving trip *i* at stop *k*; A_{ik} is the number of passenger alighting the vehicle serving trip *i* at stop *k*; δ_B is the marginal dwell time per boarding passenger; δ_A is the marginal dwell time per alighting passenger.

This model suggests that the total dwell time for a vehicle can be estimated by a fixed time including acceleration and deceleration and opening and closing of doors, and a variable time depending on the number of passengers boarding and alighting the vehicle. If the vehicle has separate doors for boarding and alighting passengers these events happen independently of each other, and the variable term of the dwell time then depends on the event which takes the longest time. However, if the vehicle has only one door, or the doors are used for both boarding and alighting, the events cannot happen simultaneously. For BRT and LRT the latter will to some extent be the case as the doors are used by both boarding and alighting passengers hence creating conflicts.

The number of boarding passengers at a stop, i.e. passengers arriving at a stop, is assumed to be random as the frequency is high with headway times of less than 5 min (Nakanishi 1997). At such low headway times the proportion of passengers arriving in coordinated arrival patterns is rather low (Neumann et al. 2013). Hence, the arrival intensity is assumed to follow the Poisson distribution similar to the study by Cats et al. (2010). From this it follows that the time between passenger arrivals, the passenger headway time, is exponentially distributed. Hence, the number of boarding passengers at a given departure at a given stop can be calculated based on the mean passenger arrival intensity for that given stop. The number of alighting passengers at a given stop is assumed to follow the binomial distribution (Andersson and Scalia-Tomba 1981; Liu and Wirasinghe 2001; Toledo et al. 2010). Hence, it is calculated based on the occupancy of a given vehicle at a given stop and the share of passengers alighting at that stop in the given time period.

2.3.3 Output

The output of the model consists of the time, position, and occupancy for all modelled vehicles at all events. This is then used to evaluate level of service parameters such as waiting times at stops, travel time for vehicles and passengers, and headway time distributions. By this it is possible to evaluate the operations, including the experienced service reliability as experienced by passengers, and to compare the effects obtained by implementing various technologies, including APTS elements, individually as well as full BRT or LRT scenarios.

2.3.4 Mode choice and traffic assignment model

The model framework includes a feedback algorithm between the mesoscopic simulation model and a combined mode choice and traffic assignment model. The feedback algorithm allows for modelling changes to passenger flows in the public transport network resulting from improvements to the service operations on a single public transport line as modelled by the mesoscopic simulation model. The output from the mesoscopic model in terms of dwell times and running times between stops are used as input to the traffic assignment model which estimates the impacts of the updated travel times on mode choice and passengers' route choices in the public transport network. The output in terms of a new OD-matrix for passengers on the public transport line is then used as input to the next iteration of the mesoscopic simulation model. The feedback continues until steady-state conditions are attained. In this model framework such conditions are attained when the total running time for the public transport line changes by less than 1 min. This threshold was chosen because the input of running times to the traffic assignment model is given in whole minutes. The feedback loop requires car and public transport networks as well as origin–destination matrices as input. Mode choices and route choices are estimated based on random utility theory using utility functions and impedance functions taking into account volume-delay relationships. The traffic assignment model makes it possible to describe passengers' different preferences towards public transport modes and transfers in a schedule-based configuration (Nielsen 2004) within a reasonable calculation time (Nielsen and Frederiksen 2006). The feedback algorithm is optional, and the mode choice and route choice models can be run individually.

2.4 CASE STUDY CORRIDOR

The selected case study corridor is part of the busiest bus line in the Copenhagen area, 5A, which runs between Husum Torv and Sundbyvester Plads, cf. Figure 2.4. The bus line is part of the high-frequency A-bus network covering the densely populated areas of Copenhagen with short distances of 300 to 400 m between stops. The bus line 5A links the city centre with two of the most densely populated city districts, namely Amagerbro in the southern part and Nørrebro in the north-eastern part of Copenhagen. The passengers on this line travel an average of 2.60 km which is shorter than on other bus lines, partly because they use the bus as a feeder to metro or suburban railway lines. Hence, only 16% of passengers on line 5A travel across both corridors. The paper analyses the southern section between Nørreport Station and Sundbyvester Plads. This segment is 6.5 km long and currently covers 18 stops.

Currently, approximately 40% of the corridor has dedicated bus lanes and several APTS elements are already implemented including bus priority in selected traffic signals and real-time traffic information for passengers based on automatic vehicle location (AVL).

Despite these elements the operation suffers from low reliability and slow travel speeds (Ingvardson and Jensen 2012a).

2.4.1 Data

The base scenario was based on manually collected data as well as AVL bus data for the current bus operations of 5A in Copenhagen. Manually collected data was used for bus speeds and headway time distributions at Amagerbro Station and Nørreport Station (Ingvardson and Jensen 2012a) because the AVL data available did not include distributional data. AVL aggregated data for autumn 2014 was used for passenger numbers and to validate the model.

Figure 2.4; The 5A corridor between Nørreport Station in central Copenhagen and Sundbyvester Plads on Amager

2.4.2 Model replication

The model was run for a typical morning peak period, 7 a.m.–9 a.m., including 72 buses (18 per hour per direction). The input parameters were altered randomly to introduce noise, and the results are averages of 50 runs.

The validation of whether the simulated model results accurately replicate the real world has been done by two-sample Kolmogorov–Smirnov tests, similar to the study by Cats et al. (2010). Statistical distributional data of the actual operations were only available for Amagerbro Station in both directions and at Nørreport Station in the northbound direction. Hence, the parameter being tested is the distributions of headway times at these locations. The test results shown in Table 2.3 imply that the model replicates real-world operations sufficiently well.

Test parameters	D	KSa	Pr > KSa
Amagerbro st. Southbound	0.1313	0.9033	0.3882
Amagerbro st. Northbound	0.1214	0.8565	0.4555
Nørreport st. Northbound	0.1112	0.7844	0.5697

Table 2.3; Kolmogorov-Smirnov tests for validating the model replication of the headway distributions

Optimally this validation method should be used for all relevant parameters in the validation process. However, the observed data on running times and time use shares only included mean values from the buses and not distributional data. Hence, it was not possible to validate the model in this manner with regards to running time and time use shares. Instead the validation of these parameters was done by use of mean and standard deviation values, cf. Table 2.4.

Northbound	Average running time	Running time variability	Commercial speed [km/h]	Headway time regularity[4]
Observed base	27 min 29 sec	9.2%	14.2	54%
Modelled base	27 min 25 sec	6.3%	14.2	56%

Southbound	Average running time	Running time variability	Commercial speed [km/h]	Headway time regularity[5]
Observed base	23 min 59 sec	6.2%	16.3	47%
Modelled base	23 min 50 sec	6.0%	16.4	58%

Table 2.4; Model simulation results for the base situation compared to the real base situation

The comparison shows that the model replicates reality well with regards to travel time. However, the modelled service reliability measures differ from the observed values, i.e. lower running time variability and higher headway time regularity. Hence, it seems that the model has difficulties in simulating large reliability problems. One of the reasons for this might be the models' lack of ability to model larger breakdowns in the network, e.g. traffic jams, or taxis or trucks blocking bus lanes. A detailed overview of the running time adherence of the modelled base situation is shown in Table 2.5.

[4] Headway time regularity as average of Amagerbro station and Nørreport station.

[5] Headway time regularity at Amagerbro station only.

	Southbound				Northbound			
Stop	**km**	**Obs.**	**Mod.**	**Diff.**	**km**	**Obs.**	**Mod.**	**Diff.**
Nørreport st	0.000	0	0	0	6.517	1,649	1,645	-4
Larslejsstræde	0.408	96	109	13	6.109	1,540	1,553	13
Jarmers Plads	0.722	173	184	11	5.795	1,505	1,521	16
Rådhuspladsen	0.943	220	244	24	5.574	1,386	1,395	9
Vesterport st	1.215	298	319	21	5.302	1,297	1,311	14
Hovedbanegården	1.695	466	459	-7	4.822	1,111	1,131	20
Polititorvet	2.116	624	622	-2	4.401	958	970	12
Otto Mønsteds Plads	2.366	667	667	0	4.151	905	901	-4
Klaksvigsgade	3.127	796	805	9	3.390	761	757	-4
Ørestad Boulevard	3.486	890	877	-13	3.031	696	690	-6
Amager Fælledvej	3.972	966	967	1	2.545	600	587	-13
Sønderport	4.214	1,005	1,004	-1	2.303	549	536	-13
Amagerbro st	4.580	1,083	1,073	-10	1.937	430	429	-1
Tingvej	4.930	1,160	1,154	-6	1.587	323	338	15
Øresundsvej	5.118	1,196	1,186	-10	1.399	234	238	4
Tycho Brahes Alle	5.627	1,272	1,267	-5	0.890	158	157	-1
Smyrnavej	6.070	1,347	1,349	2	0.447	74	76	2
Sundbyvester Plads	6.517	1,439	1,430	-9	0.000	0	0	0

Table 2.5; Running time adherence of the model results compared to base situation (in seconds) (Obs. = observed, Mod. = modelled.)

The model estimates of the travel time between stops reflect the observed values in an acceptable manner, i.e. the variation between the observed and modelled estimates of accumulated times at stops are less than 30 s for all stops.

2.4.3 Scenarios

The model was applied to analyse the effects of different APTS upgrades of the current 5A bus line in Copenhagen. Furthermore, the effects of implementing full BRT and LRT systems involving multiple APTS elements were analysed. The scenarios are outlined in Table 2.6.

	Scenarios			
Infrastructure only	Fully segregated busways and additional bus lanes			
Planning and technology only	Pre-board fare collection	Specialised vehicles with multiple doors	Bunching controls	All planning and technology elements.
Full system solutions	Full BRT system including a combination of segregated infrastructure, and planning and technology elements.		Full LRT system including a combination of segregated infrastructure, and planning and technology elements.	

Table 2.6; Overview of the performed analyses of upgrades to the current bus operations

2.4.3.1 *Infrastructure scenarios*

Whenever possible, the infrastructure only scenario applied segregated busways on segments, while ensuring that existing traffic was not influenced significantly. The corridor was hence upgraded with a total of 2.8 km busways fully segregated from car traffic along the 6.5 km corridor. On these segments the transit vehicles ran in the middle of the road physically separated from car traffic to ensure the fastest possible operation. In addition, 1.2 km had dedicated lanes for public transport vehicles. An overview of the upgraded infrastructure is shown in Figure 2.5.

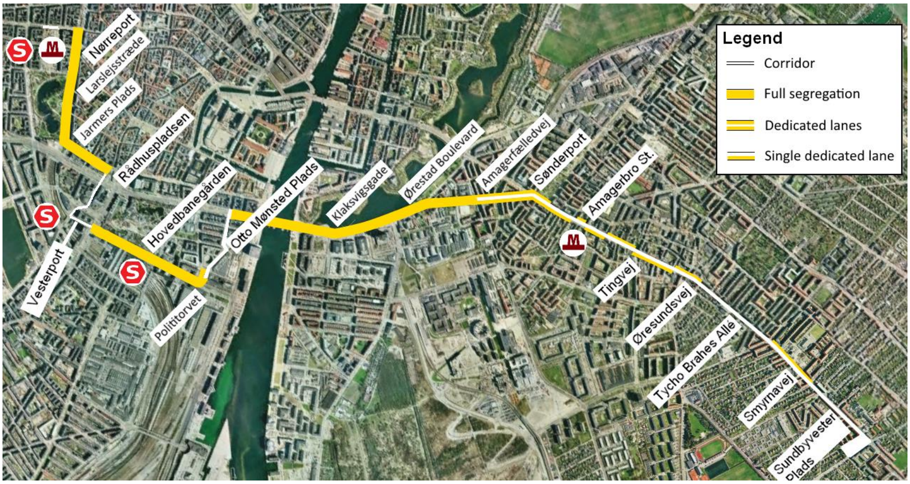

Figure 2.5; The layout of the proposed infrastructure upgrades of the 5A corridor between Nørreport Station and Sundbyvester Plads

2.4.3.2 *Planning and technology scenarios*

The planning and technology scenarios only included upgrades to the vehicle fleet and the operation of vehicles. Pre-board fare collection was implemented, and vehicles with different door configurations were tested. Adding additional doors will allow a faster exchange of boarding and alighting passengers, and automatic fare collection allows for faster and more homogeneous passenger boarding times. Also, dynamic holding was analysed in order to prevent bunching of vehicles. Finding the optimal holding strategy has been the focus of many studies, see a review of strategies in Strathman et al. (2001). Cats et al. (2012) test different holding strategies in terms of holding criteria and time point and find that headway-based strategies are superior to schedule-based strategies. Reliability is further improved by adapting holding to both the preceding and following buses. Other studies have seen improved results by proposing adaptive control schemes that hold back or slow buses continuously based on real-time information of headways rather than on specific stops (Daganzo and Pilachowski 2011; Xuan et al. 2011). Two holding strategies were adopted;

The *first strategy* was based on continuously holding back vehicles if the headway time becomes smaller than a defined threshold. As the reliability measure is defined based on headway times in the interval ±50% of the scheduled headway time, the same threshold was applied for the holding strategy. Hence, a vehicle was told to slow down if the headway time to the vehicle in front was less than 50% of the scheduled headway time. Similarly, vehicles running ahead of a delayed vehicle were slowed down to ensure even headways between vehicles. Nagel and Neumann (2010) show that such a strategy helps to reduce the average delay of the vehicle, the passengers' travel time and bus bunching caused by minor delays. In the model this was achieved by adding 2 s to the running time at links and dwell time at stops if the headway time was less than 50% or more than 150% of the scheduled headway, respectively.

The *second holding strategy* was simpler as vehicles were only held back at stops. The same thresholds were applied, but the vehicles were held back for 5 s.

A *BRT Lite* scenario incorporating pre-board fare collection, vehicles with four double doors, and the dynamic holding strategy that slows down vehicles at stops and links was also analysed.

The scenarios involving different public transport vehicles incorporate different dwell time parameters as listed in Table 2.7.

Number of double doors for boarding	**Boarding time per pax. [sec]**	**Alighting time per pax. [sec]**	**Dead time [sec]**	**Source**
1	1.45/1.82/10.55[6]	0.50	10.95	Ingvardson and Jensen (2012a)
1	1.53	0.39	8.70[7]	Ingvardson and Jensen (2012a)
2	0.70	0.60	8.00 (+3.52)[8]	Ingvardson and Jensen (2012a), Highway Capacity Manual (2000)
3	0.50	0.40	8.00 (+3.52)[8]	Ingvardson and Jensen (2012a), Highway Capacity Manual (2000)
4	0.25	0.46	8.00 (+3.52)[8]	Ingvardson and Jensen (2012a)

Table 2.7; Dwell time parameters used in the analyses

[6] Boarding times in base situation with on-board fare collection using different ticket types (62% prepaid, 32% stamp card, and 6% cash-ticket). More information can be found in Ingvardson and Jensen (2012a).

[7] Boarding and alighting from different independent doors. Adapted from Ingvardson and Jensen (2012a).

[8] Boarding and alighting from multiple doors with a congestion penalty of 3.52 seconds if the bus is near capacity limit. Adapted from Ingvardson and Jensen (2012a).

The parameters used for the analyses were collected from buses in Copenhagen and Istanbul (Ingvardson and Jensen 2012a). Pre-board fare collection was not implemented in the base scenario; hence passenger boarding times depend on the ticket type used ranging between 1.45 sec for a pre-paid ticket, 1.82 sec for so-called stamp cards, and 10.55 sec if buying a cash ticket from the driver. In the base situation 62% of the passengers use pre-paid tickets, 32% use stamp cards, and 6% buy cash tickets according to the public transport agency in Copenhagen. When implementing pre-board fare collection while only boarding through the front door, the boarding time per passenger is reduced only marginally. This is due to the narrow layout of the buses which requires passengers to board in one single line. Vehicles that allow for boarding and alighting through more doors reduce the boarding times notably as multiple passengers can board simultaneously without being hindered by potential jams at the front door (Neumann et al. 2014).

The boarding and alighting times were based on the Highway Capacity Manual (Highway Capacity Manual 2000; Ingvardson and Jensen 2012a).

2.4.3.3 Full system scenarios

The individual upgrades were combined into two different system scenarios, BRT and LRT. These scenarios included the same upgrades to infrastructure ensuring segregation from car traffic where possible. Both scenarios incorporated the same improvements to the boarding and alighting processes including pre-board fare-collection, traffic signal priority and bunching controls. Hence, the systems were meant to replicate systems such as the Malmö Express BRT and Bergen Bybanen LRT.

Due to unavailability of statistical distributional data for LRT the calculation of running time on links was performed differently than specified in Sect. 2.3.2.1. Running times for the light rail vehicles were then calculated based on vehicle characteristics. Hence, travel times on links were calculated based on the maximum allowed speed on the links. In fully segregated busways and bus lanes this was set to 60 km/h. In mixed traffic it was set to 40 or 50 km/h depending on the link type. The actual average speeds on links are lower because the model takes into account potential acceleration and deceleration prior to and after the link. Also, the top speed can only be reached by the vehicle if travelling a sufficiently long distance. In addition a running time supplement was added to links ranging from 5 to 20% depending on the congestion levels. The simulation of dwell times was performed using characteristics for a bus with four double doors. Hence, the modelling of the two scenarios was identical, except for the speed calculations.

2.5 Results

The main results of the various scenarios with regards to travel time and reliability are summarised in Table 2.8 for the morning peak period (7–9 a.m.). All scenarios required one single iteration of the feedback loop, i.e. one assignment model and two runs of the mesoscopic model per scenario.

Scenario	Avg. running time	Commercial speed [km/h]	Change [%]	Running time variability	Change [%]	Headway time regularity[9]	Change [%]
Base	25 min 38 sec	15.2	-	6.2%	-	53%	-
Infrastruc-ture	23 min 08 sec	16.9	-10%	7.6%	+1.4%	50%	-3%
Pre-board, 1 door	25 min 18 sec	15.4	-2%	5.8%	-0.4%	54%	+1%
Pre-board, 2 doors	24 min 30 sec	15.9	-5%	5.6%	-0.6%	55%	+2%
Pre-board, 3 doors	23 min 59 sec	16.3	-7%	5.7%	-0.5%	56%	+3%
Pre-board, 4 doors	23 min 50 sec	16.4	-7%	5.5%	-0.7%	57%	+4%
Holding	26 min 06 sec	14.9	+1%	5.0%	-1.2%	67%	+14%
Holding, stops only	26 min 13 sec	14.9	+2%	4.9%	-1.3%	68%	+15%
BRT Lite[10]	24 min 18 sec	16.0	-6%	4.8%	-1.4%	71%	+18%
Full BRT	20 min 00 sec	19.5	-22%	5.0%	-1.2%	73%	+20%
Full LRT	19 min 57 sec	19.6	-23%	5.2%	-1.0%	80%	+27%

Table 2.8; Main results of the modelled scenarios aggregated for both directions

The results showed that the travel time decreased by 10% when implementing upgrades to infrastructure. However, reliability was not improved notably in terms of headway time regularity. Instead, the running time variability increased, mainly due to the increased travel speed. When implementing improvements to the boarding procedure the travel times were reduced by up to 7% depending on configuration. The implementation of pre-board fare collection resulted in a marginal decrease of 2%, whereas larger travel time reductions of 5–7% were obtained when implementing vehicles with more doors. These results are a bit lower than estimated by Stewart and El-Geneidy (2014) and Neumann et al. (2014) which found running time reductions of up to

[9] Headway time regularity as average of Sundbyvester Plads, Amagerbro station, Hovedbanegården and Nørreport station.

[10] Includes pre-board fare collection, vehicles with 4 double doors, and holding strategy.

15 and 20%, respectively, when implementing boarding at all doors. Also, headway time regularity was improved when adding more doors. In this way, dwell times, and variation of dwell times at the stops, were reduced ensuring a more reliable service for the passengers. The best reliability was obtained when implementing bunching controls that actively reduce bunching of vehicles, however at the cost of a lower average travel speed. But passengers perceive an improvement as the increase in in-vehicle time is offset by the decrease in waiting time which is valued higher by passengers (Nielsen 2000; Balcombe et al. 2004; Fosgerau et al. 2007), cf. Table 2.9.

Scenario	Avg. in-vehicle time [sec]	Avg. waiting time [sec]	Avg. travel time [sec]
Base	529	120	649
Infrastructure	482	124	605
Pre-board, 1 door	518	120	638
Pre-board, 2 doors	498	119	616
Pre-board, 3 doors	485	118	603
Pre-board, 4 doors	481	117	598
Holding	535	113	648
Holding, stops only	537	115	652
BRT Lite	489	111	599
Full BRT	406	111	516
Full LRT	387	111	497

Table 2.9; Main results from the modelled scenarios in terms of passenger effects

Comparing the two holding strategies the best results were obtained by continuous holding rather than only holding at certain stops which is in accordance with the findings of Xuan et al. (2011) and Daganzo and Pilachowski (2011).

As expected, the best results were obtained when implementing a full system design, either as a light rail or BRT system. Hence, travel times were reduced by 22 and 23% for the BRT and LRT systems, respectively, resulting in an increase in the amount of passengers on the line of 42 and 43%, respectively. In addition, running time variability was reduced significantly and headway time regularity increased from 53 to 73% and 80%, respectively. The travel time reduction in the Full BRT scenario is higher than the sum of the reductions obtained by only implementing improved infrastructure or by only improving the planning and technology elements (BRT Lite). This indicates that synergies can be obtained when focusing on not only the travel time between stops, but also the dwell time at stops. As the dwell times and running times become more predictable the system becomes more reliable and the signals can be adjusted more efficiently thereby creating larger synergies. Hence, this suggests that it is important to plan a coherent project when implementing APTS elements in public transport.

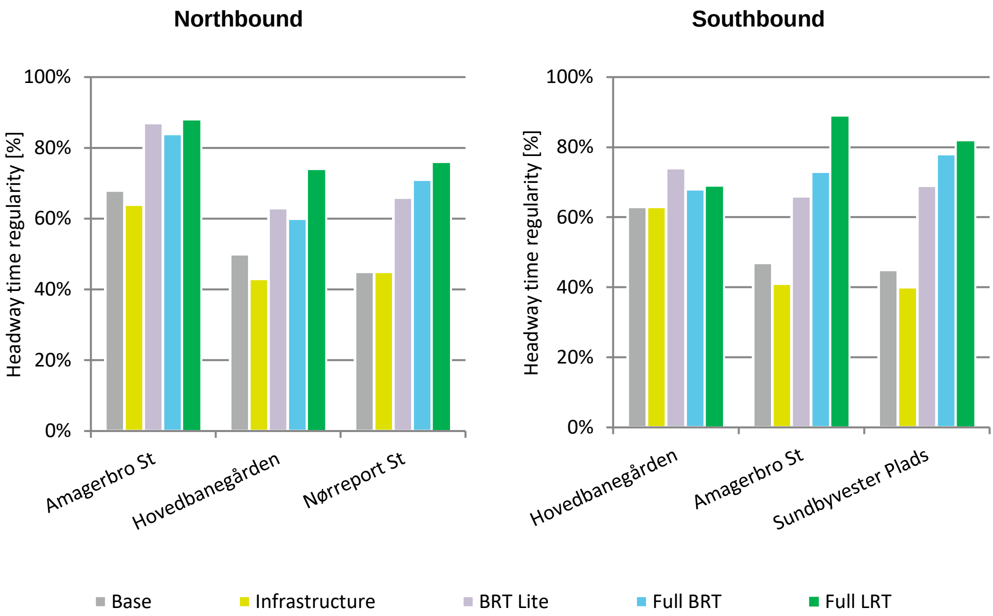

Figure 2.6; Headway time regularity (percent of departures within ±50% of the scheduled headway time) on selected stations during the morning peak period for the analysed scenarios

The results in terms of headway time regularity on selected important stations, cf. Figure 2.6, underline the importance of boarding procedures and intelligent solutions when improving the reliability of on-street public transport. By doing so headway time regularity is improved so that buses are not increasingly bunching when travelling through the corridor which was the case in the base scenario. The best results were obtained in the full system scenarios. The improvement for the BRT scenario of 20% is larger than the sum of improvements of the infrastructure (-3%) and BRT Lite (+18%) scenarios. Considering the standard deviation of the average headway time regularity of 4–6% depending on scenario, the results suggest that infrastructure improvements alone do not improve the headway time regularity significantly since the key driver for bus bunching is the dwell time. Instead it is important to consider the dwell procedures and/or bunching controls. More efficient boarding and alighting procedures and bunching controls positively affect both travel times and service reliability as perceived by the passengers. Even larger improvements occur if also implementing infrastructure improvements even though infrastructure improvements alone did not improve headway time regularity. This is likely due to a more efficient use of the infrastructure and signal prioritisation, i.e. the travel time between signals is less random when the running time variability on links and dwell time variability at stops are both reduced. This will make it easier to create green waves for public transport vehicles, thereby improving the use of signal priority.

2.6 DISCUSSION AND CONCLUSIONS

Improvements to public transport are on the political agenda in many cities around the world. The low costs of BRT and LRT systems as compared to subways make them popular choices; hence they are being implemented throughout the world (Hidalgo and Muñoz 2014). These systems provide many opportunities to improve public transport systems of intermediate and developed cities. However, benefits are limited by the application; a system which consists of expensive infrastructure elements may not yield the anticipated effects. For the system to be successful it requires intelligent service planning and active use of the technology available. This includes APTS elements that are shown to have significant importance for creating an attractive public transport system.

When assessing high-frequency public transport systems from the passengers' point of view it is important to also consider service reliability (Parbo et al. 2014). The paper proposes a joint measure of reliability which consists of evaluating both the headway times and the running times. More specifically, the service reliability measure is proposed to include (1) the coefficient of variation of the running time, and (2) the proportion of headway times that are within ±50% of the scheduled headway time. This makes it possible to evaluate the quality of service and reliability of public transport operations in a systematic manner. In addition, by implementing a service reliability measure it will be possible for the transport agency to incentivise the operators.

The mesoscopic model approach proposed by this paper makes it possible to evaluate public transport operations by taking into account traffic dynamics while maintaining simplicity and transparency. This makes it appropriate for assessing the reliability of operations as well as analysing the impacts of improvements, individually or in combination, in earlier planning stages. This is achieved by simulating the actual operation of transit vehicles in detail while the impacts of other traffic are taken into account using statistical distributions. The model builds upon a simpler version developed as part of Ingvardson and Jensen (2012a), subsequently enhanced in several ways as part of the present paper. Most importantly it now features a feedback algorithm between the mesoscopic simulation model and a mode choice and route choice assignment model which allows modelling changes to passenger flows in the entire transport network resulting from improvements to the bus operations. The mesoscopic model also includes more realistic interaction between successive vehicles which allows for dependency between travel speeds and possibility of overtaking, and the dwell time procedure was improved by incorporating stochastic alighting times.

The approach proved to replicate the current bus operations in an acceptable manner in terms of running times, service reliability (running time variability and headway time regularity), and headway time distributions at selected stops. In addition, the calculation time for running a scenario of 50 runs is less than one minute on a quad-core, 3.00 GHz CPU, 8 GB RAM standard desktop computer. Hence, the model approach appears promising for modelling public transport operations in an efficient manner at early planning stages. Still, the model approach does have some limitations which future studies could address.

Firstly, it could be improved to better model larger traffic breakdowns where transit vehicles are caught in traffic, e.g. due to taxis or trucks in the bus lane, or traffic jams when running in mixed traffic lanes. This could be achieved by incorporating a risk probability of such events happening on the various link types in the model and could be based on empiric data for the local street network.

Secondly, the running times of light rail transit were estimated based on speed and acceleration characteristics for light rail vehicles rather than empiric data. To add uncertainty to the running times this model adopted a running time supplement dependent on the influence from surrounding traffic. This supplement was implemented as a fixed time supplement, hence decreasing the stochasticity of the model results. Future improvements should address this, e.g. by utilising AVL data which are collected by many transit operators. This would also make it possible to easily adapt the model to a different setting by allowing the usage of bus speed data for other bus lines.

Thirdly, validation of the model could be further improved by utilising statistical distributions of running times and headway times at all stops in the corridor.

Fourthly, the combined mode choice and route choice model ensures that car travel times are endogenous to the model. However, bus running times are exogenous to the model framework as they are based on specific input. Hence, the estimation of bus running times when changing the road geometry is based on exogenous data. This framework was chosen because of the simplicity and the possibility of using representative real-life data. Another approach could be to estimate running times endogenously, e.g. by speed-density relationships and/or queue models.

Lastly, the combined mode choice and route choice model does not take into account congestion in the public transport network. Hence, in-vehicle crowding will not influence the route choices of passengers in the public transport network. This limitation could be relaxed by deploying a route choice model that includes vehicle capacities and hence in-vehicle crowding.

The approach was demonstrated on a case study corridor in Copenhagen where various improvements to the existing bus line 5A were evaluated. The results showed travel time reductions of up to 10% when upgrading the infrastructure in terms of adding fully segregated busways and bus lanes in approximately 60% of the corridor. However, improvements to reliability were insignificant. The results of implementing public transport vehicles with more doors for boarding and alighting showed travel time reductions in the corridor of 5–7%. As expected, travel time reductions increased when adding more double doors. The running time variability improved as the number of doors increased, whereas the marginal increases to headway time regularity were insignificant (2–4 percent points depending on the number of doors). The best results in terms of both headway time regularity and running time variability were obtained when implementing holding strategies. Furthermore, major improvements were obtained when combining APTS elements and improved infrastructure into full BRT and LRT systems, i.e. travel time reductions of 22–23% for the BRT and LRT scenarios, respectively. Simultaneously, the reliability of the operations improved significantly in terms of headway time regularity increasing from 53% in the base situation to 73 and 80% for the BRT and LRT systems, respectively, as well as running time variability improving from 6.2 to 5.0% and 5.2%, respectively. This suggests that synergy effects can be obtained when planning a coherent on-street public transport system. By this, it is possible to utilise the infrastructure and signal prioritisation more efficiently. Hence, it is important to focus on planning and technology, e.g. APTS elements to ensure an efficient boarding and alighting process as well as holding strategies to reduce bunching of vehicles, when improving the reliability of public transport operations. Such results are in line with other studies suggesting that it is possible to improve reliability by implementing a combined infrastructure-technology approach, for example intermittent bus lanes and green waves and bus pre-emption (Viegas and Lu 2001), while showing the insufficiency of the infrastructure only solution.

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3 PASSENGER ARRIVAL AND WAITING TIME DISTRIBUTIONS DEPENDENT ON TRAIN SERVICE FREQUENCY AND STATION CHARACTERISTICS: A SMART CARD DATA ANALYSIS

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ABSTRACT

Waiting time at public transport stops is perceived by passengers to be more onerous than actual in-vehicle time, hence it largely influences the attractiveness and use of public transport. Transport models assume traditionally that average waiting times are half the service headway by assuming random passenger arrivals. However, research agree that two distinct passenger behaviour types exist: one group arrives randomly, whereas another group actively tries to minimise their waiting time by arriving timely at the scheduled departure time. This study proposes a general framework for estimating passenger waiting times which incorporates the arrival patterns of these two groups explicitly, namely by using a mixture distribution consisting of a uniform and a beta distribution. The framework is empirically validated using a large-scale automatic fare collection system from the Greater Copenhagen Area covering metro, suburban, and regional train stations thereby spanning service frequencies from 2-60 minutes. It was shown that the proposed mixture distribution is superior to other distributions proposed in the literature. This can improve waiting time estimations in public transport models. The results show that even at 5-minute headways 43% of passengers arrive timely to stations when timetables are available. The results bear important policy implications in terms of providing actual timetables, even at high service frequencies, in order for passengers to be able to minimise their waiting times.

Keywords: Automated fare collection data; Smart card; waiting time; public transport; frequency-based timetables, arrival time, mixture distributions, beta distribution.

HIGHLIGHTS

- Passenger waiting times are modelled as a uniform and beta mixture distribution
- Validated framework that can improve waiting time estimations in transport models
- Results show that many passengers arrive timely to stations even at short headways
- Results highlight the importance of published timetables

3.1 INTRODUCTION

Waiting time at public transport stops is perceived by passengers to be more onerous than in-vehicle time (Nielsen, 2000; Fan et al., 2016; Fosgerau et al., 2007). Reducing waiting time is therefore of great importance when designing public transport systems. For en-route transfers this can be achieved by optimising public transport timetables in order to ensure short transfers (Parbo et al., 2014). However, this only affects transferring passengers which in the Greater Copenhagen Area corresponds to 45% (Christiansen, 2015). For all passengers it is also important to consider the waiting time experienced pre-route at the departure stop so that passengers can actively reduce their waiting time.

In general, when timetables are available to passengers, two distinct types of travel behaviour are observed when arriving to a departure stop: i) one group arrives randomly, and ii) a second group will try to minimise the waiting time by arriving timely at the scheduled departure time (Csikos and Currie, 2008; Jolliffe and Hutchinson, 1975; Luethi et al., 2007). The shares of the two groups are influenced by service characteristics such as headway time and reliability as well as other factors, such as time of day (Csikos and Currie, 2008; Luethi et al., 2007; Nygaard and Tørset, 2016). As headway time or reliability decreases, the share of passengers arriving randomly increases as the potential benefit of reduced waiting time is reduced (Bowman and Turnquist, 1981). Capturing such behaviour accurately in transport models is important for estimating impacts of public transport investments. However, most traditional public transport assignment models assume all passengers to arrive randomly to the stop, hence assuming the average waiting time to be half the headway time (Fu et al., 2012; Nielsen, 2000; Nökel and Wekeck, 2009; Schmöcker et al., 2011; Szeto et al., 2013, 2011). Therefore such models might overestimate waiting times as more passengers will time their arrival to the station leading to lower actual waiting times (Csikos and Currie, 2008).

This paper contributes to the existing literature by analysing a large-scale empirical data set of passenger arrivals and waiting times at train stations in the Greater Copenhagen Area. The contribution is three-fold.

Firstly, this study proposes a general methodology to model passenger waiting times at public transport stations by explicitly taking into account passengers arriving randomly and non-randomly. The methodology is an extension of the approach proposed in Luethi et al. (2007) where the arrival patterns of passengers were modelled as a mixture of a uniform and a Johnson SB distribution, thus taking into account random and non-random passenger arrivals, respectively. In this present study the method is further developed by proposing a general mixture of a uniform and a beta distribution which can be fitted to specific service frequencies by adjusting the share of uniform passenger arrivals as well as the parameters for the beta distribution. The simple and general formulation makes it easily adoptable in public assignment models.

Secondly, data used for this study is based on a large-scale automated fare collection (AFC) system containing more than 1.5 million trips covering all modes of public transport in the Greater Copenhagen Area during September and October 2014. Hence, the analysis covers stations with headways ranging from 2 minutes on the metro to 60 minutes on regional train lines. In addition, it includes modes with traditional published timetables (suburban and regional trains) and frequency-based timetables where actual departure times at stations are not published (metro). This makes it possible to compare results across a wide range of service frequencies and timetable types.

Thirdly, this study takes into account the effects of multiple station characteristics on the arrival patterns and waiting times of passengers. This data is joined onto databases including information on station layouts, station amenities and land use types surrounding the stations. This makes it possible to estimate the importance of such characteristics on passenger waiting times.

The paper is organised with a review of the existing literature on analysing passenger waiting times in public transport in section 2. The methodology and data used in this study is described in section 3 while the results are presented and discussed in section 4. In section 5 conclusions are drawn while policy implications are highlighted in section 6.

3.2 LITERATURE REVIEW

3.2.1 Estimation of waiting times

Some of the earliest studies focusing on passenger arrival patterns analysed the relationship between waiting time and headway time by a simple linear relationship. O'Flaherty and Mangan (1970) found that average passenger waiting time, W, could be related to average bus headway time, h (measured in minutes) by the simple linear relationship $W = 1.79 + 0.14h$ during an evening peak period in Leeds, UK. Seddon and Day (1974) improved the simple model by adding the influence of random bus arrivals. In their study the relationship was found to be $W = 2.34 + 0.26h$ (measured in minutes) for stops in Manchester during both peak and off-peak hours. Hence, evidence of non-random arrivals were found as random arrivals would have implied $W = 0.5h$. Jolliffe and Hutchinson (1975) further improved the estimation of passenger waiting times by analysing the influence of day-to-day variability of bus arrivals. The study also proposed a three-fold categorisation of passengers based on their behaviour: i) those who arrive to minimise their waiting time, ii) those who arrive randomly, and iii) those whose arrival coincides with the bus, i.e. by running to catch it. Based on an analysis of ten bus stops with varying headways at 6-31 minutes in London they found that actual passenger waiting times were 30% less than if passengers arrived randomly. Bowman and Turnquist

(1981) extended the estimation of passenger waiting times by modelling explicitly the arrival distribution of passengers timing their arrival to stops by using a decision model of arrival time choice to the bus stop. By using this model the study found that passengers are more sensitive to reliability than to scheduled headway times when deciding between arriving randomly or timing their arrival.

Later studies investigated aggregate passenger arrival patterns with the purpose of estimating the threshold for when passengers arrive randomly. Fan and Machemehl (2002) found that 10 minute headway was the limit between random and non-random passenger arrivals based on 2,491 observations of bus passengers from Austin, Texas. In a later study, the same authors found that 11 minutes was the transition point between practically random arrivals to less random arrivals, and that all passengers timed their arrival at headways of over 38 minutes (Fan and Machemehl, 2009). Similar results were found in a study on bus passenger arrivals in Trondheim, Norway, where passengers were found to time their arrival at headways of 10 minutes (Nygaard and Tørset, 2016). These studies only analysed arrival patterns of bus passengers. Luethi et al. (2007) analysed passengers across public transport modes, i.e. bus, tram, and commuter rail based on data from Zürich, Switzerland. The study estimated the threshold for random arrivals even lower at 5 minutes for which a significant group of passengers timed their arrival. This study also found that the share of passengers arriving non-randomly was higher at 5-minute headways than at 6-minute headways, hence highlighting the importance of timetables that are easy to remember.

Several studies investigated the arrival patterns using statistical distributions. Luethi et al. (2007) proposed an advanced framework for modelling passenger arrivals using a mixture of uniform and Johnson SB distributions, hence taking into account the behaviour of passengers arriving according to the timetable and those arriving randomly. Several later studies have used a simpler approach. An analysis of transferring passengers were conducted in Beijing showing that the lognormal and gamma distributions had the best fit for direct and non-direct passengers, respectively (Guo et al., 2011). And, at Beijing bus stops Gong et al. (2016) found that gamma and lognormal distributions best fitted passenger waiting times during evening peak hours. Nygaard and Tørset (2016) analysed bus stops with 10-20 minute headways in Trondheim, Norway. They concluded that passenger arrivals were non-uniform without giving further details on alternative descriptions.

The influence of travel and station characteristics on waiting times has also been the focus of recent research. Fan and Machemehl (2009) investigated the influence of stop location, gender and travel period, but did not find any effect on waiting times. However, the study found that passengers with car as access mode wait shorter than others. Currie and Csikos (2007) found time-of-day effects as random passenger arrivals were more common during off-peak hours as compared to travellers during peak hours. Similar results were found in Luethi et al. (2007) where travellers during morning and afternoon commute periods experienced shorter waiting times than those travelling mid-day. The study also found lower average waiting time for passengers at stations where the perceived service reliability was high, hence highlighting the importance of reliable operations. However, each station only had observations for one time period, hence the effect could be related to the station rather than the time period. The study suggested further research on the topic including the effects of time-of-day, route reliability, travel purpose, station location (in network), station environment, and previous activity (work, school, etc.). In a more recent study Fan et al. (2016) found significant effects of station amenities and perceived safety on the perceived waiting time using data from 36 light rail, commuter rail and bus stops in the Minneapolis-Saint Paul metropolitan area. If stations had limited amenities in terms of shelters and benches the waiting time was perceived 30% longer, and for women waiting in insecure places for more than 10 min the wait was perceived as much longer.

While these studies have investigated waiting times in detail across various study areas with different public transport structures including the influence of service frequency and station characteristics they all rely on manual data collection making sample sizes for specific combinations of mode, time-of-day and service frequency relatively small. Furthermore, most studies relied on data covering only one mode of public transport, most often buses.

3.2.2 Implementation in transport models

The first studies on public transport assignment models implemented passenger arrival patterns at departure stops simply by the so-called half-headway approach (Clerq, 1972; Dial, 1967). This approach relies on three important assumptions: i) deterministic transit vehicle headways hence assuming perfect service regularity, ii) passengers can board the first arriving vehicle, and iii) random arrival of passengers at stops (Fan and Machemehl, 2002). The first two assumptions are related to the operations of the public transport system which are not the main focus of this paper. A description of these assumptions can be found in Gentile et al. (2016). The third assumption is related to the travel behaviour of passengers which in this case are assumed to not consider the timetable of the public transport service. Hence, the average of the waiting time is estimated to be half the headway time. The simplicity made the approach very popular resulting in wide usage within assignment models (Ceder and Marguier, 1985; Hess et al., 2004; Liu et al., 2010). This includes most frequency-based transit assignment models (Fu et al., 2012; Nökel and Wekeck, 2009; Schmöcker et al., 2011; Szeto et al., 2013, 2011).

However, as previous research states such an assumption can only be reasonably assumed at short headways. Hence, such models might overestimate average waiting times as more passengers will time their arrival to the station (Csikos and Currie, 2008). Therefore, other transit assignment models assume half headway for short frequencies with a maximum waiting time for longer headways, e.g. the schedule-based model suggested in Nielsen (2000), thus resolving the issue slightly. In other schedule-based models the waiting time is modelled implicitly as part of the departure time choice of passengers based on the timetable of the public transport system (Nielsen, 2004; Nielsen & Frederiksen, 2006; Gentile et al., 2016; Nuzzolo et al., 2001). However, actual passenger arrivals at stops, and hence actual passenger waiting times, are not affected by the timetable due to high service frequency (Nuzzolo et al., 2015, 2012, 2001). By this, both model types do not accurately take into account the actual passenger arrival patterns and waiting time distributions, thus highlighting the need for a simple approach to estimate passenger waiting time patterns.

3.3 Methodology

The framework developed in this study was to analyse passenger waiting time distributions using Automatic Fare Collection (AFC) systems. Specifically, the analysis was tailored to investigate explicitly the ratio between passengers arriving randomly and those arriving non-randomly. This can be modelled by a mixture distribution holding two distributions which was first introduced in Luethi et al. (2007).

Passengers who do not consider the timetable are assumed to arrive according to a Poisson arrival process. Hence, they arrive randomly to stations and their waiting times follow the uniform distribution as also suggested in several studies (Fu et al., 2012; Luethi et al., 2007; Nielsen, 2000; Nökel and Wekeck, 2009; Schmöcker et al., 2011). The other group of passengers who do consult timetables will arrive with varying arrival intensity as this group of passengers will try to minimise their waiting time by arriving close to the departure time. The waiting time distribution will therefore not follow a uniform distribution. Instead this study proposes that the waiting time distribution of this group of passengers can be described by a beta distribution. This was done because the beta distribution possesses three important characteristics;

1. It is bounded on a defined interval which fits with the operational characteristics of public transport where passengers' waiting times are bounded by the service headway.

2. The beta distribution can handle the specific characteristics of passengers knowing the timetable. Namely, that they are assumed to add a buffer time to their arrival time at stations in order to not miss the departure (Fonzone et al., 2015). As the buffer time varies across passengers and service frequency, the arrival intensity is assumed to be highest a few minutes before the departure time and be decreasing towards the time of the next departure, cf. Figure 3.1. The shape parameters of the beta component (α and β) can explicitly model this as they define the skewness which might also vary across service frequency.

3. The uniform distribution is a special case of the beta distribution. By this there is a strong link between the distribution of the random passenger arrivals and those arriving according to the timetable.

Hence, with $\Gamma(z)$ denoting the gamma function defined as $\Gamma(z) = \int_0^\infty x^{z-1}e^{-x}dx$, the probability density function (PDF) of the mixture distribution, $f(x)$, proposed by this study can be written as:

$$f(x) = \varsigma \cdot \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\cdot\Gamma(\beta)} \cdot x^{\alpha-1} \cdot (1-x)^{\beta-1} + (1-\varsigma) \tag{1}$$

The ς denotes the proportion of the beta component whereas (1 - ς) denotes the proportion of the uniform component. Figure 3.1 shows the PDF with the y-axis denoting the density and the x-axis denoting the normalised waiting time (i.e. share of full headway).

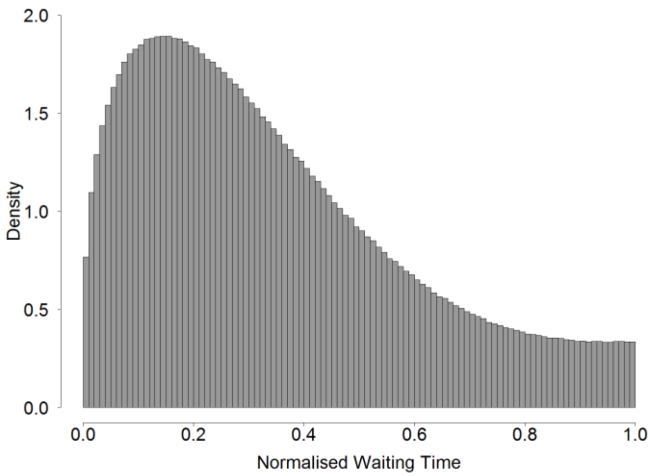

Figure 3.1; Illustration of the density function of a mixture distribution with ς=0.67, and the shape parameters of the beta component α=1.5 and β=4.

Maximum likelihood estimation was used to fit the waiting times calculated from the AFC data to the specified mixture distribution framework using the R statistical software package (R Core Team, 2017). This was done for all headway times in the data (2/3/4/6/10 minutes for metro, 5/10/20 minutes for suburban trains, and 20/30/60 for regional and intercity trains). By this, a mixture distribution for each headway was estimated including the share of observations contained in the uniform and beta parts, respectively. Finally, the fit was compared to that of a mixture distribution containing one part uniform and one part Johnson S_B distribution as proposed by Luethi et al. (2007) to evaluate the methods.

3.3.1 Case study: Greater Copenhagen Area

The study area covers the commuting area[11] of Copenhagen in the eastern part of Denmark in which approximately 2 million people live. The study utilised the Danish *Rejsekort* (English: Travel card) which is a tap-in-tap-out AFC system. This holds information on when and where passengers check into and out from the public transport system as well as intermediate transfer locations. The system covers all modes of public transport in Denmark, i.e. buses, metro and railways, and is used for more than 100 million trips annually (Rejsekort A/S, 2017). However, not all passengers use it for all trips as monthly passes are not currently implemented in the card. Hence, most commuting trips are not included in the data. For this study a data sample covering 1,767,858 public transport trips for the months of September and October 2014 was utilised corresponding to 12% of all public transport trips during that period.

The AFC data was linked to timetable data for suburban trains (S-trains) and regional trains in order to calculate the waiting times for passengers. For metro trains no public timetable is available due to the system running at high service frequency, i.e. every four minutes during rush hour, every six minutes during other hours, and every 10-20 minutes during the night. As the two metro lines run partly in parallel service frequency is doubled within the city centre. Hence, for the metro a synthetic timetable based on the time-of-day-dependent service frequency was produced in order to calculate waiting times for metro passengers.

The effects of various travel and station characteristics on waiting time distributions were analysed using different data sources, cf. . Station characteristics were taken from a study on transfer attributes (Dyrberg and Christensen, 2015). This included whether stations were located underground or had platform shelters to protect from weather, and a subjective measure of station layout ranking stations in terms of wayfinding. The inclusion of this measure was not straight-forward, but was included to analyse whether stations with simple layout and easy access to platforms from the street level influenced passenger arrival behaviour. In addition, detailed land use data comprising 44 categories of land use types were tested and eventually aggregated into only two types, i.e. leisure and commute. By this, land use types such as offices, industry and residential areas were categorised as being related to commuting travel whereas land uses such as nature, recreational areas, shopping and cultural institutions were categorised as leisure. For each station the land uses within 500 meters of the station were identified since the Danish travel survey suggest that the mode share of public transport is notably higher for trips originating and terminating within 500 meters of a station (Christiansen, 2015). The land use type with the largest share was assigned to that station. However, if the land

[11] This also includes towns located throughout Zealand from which extensive commuting patterns towards Copenhagen, e.g. Kalundborg, Korsør, and Vordingborg.

uses surrounding a station were mixed, i.e. either no share larger than 30% or several shares larger than 30%, the land use was specified as mixed. Lastly, results from a passenger survey conducted during the years 2013-2015 was included to test the influence of perceived safety.

Parameter	**All values**	**Used values**
Shelters*	None Small Large	No Yes
Underground*	No Yes	No Yes
Station layout / Ease of wayfinding*	Easy Little confusing Somewhat confusing Very confusing	Easy Difficult
Land use[13]	42 different types	Leisure-oriented Commute-oriented
Time-of-travel	Morning peak (6-9) Midday (9-15) Afternoon peak (15-18) Evening (18-00) Night (00-6)	Weekday, Peak (6-9, 15-18) Weekday, Off-peak (9-15, 18-0) Weekday, Night (00-06) Weekend, Day (06-00) Weekend, Night (00-06)

Table 3.1; Station characteristics included in the analyses (based on Dyrberg and Christensen (2015))*

3.3.2 Data preparation

An algorithm was developed to connect passenger arrivals to train departures on the origin station. It was designed to accommodate all passengers, namely those travelling directly from origin station to destination station using only one mode of transport as well as passengers transferring midway. Each passenger was assigned on the first train that travelled between i) the station of check-in, and ii) the station of check-out (or transfer point). The waiting time was then calculated as the time from check-in to the scheduled departure time of the assigned train.

Simultaneously, the algorithm calculated the number of scheduled departures between the station-pairs within the next 180 minutes. For the analysis of waiting time distributions it was required that headway times were constant, hence headway times for the next three departures were required to be fixed, e.g. exactly 20 minutes. The procedure did require a number of assumptions;

[13] This data is based on the Danish HSK land use data, which is a database containing detailed disaggregate information on the land uses in the Greater Copenhagen area.

Firstly, the waiting times were calculated based on the time of check-in at the check-in stands. By this, it is assumed that passengers tap in when they arrive to the station instead of waiting for the train to arrive before checking in. This was assumed to be reasonable as most often there is no financial incentive to wait for the train before checking in. Also, all stations had tap-in stands at the platforms which made it possible for passengers to check in when they arrived. Most stations do not have tap-in stands at the waiting hall, but underground metro stations have stands at the intermediate level. Hence, for these stations there could be some walking time from tap-in to arrival at the platform. However, the intermediate level is within visible range of the platform, i.e. short walk on escalators, hence this assumption was assumed to be reasonable also for these stations. The assumption of check-in was addressed specifically by controlling the timestamp for the next tap-out at the destination station (or tap-in if transferring) to ensure that the passenger actually travelled on the assigned train. Finally, the validity of this first assumption was tested by use of manually collected passenger arrival data.

An important element to consider from this first assumption is the provision of real-time information to passengers before arriving at the check-in stands. In Copenhagen the widely used online travel planner is updated with real-time information on delays, hence for passengers planning their trips real-time information is easily available before and during the trip. This makes it possible for passengers to change plans in case of delays if multiple travel alternatives are present for their trip. But, if passengers try to arrive timely to the station that entails that passengers are performing their route choice prior to arriving at the station. As some stations in the network have multiple lines the route choice might be affected when arriving to the station, both in case of delays or even just based on the actual arrival time at the station. Specifically, passengers might choose other lines or routes based on real-time information, either from their smart-phone or from information shown at the station. As most stations in the Copenhagen area have information shown to passengers physically close to platforms the influence on actual waiting time is probably small. However, it might affect the route choice on stations where passengers have multiple options, e.g. stations served by multiple lines. Hence, a separate analysis was performed to test this assumption specifically (refer to section 4.2).

Secondly, buses were not included because check-in happens inside the vehicles making it impossible to estimate the arrival time of the passengers at the bus stop.

Thirdly, only the first trip leg[14] of each trip was included in the analysis. This was done to ensure that waiting times were not influenced by possible prior public transport modes as it is only the first trip leg that is affected by the access mode, e.g. walk or bicycle. By

[14] A trip is defined based on having one single travel purpose. One trip might contain more trip legs, e.g. in public transport which includes access and egress and possibly several modes due to transfers.

this, it is ensured that arrival times were not influenced by transferring passengers arriving simultaneously in larger groups.

Fourthly, the main analyses only included trips performed on weekdays. However, a separate analysis was performed to test possible differences between weekdays and weekends as well as possible time-of-day effects.

Lastly, as the metro does not have an official published timetable this study adopted a pseudo-timetable based on the local service frequency which ranged from 2-6 minutes during day hours and 7-20 minutes during night hours. This assumption was important for calculating passenger waiting times and was assumed to be reasonable when taking into account that passengers are not able to look up a timetable for the metro trains as they can only know the service frequency at their preferred station. Hence, they are hypothesised to arrive randomly, and the analysis of whether this is true is not affected by the use of a pseudo-timetable.

By the end of these procedures the sample included 701,252 trip legs for weekdays and 308,091 for Saturday and Sundays.

3.3.3 Effects of realised timetables

The initial calculation of passenger waiting times based on the scheduled timetable revealed problems in the dataset that needed to be corrected, cf. Figure 3.2 (left). As expected the largest arrival rate of passengers happens just prior to a departure. This points towards a trend of passengers trying to minimise their waiting time, but still adding a buffer time in order to not miss the departure (Fonzone et al., 2015). The arrival rate then decreases steadily until the next departure. However, in the first minutes after the prior departure the arrival rate increases which is due to three reasons.

1. The timetable data for S-trains was based on arrival times rather than departure times. This meant that platform dwell times were not taken into account even though they range from 10-30 seconds depending on the station. Hence, S-train departure times were corrected by adding the official station-specific minimum dwell times to the timetable arrival times.

2. Passengers being on the verge of catching a train might run for it. This leads to a larger intensity of passengers arriving just before and after the scheduled departure time. For the passengers arriving just late according to the timetable they will not catch the train and have to wait for the next departure hence experiencing a waiting time of almost the headway time. However, if the train is delayed these people might slow down when arriving at the station because they can see that the train is delayed. Hence, these passengers will check in after the scheduled departure time, but still catch the delayed train thereby showing up in the tail-end of the distribution.

3. There might be some passengers that check in just prior to entering the train which in the case with delayed trains will be just after the original departure time.

By taking actual delays into account it was possible to verify that many of the trip legs from the tail of the distribution were indeed passengers who actually were able to catch the previous delayed train. Official delay data from the Danish railway manager was used, but the procedure also required implementation of delay correction factors to accurately estimate the actual departure times from the station platforms (Richter et al., 2013). By removing these trip legs using the realised timetable of delayed trains the distribution looked more as expected, cf. Figure 3.2 (right). These trip legs could have been included with updated, realised waiting times. However, in order to not conflict the general assumption of passengers timing their arrival to the *scheduled* timetable they were removed. Hence, only scheduled departure times were used for the calculation of waiting times. As delay data was not available for all data this procedure resulted in a smaller sample of 617,996 observations for weekdays and 277,958 for weekends.

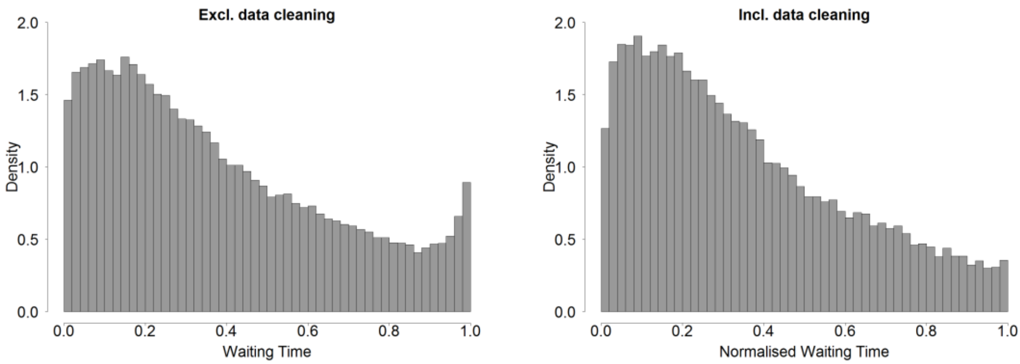

Figure 3.2; Distribution of passenger waiting times before and after data cleaning. Left: Full data for headway times of 20 minutes. Right: After data cleaning by taking into account realised timetable and delayed trains as well as corrected dwell times for suburban trains.

3.3.4 Validation

The waiting times deducted from the AFC system were validated using manually collected data of passenger arrivals at Bernstorffsvej S-train station. A total of 182 observations were collected during a morning peak period on August 11, 2016 from 7:30 to 8:45. During the data collection efforts were made to not include passengers arriving to the station by bus. The manually collected data was compared to 440 observations from the AFC data, cf. Figure 3.3. Unfortunately, data were not available for the exact same period. Instead data from similar morning peak periods during September and October 2014 were used.

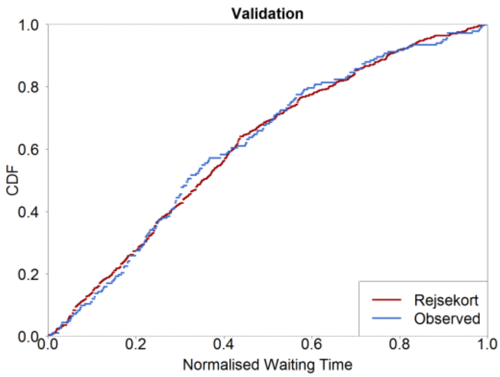

Figure 3.3; Comparison of manually collected data and Rejsekort data for passenger arrivals at Bernstorffsvej station on August 11, 2016.

The validation was performed using the Kolmogorov-Smirnov statistical test which showed that it cannot be rejected that the distributions are identical. This finding also validates the assumption that passengers do not generally wait until the time of departure before checking in using their Rejsekort. If that was the case the distributions of waiting times for the AFC data would be more positively skewed than that of the manual data which is not the case. Although not statistically significant, it can be seen that the largest deviation is concentrated around the middle, i.e. at half the headway. However, no obvious reasons for this were identified, and the deviation is still small when taking into account the relative small sample sizes used for the validation. Furthermore, when considering the full range there seems to be no systematic deviations.

3.4 Results

3.4.1 Main findings

The full dataset of 617,996 weekday trip legs were analysed to estimate the fit of the two mixture distributions, i.e. the mixture of uniform and beta proposed by this present study, and the mixture of uniform and Johnson proposed by Luethi et al. (2007). Table 3.2 shows the results of the fit for each headway of the schedule-based public transport services. The fit of each mixture distribution to the data was evaluated using the two-sample Kolmogorov-Smirnov test statistic, *D*, and the corresponding p-value, whereas the Akaike information criterion (AIC) was used to compare the fit of the two mixture distributions with a lower number signifying better fit (Akaike, 1974). The results are illustrated specifically for 20-minute headways in Figure 3.4.

The results from the 20-minute headway illustrated in Figure 3.4 visually suggest a better fit from the beta-mixture distribution as compared to the Johnson-mixture distribution while the traditional simple uniform distribution has a much worse fit. When analysing the fits across all service headways this tendency is clear. The assumption of a Johnson-mixture distribution is rejected at the 99% confidence level at all service headways except for 5-minute headways. This can be compared to the fit of the beta-mixture which can only be rejected for 10-minute headways. The beta-mixture fit is visualised specifically in Figure 3.5 together with the remaining service headways.

		Beta-mixture			Johnson-mixture		
Headway	**No. obs**	**D**	**p-Value**	**AIC**	**D**	**p-Value**	**AIC**
5	39,140	0.0064	0.08442	-949.70	0.0079	0.01566	-888.34
10	184,917	0.0051	0.00015	-14,917.55	0.0084	<0.00001	-14,523.44
20	48,670	0.0063	0.03940	-13,843.48	0.0144	<0.00001	-13,444.79
30	24,589	0.0098	0.01845	-20,701.18	0.0265	<0.00001	-20,109.29
60	12,702	0.0096	0.19566	-22,259.63	0.0382	<0.00001	-21,715.79

Table 3.2; Statistical tests of the fit of beta-mixture and Johnson-mixture to passenger waiting times for schedule-based public transport services (suburban and regional trains).

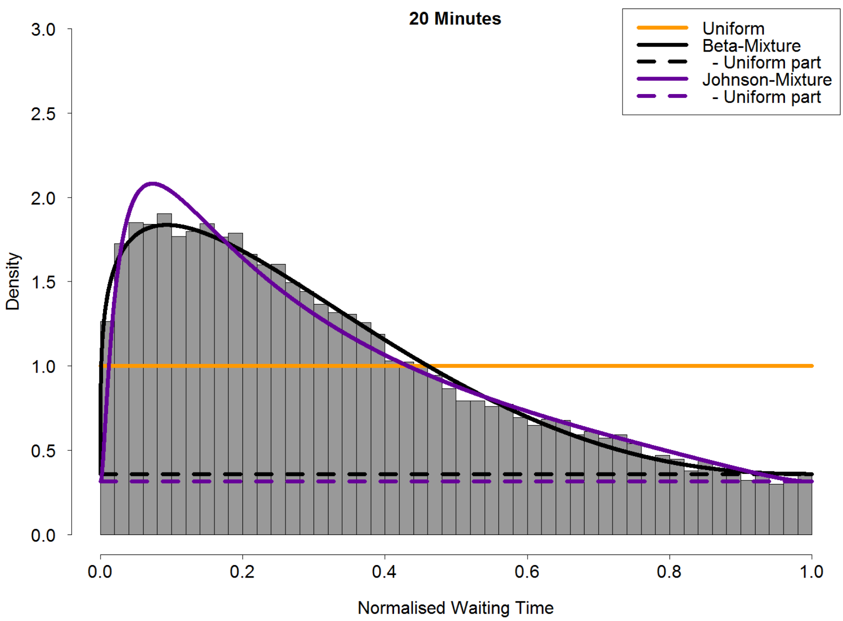

Figure 3.4; Comparison of the fit of various distributions to passenger waiting times.

As the headway time between train departures increases the share of random passenger arrivals decreases. Hence, at short five minute headway 57% of train passengers arrive randomly which decreases to 7% at 60 minute headway. At 10 minute headway the share is 48% suggesting that approximately half will try to time their arrival to stations. These results are consistent with previous studies which found that passengers will start timing their arrival if headway times are larger than 5-10 minutes (Jolliffe and Hutchinson, 1975; Luethi et al., 2007; O'Flaherty and Mangan, 1970; Seddon and Day, 1974).

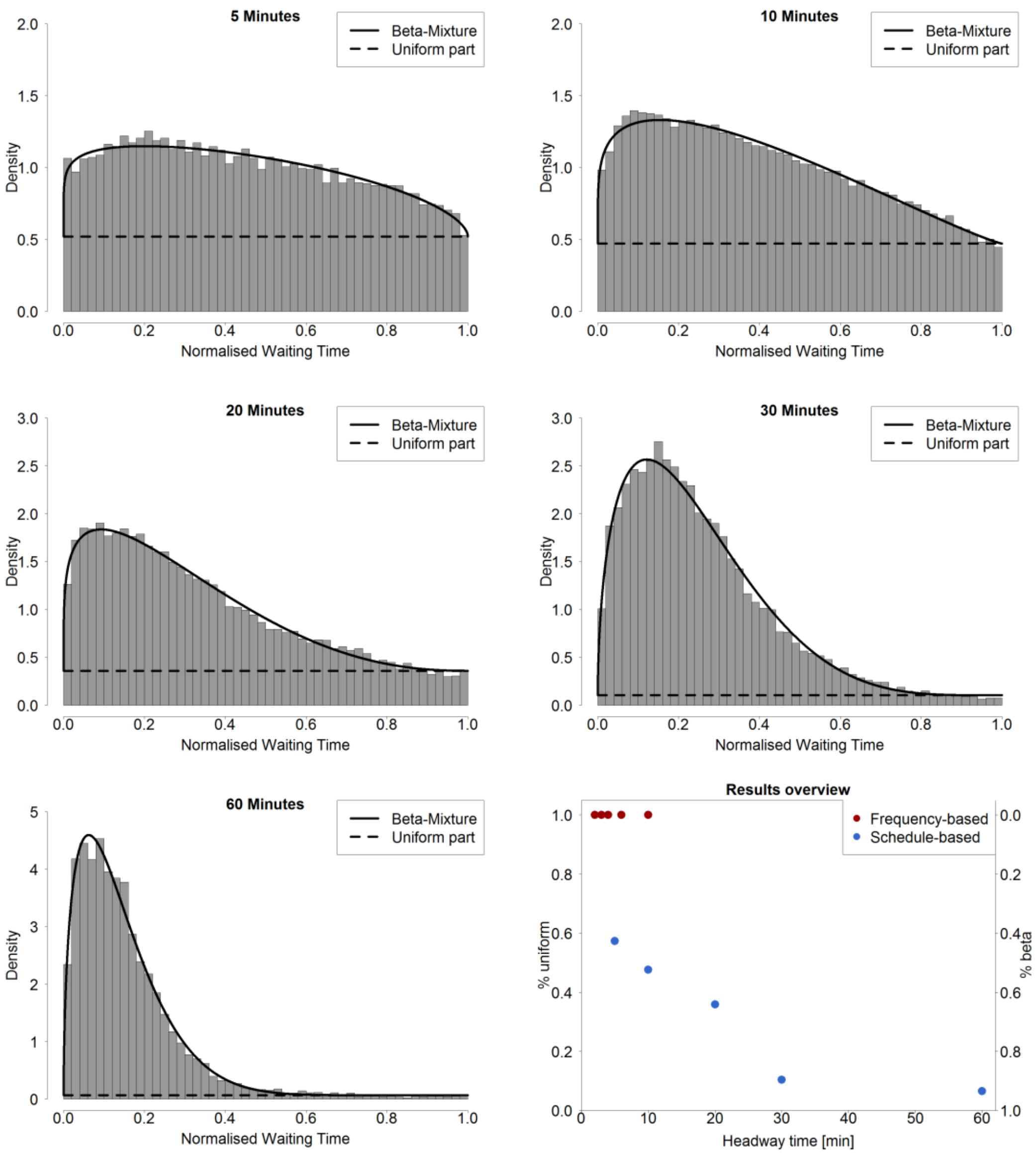

Figure 3.5; Mixture of uniform and beta distributions of passenger waiting times for headway times of 5-60 minutes, and results overview (lower right).

Table 3.3 shows the shares of the beta component (ς) and the uniform component (1 - ς) of the mixture distribution including the shape parameters of the beta component (α and β). As headway time increases, α decreased consistently from 0.41 at 5 minute headways to 0.14 at 60 minute headways. Similarly, β increased consistently from 2.85 at 5 minute headways to 11.2 at 60 minute headways, hence suggesting increasing positively skewness as headway time increases.

Headway	**Beta-share**	**Uniform-share**	**Beta-component**	
	ς	$1 - \varsigma$	α	β
5	0.43	0.57	0.41	2.85
10	0.52	0.48	0.36	3.39
20	0.64	0.36	0.27	4.57
30	0.90	0.10	0.24	6.52
60	0.93	0.07	0.14	11.20

Table 3.3; Parameter values for the beta-component of the mixture distributions at the evaluated headway times for schedule-based public transport services.

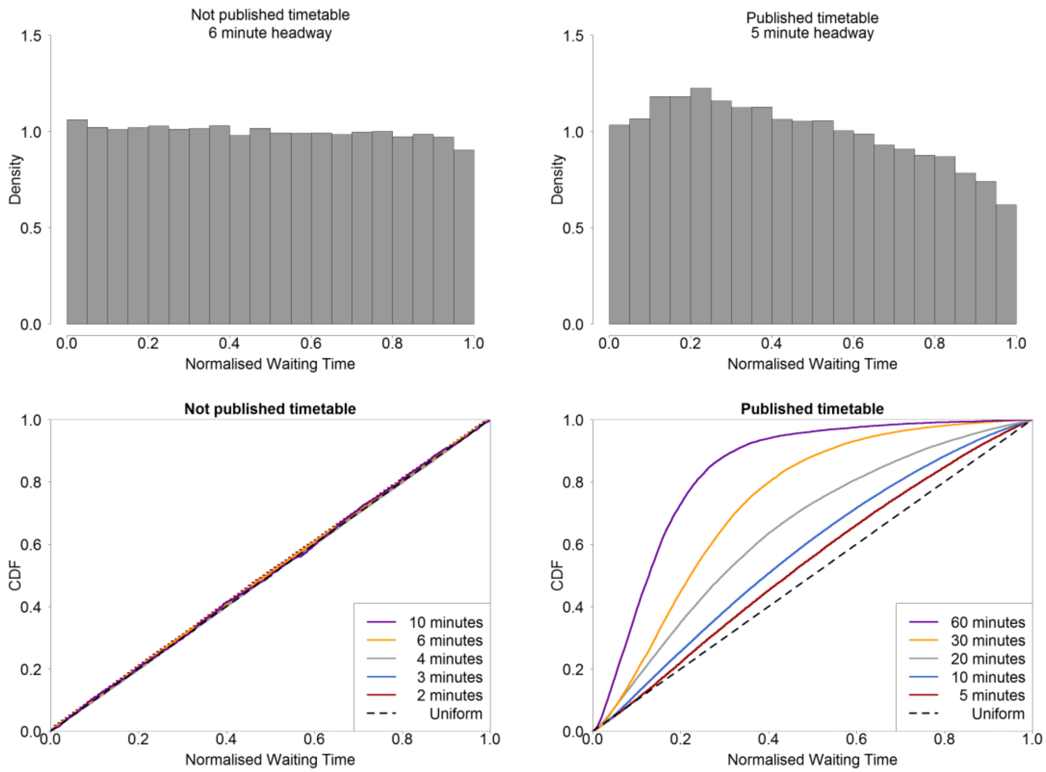

Figure 3.6; Comparison between effects of traditional timetables and frequency-based timetables on passenger waiting time distributions.

For metro passengers (i.e. frequency-based timetable) the estimated mixture distributions did not include a significant beta component for any of the analysed service headways. Instead, the best fit was a uniform waiting time distribution, hence suggesting random passenger arrivals, cf. the results overview in Figure 3.5. This suggests that passengers are unable to time their arrival to public transport services that use frequency-based timetables where actual departure times are not published. This can be seen specifically when comparing the waiting time distributions of metro passengers at 6 minute headways with those of S-train passengers at 5 minute headways, cf. Figure 3.6. Despite the similar headway times the waiting time distribution of metro passengers is estimated as fully uniform, whereas that of S-train passengers is 57% uniform and 43% beta. The results are pronounced at all headways of the metro where there is no significant beta-component for a mixture distribution resulting in the uniform component being estimated at 100%. However, it should be noted that statistical tests for fully random arrivals, i.e. fully uniform waiting time distributions, were rejected at the 95% confidence level for all but 10-minute headways.

The results imply that average waiting times for passengers are higher when timetables are not published, i.e. in the example case 49% of headway time for metro passengers as compared to 46% for S-train passengers, cf. Figure 3.6. In these cases the average waiting time is approximately half the headway. However, as headway time increases for scheduled public transport the average waiting time decreases to 35%, 26% and 16% of the headway time for 20, 30 and 60 minute headway, respectively, hence suggesting the importance of using actual timetables.

3.4.2 Influence of route choice

The stations in the public transport network vary in terms of number of lines served. As some stations are served by several lines going to the same destination, it is possible for passengers to adapt their route choice dependent on their arrival time at the station, whereas arrivals to specific lines might follow different patterns. For the data in Copenhagen two main cases were identified;

1. Trip legs from S-train stations served by multiple S-lines versus those served by one line
2. Trip legs from stations served by multiple train types, e.g. regional trains, suburban trains and metro

The first case compares the arrival pattern of passengers at the suburban train network, namely at stations which have only one line with that of stations with multiple lines serving the station. As headway time needs to be similar in order to perform a consistent comparison this analysis only compares Lyngby station, which is served by both a slow and a fast train, with the stations on the S-train Ring line which only has one service type stopping at all stations. As can be seen in Figure 3.7 the arrival distributions were very similar, and statistical tests revealed that the hypothesis of similar arrival behaviour could not be rejected for these cases at 5-minute headway.

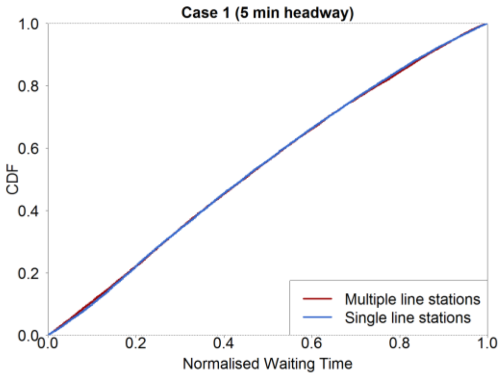

Figure 3.7; Comparison of waiting time distributions for passengers at stations with choice options at origin station.

The second case covers trip legs where the passenger can choose between multiple train types, namely between metro, regional, and S-trains. These cases cover services with quite far proximity between train and metro stations with long walking distances and several escalators up and down, no visual sight between platform, and with no joint information systems on departures. In addition, the service frequency for metro services is very high, hence reducing the potential benefit of an adapted route choice. However, as these cases relates to multiple public transport modes with varying service headways at all operating hours the actual service headway experienced by the passengers is uneven. As constant headway is required for the analyses these cases could not be compared.

3.4.3 Influence of time of travel

The effects of time of travel shown in Table 3.4 indicate that more passengers arrive randomly outside of peak hours than those traveling during peak hours.

This suggests that travellers during peak hours are frequent travellers who know the timetable better and are more eager to time their arrival to their preferred departure. This is in contrast to travellers outside peak hours and during weekends which seem to have less focus on minimising their waiting time. This difference in travel behaviour leads to increased waiting times for passengers outside peak hours as also seen in Figure 3.8 for 20-minute and 30-minute headways whereas the difference is minimal at 60-minute headways.

Headway	Weekday All hours	Weekday Peak hours	Weekday Off-Peak hours	Weekday Night hours	Weekend Day hours	Weekend Night hours
5	57% (2.3)	41% (2.3)	67% (2.3)	-	-	-
10	48% (4.3)	45% (4.2)	50% (4.3)	60% (4.4)*	50% (4.3)	65% (4.1)**
20	36% (7.1)	26% (6.4)	37% (7.2)	30% (6.3)**	28% (7.0)	47% (7.6)*
30	10% (7.9)	10% (7.6)	11% (8.2)	6% (6.3)**	12% (8.4)	31% (9.2)
60	7% (9.8)	8% (10.2)	6% (9.7)	4% (8.0)**	7% (9.2)	8% (9.7)*

*Table 3.4; The percentage of passengers arriving randomly as function of time of travel. Average passenger waiting times in parenthesis [minutes]. ** <200 observations; * <500 observations.*

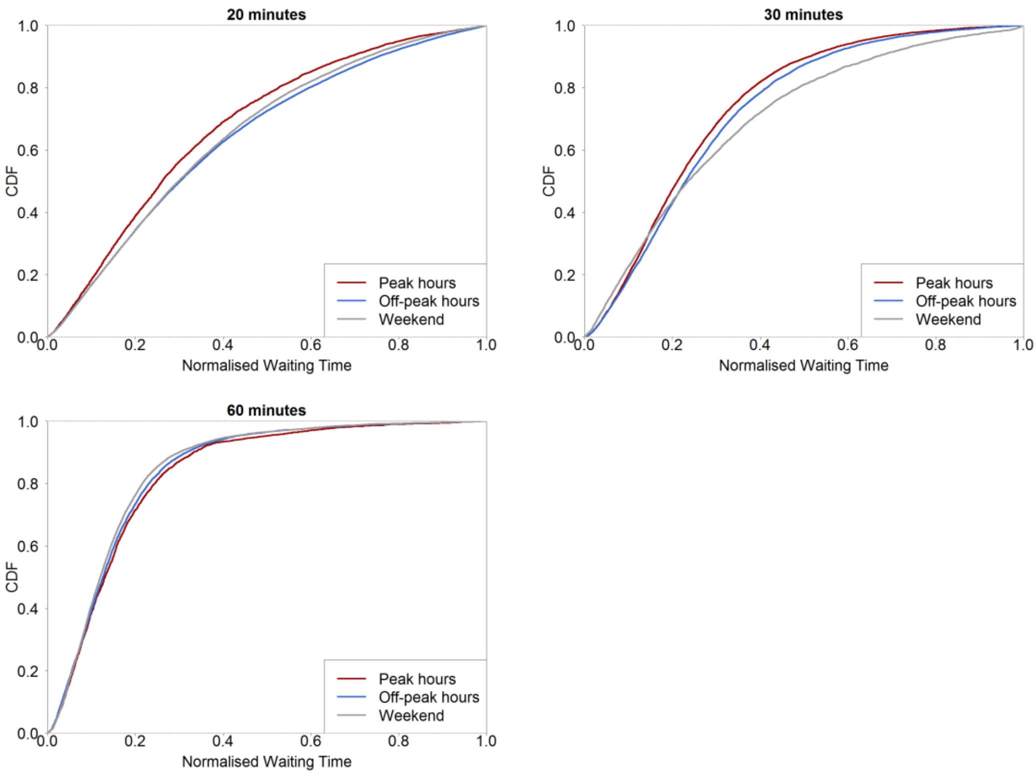

Figure 3.8; Difference between passenger waiting time distributions for passengers travelling during peak hours and off-peak hours for headway times of 20 minutes (left) and 30 minutes (right).

3.4.4 Influence of station characteristics

The characteristics listed in were analysed to investigate their influence on passenger waiting time distributions. Of the parameters tested notable effects were found for station layout in terms of ease of wayfinding whereas no effects were found for characteristics such as availability of various types of shelters, perceived safety level or being located underground or in close proximity to specific land use types.

Headway	All stations	Easy wayfinding	Difficult wayfinding
5	57% (2.3)	38% (2.3)	63% (2.3)
10	48% (4.3)	42% (4.2)	50% (4.3)
20	36% (7.0)	31% (6.5)	38% (7.3)
30	10% (7.9)	7% (6.7)	11% (8.3)
60	7% (9.8)	5% (7.1)	7% (9.8)

Table 3.5; The percentage of passengers arriving randomly as function of station layouts. Average passenger waiting times in parenthesis [minutes].

The results showed in Table 3.5 suggests that waiting times are generally longer when station layouts are more complicated and confusing. Hence, at headway times of 20, 30 and 60 minutes passengers arrive earlier at the station platform if stations are perceived as more confusing. This could suggest that passengers require a larger access time buffer for such stations in order not to risk missing their departure. As many of the stations with complicated layouts also have many passengers this result could also be related to congestion. At 5 and 10 minute headways no significant differences were found suggesting less incentive for buffer times at shorter headways.

3.4.5 Discussion and study limitations

While the methodology proposed by this study proved suitable across various service frequencies and station characteristics, still some assumptions could be addressed in future studies.

Firstly, the fundamental assumption of this study was that the actual waiting time of passengers can be calculated as the time from check-in to the time of the first departing train that also stopped on the destination (or transfer) station of the passenger. This require i) that passengers check in immediately on arrival, ii) that there is a very short distance from check-in to boarding the public transport vehicle, and iii) that the passengers do not change plans after arriving at the station, e.g. changes to another route due to delays. Several measures were taken to address the implications of these assumptions. As the check in stands are located on station platforms, the assumption of check-in on arrival is reasonable. This was also seen from the validation in section 3.3.4 which showed that there was not significantly more tap-ins immediately before departures, hence there was no evidence of this assumption being violated. Similarly, it was checked that the designated train did not arrive prior to the next tap-in of the passenger, hence eliminating the risk of passengers being assigned to a train that they did not catch. Finally, the possible effects of changes to route choice decisions were evaluated in section 3.4.2. This analysis was also performed to test the influence of provision of (real-time) information at the station. This might influence the behaviour of passengers before arriving to the station, but also after arriving where passengers might choose another travel alternative than originally planned due to delays. The results shown in section 4.2 revealed no significant differences between waiting time distributions for stations served by suburban skip-stop services and normal suburban train services.

Secondly, the present study did not include bus trips. This was not possible as the arrival time of bus passengers at the stop cannot be determined due to the check-in hardware being located inside the bus. However, recent research efforts have enabled the use of new technology such as capturing waiting passengers using Bluetooth or Wi-Fi detection from smartphones (Shlayan et al., 2016).

Thirdly, this study adopted a pseudo-timetable for metro trains as no published timetable is available for passengers. This included the correct service frequency, but no accurate departure times. However, as the results showed that passenger arrivals were almost entirely random independent of service frequency, using an actual planned timetable would similarly result in almost entirely uniform waiting time distributions. Hence, the general conclusions would not change notably.

Fourthly, the approach in this paper suggests that the waiting time distributions at each station is a mixture of a uniform and a beta distribution. Methodologically, it can be argued that the full distribution of each headway time is a weighted sum of mixture distributions due to aggregating waiting times over multiple stations. This entails that a mixture distribution should be estimated for *each* station. However, that would require extensive data requirements making it infeasible for practical use. In this study we therefore validated the *aggregate* distribution making the approach easily adaptable for use in transport models.

Finally, a path for future research on the topic could be how other travel characteristics influence waiting time distributions and the share percentages of random and timely passenger arrivals. Specifically, this could include the influence of weather or seasons which have been highlighted to have an effect on ridership (Arana et al., 2014; Zhou et al., 2017). In Copenhagen this might have an effect as the weather conditions changes notably during the year, and even during the same day. It could therefore be an interesting extension to analyse whether passenger arrival behaviour at stations is affected by local weather conditions. Unfortunately it was exorbitant expensive to acquire local weather data from the Danish Meteorological Agency to carry out this analysis.

3.5 CONCLUSIONS

The paper presents an approach to model passenger waiting time as a mixture distribution to explicitly take into account the arrival behaviour of public transport passengers at stations. Specifically, arrival patterns of passengers can be grouped into two groups: i) one group arriving randomly, e.g. due to not knowing the timetable, and ii) another group arriving according to a beta distribution, e.g. due to timing their arrival to the station in order to minimise the waiting time at the station. The approach was tested using a large-scale Automatic Fare Collection (AFC) system from the Greater Copenhagen Area revealing better fit than prior arrival models proposed in the literature. The measurements were also validated against manually collected data to ensure that the passenger arrival times matched the check-in time, which was a fundamental assumption used in the calculation of waiting times. The data source used ensured a large sample covering trip legs in metros, suburban, regional and intercity trains across headway times of 2-60 minutes.

The results showed that the share of passengers arriving randomly decreases as the headway time increases. Even at short headway times a large share of passengers are trying to minimise their waiting time by timing their arrival time at stations. At 5- and 10-minute headways this share was estimated at 43% and 52%, respectively, increasing with higher service frequencies. These results were only evident for train stations with public schedule-based timetables whereas arrival patterns at metro stations with frequency-based timetables were random independent of headway time. This finding points towards the importance of publishing real timetables to passengers even at short headway times typically seen in high-frequency metro services. However, if severe regularity issues are observed published timetables will be less important.

In addition, the study revealed more timed arrival patterns at rush hours as compared to other time of day and weekends. The results of station characteristics showed that stations with confusing station layout led to increased passenger waiting times. This was probably due to the need for passengers to add an extra time buffer to their access time when arriving to the station. Hence, it is of great importance to ensure easy accessibility to stations in order to reduce passenger waiting times and thus to ensure attractive public transport systems.

3.6 IMPLICATIONS

The study has two important implications for policy and practice. Firstly, the findings highlight the importance of providing passengers real timetables whenever possible. This makes it possible for passengers to be able to time their arrival at the station in order to minimise their waiting time. Even at high service frequency this study found empirical evidence that many passengers actively time their arrival to the train departure. By not providing exact timetables passengers are forced to arrive randomly, thus prolonging their waiting time. Taking into account that passengers value waiting time higher than other time components further highlights the importance.

Secondly, the proposed framework of modelling passenger waiting times points towards new alternative ways of incorporating passenger behaviour in transport assignment models. Instead of assuming fixed hidden waiting times based on scheduled service frequency transport models can be improved by explicitly model the actual passenger arrival patterns at stations. The present study found that a mixture distribution consisting of one part uniform and one part beta distribution fitted actual arrival patterns well, and that the actual distribution parameters depend on service frequency.

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4 Effects of new bus and rail transit systems – an international review

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Abstract

Cities worldwide are implementing modern transit systems to improve mobility in the increasingly congested metropolitan areas. Despite much research on the effects of such systems, a comparison of effects across transit modes and countries has not been studied comprehensively. This paper fills this gap in the literature by reviewing and comparing the effects obtained by 86 transit systems around the world including Bus Rapid Transit (BRT), Light Rail Transit (LRT), metro, and heavy-rail transit systems. The analysis is two-fold by analysing i) the direct operational effects related to travel time, ridership, and modal shifts, and ii) the indirect strategic effects in terms of effects on property values and urban development. The review confirms the existing literature suggesting that BRT can attract many passengers if travel time reductions are significantly high. This leads to attractive areas surrounding the transit line with increasing property values. Such effects are traditionally associated with attractive rail-based public transport systems. However, a statistical comparison of 41 systems did not show significant deviations between effects on property values resulting from BRT, LRT, and metro systems, respectively. Hence, this paper indicates that large strategic effects can be obtained by implementing BRT systems at a much lower cost.

Keywords: Bus Rapid Transit (BRT), Light Rail Transit (LRT), property values, traffic impacts, urban development, public transport systems, system comparison.

4.1 INTRODUCTION

Public transport systems are important for improving mobility and relieving traffic congestion in the increasingly congested metropolitan areas. Hence, cities around the world are searching for the most efficient way of upgrading their public transport networks. This involves planning the appropriate cost-effective system for a given context ranging from low-cost Bus Rapid Transit systems (BRT) over modern Light Rail Transit (LRT) to more costly, but highly attractive metro or urban railway systems. With the increasing focus on cost-effectiveness in transport investments it is important to know the possible effects when upgrading public transport networks. This reveals the strengths and weaknesses of various systems including the drivers for ensuring that the systems will be attractive for passengers.

Over the past decades BRT and LRT systems have experienced increased popularity due to their ability to deliver attractive service levels at a lower cost than those of heavy rail and metro systems. In Europe the first modern light rail system was opened in 1985 in Nantes. Due to the success of the system, several other French cities implemented light rail systems in the following years in corridors where the ridership was too small to justify an expensive metro solution, but where there was a wish to upgrade the existing bus operations (Bottoms, 2003). In Latin America several cities have focused on BRT systems, primarily due to the lower construction costs. The first systems were established in the 1970s and 1980s in the aftermath of the successful *Rede Integrada de Transporte* in Curitiba, Brazil, which was established in 1974. The number of BRT systems has increased significantly, particularly within the last 10 years, and currently, 200 cities have BRT systems serving 33 million passengers every day, 88% of them located in Latin America or Asia (“Global BRT Data,” 2016). However, BRT systems are also becoming increasingly popular in Europe, where they are often also referred to as Buses with High Level of Service (BHLS) (Hidalgo and Muñoz, 2014). Hence, successful systems now exist in many European cities including Paris, Nantes, Rouen, Madrid, Amsterdam and many others (Finn et al., 2011).

The systems vary greatly between countries, especially for BRT which is not a strict definition. Much literature therefore focuses on the design concepts and system characteristics of BRT (Levinson et al., 2002), (Wright and Hook, 2007), (Hensher and Golob, 2008), (Nikitas and Karlsson, 2015), (Wirasinghe et al., 2013), and others. Some studies investigate the individual attractiveness of such characteristics on ridership for BRT (Currie and Delbosc, 2011) and for LRT (Currie et al., 2011), while studies also exist that compare across the two modes (Currie and Delbosc, 2013). In addition, many single transit systems have been analysed in terms of effects on ridership, urban development and property values (Cao & Schoner, 2014; Cervero, 1984; Dueker & Bianco, 1999; Knowles, 1996, and many others). These studies include a review of the relevant literature, but often focus on either BRT or LRT systems only.

A few papers review the urban development effects focusing on either BRT (Currie, 2006a; Stokenberga, 2014) or LRT systems (Knowles and Ferbrache, 2015). In (Ryan, 1999) the effects of property values are compared across the modes of light rail, heavy rail and highways while also focusing on methodological differences between studies throughout the 1960s-1990s. Several other studies compare the effects between BRT and metro in Beijing (Ma et al., 2014) and Guangzhou (Salon et al., 2014), and between BRT and LRT in Pittsburgh (Perk et al., 2010). The limitations of these studies consist in them either focusing on the effects of a single public transport mode (Currie, 2006a; Knowles and Ferbrache, 2015; Stokenberga, 2014), not including the three main high-class public transport modes of metro, LRT and BRT (Ryan, 1999), and/or only reviewing a few studies (Ma et al., 2014; Perk et al., 2010; Salon et al., 2014).

This paper fills the gap in the literature by reviewing the effects of a large sample of 86 transit systems including BRT, LRT and metro/heavy rail. The effects have been analysed in terms of changes in demand, including modal shifts (section 2), and strategic effects in terms of changes in property values (section 3). Furthermore, section 4 presents a number of examples on the impacts on city development. Section 5 discusses the methodological considerations and points to future work while section 6 concludes the review by highlighting the impacts caused by the various public transport modes and thus compares the mode-dependent effects.

4.2 TRAFFIC IMPACTS

One of the main reasons for upgrading and extending public transport is to obtain travel time benefits for the users of the system. It is therefore essential to study the potential travel time improvements of metro, LRT and BRT, respectively. In urban areas the construction of a metro provides the biggest travel time benefits as metros run in fully segregated right-of-way as opposed to light rail systems and BRT which are often constructed at street level with crossings. High speeds with light rail systems and BRT can however be obtained by implementing dedicated right-of-way, signal priority, and other Advanced Public Transport Systems (APTS) elements (Ingvardson et al., 2015). The various elements of BRT make it easy to adapt the concept to a local context. However, this flexibility may lead to the implementation of half measures where one or often several elements have been left out to save construction costs (Rodríguez and Targa, 2004). As a consequence, big variations exist between the various systems around the world. Some systems are just conventional bus lines that have been upgraded with a few BRT elements, for instance bus lanes, signal priority or special vehicles. Other systems contain entire corridors with completely segregated bus lanes, station-like bus stops with ticketing systems on the platform, real-time information and signal priority along the entire corridor. Such large differences between system solutions make it difficult to establish general impacts as they will depend on the design of the system and the degree of improvement with respect to the original solution.

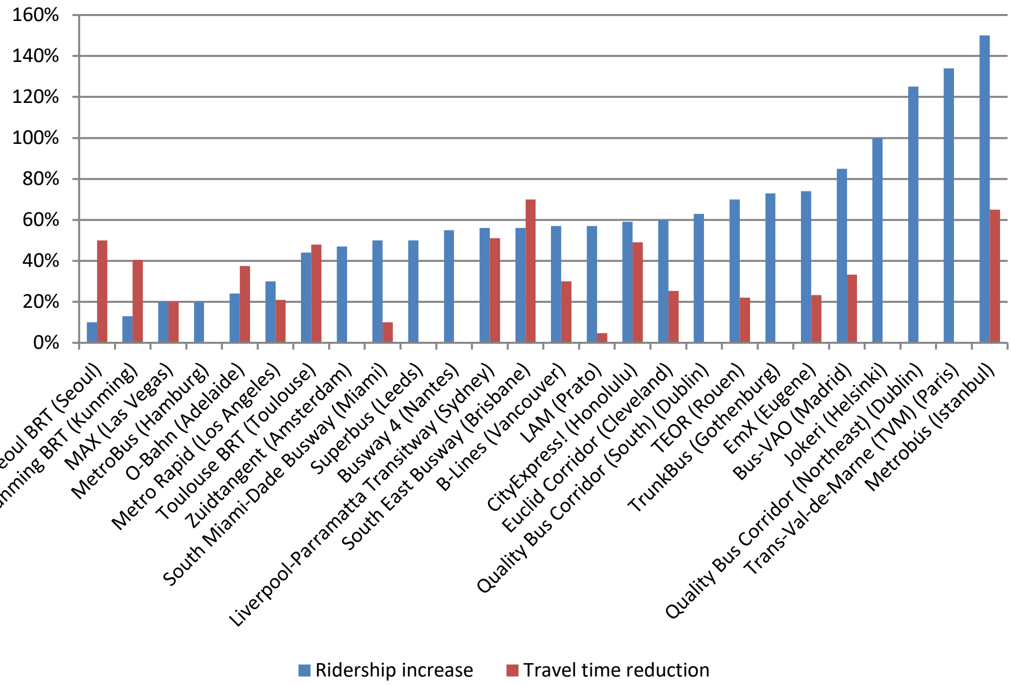

Figure 4.1: Relationship between travel time reductions and increase in ridership for selected BRT systems.

clearly shows the large variation in ridership effects of various BRT systems. Some of the largest increases in ridership were obtained by Metrobús in Istanbul, where a thorough implementation of BRT elements, including an almost fully segregated infrastructure, ensured travel time reductions of 65% resulting in 150% more passengers (Yazici et al., 2013). In Paris, the Trans-Val-de-Marne route was reported to gain an increase of 134% in ridership after opening; this increase however possibly included effects of general traffic growth as it was measured over a longer period of time. The system induced significant improvements to travel time in terms of 16 minutes decrease in travel time through the 20 km corridor (Finn et al., 2011). In Dublin, the implementation of Quality Bus Corridors resulted in significantly increased ridership of up to 125% for the northeastern Malahide corridor (Finn et al., 2011) and 63% for the southern Stillorgan corridor (O'Mahony, 2002). This despite the corridors not being full BRT systems as they mainly included bus lanes (shared with taxis and bicyclists) and some service improvements including higher frequency and bus priority. This resulted in significantly increased bus travel speeds and faster than car travel speeds during peak hours, however, primarily because of simultaneous closure of road traffic lanes (O'Mahony, 2002). In Madrid, the Bus-VAO system obtained a 33% travel time reduction due to its running almost fully segregated. Together with strong connections to the metro network ridership increased by 85% (Heddebaut et al., 2010). Several systems were implemented in the United States with dedicated infrastructure and strong branding resulting in increased travel speed and ridership, e.g. the EmX BRT system in Eugene which attracted 74% more passengers by implementing off-board fare collection and dedicated busways. Combined with strong branding it resulted in a 23% travel time reduction. The Cleveland Euclid corridor BRT resulted in a 60% ridership increase after two years of operation due to a largely segregated system ensuring a 34% speed increase (Weinstock et al., 2011). In Honolulu, a 49% travel time reduction resulted in a 59% ridership increase after one year of service (City and County of Honolulu, 2001). And in Miami, the South Miami-Dade Busway resulted in a 50% increase in ridership resulting from a travel time reduction of less than 10% (National BRT Institute, 2003). The system incorporated fully segregated busways and special stations equipped with information and shelters. In Europe, similar impacts were obtained in several cities, including Rouen, Prato and Nantes, which saw passenger ridership increases in the same ranges around 60%. In Prato, Italy, a relatively small improvement in travel time resulted in a big increase in ridership due to a simultaneous doubling of frequency and strong branding (Heddebaut et al., 2010). The systems in Nantes and Rouen both included almost full segregation, special branding and some pre-board fare collection resulting in high levels of reliability and ridership increases of 55-70%. Also in Australia several systems obtained large positive effects. In Brisbane, ridership increased by 56% due to a fully segregated system with signal priority and high frequency resulting in a 70% travel time reduction (Currie, 2006b). The Liverpool-Parramatta Transitway in Sydney implemented dedicated busways and bus lanes as well as Intelligent Transport Systems (ITS) elements including traffic signal priority, real time passenger information and some off-board fare collection (Currie, 2006b). The implementation ensured a 51% travel time reduction and 56% ridership increase.

In other places, only smaller effects were seen despite implementing thorough and high-class systems with travel time reductions of 40-50%. In Seoul, the effect of the BRT on ridership was only a 10% increase within one year after opening, which however should be compared to a general decline in ridership for buses during the same period as well as a very high attractiveness of the Seoul subway carrying 35% of all trips in Seoul (Cervero and Kang, 2011). Hence, the public transport system was quite attractive already before implementing BRT. In Kunming, ridership increased by 13% at its opening, but an increase of 100% was seen five years after opening (Darido, 2006). The Las Vegas MAX bus line resulted in a 25% ridership increase when implementing segregation in 60% of the corridor, off-board fare collection and specially branded buses resulting in a travel time reduction of 20% (Weinstock et al., 2011). The Metro Rapid system in Los Angeles did not feature segregated infrastructure, but relied on efficient route design with longer stop spacings, signal priority, special branding of vehicles and stations that allowed for faster dwell times (Hoffman, 2008). The average travel time reductions of 21% resulted in increased ridership of 15-20%, for some corridors up to 33% (Levinson et al., 2002). In

Hamburg, the Metrobus system improved the existing bus line by implementing segregation on 27% of the corridor, some branding, strong integration and signal priority resulting in minor increases to travel speed and ridership (Finn et al., 2011).

These results show that all systems had notable effects on travel time and thus ridership. Systems that included thorough implementations of many BRT elements such as dedicated bus lanes on most segments, signal priority, pre-board fare collection and special branding obtained significant improvements of travel time and ridership. When combined, these elements can notably improve not only travel times, but also reliability which is often difficult to improve in bus operations, hence causing bus bunching, e.g. in Gothenburg (Heddebaut et al., 2010) and Copenhagen (Ingvardson et al., 2015). The results however also show that effects vary notably between systems and cannot only be explained by travel time improvements. Several other factors influence the effects such as the attractiveness of the existing public transport network and the car traffic conditions, including road congestion and car use restrictions. But also factors related to the local context seem to play a role which has not been fully investigated in the reviewed studies. Hence, there seems to be a knowledge gap regarding the influence and importance of factors not related to the actual improvement of the public transport line which may explain the attractiveness of the public transport line.

4.2.1 Modal shift

The increased ridership when implementing new public transport systems is caused by both induced traffic and a mode shift effect. In several places it has thus been observed that the new system has attracted users who previously used other modes, e.g. cars. Mode shifts from cars are especially important for two major reasons. Firstly, shifting car users to public transport will relieve congestion in the often very congested road network in large metropolitan areas. Secondly, there is an increasing focus by policy makers to promote sustainable transport for environmental reasons. In Table 4.1 the mode shift from cars is listed for a range of public transport systems. The systems mentioned gave rise to significant mode shifts from other modes, especially from buses, e.g. in Copenhagen and Istanbul (Vuk, 2005; Yazici et al., 2013), from bicycles in Utrecht (Finn et al., 2011) and from metro in Stockholm (Finn et al., 2011).

Again, effects vary notably across all systems. However, it should be observed that several of the figures represent relatively small lines. For instance, 22% of the passengers on the Sheffield Supertram were former car users. When comparing with the market share of LRT of 17% the mode shift was only around 4%. This is general for all studies as the numbers represent the percent of passengers who previously travelled by car. In the case of San Diego Trolley 30% of the passengers after the opening of the first line in 1981 were former car users. In 1990 the share was estimated at 50% after the opening of the second line in the same light rail system (Lee and Senior, 2013). Another example worth mentioning was the 19% mode shift obtained for the Los Angeles Orange Line, which was established in a new segregated corridor. A passenger survey showed the same level of satisfaction with the BRT line as with the Gold Line LRT and a higher level of satisfaction than with the Blue Line LRT. This was probably due to the high level of service thanks to the segregated infrastructure (Cain et al., 2009). However, the Blue Line also obtained a similarly large mode shift (21%) of passengers from car traffic which in absolute numbers was significantly larger, since the line serves three times as many passengers than the Orange Line. On the other hand, no significant shift from car traffic was obtained for the LRT system in Angers, probably due to the fact that the LRT did not reduce the travel time as compared to the existing bus lines. Instead the LRT was implemented to attach the central urban areas to a high-class public mode of transport (Olesen, 2014).

System	Mode shift[15]	Source
Metrobús (BRT, Istanbul)	4-9%	Yazici et al. (2013) Alpkokin and Ergun (2012)
Stombuss (Blue buses) (BRT, Stockholm)	5%	Finn et al. (2011)
Trans-Val-de-Marne (BRT, Paris)	8%	Finn et al. (2011)
BRT Line 1 (BRT, Beijing)	12%	Deng and Nelson (2013)
Jokeri line (BRT, Helsinki)	12%	Finn et al. (2011)
TransJakarta (BRT, Jakarta)	14%	Ernst (2005)
Bus-VAO (BRT, Madrid)	15%	Finn et al. (2011)
QBC – Malahide corridor (BRT, Dublin)	17%	O'Mahony (2002)
Kent Thameside (BRT, Kent)	19%	Deng and Nelson (2011)
Orange Line (BRT, Los Angeles)	19%	Callaghan and Vincent (2007)
South Miami-Dade Busway (BRT, Miami)	21%	National BRT Institute (2003)
Nantes BHLS (BRT, Nantes)	29%	Rabuel (2010)
O-Bahn (BRT, Adelaide)	40%	Currie and Sarvi (2012)
Angers Tramway (LRT, Angers)	0%	Olesen (2014)
Midland Metro (LRT, Birminigham)	13%	Harper and Bird (2000)
Nantes LRT (LRT, Nantes)	17-37%	Lee and Senior (2013)
Croydon (LRT, Croydon)	19%	Copley et al.(2002)
Metrolink (LRT, Manchester)	21%	Knowles (1996)
Blue Line (LRT, Los Angeles)	21%	Lee and Senior (2013)
Sheffield Supertram (LRT, Sheffield)	22%	Lee and Senior (2013)
Blue Line (LRT, San Diego)	30%[16]	Lee and Senior (2013)
Orange Line (LRT, San Diego)	50%[16]	Lee and Senior (2013)
Avg. 14 European systems (LRT)	11%	Hass-Klau et al.(2003)
Copenhagen Metro (Metro, Copenhagen)	8-14%	Vuk (2005)
BART (Metro, San Francisco)	35%	Richmond (1991)

Table 4.1: Mode shift from car traffic for selected public transport systems.

[15] Percent of passengers who previously travelled by car.

[16] Mode shift for commuting trips based on travel surveys.

In general, the findings show that both BRT and LRT systems obtained a sufficiently high attractiveness to attract users from other modes of transport, including former car users. This could indicate that the quality of the upgrade is more important than the choice of system. But as the capacity is often highest for metro systems and lowest for BRT systems a similar mode shift will induce different impacts on car traffic, i.e. metro systems can have larger impacts on road congestion than BRT systems. However, exceptions do exist, e.g. the Metrobús corridor in Istanbul which carries 600,000 passengers per day and hence is running at a very high capacity (Yazici et al., 2013). Hence, in order to obtain notable impacts on car traffic attractive high-capacity systems are needed.

4.3 STRATEGIC EFFECTS

Generally, major improvements to public transport systems will, all other things being equal, result in significant changes in real estate prices (Pagliara and Papa, 2011). Many examples exist of how large infrastructure projects have had a positive influence on urban development, as the accessibility of an area is increased when the transport system is improved resulting in lower travel times. This makes the areas more attractive which is reflected in higher real estate prices for existing buildings, and it makes the areas more attractive for investors resulting in new urban development. The strategic effects of extending the public transport network may be bigger than the pure traffic effects (Al-Dubiki and Mees, 2010). Many analyses attempt to quantify the effects of real estate prices on various transport systems. Tables 4.2-4 provide an overview of the influence of BRT, LRT and metro systems on real estate prices.

There are thus big differences between the listed projects. There are two important factors that are important to highlight before comparing the figures.

Firstly, there is no general standardised method for the calculation of changes in real estate prices (Banister and Thurstain-Goodwin, 2011). Consequently the different studies used a variety of methods of analysis and data sources (Munoz-Raskin, 2010). For example, different distances were used to define when a property was placed close to a station. However, the impact area was considered to be approximately 1000 m for residential properties and 400 m for commercial properties such as shops and offices (Banister and Thurstain-Goodwin, 2011). There was however a high degree of variability since some studies analysed properties within a distance of 200-400 m (Hess and Almeida, 2007) and others examined properties within a distance of 1,000 m (Rodríguez and Mojica, 2009) or just indicated that the property was within an urban area served by a station (Armstrong and Rodríguez, 2006; Voith, 1993).

Secondly, the projects were very dependent on local conditions (Martínez and Viegas, 2009). This was observed even between corridors within the same study. In San Diego considerably higher sales prices (between 4% and 17%) could be demonstrated for properties within walking distance of a light rail station, depending on the corridor in which the property was situated (Cervero and Duncan, 2002a). In one of the corridors no relationship between price and distance to the station could be found. This was also reflected in a similar study of the effects of various systems in Los Angeles (Cervero and Duncan, 2002b). Here the results varied considerably depending on the type of property (house, flat and commercial property) and station type (bus, metro and light rail). The same result was found in connection with the establishment of the LRT system in Phoenix where the results to a large extent depended on the types of dwellings (Golub et al., 2012). In Philadelphia very different effects were also found for different networks, since real estate prices for properties close to PATCO stations were 10% higher, whereas the prices of properties situated closer to SEPTA stations were only 4% higher than those of comparable properties. However, in this case the difference could be partly explained by other factors, one of them being that PATCO provided better travel times as compared to car and SEPTA (Voith, 1991).

System	Property value change	Source
BRT Line 1 (Beijing)	0	Ma et al.(2014)
Seoul BRT (Seoul)	+5-10%	Cervero and Kang (2011)
TEOR (Rouen)	+10%	Martínez and Viegas (2009)
TransMilenio (Bogotá)	+11-13%	Perdomo Calvo et al. (2007), Rodríguez and Targa (2004)
East Busway (Pittsburgh, USA)	+16%	(Perk et al., 2010)
South-East Busway (Brisbane)	+20%	Levinson et al. (2003b)
Guangzhou BRT (Guangzhou)	+0-30%	Suzuki et al.(2013), Salon et al. (2014)

Table 4.2: Effects of BRT systems on property values.

System	Property value change	Source
Supertram (Sheffield, UK)	0	Dabinett et al. (1999)
Sacramento RT Light Rail (Sacramento, USA)	0	Landis et al. (1995)
Metrolink light rail	0	Martínez and Viegas (2009)
(Manchester, UK)	-6%	Forrest et al. (1996)
MetroRail (Houston, USA)	+/-	Pan (2012)
Eastside MAX (Portland, USA)	+0-10.6%	Al-Mosaind et al. (1993), Chen et al. (1998)
San Diego Trolley (San Diego, USA)	+0-17.3%	Cervero and Duncan (2002a), Landis et al.(1995)
Buffalo Metro Rail (Buffalo, USA)	+2-5%	Hess and Almeida (2007)
Bybanen (Bergen)	+4%	Fredriksen (2013)
DART (Dallas, USA)	+10-25%	Weinstein and Clower (2002)
Metro Light Rail (Phoenix, USA)	+25%	Golub et al. (2012)
Metrolink (St. Louis, USA)	+32%	Martínez and Viegas (2009)
Tramlink (Croydon, UK)	+	ATISREAL et al. (2004)
Docklands (London, UK)	+	Knowles and Ferbrache (2015), Martínez and Viegas (2009)

Table 4.3: Effects of LRT systems on property values. Note: + denotes significant, but non-quantified positive effects, and +/- denotes mixed positive and negative non-quantified effects.

System	Property value change	Source
Coaster (San Diego, USA)	-7.1%	Cervero and Duncan (2002a)
Caltrain (San Francisco, USA)	0	Landis et al. (1995)
Miami metrorail (Miami, USA)	0	Gatzlaff and Smith (1993)
MARTA (Atlanta, USA)	+/-	Bollinger and Ihlanfeldt (1997)
BART (San Francisco, USA)	+0-4%	Landis et al. (1994), Landis et al. (1995), Dueker and Bianco (1999)
Lindenwold line (Philadelphia, USA)	+0-8%	Voith (1993)
Tyne and Wear Metro (Newcastle, UK)	+2%	Pickett (1984)
Copenhagen Metro	+3.8%	Kolstrup (2006)
SEPTA (Philadelphia, USA)	+3.8%	Voith (1991)
MBTA (Boston, USA)	+6-10%	Armstrong and Robert (1994)
Belfast suburban rail (Belfast)	+8%	Adair et al. (2000)
Helsinki metro (Helsinki)	+8%	Hack (2002)
Seoul Subway (Seoul)	+9%	Bae et al. (2003)
PATCO (Philadelphia, USA)	+10%	Voith (1991)
Midway line (Chicago, USA)	+17%	McDonald and Osuji (1995)
Metra (Chicago, USA)	+20%	Lin (2002)
Toronto subway (Toronto)	+20%	Hack (2002)
Jubilee Line Extension (London, UK)	+	Jones et al. (2004), Martínez and Viegas (2009)
Guangzhou Metro (Guangzhou)	+	Salon et al. (2014)

Table 4.4: Effects of metro and heavy rail systems on property values. Note: + denotes significant, but non-quantified positive effects, and +/- denotes mixed positive and negative non-quantified effects.

When analysing the impacts on property values further, several findings were observed. For several of the systems the analyses showed that the effects occurred even before the system was implemented. The prices thus increased due to the *expectation* of improved accessibility. This was observed in connection with the establishment of the railway line between Chicago and the Midway Airport where the property prices rose by 17% within a distance of 800 m from the future stations. This observation was made three years before the connection actually opened (McDonald and Osuji, 1995). A similar effect was observed in Seoul where the station distance only affected property values significantly prior to the opening of the line 5 subway (Bae et al., 2003). In Portland land values increased significantly when the construction of the MAX LRT system was announced (Knaap et al., 2001), and they increased even more after the system had been implemented (Chen et al., 1998).

In addition to the projects mentioned in Tables 4.2-4.4 there are many other examples of projects where a general significant tendency of decreasing real estate prices can be observed when the distance to the nearest station increases. However, this tendency is not found for all distances. In particular, several studies found a direct negative effect within a very short distance from the station (Brandt and Maennig, 2011; Chen et al., 1998; Debrezion et al., 2006; Landis et al., 1994). This was explained by increased noise annoyances and, to some extent, higher crime rates. In Phoenix this relationship was analysed explicitly since shorter distances to light rail stations resulted in higher real estate prices, whereas shorter distances to the light rail alignment resulted in lower real estate prices (Golub et al., 2012). Similarly, in Houston close proximity to LRT stations had significant negative impacts on property values whereas positive effects were seen for properties located longer away from stations (Pan, 2012). In Chen et al. (1998) the relative influence of the negative nuisance effects and the positive improved accessibility effects for the Portland MAX LRT system was compared. It was found that the improved accessibility outweighed the nuisance effects, but the study highlighted the importance of taking into account the nuisance effects which vary depending on the type of public transport system.

Such effects have also been observed for BRT systems. In Guangzhou real estate prices within 1,000 m from the BRT stations decreased whereas they increased for properties more than 1,000 m away from the stations. This tendency was not found for metro stations and was to a large extent due to noise annoyances and congestion problems (Salon et al., 2014). However, for the TransMilenio in Bogotá such an effect was not found (Munoz-Raskin, 2010). Here higher real estate prices were observed within a distance of 250 m from a BRT station than in a 250-500 m band around the stations.

Several of the examined BRT systems have shown to have a relatively large impact on property values with increases of up to 20-30% in Brisbane in Australia. This large increase followed a significant upgrade where a completely segregated bus lane was established in a corridor from the city centre to the university southeast of the city which resulted in a reduction of the travel time by more than 30% (Currie, 2006b). In the time following the opening of the system real estate prices in the corridor rose 2-3 times faster than those of similar properties, and the prices of residential properties within walking distance from the bus corridor were 20% higher after the opening than those of other comparable properties (Levinson et al., 2003a). Bogotá also saw an increase of 13-15% for residential properties situated within 1,000 m of the TransMilenio system after the opening of an extension of the network (Rodríguez and Mojica, 2009). A minor effect was observed in Seoul where the price of residential properties within 300 m from the new BRT line rose by 5-10% after the opening of the line (Cervero and Kang, 2011). According to the same study the price of commercial properties within 150 m from a station rose by up to 26%. In Pittsburgh, Perk et al. (2010) found that the East Busway BRT had a significant positive effect on real estate prices, and the effect of being close to a BRT station was bigger than that of being close to an LRT station.

Other studies have compared the effects of BRT, LRT and metro, respectively. Debrezion, Pels & Rietveld (2007) concluded that real estate prices of properties situated within 400 m from so-called commuter rail stations were 14.1% higher, based on a comparison of 73 local public transport systems. However, no significant differences were found for properties situated close to LRT and BRT stations. In addition, the same study found that the effect on real estate prices was bigger for commercial properties than for residential properties when the property was situated within 400 m from a station. On the other hand, the effect was higher for residential properties situated more than 400 m from the station. In Beijing the effects of the newly established BRT line, Line 1, were compared with the effects of the metro (Ma et al., 2014). Here it was found that real estate prices were 5% higher for properties close to metro stations (within 800 m), whereas no significant effect for properties situated close to BRT stations could be found. However, Deng & Nelson (2013) report that the BRT line had positive effects on property development including rising property values along its corridor. This was based on a survey distributed to real-estate agents. In Guangzhou a minor effect for properties situated close to BRT stations could be observed, but it was not nearly as big as the effect observed for properties near the metro (Salon et al., 2014). This could both be because the metro was more attractive, and also because the station areas around the metro had more attractive shops and were perceived as being less influenced by externalities, e.g. noise and congestion. Generally, the largest effects were found for the lines providing the biggest travel time benefits.

There is also a tendency that the effect was biggest in low-income areas whereas high-income areas did not experience the same increase in property values (Salon et al., 2014). This was probably because the inhabitants of these areas did not use public transport to the same extent as the low-income groups where car ownership was generally lower. This, however, was not unequivocal as the opposite effect could be observed in Buffalo, USA (Hess and Almeida, 2007). Here the high-income areas experienced a positive effect from the light rail system whereas the low-income areas experienced a negative effect.

A number of studies found decreasing real estate prices after the implementation of rail systems. In Manchester the proximity effect was -6% which was probably due to an average distance to stations within the entire area of analysis of only 1.36 km. Hence, many residents already had access to stations (Forrest et al., 1996). Similarly, a decrease of 7% was found in San Diego which was explained by a very low ridership in a corridor with generally very high average incomes. Thus, the residents in the corridor did not find the system attractive (Cervero and Duncan, 2002a). In Atlanta, up to 19% lower real estate prices were found within 400 m of MARTA stations. On the other hand, the prices were highest in a 1-3 mile band around the stations, probably because the negative externalities in the form of noise and crime close to the stations had a higher impact than the attractiveness of the system (Bowes and Ihlanfeldt, 2001).

An overview of the magnitudes of impacts on property values of BRT, LRT and metros is shown as a histogram in Figure 4.2. Note, however, that the graph only shows selected results from Tables 4.2-4.4 since many studies only concluded whether or not a significant effect could be observed. As a consequence, the histogram only includes 41 of the 86 systems reviewed. Furthermore, as mentioned many big differences generally exist between the projects. A conclusion based directly on the histogram would imply a significant degree of uncertainty.

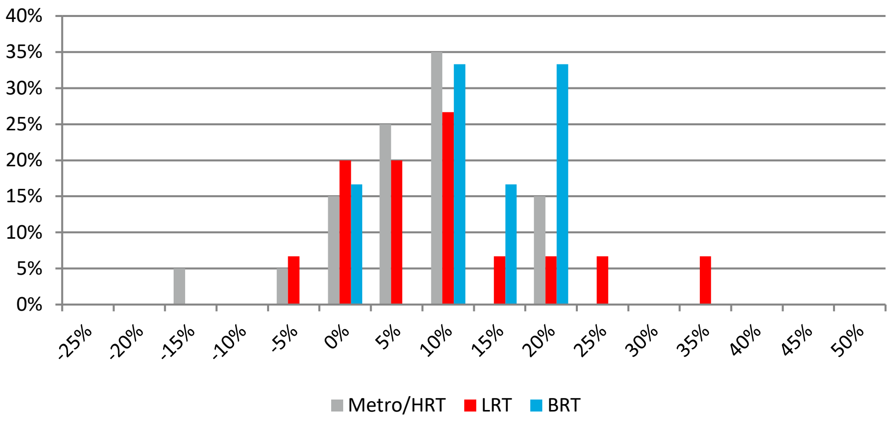

Figure 4.2: Change in property values after implementation of public transport systems.

The distributions of the changes in property values were tested using two-sample t-tests across the three modes, i.e. BRT, LRT, and metro/heavy rail. The three subsamples showed no significant differences between variances, hence the pooled test statistic was preferred.

System	**DF**	**t value**	**Pr > |t|**
Metro vs. LRT	33	0.89	0.3811
Metro vs. BRT	24	1.41	0.1719
LRT vs. BRT	19	0.61	0.5509

Table 4.5: Statistical t-tests of the difference in means of property value effects across public transport modes.

Generally, the results showed no significant differences across the three modes, i.e. significant strategic effects in terms of increases in property values were not limited to rail-based public transport systems, cf. Table 4.5. Projects that resulted in big increases in property values, as well as projects with less or no influence, were found across all three modes. Based on the subsample of projects in this study there seems to be a more certain difference between BRT and metro/heavy rail projects (83% confidence level) whereas the least certain difference is seen when comparing LRT and BRT (45% confidence level). Hence, the present study finds the largest effects for BRT systems and the lowest effects for metro/heavy rail, cf. Figure 4.2. However, the effects for all systems are significantly positive, and not significantly different from each other. Hence, based on these simple key figures it is not possible to draw any general conclusions about the influence of each of the three transport systems on the real estate market. Instead, the findings suggest that effects are rather due to other reasons than the choice of type of system. Most importantly, large effects were observed when notable improvements were implemented. In addition, negative effects were seen close to station areas due to externalities which highlights the importance of creating attractive station areas when implementing public transport systems. Thorough implementation is thus important in ensuring positive effects on property values.

4.4 URBAN DEVELOPMENT

As could be seen in the previous section, increases in real estate prices are not exclusively associated with rail-based public transport systems. It should therefore be possible to obtain urban development effects in relation to BRT. However, there are not many examples of urban development in connection with BRT in Europe and Asia reported in the literature (Cervero, 2013; Deng and Nelson, 2011). Several studies argue that some of the reasons for this are the lack of permanence (Dittmar and Ohland, 2004; Parker et al., 2002; Rodríguez and Targa, 2004) and lack of newness (Parker et al., 2002) of bus-based systems as compared to rail-based systems. However, a review of possible reasons in Currie (2006a) showed that the largest weaknesses were related to weak industry capabilities regarding bus-based transit-oriented development (TOD), the lack of a positive track record for already implemented systems and the availability of park-and-ride facilities as they limit TOD opportunities (Currie, 2006b). In Kamruzzaman et al. (2014) a comparison of different types of TOD in Brisbane was conducted which confirmed well-known effects of increased transit ridership and the use of active travel modes for people living in TODs. These results were found for both bus-based and rail-based TOD, hence suggesting that effects are not mode-specific, but rather a result of coherent planning.

The best examples of urban development in corridors served by buses are probably Curitiba and Ottawa (Currie, 2006a). In Curitiba, the BRT system became a big success, since 45% of the longer trips which were not made by foot or bicycle, were made by the BRT system (Cervero and Dai, 2014). The urban development was assured by means of planning laws that dictated that urban development should take place along the BRT corridors (Cervero, 1998). Hence, the system was not only implemented as a tool to improve the traffic situation in the city, but rather also as an instrument to form the urban development in a more sustainable direction. In Ottawa, a significant urban development was also seen in connection with the implementation of the BRT system Transitway. Due to the big success of the system, the urban development was concentrated along the bus lines, and the largest economic effect was precisely the urban development which was assessed to be worth about $675 million (Levinson et al., 2003b). Almost the same high investment level was obtained as a result of the BRT line in Pittsburgh where renovations and new constructions worth about $302 million were carried out in connection with the stations along the East Busway (Levinson et al., 2003a). Similar trends were seen in Boston where properties near the BRT line were densified after the implementation of the Silver Line BRT. The properties were to a great extent converted into apartment buildings. The total amount of money put into the urban development reached more than $600 million (Perk et al., 2012). Even larger effects were observed along the Euclid Corridor transportation project in Cleveland totalling $4.3 billion in real-estate developments (Weinstock et al., 2011). The Orange Line in Los Angeles also gave rise to urban development near the stations due to the significantly improved travel time and the generally high attractiveness of the system after the opening (Callaghan and Vincent, 2007). Furthermore, a certain urban development was obtained in connection with the BRT line in Seoul (Cervero and Kang, 2011). Here the areas around the BRT stations were developed, and a densification of the dwellings from one-family houses to flats was seen. It was assessed that notably improved travel times and regularity were more important parameters for a potential urban development than the type of system which was implemented. This suggested that urban developments could be obtained by both BRT and rail-based systems if urban development was integrated into the planning of station areas as early as possible in the planning process (Levinson et al., 2002).

Other BRT systems did not obtain the same effects. In Adelaide, no evidence of increased urban development was seen in relation to the O-Bahn system (Currie, 2006b). One important reason was that more than 50% of boarding passengers used car as access mode hence requiring large park-and-ride facilities at station areas which restricts the urban development potential (Dittmar and Ohland, 2004). Similarly, in Ahmedabad in India and Bogotá in Columbia no significant effect on urban development was observed despite the fact that TransMilenio in Bogotá is one the world’s most advanced BRT with a large extension and high ridership (Cervero and Dai, 2014). For these two cities the main reason was assessed to be unattractive station conditions. During the construction phase focus was on creating a cost-effective and fast system which was out of tune with the development of the station areas. Many stations were placed in the middle of large roads to ensure the highest possible travel speed at the lowest possible price. This resulted in low accessibility for pedestrians and unattractive station areas. This is underpinned by other analyses from Bogotá which showed that attributes such as pavements and zebra crossings were highly valued by the passengers of the system. Hence, stations with easy access had significantly more passengers than other stations (Estupiñán and Rodríguez, 2008). Furthermore, Cervero et al. (2004) emphasised that good pedestrian access is crucial for ensuring succesfull TOD. It is therefore important to bear these considerations in mind during the planning phase of public transport projects. This is especially important for BRT systems where the challenge with respect to creating the potential for urban development at stations is bigger than for metros which do not create externalities at the surface level due to them being underground systems.

4.5 DISCUSSION

While the current study provides a thorough review of the existing literature and compares the effects of various modes of public transport, the data source used in this study is not without limitations.

Firstly, the study compiled a large sample of 86 public transport systems. Though it is comprehensive and of a sufficient size to not being random data, it is not complete as it for obvious reasons does not include all systems ever implemented. Neither is it fully representative in terms of systems from specific countries, city sizes, etc. Hence, future work could focus on investigating the impacts from transit systems as a function of local economic or demographic characteristics as well as the actual level of service improvements, effects on ridership, changes in mode choice and property values.

Secondly, the data were collected from numerous different sources which applied different methodologies hence giving rise to lacking consistency. For studies on traffic impacts the reported improvements were measured at different time points after completion or implementation of the systems. Hence, ridership increases and modal shifts were not directly comparable between studies. The systems included in this study all reported effects obtained after up to 3-4 years after completion in order to reduce the effect of general traffic growth or other factors. Some studies were deliberately not included as they reported effects after up to 10 years after completion.

The inconsistency also applied to the studies on property values. As previously mentioned different definitions of station proximity were used, but studies also used different methodological approaches when estimating the station proximity impact. Most studies used the hedonic pricing method, but studies differed in estimation methods with only some studies taking into account spatial autocorrelation, e.g. Rodríguez & Targa (2004). Other studies reported changes in property values based on comparisons with control group areas, e.g. V. Perk & Catalá (2009), Salon et al. (2014), Weinstein & Clower (2002), and others.

For the urban development effects no consistent definition exists of what impacts to include among urban regeneration, development projects, TOD or densification of existing properties. Hence, the present paper summarises findings from numerous papers on this topic with the purpose of highlighting possible effects rather than creating specific comparisons between transport modes. Further research could investigate the link between urban development effects and the public transport systems in more detail, including the most important elements contributing to an improved level of service and urban development, a research area also highlighted by other studies, e.g. in Stokenberga (2014).

Thirdly, this paper operates with a division into three groups of transit systems, namely BRT, LRT and metro/commuter rail systems. While many systems are easily classified, others are more difficult to classify. This is especially the case for many improved bus systems incorporating scattered bus lanes and single ITS features. However, in order to being able to analyse strategic effects this paper has only included BRT systems that are notably upgraded from conventional bus lines in terms of (almost) fully segregated infrastructure and multiple ITS elements. Similar definition challenges exist for rail lines. For example the Metrolink network in Manchester was upgraded from an existing suburban, heavy rail system into a LRT system by adding newly constructed lines on city centre streets with stations in the downtown area (Forrest et al., 1996; Knowles, 1996). Hence, parts of the system could be categorised as commuter rail even after the transformation of the network. In the present paper this system was categorised as LRT. The LRT systems included vary with regards to the degree of segregation from other traffic, as many otherwise successful LRT systems are mixed with car traffic, especially in narrow city centre street networks. The last group of systems include commuter rail and metro systems which are characterised by being heavy rail systems running at higher speeds with longer stop spacings. The final division into three groups was a compromise between creating as few groups as possible while at the same time ensuring their homogenity. Hence, a division into more groups could be reasonable; for example by further dividing BRT systems based on the BRT level as suggested by Wright & Hook (2007), splitting LRT and traditional tram systems, possibly taking into account the degree of segregation from other traffic, or creating independent groups for heavy rail dependent on whether they are underground or overground systems or dependent on train type used, e.g. large regional trains or small metro trains. However, a further division of systems would reduce the sample size for each system.

Lastly, this study did not focus on whether effects on property values are in fact generative. Several sources question this suggesting that effects are rather distributive (Handy, 2005). By this, the positive effects should not be seen as pure growth, but rather as a redistribution of growth in the area close to the new public transport system which is outweighed by the decreasing property values in other areas (Giuliano, 2004). However, even if impacts are redistributive, Cervero (2009) suggests that a total positive effect is realised because of the agglomeration effects occurring from the spatial redistribution, thus creating generative economic growth. Further research should investigate this aspect in greater detail in order to draw conclusions on this aspect.

4.6 CONCLUSIONS

This present paper showed that large effects on travel time can occur by implementing BRT and lead to significant modal shifts similar to those found when implementing rail-based public transport systems such as LRT and metro. In addition, the review of 86 public transport systems showed that significant positive impacts on property values can be obtained by investing in public transport systems independent of system choice, i.e. BRT, LRT or metro/heavy rail. For the 41 projects which were analysed statistically in this study no significant differences between system choices were found, but BRT systems seemed to show the largest effects. The results suggested that the impacts depend more on the extent to which the system improves the existing situation, the competition with car traffic and how the system is implemented in the local context.

For BRT systems, notable improvements with respect to travel times compared to the basis situation are needed in order for people to consider the system as being more attractive than ordinary bus lines. This also includes measures to improve the overall travel time, e.g. service frequency, and comfort, e.g. guidance. Furthermore, it is important to ensure good accessibility to the station areas to obtain positive strategic effects in the form of urban development and increased property values. However, it can be difficult to combine short travel times and improved urban spaces, as high-class BRT systems take up large areas at the surface level as compared to underground metro systems. The largest travel time reductions and increases in ridership were thus seen in cities where the BRT line was segregated from other traffic, for instance in the middle of a large road, and where operations were frequent thus reducing waiting times. Such system designs make it difficult to create attractive urban spaces around BRT stations due to the significant intervention in the urban space as compared to the establishment of for instance sub-surface metro systems. This was confirmed by several analyses that showed decreasing real estate prices in the immediate vicinity of BRT stations as the benefits from the increased mobility did not compensate for the negative externalities, e.g. noise and barrier effects. To create successful BRT systems it is thus essential to consider how to obtain large benefits in the form of travel time and improved accessibility while at the same time creating an attractive and accessible environment around the stations.

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5 How urban density and network topology influence public transport ridership: Empirical evidence from 48 European metropolitan areas

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Abstract

Understanding the determinants of public transport ridership is important in order to plan attractive public transport systems efficiently. This study analyses at a meta-level public transport ridership across 48 European cities based on a rich database collected as part of this study. The dataset includes detailed mode-specific information about the public transport networks, hence extending previous research by analysing each public transport mode separately while simultaneously taking into account the main determinants of ridership identified by a thorough literature review of 36 previous studies, e.g. urban demographics and land uses. Factor analysis was deployed revealing four main composite determinants, namely i) metro coverage, network connectivity, and urban density, ii) suburban rail coverage, iii) economic inequality, and iv) light rail coverage. Subsequent multiple regression analysis confirmed the a priori hypothesis of ridership being positively associated with the extent of network coverage in terms of both metro, suburban rail and light rail transit. The importance of network connectivity was included with results suggesting that the number of transfer stations were more important than the cyclomatic number of the public transport network. Cities with higher economic inequality in terms of mainly higher unemployment, lower per capita GDP and higher GINI-coefficient showed lower public transport ridership. Finally, the analyses highlighted the importance of proper definitions of urban areas in order to perform consistent analyses of data across cities. This revealed the importance of urban density defined as population and especially job intensity per km^2 for transit ridership.

Keywords: Public transport ridership, network topology, factor analysis, urban density, rail factor

5.1 INTRODUCTION

Attractive public transport systems are more and more important in ensuring mobility in the increasingly congested metropolitan areas. Knowing the key drivers for attracting passengers is essential when developing successful public transport systems.

Much research has been devoted to analysing the main determinants of ridership (Taylor and Fink, 2013). Studies have ranged from focusing on single lines based on data on the individual level, e.g. Buehler (2011), or aggregate data, e.g. Cervero et al. (2010); Chen et al. (2010), to covering larger metropolitan areas using aggregate characteristics, e.g. Gutiérrez et al. (2011); Kuby et al. (2004); Taylor et al. (2009). Other studies have compared determinants across different countries to highlight potential differences and similarities, e.g. Buehler (2011); Currie et al. (2011); Loo et al. (2010). These studies include factors related to the public transport system itself in terms of general level of service, travel costs and accessibility as well as external factors such as socio-economic characteristics of the travellers or the study area and the availability and characteristics of substitute modes (Chen et al., 2010; Jun et al., 2015; Syed and Khan, 2000; Taylor et al., 2009). Focusing on public transport systems key determinants have been highlighted to be service coverage in terms of high accessibility and frequent services resulting in low travel times. Such improvements have been seen to be more important than pricing (Taylor and Fink, 2013).

Another important parameter for public transport ridership is the network connectivity and the interaction between different public transport networks. Much research have focused on analysing public transport network connectivity on the micro-scale focusing on level of service (Ceder et al., 2009; Hadas and Ranjitkar, 2012) and transport equity (Kaplan et al., 2014b), and on a macro-scale evaluating the general network topology (Derrible and Kennedy, 2010; Sienkiewicz and Hoo, 2005) and resilience in cases of disruption, e.g. Cadarso et al. (2013); Cats (2016); Zhang et al. (2015). However, research on the influence of macro-scale connectivity measures on ridership is limited. Derrible and Kennedy (2009) showed a positive influence of network topology indicators of connectivity on ridership using data from 19 subway networks, and Sohn and Shim (2010) found connectivity to be influential on station boarding on the Seoul subway system. While both studies highlight the importance of connectivity they do have shortcomings in either only using data from a single network (Sohn and Shim, 2010) or not controlling for important ridership determinants (Derrible and Kennedy, 2009).

The present study addresses these previous shortcomings by analysing public transport ridership across 48 European metropolitan areas taking into account characteristics related to the traffic systems and the urban areas. The contribution is three-fold.

Firstly, the main determinants of public transport ridership are identified via a thorough literature review of previous research. This allows for formulating a ridership model capable of analysing the effects of networks while taking into account other main determinants. Secondly, this study analyses the influence of various public transport networks separately, i.e. metro, suburban rail and light rail, in order to investigate possible differences in attractiveness. This makes ít possible to analyse the relative significance of different modal networks. Thirdly, the focus on network topology allows for analysing whether network topology better explains ridership as compared to simple service coverage characteristics such as number of stations and length of network.

The remainder of this paper is structured as follows. Section 2 reviews the literature on the determinants of public transport ridership. In section 3 the data sources and measures used for the modelling are described while the analytical approach is described in section 4. The results are presented in Section 5 while section 6 concludes the work by highlighting relevant implications.

5.2 LITERATURE REVIEW

Most studies have investigated the determinants of public transport ridership focusing on the influences of land uses, built environment, public transport characteristics and socio-economic characteristics.

Many studies have deployed an ordinary least square (OLS) regression approach (Cordera et al., 2015; Guerra et al., 2012; Gutiérrez et al., 2011; Kuby et al., 2004; Liu et al., 2014; Loo et al., 2010; Sohn and Shim, 2010; Souche, 2010; Sung and Oh, 2011; Zhao et al., 2013). This method is simple, but assumes uniform relationships over the study area. Hence, geographically weighted regression (GWR) models have been suggested to better account for the spatial variation between public transport ridership and explanatory variables (Cardozo et al., 2012; Chiou et al., 2015; Chow et al., 2006; Jun et al., 2015). Two-stage least square (2SLS) has been proposed to take into account correlation between the dependent variable and independent variables (Cordera et al., 2015; Estupiñán and Rodríguez, 2008; Souche, 2010; Taylor et al., 2009). Several studies have compared the methods for different purposes. In a study from Florida Chow et al. (2006) found that GWR models better predicted transit use among commuters than simple OLS. Similarly, Blainey (2010) found that GWR was better than linear and loglinear regression in estimating annual boadings at local rail staions in England and Wales. And Cardozo et al. (2012) deployed GWR finding better fit than OLS in modelling boardings of Madrid metro.

An overview of explanatory variables[17] and their influence on public transport ridership are shown in Table 5.1. The included studies all analyse ridership, but using different

[17] Note that some parameters were grouped to fit in the table., e.g. service frequency and service headway while ensuring to reverse the sign of headway making it compatible with service frequency. Also, parameters that could not easily be grouped with other variables and which were

measures such as number of boardings for bus stops (Cervero et al., 2010; Pulugurtha and Agurla, 2012), light rail stations (Gordon and Willson, 1984; Kuby et al., 2004), metro stations (Cardozo et al., 2012; Gutiérrez et al., 2011; Jun et al., 2015; Loo et al., 2010; Sohn and Shim, 2010; Zhang and Wang, 2014; Zhao et al., 2013), or a combination (Cervero, 1996; Guerra et al., 2012; Liu et al., 2014). Other studies have analysed public transport usage rates (Buehler, 2011; Chiou et al., 2015; Chow et al., 2006; Cordera et al., 2015; Derrible and Kennedy, 2009; Taylor et al., 2009), and aggregate public transport ridership per route level (Chen et al., 2010; Currie et al., 2011; Currie and Delbosc, 2011; Rahman and Balijepalli, 2016), or as flows between O-D pairs (Choi et al., 2012; Thompson et al., 2012).

Most studies reported consistent findings. Population and employment densities are important determinants of ridership in most studies, however they have been included differently across studies. While simple densities have been included in many studies, segregated employment densities have also been investigated. This includes the amount of office area (Choi et al., 2012; Sohn and Shim, 2010; Sung et al., 2014; Zhao et al., 2013), commercial area (Cervero and Murakami, 2008; Loo et al., 2010; Pulugurtha and Agurla, 2012; Sohn and Shim, 2010; Sung et al., 2014; Sung and Oh, 2011), retail area (Zhang and Wang, 2014; Zhao et al., 2013), institutions (Pulugurtha and Agurla, 2012), and educational facilities (Choi et al., 2012; Zhao et al., 2013). These all led to higher ridership. Similar positive effects have been found for specific land use areas such as entertainment venues (Zhao et al., 2013), airports (Guerra et al., 2012; Kuby et al., 2004), and harbours (Blainey, 2010). Similarly, other studies found a positive effect of being located in the CBD or city centre, or a negative distance effect, further highlighting the influence of denser areas on ridership. Furthermore, walkable areas surrounding stations were found to be significantly related to increased public transport use in several studies (Estupiñán and Rodríguez, 2008). On the other hand, employment land uses with less travel demand such as industry and garage areas had negative effects on ridership (Loo et al., 2010; Pulugurtha and Agurla, 2012; Zhang and Wang, 2014).

Among individual socio-economic characteristics income was found significant in most studies. Generally, a negative income effect was reported suggesting lower ridership among high-income households. In some studies this effect was observed by a positive effect of the percentage of low-income households (Chiou et al., 2015; Taylor et al., 2009) or of a proxy indicator such as percent renters (Kuby et al., 2004). In Zhang and Wang (2014) it is found to be due to an increased general travel frequency of high-income households. And in Cervero (1996) income is only significant for the more expensive commuter rail, and not for light rail, possibly due to higher fare levels. Unemployment

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only found in a single study were omitted in Table 5.1. This included variables such as age of buses (Chiou et al., 2015), years of operation (Loo et al., 2010), electrification (Blainey, 2010), and number of station entrances (Sung et al., 2014) were found significant in several studies, mostly with a negative effect on ridership. However, in Cordera et al. (2015) a positive effect was observed in Spain during the financial crisis where large unemployment resulted in increased bus usage. Other socio-economic variables have been tested in research showing effects on ridership locally, e.g. share of foreign population (Gutiérrez et al., 2011; Taylor et al., 2009), gender balance (Chu, 2004), and age (Chiou et al., 2015).

The effects of private transport have most often been taken into account by aggregate car ownership rates or percentage of households without access to cars. However, in one study the motorcycle ownership was used as explanatory variable (Chiou et al., 2015). Generally, access to cars was associated with lower public transport ridership, and in many studies this has more impact on ridership than characteristics related to the public transport system (Taylor and Fink, 2013). However, a few exceptions exist. In four out of five Indian study areas public transport ridership was positively associated with the total number of vehicles, however also including buses (Rahman and Balijepalli, 2016), and in New York City and Hong Kong railway stations located in areas with higher car ownership had more passengers, arguably because of higher total trip rates for people owning a car (Loo et al., 2010). Finally, a general finding across studies was also that travel costs related to using private vehicles in terms of fuel prices or parking costs were associated with higher public transport ridership.

	Socio-economic			Land use and built environment								Private transp.			Public transport													
Study	Income	Unemployment	Ethnic, racial, age, etc.	Population	Employment	Commercial/office/ retail/institutions	Education buildings	Attractions (e.g. airports)	Mixed land uses	CBD / city centre location	Walkability	Car ownership	Road network density	Costs	Service coverage	Parking availability	Accessibility	Transfer stations	Feeder services	Service frequency	Costs	Terminal/end station	Distance to other PT modes	Stop density	Travel time	Bicycle amenities	Integrated ticketing	Connectivity measures
Gordon and Willson (1984)	-			+								-												+				
Cervero (1996)	+			+	+					+/-						+			+			+	+					
Crampton (2002)				+							+				+	+					-				+		+	
Chu (2004)	-		x	+	+						+	-			+		+	+					+					
Kuby et al. (2004)	-			+	+			+							+	+	+	+	+			+						
Chow et al. (2006)			x		+							-					+											
Holmgren (2007)	-											-		+	+						-							
Cervero and Murakami (2008)				+		+				+									+				+					
Derrible and Kennedy (2009)																		+										+
Taylor et al. (2009)	-	-	x	+								-	+	+	+					+	-							
Blainey (2010)				+	+			+								+	+			+		+					+	
Cervero et al. (2010)				+												+			+	+			+					
Chen et al. (2010)		-												+	+						-							
Loo et al. (2010)				+		+				+		+						+			-			+				
Sohn and Shim (2010)				+	+	+												+	+									+
Souche (2010)	-			(+)	(+)									+	+						-							
Buehler (2011)	-		x	+					+/-			-					+											
Currie et al. (2011)					+															+					+		+	

Table 5.1; Significant factors related to public transport ridership of selected studies. +/- is used where relationship depended on corridor, time-of-day, etc.
** denotes various socio-economic variables, e.g. age, gender, ethnicity, racial or educational background.*

	Socio-economic			Land use and built environment								Private transp.			Public transport													
Study	Income	Unemployment	Ethnic, racial, age, etc.	Population	Employment	Commercial/office/ retail/institutions	Education buildings	Attractions (e.g. airports)	Mixed land uses	CBD / city centre location	Walkability	Car ownership	Road network density	Costs	Service coverage	Parking availability	Accessibility	Transfer stations	Feeder services	Service frequency	Costs	Terminal/end station	Distance to other PT modes	Stop density	Travel time	Bicycle amenities	Integrated ticketing	Connectivity measures
Currie and Delbosc (2011)				+								-								+				+	+			
Gutiérrez et al. (2011)		-	x	+	+				+						+	+	+		+									
Sung and Oh (2011)				+		+			+				+/-		+					+			+	+				
Cardozo et al. (2012)		-			+										+				+									
Choi et al. (2012)				+	+	+	+			+	+								+									
Guerra et al. (2012)				+	+			+		+						+			+	+		+						
Pulugurtha and Agurla (2012)	-			+		+						-																
Thompson et al. (2012)	-			+	+						-			+											-			
Blainey and Mulley (2013)				+						+		-				+			+	+						+		
Zhao et al. (2013)				+	+	+	+	+		+			+					+	+							+		
Liu et al. (2014)					+					+									+	+		+		-				
Sung et al. (2014)				+		+			+/-						+													
Zhang and Wang (2014)	+			+	+	+		+							+			+										
Chiou et al. (2015)	-		x									-	-		+					+								
Cordera et al. (2015)		+																			-							
Jun et al. (2015)				+	+				+				-					+						+				
Chakour and Eluru (2016)				+		+														+				+		+		
Rahman and Balijepalli (2016)	+/-			+/-								+/-		+	+/-						-							

Table 5.1 cont.; Significant factors related to public transport ridership of selected studies. +/- is used where relationship depended on corridor, time-of-day, etc.
** denotes various socio-economic variables, e.g. age, gender, ethnicity, racial or educational background.*

The effects of public transport characteristics have been analysed thoroughly in most studies including one or several indicators of public transport service quality, i.e. service coverage, service frequency (or reciprocal service headway) and availability and amount of feeder services and transfer possibilities were all positively related to public transport ridership. Looking at the individual station level, a number of station-specific characteristics was found to be positively associated to public transport use such as integrated ticketing (Crampton, 2002; Currie et al., 2011), availability of bicycle ameneties (Blainey and Mulley, 2013; Zhao et al., 2013), and park-and-ride (Cervero et al., 2010; Guerra et al., 2012; Kuby et al., 2004). Finally, some studies also found significant positive effects of network characteristics such as the average travel time to all other stations (Kuby et al., 2004), or the average number of transfers from a station to all other stations in network (Sohn and Shim, 2010). In a more thorough study three different network topology indicators were all found to be positively related to public transport ridership (Derrible and Kennedy, 2009). Based on 19 subway systems from around the world this study found that ridership was significantly positively related to three network topology indicators, namely i) network coverage, ii), directness measured as the number of lines divided by the maximum number of transfers from one vertex to another, and iii) connectivity measured as transfer possiblites. However, Sohn and Shim (2010) did not find any significant effects using data from the Seoul metro for neither of three network indicators measuring closeness as the reciprocal mean distance to all other nodes, betweenness as the number of shortest paths going through the station, nor straightness as the ratio of direct distance to shortest distance between nodes.

To summarise the literature review much research has been devoted to identifying the main determinants of public transport ridership focusing on different aspects of socio-economic characteristics, land uses and attributes related to private and public transport. Most studies agree on the importance of population and workplace density, and an attractive public transport system based on high service frequencies, widespread coverage and generally low travel times through the network. In this respect network attributes ensuring good connections through the network such as many transfer possibilities resulted in higher ridership suggesting the importance of well-connected networks. While these findings are well documented no studies have fully analysed the influence of network topology and differences across public transport modes on ridership. This present study addresses these shortcomings by jointly analysing public transport ridership across public transport modes and including network topology characteristics as well as taking into account the main determinants identified by the literature review.

5.3 DATA SOURCES AND MEASURES

To analyse the influence of various public transport networks on ridership a large database was collected consisting of urban demographics, network data characteristics, and economic variables for a wide range of European cities. The cities listed in Table 5.2 were selected ensuring a broad range of networks and network combinations. Hence, some cities included all modes of public transport (metro, suburban rail, light rail, and bus), others included only different subsets of modes, and three cities included only buses.

Country	City
Austria	Salzburg (S), Vienna (M,S,L)
Belgium	Antwerp (L), Brussels (M,L)
Czech Republic	Prague (M,L)
Denmark	Copenhagen (M,S), Odense, Aalborg, Aarhus
Finland	Helsinki (M,S,L)
France	Bordeaux (L), Lille (M,L), Lyon (M,L), Marseille (M,L), Nantes (L), Paris (M,S,L), Rennes (M), Strasbourg (L), Toulouse (M,L)
Germany	Berlin (M,S,L), Cologne (S), Dresden (S,L), Frankfurt am Main (M,S,L), Hamburg (M,S), Leipzig (S,L), Munich (M,S,L), Nuremberg (M,S,L)
Ireland	Dublin (S,L)
Netherlands	Amsterdam (M,L), Rotterdam (M,L)
Northern Ireland	Belfast (S)
Norway	Bergen (L), Oslo (M,S,L), Trondheim (L)
Portugal	Lisbon (M,S,L), Porto (S,L)
Spain	Barcelona (M,S,L), Madrid (M,S,L), Málaga (S), Palma de Mallorca (M), Sevilla (M,S,L)
Sweden	Gothenburg (L), Stockholm (M,S,L)
Switzerland	Bern (S,L), Lausanne (M,S), Zürich (S,L)
UK	London (M,S,L), Liverpool (S)

Table 5.2; The 48 included cities in this study and public transport networks. For each city it is noted whether metro (M), suburban rail (S), and/or light rail networks (L) are included.

5.3.1 Urban demographics

Strong relationship between land uses and ridership were observed in all studies of the literature review emphasising the importance to include it properly in the dataset. Hence, population and employment densities were included in this study. Most previous studies included this directly from land use data based on a defined station catchment area. However, as this study analyses ridership in aggregate city-wide measures the inclusion of population and employment densities was not straightforward. Efforts were made to collect these data ensuring comparability between urban demographics and the actual service coverage area. However, data from national and regional statistics offices and public transport authorities did often not match due to differences between the area in which the public transport network is located and the administrative regions. Similar problems were experienced by Derrible and Kennedy (2009) which ended up using the simple mean of city population and metropolitan population as a proxy for the service coverage area for 15 of their 19 included cities. While being a practical approximation this study analysed four distinct definitions of cities in Europe proposed by the EU Urban Audit 2012, namely i) the core city based on an administrative definition, ii) the Greater City making urbanised areas more comparable across regions, iii) commuting zones representing functional urban areas (Dijkstra and Poelman, 2012), and iv) high-density clusters based on coherent high-density urban statistical cells. The four measures were compared to the extent of the public transport networks for each urban area in the dataset. Based on these individual assessments no general designation could be made due to national differences in administrative borders of cities. Hence, a combined dataset was constructed based on all four measures, and professional judgements.

5.3.2 Public transport network characteristics

Ridership data was collected through annual reports and statistics for the public transport agencies and authorities for the selected cities in the study. This was chosen due to limitations of possible data sources such as the Millenium Cities database (Kenworthy and Laube, 2001) which are not current (data are from 1995 and 2010). By collecting the data directly from operators data could be split between modes of transport so that light rail, suburban rail and metro networks were separated in order to analyse their different effects on ridership. This was important for two reasons. First, the capacity of the various systems are very different with metro carrying more passengers than light rail systems (Kittelson & Associates et al., 2003). Secondly, the attractiveness of the various systems are often perceived differently by passengers due to for example varying travel speeds and/or comfort levels (Scherer and Dziekan, 2012). Hence, their influence on ridership might be different. It should be noted that the ridership figures for each mode are the number of boarding passengers. Hence, when evaluating total ridership there will be some double-counting as passengers transferring between different modes are counted as two passengers. However, transfers within a single mode are most often counted as one boarding. The dataset also included network length and number of stations for each mode of the public transport network, and the coverage was then calculated by dividing with the city area.

To analyse the influence of network topology two indicators were chosen based on the literature review, namely i) the amount of transfer terminals, and ii) the cyclomatic number of the network, i.e. the number of fundamental circuits. First, a significant parameter found across many studies was the possibility to transfer between lines as it ensures network robustness in terms of higher mobility through the network for passengers. Also, it was found specifically that the number of terminals was more important for robustness rather than the total number of transfer options, i.e. two stations with two transfer options each are better than one station with four transfer options (Derrible and Kennedy, 2010). Second, the cyclomatic number defined by the number of fundamental circuits in the network (Grubesic et al., 2008; Zhang et al., 2015). This was chosen as a network robustness indicator due to its simplicity while still indicating mobility in terms of travel opportunities as well as general network robustness. Other network indicators such as the node degree proposed by Cats (2016) could also have been relevant, however due to not having digital representations of the 48 city networks this was not possible.

As no digital representations of the 48 city networks were available the calculations were performed manually. For the number of terminals in the public transport networks main focus was on transfer possibilities. Hence, for networks where multiple lines run in parallel through two stations the number of terminals is only regarded as one. This applies for several networks, e.g. the Copenhagen metro and the Lille light rail. The rationale was that despite the possibility to transfer at multiple stations it is in reality only a possibility to transfer between the respective two lines. Hence, this was counted as one terminal, except for longer parallel segments thorugh three or more stations in which it was counted as two terminals. This was due to passengers arriving from each end of the line probably would perceive this as two distinct transfer possibilities. The number of fundamental circuits in the network was similarly measured manually based on official network maps of the respective systems. As the network indicators were included to take into account network connectivity it was important to consider not only single-mode networks. Hence, they were measured based on the combined metro and suburban rail networks. However, the light rail network was not considered due to only having access to combined network maps for few cities in the database.

5.3.3 Socio-economic characteristics

A number of socio-economic indicators were collected to take into account the economic differences between cities. Based on the literature review income was a dominant variable making it important to include. It was decided to use the aggregate measure of GDP per capita to measure the economic development of the area. It would have been preferred to use a GDP indicator which also takes into account the purchasing power, but this was not possible to collect at the urban level. Hence, it was prioritised to capture differences across cities in the same country by using the simple GDP per capita indicator. As several of the listed studies from the literature review found significant effects of low-income households it was prioritised to include the unemployment rate and the GINI-coefficient. These indicators were hypothesised to be related to the percent low-income households thereby taking these effects into account.

To capture the effect of competing modes data on car ownership rates were collected at the urban level. It was not possible to collect data on bicycle usage. Instead dummy variables were created based on whether the city was among the top 20 bicycle-friendly cities according to the Copenhagenize index (Copenhagenize, 2013).

5.3.4 Sample statistics

An overview of the variables including summary statistics can be seen in Table 5.3 while Figure 5.1 and Figure 5.2 illustrates the ridership and coverage of each rail-based mode across cities. Generally, it can be seen visually that particularly the intensity of metro and suburban rail coverage per km^2 significantly influence overall ridership – not only within these modes, but also in general. It can also be seen that cities with no rail-based coverage has a quite low overall public transport ridership. This is illustrated by all cities with more than 400 annual boardings per capita have metro or suburban rail networks whereas many of those with fewer than 200 annual boardings per capita rely on only bus and light rail transit. More specifically, the three Danish cities only relying on bus-based public transport attracts less than 100 boardings per capita per year whereas cities with all public transport modes such as Paris, London and Madrid attracts annual per capita boardings of 4-600. These observations are confirmed by the statistical analysis in the following section 5.4.1 and 5.4.2.

	Mean	Std. Dev.	Min	Max
Dependent variable				
Yearly public transport boardings per capita	340.77	225.87	30.44	1049.55
Explanatory variables – urban demographics				
Population density [per km^2]	2,399.31	1,711.14	169.01	8,478.24
Job density [per km^2]	683.94	756.24	8.73	3,930.24
Explanatory variables – network characteristics				
Metro length [km/km^2]	0.09	0.11	0	0.47
Metro stations [stations per km^2]	0.10	0.13	0	0.40
Suburban railway length [km/km^2]	0.47	0.71	0	3.44
Suburban railway stations [stations per km^2]	0.17	0.24	0	0.98
Light rail length [km/km^2]	0.15	0.19	0	0.75
Light rail stations [stations per km^2]	0.35	0.56	0	2.58
Cyclomaticity [circuits/ km^2]	0.01	0.02	0	0.09
Terminals [per km^2]	0.02	0.03	0	0.11
Explanatory variables – socio-economic characteristics				
GDP per capita [1,000$]	39.31	13.05	16.98	63.39
Car ownership [vehicles per 1.000 inhabitants]	401.51	82.11	233.40	570.50
GINI coefficient	28.86	3.05	22.70	34.20
Unemployment rate [%]	10.44	6.23	1.90	31.40

Table 5.3; Summary statistics for the variables included (2012-data).

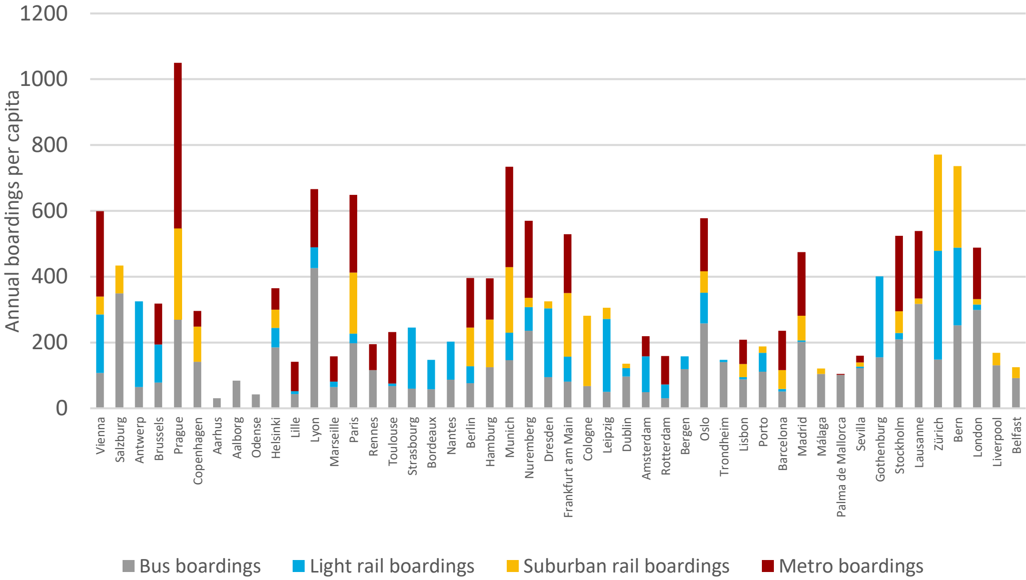

Figure 5.1; Public transport ridership per mode for the 48 cities included in this study.

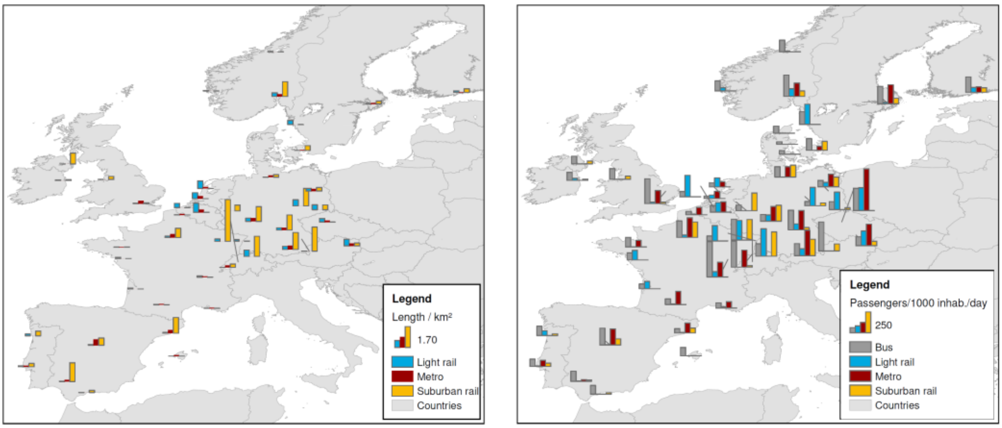

Figure 5.2; Rail-based network densities (metro, suburban rail and light rail transit) and ridership (passengers per inhabitant) on the same systems.

Figure 5.3 illustrates population density, job density, length of rail-based public transport, and public transport trip frequency across the cities in the study. Visually, a quite clear relationship between the density of rail-based public transport networks and ridership can be seen. A similar, but weaker, relationship can also be seen between the urban density and the density of the rail-based public transport network and the ridership. This indicates the clear positive relationship between dense cities, dense rail-based public transport systems, and ridership, whereas more "sprawled" cities with less dense rail-based public transport systems have lower ridership.

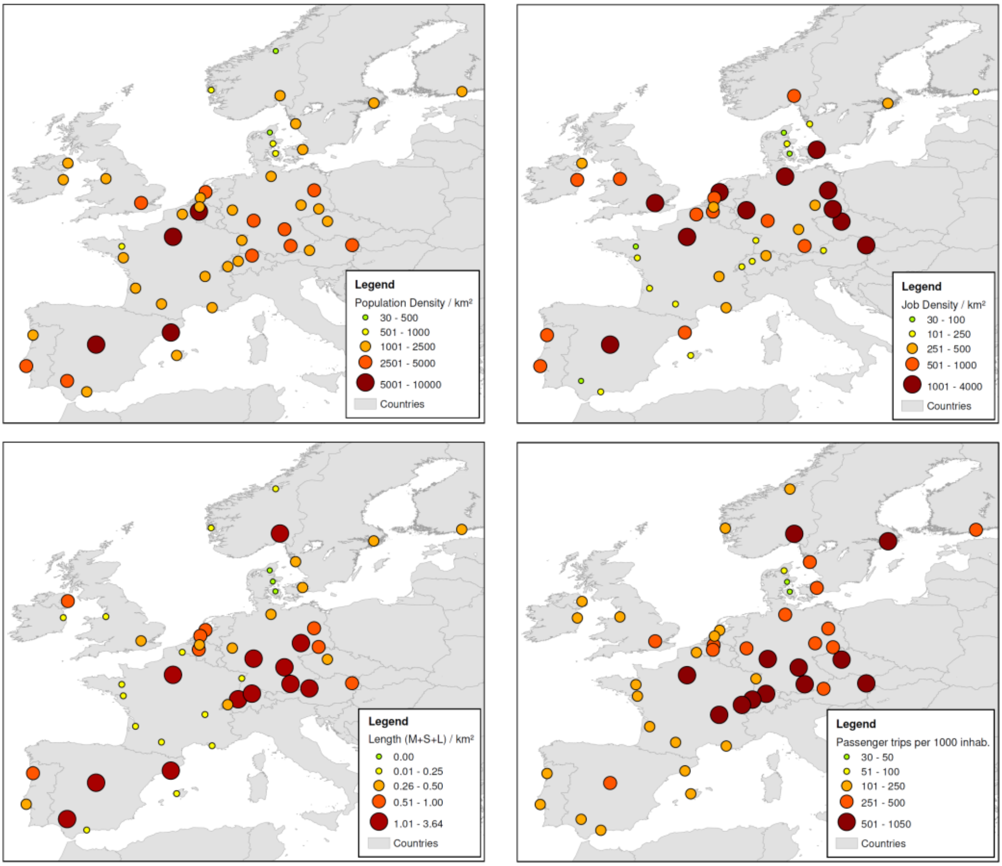

Figure 5.3; Maps of population density, job density, length of rail-based public transport per km2 (metro + suburban railways + light rail) and yearly per capita public transport ridership.

Figure 5.4 illustrates the positive relationship between network indicators, network coverage, urban density and public transport ridership. As network coverage is more dense people make more public transport trips per year. This is the case for both the network indicators and the coverage of rail networks, i.e. the combined metro and suburban rail network.

More dense cities are associated with higher per capita ridership, hence emphasizing the importance of compact cities in generating ridership for public transport systems. Similar to previous research density of workplaces seems to have larger influence on ridership.

The influence of density on ridership is further highlighed when comparing ridership with both population density and logarithm of the population size.

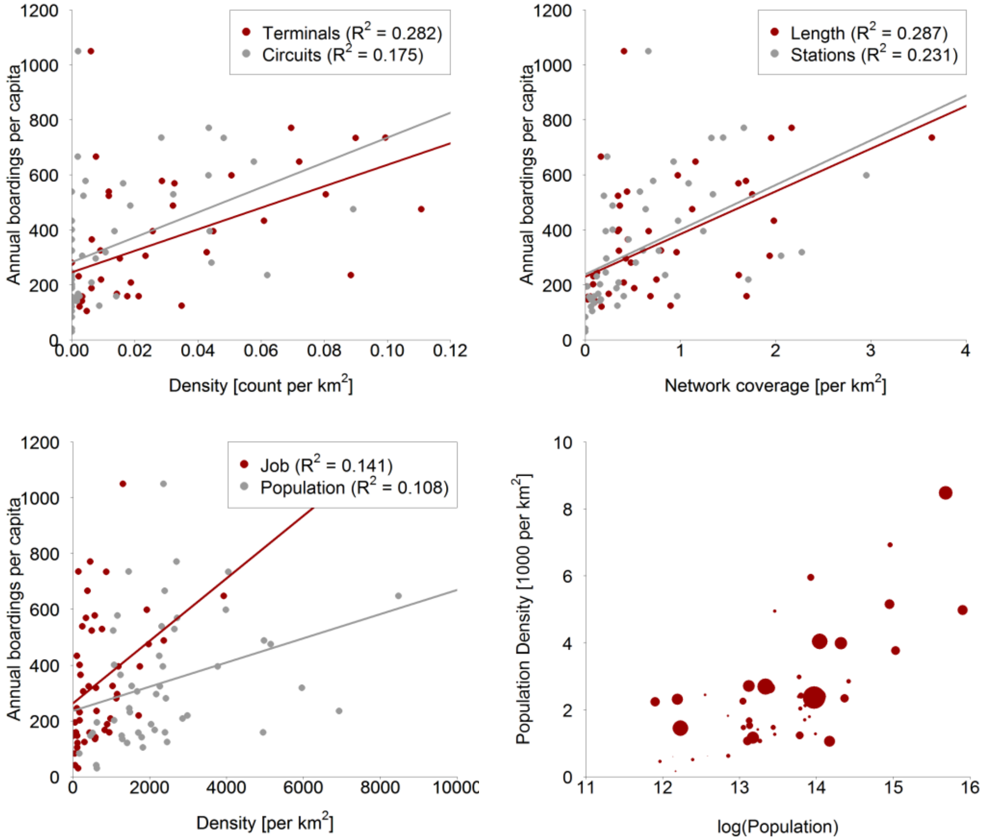

Figure 5.4; The relationship between per capita ridership and network density in terms of network indicators (upper left), rail network coverage (upper right), and urban density (below left). And relationship between population density and city size with size of dots representing ridership (below right).

5.4 Analyses and Results

The study used the traditional approach of multiple linear regression models based on OLS in order to study the relationship between public transport ridership and the urban demographics, public transport network, and socio-economic characteristics. Possible country-specific and regional fixed effects were taken into account by adding dummy variables. This was preferred over the increasingly popular GWR method because of the hypothesis of similarities being more pronounced between cities of the same country than solely being based on geographical distances between observations.

Due to the small sample size two sets of regression models were estimated, namely the first set being based on the raw dataset, and the second set being based on factor analysis and factor scores. This latter option was chosen to reduce the number of explanatory variables thereby obtaining a higher degree of freedom in the regression (Crampton, 2002). This approach was similar to that of other studies where multiple variables were reduced to fewer factors which then was regressed on the observed dependent variable of ridership (Estupiñán and Rodríguez, 2008; Kobayashi and Lane, 2007; Syed and Khan, 2000). The approach was adopted for the 14 continuous explanatory variables whereas dummy variables were added in the final multiple regression analysis.

5.4.1 Initial multiple linear regression

Two separate model formulations were tested based on two distinct indicators of public transport network coverage, namely based on station density (cf. Table 5.4) and network length density (cf. Table 5.5). The models were estimated with and without controlling for country and regional fixed effects, and insignificant variables were removed, and are not reported.

Variable	Model I-A		Model I-B		Model I-C	
	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
Metro coverage [km/km^2]	-	-	645.65***	3.22	799.86***	4.35
Suburban coverage [km/km^2]	165.98***	4.98	68.53**	2.27	106.32***	3.55
Light rail coverage [km/km^2]	-	-	-	-	312.76**	2.22
Job density [1.000 per km^2]	0.19***	5.24	-	-	-	-
GDP per capita [1,000$]	-	-	0.006**	2.58	-	-
Car ownership [per 1.000 inhab.]	1.09***	3.21	-	-	-	-
GINI coefficient	-29.58***	-3.71	-	-	-	-
Constant	544.70**	2.26	-153.48	-1.40	225.60***	5.72
Country fixed effects	No		Yes		No	
Regional fixed effects	No		No		Yes	
N	48		48		48	
R^2	0.504		0.794		0.675	

*Table 5.4; Multiple regression model of per capita annual ridership using network length density. Model I-A with no country or regional dummies, I-B with country dummies and I-C with regional dummies. * p<0.10, ** p<0.05, *** p<0.01.*

Variable	Model II-A		Model II-B		Model II-C	
	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
Metro coverage [stations per km^2]	813.95**	2.67	470.74**	2.46	708.65***	4.22
Suburban coverage [stations per km^2]	471.71***	4.41	273.76**	2.41	382.68***	4.18
Population density [1.000 per km^2]	-0.06**	-2.26	-	-	-	-
Job density [1.000 per km^2]	0.18***	3.32	0.07**	2.08	-	-
Car ownership [per 1.000 inhab.]	0.80**	2.22	-	-	-	-
Constant	-113.29	-0.70	72.03	1.18	234.33***	5.56
Country fixed effects	No		Yes		No	
Regional fixed effects	No		No		Yes	
N	48		48		48	
R^2	0.431		0.719		0.627	

*Table 5.5; Multiple regression model of per capita annual ridership using network station density. Model I-A with no country or regional dummies, I-B with country dummies and I-C with regional dummies. * p<0.10, ** p<0.05, *** p<0.01.*

Generally, only few variables showed significance at the 95% confidence level, especially when including fixed country or regional effects. Total city-level ridership were positively associated with mainly network coverage with metro being the most influential. This highlights the attractiveness of metro networks contributing to high ridership. But it is probably also a result of metro networks being implemented in metropolitan areas where there is a higher potential for riders due to increased urban density. Suburban rail coverage was also positively associated with ridership, but the lower parameter estimates suggest weaker influence on ridership.

Job density showed stronger correlation with ridership than population density, which confirmed the initial data analysis. This could suggest a larger importance of urban density at the destination-end of a trip, which most often is the workplace location. However, both were insignificant when taking into account country and regional differences explicitly using dummy variables. Car ownership was positively associated with ridership in Models I-A and II-A. This finding was somewhat surprising as most previous studies highlighted in the literature review identified a negative correlation. However, it might be due to income on an aggregate level generally increase transport activities. The GINI-coefficient was negatively associated with ridership suggesting lower ridership in cities with higher economic inequality. However, these effects were insignificant when controlling for fixed geographical effects resulting in models solely based on network coverage, and job density and/or GDP per capita.

Finally, the models showed slightly better fit when basing network coverage on length rather than the number of stations. This could be due to long networks with fewer stops are more important in attracting ridership than shorter networks with many stations. While being more accessible for passengers a higher density of stations will result in slower operations, hence creating a less attractive travel option compared to other travel modes.

5.4.2 Factor analysis

The full survey dataset showed good sampling adequacy with Kaiser-Meyer-Olkin (KMO) = 0.70. The determinant of the Spearman correlations matrix equalled $4.122*10^{-7}$ indicating existence of correlations without multi-collinearity, and the hypothesis of an identity correlations matrix was rejected using the Bartlett's test for sphericity. Based on the scree plot and an eigenvalue criteria of 1, four factors were extracted using principal components with orthogonal Varimax rotation, cf. Table 6.3. Dominant items were defined as those with an absolute value greater than 0.30 with each item only being allowed in one factor (Kline, 1994). The resulting factors also showed good internal consistency as standardised Cronbach's alpha's were all above 0.70 (Miller, 1995). The four factors together explained 82% of the variation in the variables with all communalities larger than 0.60, except for car ownership at 0.45. Hence, except for car ownership the factors were appropriate for factor regression (Maccallum et al., 1999).

Item	F1 Metro network, connectivity and urban density	F2 Suburban rail network	F3 Economic inequality	F4 Light rail network	Communality
Metro network, length	0.901	0.083	-0.025	0.088	0.826
Population density	0.881	0.160	0.165	0.146	0.850
Metro network, stations	0.868	0.091	-0.013	0.172	0.791
Job density	0.816	-0.119	-0.196	0.057	0.722
Masks / cyclomatic number	0.781	0.439	0.024	-0.008	0.803
Suburban railway, length	0.057	0.962	-0.007	0.052	0.932
Suburban railway, stations	0.059	0.954	-0.101	-0.013	0.924
Terminals	0.627	0.720	-0.023	0.108	0.923
Unemployment rate	0.152	-0.239	0.885	-0.027	0.864
GDP per capita (R)	-0.195	-0.070	0.823	-0.058	0.724
GINI coefficient	0.288	0.138	0.795	-0.316	0.834
Car ownership	-0.396	0.085	0.532	-0.017	0.448
Light rail, length	0.133	0.047	-0.162	0.946	0.941
Light rail, stations	0.183	0.035	-0.086	0.941	0.927
Eigenvalue	4.958	2.484	2.060	1.257	-
Std. Cronbach's alpha	0.919	0.908	0.772	0.940	-
Average communality	-	-	-	-	0.822

Table 5.6; Rotated factor analysis. (R) indicates reversed variables.

The first factor contained the variables related to the metro network and land use density in terms of population and employment, hence it is associated with dense urban areas which is often much correlated with the presence of metro networks. The second factor was related to the suburban rail network, and also contained the connectivity indicator of number of terminals. Note that this variable also had a high loading on the first factor. The third factor was associated with the three variables related to economic performance, and car ownership. Finally, the fourth factor contained the two variables related to light rail networks.

The main model results based on factor loadings confirmed the expected correlations between public transport ridership and the various explanatory variables, cf. Table 5.7. Increased public transport ridership was seen in cities with dense urban structure and presence of metro, suburban and light rail networks whereas economic inequality was associated with lower ridership. These main results were consistent across the three models when controlling for country-specific or regional fixed-effects. However, the significance of the factors decreased to the 90% level for Model I-B while economic inequality was insignificant in Model I-C. Hence, the results suggest that the regional dummy variables capture regional economic differences. Finally, no effects were observed for bicycle-friendly cities in any of the models.

	Model III-A		Model III-B		Model III-C	
Variable	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
F1 – Metro network, connectivity, and urban density	74.38***	2.81	60.01*	1.94	82.28***	3.28
F2 – Suburban rail network and terminals	95.87***	3.63	52.67*	1.95	82.86***	3.47
F3 – Economic inequality	-57.20**	-2.16	-150.12*	-1.90	-58.62	-1.30
F4 – Light rail network	54.70**	2.07	58.85*	1.88	56.67**	2.12
Constant	340.77***	13.03	88.84*	0.94	388.01***	12.94
Country fixed effect	No		Yes		No	
Regional fixed effect	No		No		Yes	
N	48		48		48	
R^2	0.3567		0.7613		0.6618	

*Table 5.7; Multiple regression model of per capita annual ridership. Model III-A with no country or regional dummies, III-B with country dummies and III-C with regional dummies. * p<0.10, ** p<0.05, *** p<0.01.*

The results also show a positive influence of network connectivity measured by the two indicators of the cyclomatic number and the number of transfer stations. The precise estimate of their individual influence cannot readily be observed from the results. However, the results from the correlation matrix in Table 5.8 showed that the number of terminals had higher correlation with ridership than the cyclomatic number. This finding is more evident when controlling for the socio-economic variables. Hence, this not only confirms the importance of transfer stations in a network, but also suggests that transfer stations are more important in explaining ridership than the network topology indicator of cyclomatic number. However, it should be noted that it is not possible to infer causality based on these analyses.

	Cyclomatic number	Terminals
Public transport ridership	0.418 (0.164)	0.531 (0.383)

Table 5.8; Correlations between network topology indicators and ridership (conditional on population and job densities, car ownership, GDP per capita, unemployment rate, and GINI-coefficient in parenthesis).

Finally, due to the low communality of car ownership in the four-factor model, another model was tested based on adding a fifth factor. This resulted in car ownership loading highly on the fifth factor while the remaining factors remained unchanged. The resulting regression analysis based on the five factors showed similar results, however with the fifth factor of car ownership becoming insignificant, thus suggesting low correlation between car ownership and public transport usage for the urban areas included in this study.

5.5 DISCUSSION AND CONCLUSIONS

This study analysed the determinants of public transport ridership across 48 European cities using aggregate data with specific focus on the influence of different public transport networks and network topology. The database collected as part of the study included detailed information about the public transport networks split between each of the three main public transport modes, i.e. metro, suburban rail, and light rail transit as well as the most important urban and socio-economic characteristics identified by a thorough literature review of 36 previous studies.

An important finding from the data collection process was the importance of defining urban agglomerations and urban density consistently for analyses of urban public transport ridership. The inconsistencies between definitions of urban areas and the extent of the public transport network has previously been highlighted (Derrible and Kennedy, 2009). Based on multiple data sources the OECD-EC definition (Dijkstra and Poelman, 2012) was found to be the most consistent representation of the actual urban area. However, manual corrections still had to be made to ensure consistency between the definition of the urban area and the coverage of the public transport network.

The results of the two-fold multiple regression analysis based on the raw database and a factor analysis across the 48 cities confirmed the positive relationship between the extent of public transport coverage and ridership numbers, consistent with findings in previous studies of individual cities. Specifically, the extent of both metro, suburban and light rail networks were found significantly related to ridership. The intial regression models showed metro having the largest correlation suggesting the importance of metro networks for carrying large passenger numbers. The factor models showed the largest influence from factors related to metro network and suburban rail, but with light rail also being positively associated with ridership. However, it should be noted that the factor related to metro network coverage also incorporated urban density due to the large correlation between these two characteristics. This highlights the mutual dependence between urban density and metro network coverage. Dense metropolitan areas need metro networks for ensuring high-capacity, fast and reliable transport. Similarly, the high construction costs of metro networks require dense urban areas in order to ensure sufficient potential for ridership.

Network connectivity was analysed specifically in terms of network topology and transfer possibilities. While previous studies found significant influence of network topology indicators this study didn't find specific evidence of ridership being influenced by cyclicity or transfer stations. However, the factor analyses showed large correlation between network connectivity and network coverage, which together were highly associated with ridership. In addition, analyses of correlations suggested a larger influence from the number of transfer possibilities on ridership rather than network topology measures such as the cyclomatic number. Hence, this suggests the importance of ensuring transfer possibilities in public transport networks thereby increasing mobility of passengers resulting in higher attractiveness of the entire system.

Finally, as expected differences between cities in terms of socio-economic characteristics also had significant influence on ridership. While not showing statistical influence individually in the initial regression analyses a combined effect of economic inequality was found to influence ridership negatively, hence suggesting cities with more equality having higher ridership. More specifically, lower unemployment, lower GINI-coefficient, and higher per capita GDP were associated with higher ridership. These effects were greatly reduced when taking into account geographical fixed effects in the models. Hence, the regional dummy variables seemed to capture the economic differences across cities.

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6 SATISFACTION AND PUBLIC TRANSPORT USE: A COMPARISON ACROSS SIX EUROPEAN CITIES USING STRUCTURAL EQUATION MODELLING

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ABSTRACT

Understanding the motivators of travel satisfaction is essential for designing attractive public transport systems. This study investigates the key drivers of satisfaction with public transport and their relationship with travel frequency and willingness to recommend public transport to others, hence contributing specifically by analysing the influence of social norms in travel use. A large-scale passenger satisfaction survey collected in six European cities and structural equation modelling validates the framework and results across different travel cultures. The study found that travel satisfaction is positively related to i) accessibility measures, e.g. travel speed and service frequency, ii) perceived costs, e.g. reasonable ticket prices, and iii) norms, i.e. perceived societal and environmental importance of public transport. These findings were consistent across all six cities. Furthermore, the importance of social norms was confirmed as the willingness to recommend public transport to others was significantly related to public transport use at a similar level as overall satisfaction. Finally, the study found significant differences in satisfaction across user groups as young respondents and students were less satisfied with service quality than middle-aged and elderly respondents despite more frequent use. This suggests structural problems in public transport because travel habits formed in early life shapes travel behaviour throughout life. Hence, it is important to address the needs of these user groups to ensure public transport ridership in the future. The results bear important policy implications for transit planners in not only focusing on traditional measures for optimising operations, but also branding public transport as an environmentally and socially important transport mode in metropolitan areas.

Keywords: Public transport satisfaction, structural equation modelling, knowledge propagation, public transport recommendation, norms, service quality

HIGHLIGHTS

- Analysis of large-scale transit passenger satisfaction survey from six European cities
- Accessibility measures and low perceived costs are most important drivers of satisfaction
- Perceived societal and environmental importance of transit is a key factor for satisfaction
- Younger generations less satisfied despite increased public transport usage highlights the importance of focusing on user needs in planning
- Findings highlight the importance of branding public transport to attract younger generations

6.1 INTRODUCTION

The long-term effectiveness of transit systems depends on a shared-responsibility between transit operators and users. From the operator perspective, such systems should rely on a coherent planning and policy approach to ensure an advanced solution that is attractive, easy, and efficient, and facilitates the needs of travellers. Improving service quality is a powerful tool to increase the competitive edge of public transport against other travel modes (Randheer et al., 2011). However, public transport also serves other purposes such as ensuring mobility for all communities in society (Lucas, 2006; Welch and Mishra, 2013), reducing congestion in metropolitan areas (Eboli and Mazzulla, 2015), and ensuring sustainable transport with less environmental impacts (Mees, 2000). From the user perspective, a durable and sustainable transition towards higher ridership can be achieved through an evolutionary process of knowledge propagation and habit formation. Ensuring durable transit systems is grounded in passenger satisfaction as key to shared-responsibility, because passengers are co-producers of the service quality output through their satisfaction from system-user interaction (Randheer et al., 2011). Several studies have shown this by highlighting the importance of social norms in influencing use frequency, hence pointing towards the importance of peer acceptance (Bamberg et al., 2007; Heath and Gifford, 2002).

This study explores the influence of norms in the relationship between the perceived passenger satisfaction, perceived level-of-service, transit use frequency, and knowledge propagation by means of recommending travelling by public transport to others. The objective is to analyse the key drivers for creating a positive process of passenger satisfaction, transit use frequency and recommendation to others in public transport systems. The importance of this issue is three-fold. Firstly, the contribution stems from the role of satisfaction in facilitating the formation of transit use habits and a shift in habits towards transit use by future passengers. Secondly, satisfaction is a multi-dimensional construct because transit systems comprise of multiple operative dimensions including service characteristics and coverage, fleet management, passenger flows, advanced public transport systems (APTS) and human interaction. Thirdly, service disruptions result in heavy burden on transit passengers, as sources of travel time uncertainty constitute up to 50% of the total travel time by buses in Copenhagen (Ingvardson et al., 2017a). Hence, the drivers of satisfaction and their individual significance in attracting ridership are important to investigate further.

The contribution of this study is two-fold. Firstly, the present study investigates the drivers of passenger satisfaction in public transport across six European cities using a large-scale satisfaction survey. This ensures not only a validation of the applied approach, but also makes it possible to compare the importance put on various service characteristics as well as the general satisfaction levels across cities of different sizes from six European countries. Secondly, this study investigates the mutual relationships between travel use, travel satisfaction and knowledge propagation in terms of recommendation to others. Previous studies have confirmed the importance of social norms in explaining mode choice and intentions to use public transport (Chen and Chao, 2011). Furthermore, previous studies have found loyalty in terms of recommendation to others important for satisfaction levels, e.g. Figler et al. (2011) and Lierop et al. (2017). This present study further investigates the importance of social norms in choosing public transport by simultaneously comparing satisfaction levels with the desire to recommend public transport to others.

The remainder of this paper is structured as follows. In section 2 relevant literature is reviewed. Section 3 contains a description of the methodology including the data used and modelling approach while the model results are presented in section 4. In section 5 findings and limitations of the study are discussed while section 6 concludes the work by suggesting policy implications.

6.2 LITERATURE REVIEW

The perceived attractiveness of transit can be investigated by analysing passenger satisfaction. Previous studies have primarily analysed the key service characteristics that influence satisfaction levels, e.g. Cao et al. (2015), de Oña et al. (2015), de Oña et al. (2016), Eboli and Mazzulla (2007), Fellesson and Friman (2012), Mouwen (2015). Most studies find that accessibility measures including *on-time performance*, *reliability*, *service frequency* and *travel speed* are the most important characteristics for user satisfaction (de Oña et al., 2015, 2013, Eboli and Mazzulla, 2015, 2007; Fellesson and Friman, 2012; Friman and Gärling, 2001; Lierop et al., 2017; Mouwen, 2015; Shen et al., 2016; Stuart et al., 2000; Tyrinopoulos and Antoniou, 2008; Weinstein, 2000; Redman et al., 2013). However, studies also highlight the importance of other characteristics such as *comfort* (de Oña et al., 2013; Fellesson and Friman, 2012; Lierop et al., 2017; Weinstein, 2000; Redman et al., 2013), *staff behavior* (de Oña et al., 2013; Fellesson and Friman, 2012; Friman and Gärling, 2001; Lierop et al., 2017), *safety* and *security* (Fellesson and Friman, 2012; Lierop et al., 2017; Spears et al., 2013; Stuart et al., 2000), *cleanliness* (Eboli and Mazzulla, 2015; Lierop et al., 2017; Tyrinopoulos and Antoniou, 2008; Weinstein, 2000), and *availability of information* (Eboli and Mazzulla, 2015; Friman and Gärling, 2001; Lierop et al., 2017; Weinstein, 2000). Hence, studies points towards great diversity in which service aspects creates an attractive public transport system, thus highlighting the multi-dimensionality of public transport systems.

Some studies have analysed directly the influence of observed service characteristics on satisfaction levels. Friman and Fellesson (2009) found that the consistency between satisfaction and level-of-service was far from perfect by analysing objective public transport performance measures from the Millennium Cities Database. Similarly, Friman (2004) did not find increased satisfaction after service improvements to public transport services were implemented on various public transport lines in Sweden, hence highlighting the difficulty in comparing aggregate system-wide characteristics and satisfaction. However, in Carrel et al. (2016) the relationship was analysed in greater detail by linking trip-specific service characteristics and satisfaction data collected from AVL and respondents' smartphones. The study found a strong sensitivity towards in-vehicle delays which were bigger for metro trips than bus trips, and suggested that satisfaction could be modelled as the sum of a general baseline satisfaction level and a variable component based on previous experiences. The importance of past experiences in explaining satisfaction was also highlighted in Friman et al. (2001) where previous negative experiences, e.g. travel incidents and disruptions, also affected satisfaction levels negatively among Swedish travellers. As these studies suggest, satisfaction levels are not only related to service characteristics, but maybe even more to psychological aspects of the users (Carrel et al., 2016; De Vos et al., 2013; Susilo and Cats, 2014).

Ettema et al. (2011) proposed to measure satisfaction using the Satisfaction with Travel Scale (STS) which incorporated subjective well-being directly in the framework of travel satisfaction. The STS consists of an affective component related to experienced feelings of the traveller during the trip and a cognitive component related to how the traveller would evaluate the trip (De Vos et al., 2016). The method has been applied in several studies confirming satisfactory fit on real data across travel modes and study areas (Friman et al., 2013). The study found that satisfaction was higher for active modes, i.e. walking and bicycling, than public transport, hence suggesting the importance of short distances and performing health activities in attractive work commutes. Another study deployed the STS for analysing the relationships between different travel modes, satisfaction with travel and general satisfaction, and found significant effects of the travel mode on the mood of the travellers thereby influencing general satisfaction with the day as a whole (Eriksson et al., 2013).

Several studies applied the Theory of Planned Behaviour (TPB) to investigate social norms in public transport focusing on the influence on use frequency. Heath and Gifford (2002) applied the TPB to explain bus use among university students before and after implementing a bus pass scheme. The study found that both subjective norms, i.e. what significant others do, and descriptive norms, i.e. what most people do, significantly explained ridership. Bamberg et al. (2007) similarly found that personal norms including anticipated feelings of guilt and perceived social norms predicted public transport use. And, Chen and Chao (2011) found a similar positive influence of social norms on intention to shift to public transport among car and motorcycle users in Taiwan. Hence, there is strong evidence that norms are important in explaining behaviour concerning mode choice and use frequency.

While these studies show the broad and extensive research conducted within public transport passenger satisfaction and use, no studies have focused on analysing the influence of social norms on public transport passenger satisfaction while deploying a sample of both public transport users and non-users. This present study focuses on these main limitations by analysing satisfaction and willingness to recommend to others using a large-scale passenger satisfaction survey from six large European cities, namely Stockholm, Oslo, Helsinki, Copenhagen, Vienna and Geneva.

6.3 METHODOLOGY

6.3.1 Survey description

The BEST questionnaire data was used as data source for this study. This survey is administered among a sample of 1,000 interviews per year per participating city, and is not restricted to only public transport users thereby ensuring a large sample of both users and non-users. The survey data measured the participants satisfaction with the quality of service using 27 attitudinal items related to different service aspects measured on a 5-point Likert scale. Furthermore, background information on the participants were collected, i.e. age, gender, occupation and most used transport mode for all trips and for public transport trips. Finally, the data included two items measuring the overall satisfaction level and the willingness to recommend travelling by public transport to other people. A thorough description of the survey can be found in Friman and Fellesson (2009).

This study included data from the period 2009-2015 from six cities, namely Stockholm (STO), Oslo (OSL), Helsinki (HEL), Copenhagen (CPH), Vienna (VIE) and Geneva (GVA). In total, this resulted in 44,956 observations. However, as the dataset had missing values for many respondents it was decided to remove observations with missing values on more than ten percent of the survey items, i.e. a maximum of two missing values were accepted for each observation. Hence, the remaining 42,078 observations were used in the analysis.

6.3.2 Research hypotheses

Several research hypotheses were tested. Firstly, a positive correlation was expected between transit use frequency, general satisfaction, recommendation to others, and the service quality dimensions. This included a comparison of the relative role of the various dimensions to identify the strongest predictors of overall satisfaction. Secondly, the study analysed the stability of the model structure across countries. The general model structure was proposed for all cities, but by analysing each city separately, it was possible to compare differences across cities specifically. Thirdly, the relative importance of social norms in terms of willingness to recommend public transport to others on public transport use frequency was compared to the influence of overall satisfaction. Lastly, an alternative model framework was tested based on a general cyclical relationship between mode use frequency and travel satisfaction, as proposed by De Vos et al. (2016).

Such framework was also tested in Ingvardson et al. (2017b) by applying the ERG theory of human needs to evaluate travel satisfaction supporting the existence of a feedback loop between travel mode choice and travel satisfaction. Hence, this study empirically tested a model setup where travel use frequency influences satisfaction with individual public transport service elements which then influences overall satisfaction and recommendation to others.

6.3.3 Structural equation modelling

The research hypotheses were evaluated using structural equation modelling (SEM). The model setup investigated the relationship between the service quality items, individual socio-economic characteristics and overall passenger satisfaction, recommendation to others and transit use frequency. This approach was chosen because SEM allows for accommodating measurement errors when the explanatory and the dependent variables are latent multi-dimensional constructs, and modelling simultaneously endogenous latent constructs, their relationship with exogenous observed variables, and their correlation pattern. The approach was based on creating latent factors from the questionnaire based on an exploratory factor analysis. The resulting factors were then evaluated in terms of their influence on the dependent variables in a SEM model setup.

Four sets of equations were included in the full model, namely i) measurement equations (eq. 1) which link the measurement indicators (survey items) to the latent factors, ii) structural equations (eq. 2) which associate the factors with individual background variables, iii) structural equations (eq. 3) which relates the explanatory and the mediator variables, and iv) structural equations (eq. 4) which links the mediators to the dependent variable(s).

$$I_{rn} = Z^*_{ln} \cdot \alpha_r + \nu_{rn} \quad \text{and} \quad \nu_n \sim N(0, \Sigma_\nu) \quad \text{for} \quad r = 1, \dots, R \tag{1}$$

$$Z^*_{ln} = S_{ln} \cdot \beta_l + \omega_{ln} \quad \text{and} \quad \omega_n \sim N(0, \Sigma_\omega) \quad \text{for} \quad l = 1, \dots, L \tag{2}$$

$$Z^*_l = Z_i \cdot \beta_i + \varphi_l \quad \text{and} \quad \varphi_l \sim N(0, \Sigma_\varphi) \quad \text{for} \quad l = 1, \dots, L \quad , i = 1, \dots, K \tag{3}$$

$$Y_{in} = Z^*_{ln} \cdot \beta_z + \xi_{in} \quad \text{and} \quad \xi_n \sim N(0, \Sigma_\xi) \quad \text{for} \quad i = 1, \dots, I \tag{4}$$

where I_{rn} is the value of an indicator r of the latent construct Z^*_{ln} as perceived by respondent n, Z^*_{ln} is the value of latent construct l for respondent n, S_{ln} is a vector of M respondents' observed individual characteristics, and Y_{in} is a vector of travel users' satisfaction levels. Error terms are expressed as elements ω_{ln}, ν_{rn}, ξ_{in} of the vectors following a normal distribution with respective covariance matrix Σ_ω, Σ_ν, Σ_ξ, while parameters to be estimated are α_r, β_l, β_i, and β_z. Considering R indicators translates into writing R measurement equations and estimating an ($R \times 1$) vector α of parameters (i.e., one parameter is estimated for each equation), while considering L latent constructs translates into writing L structural equations and estimating an ($M \times L$) matrix of β parameters (i.e., M parameters are estimated for each equation).

The structural equation models were estimated using M*plus* 7.2 (Muthén and Muthén, 2017). The assessment of model fit was done using the relative CFI (Comparable Fit Index) and the absolute RMSEA (Root Mean Square of Approximation).

6.4 Results

6.4.1 Descriptive statistics

Basic descriptive statistics, as can be seen in Table 6.1, shows that the survey items are not normally distributed. Generally, respondents consider public transport as being good for the environment and for society as well as being attractive within city centre areas. On the other hand, satisfaction is lower for fare levels, information during disruptions, and for trips outside city centres. In Table 6.2 characteristics of the respondents' are shown for each city in the sample separately. Generally, the samples are similar concerning gender and age distributions. However, for occupation the samples are quite different. This is probably due to different job markets across the six cities. For example there is a high share of part time workers among respondents in Geneva which is possibly linked to average working hours being higher in Switzerland and that many women works part time due to expensive child-care options.

There also seems to be differences across cities in terms of general satisfaction levels and frequency of use, cf. . The respondents from Copenhagen stand out by being less satisfied with public transport and using the system less than respondents from the other cities. On the other hand, Helsinki has the fewest dissatisfied respondents and the highest number of daily users.

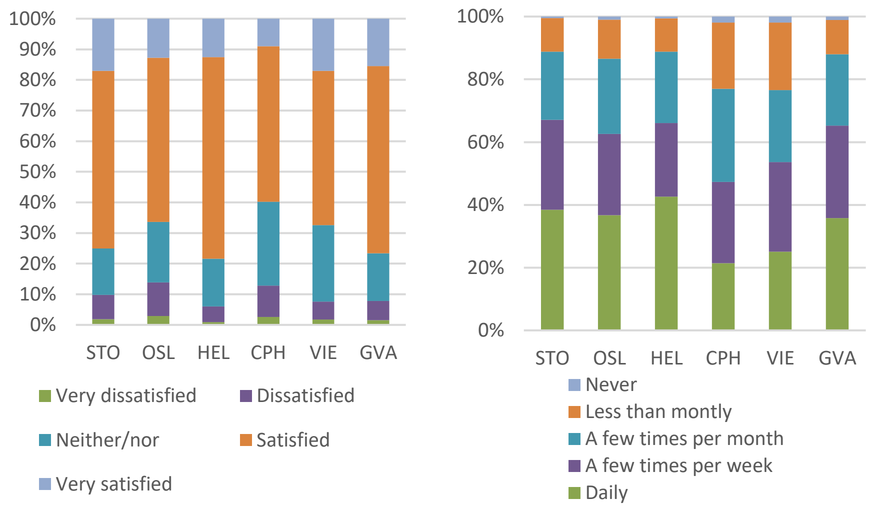

Figure 6.1; Level of satisfaction (left) and frequency of public transport use (right) for the sample.

Category	Variable	N	Mean	St. Dev.	Skew-ness	Kur-tosis
Location and purpose	Public transport (PT) is good for work/school trips	41,737	3.65	1.24	-0.69	-0.49
	PT is good for shopping, leisure etc.	43,952	3.53	1.23	-0.56	-0.67
	PT is good for trips in the city centre	43,345	4.27	0.92	-1.37	1.70
	PT is good for trips outside the city centre	41,852	3.34	1.13	-0.34	-0.64
Accessi-bility measures	Nearest stop is close to where I live	44,849	4.38	1.06	-1.84	2.55
	Travel time on public transport is reasonable	44,355	3.79	1.09	-0.81	0.03
	Waiting time is short at transfers	42,758	3.43	1.04	-0.40	-0.34
	I am satisfied with the number of departures	44,197	3.56	1.20	-0.59	-0.59
	PT mostly runs on schedule	44,123	3.55	1.06	-0.64	-0.20
	Transfers are easy	43,689	3.69	0.97	-0.61	0.06
Infor-mation	It is easy to get the information needed before a trip	43,846	3.95	1.04	-0.95	0.38
	The information is good when problems occur	42,434	2.93	1.14	0.02	-0.77
	The information is good in stops and terminals	43,788	3.40	1.15	-0.37	-0.70
	The staff answers my questions correctly	41,346	3.66	1.00	-0.44	-0.24
	The staff behaves nicely and correctly	43,580	3.84	0.96	-0.68	0.16
Safety and security	I feel secure at stations and bus stops	44,605	3.78	1.04	-0.69	-0.12
	I feel secure on board busses and trains	44,634	4.00	0.97	-0.93	0.48
	I am not afraid of traffic accidents when using PT	44,689	4.26	0.93	-1.40	1.81
Comfort	Travelling with PT is comfortable	44,635	3.68	0.99	-0.62	0.00
	The busses and trains are modern	44,569	3.80	0.93	-0.65	0.19
	The busses and trains are clean	44,571	3.40	1.01	-0.39	-0.42
	I normally get a seat when I travel with PT	44,503	3.72	1.04	-0.72	-0.02
Norms	More people will travel with PT in the future	43,424	3.96	1.00	-0.78	0.10
	PT is good for the environment	44,362	4.44	0.82	-1.64	2.72
	PT is beneficial to society	44,736	4.57	0.72	-1.93	4.24
Costs	PT gives value for money	44,365	3.26	1.20	-0.27	-0.85
	PT fares are reasonable	44,357	2.77	1.28	0.16	-1.10
Satis-faction	I gladly recommend travelling with PT to others	44,356	3.86	1.11	-0.82	0.03
	How satisfied are you with PT in general	44,730	3.73	0.85	-0.89	0.98

Table 6.1; Basic descriptive statistics, aggregated for all six cities. All items measured on the 5-point Likert scale.

Variable	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
Male	46%	48%	44%	45%	47%	45%
Female	54%	52%	56%	55%	53%	55%
Age						
16-24	11%	11%	13%	12%	11%	12%
25-44	31%	41%	34%	34%	36%	34%
45-64	35%	33%	34%	33%	34%	35%
65-79	19%	13%	18%	17%	15%	14%
> 80	4%	2%	2%	3%	3%	5%
Employment status						
Full time	53%	62%	50%	50%	44%	39%
Part time	10%	7%	6%	7%	13%	21%
Student	9%	11%	12%	14%	8%	11%
Retired	24%	16%	25%	23%	28%	22%
Other	4%	3%	8%	5%	7%	7%

Table 6.2; Sample characteristics.

6.4.2 Factor analysis

An exploratory factor analysis was performed on the data to obtain the main determinants for public transport satisfaction and use frequency. This was at first performed using subsets of the full dataset in order to investigate possible structural deviations across cities. However, the factor analyses resulted in similar factor structures across the cities of Stockholm, Oslo, Helsinki and Copenhagen, but with the Geneva and Vienna datasets each having one survey item moved from one factor to another. Due to this high degree of similarities across the datasets, it was decided to maintain the same structure for all cities in the subsequent structural equation models.

The full survey dataset showed good internal consistency (Cronbach's alpha = 0.910) and good sampling adequacy (Kaiser-Meyer-Olkin (KMO) = 0.920). The determinant of the Spearman correlations matrix equalled $8.348*10^{-5}$ indicating existence of correlations without multi-collinearity, and the hypothesis of an identity correlation matrix was rejected using the Bartlett's test of sphericity. The factor analysis resulted in seven factors based on principal axis factoring with orthogonal Varimax rotation, cf. Table 6.3. Dominant items were defined as those with an absolute value greater than 0.30 with each item only being allowed in one factor (Kline, 1994). The resulting factors also showed good internal consistency as Cronbach's alpha's were all above 0.70 (Miller, 1995). Listwise deletion for missing values were adopted and no changes to the factors were seen when using pairwise deletion of missing values or by using mean values, hence the estimated factors were robust. The seven factors based on the 26,661 observations with no missing values are listed in Table 6.3.

Item	F1 Access.	F2 Info.	F3 Staff	F4 Safety	F5 Comfort	F6 Norms	F7 Costs
I am satisfied with the number of departures	**0.640**	0.165	0.069	0.071	0.130	0.024	0.114
Travel time on public transport is reasonable	**0.636**	0.107	0.087	0.117	0.157	0.116	0.120
Public transport (PT) is good for work/school trips	**0.624**	0.140	0.052	0.063	0.107	0.142	0.089
PT is good for shopping, leisure, etc.	**0.599**	0.078	0.040	0.059	0.102	0.140	0.109
Waiting time is short at transfers	**0.597**	0.176	0.065	0.084	0.162	0.058	0.110
PT is good for trips outside the city centre	**0.546**	0.125	0.056	0.074	0.155	0.083	0.137
Transfers are easy	**0.478**	0.244	0.109	0.163	0.314	0.113	0.092
PT is good for trips in the city centre	**0.379**	0.139	0.103	0.114	0.146	0.192	0.056
PT mostly runs on schedule	**0.377**	0.311	0.117	0.110	0.240	0.099	0.152
Nearest stop is close to where I live	**0.369**	0.026	0.041	0.089	0.019	0.133	-0.015
The information is good in stops and terminals	0.223	**0.680**	0.123	0.108	0.146	0.087	0.055
The information is good when problems occur	0.252	**0.642**	0.134	0.071	0.175	0.026	0.084
It is easy to get the information needed before a trip	0.245	**0.372**	0.118	0.162	0.144	0.178	0.087
The staff behaves nicely and correctly	0.126	0.113	**0.748**	0.201	0.198	0.105	0.110
The staff answers my questions correctly	0.162	0.250	**0.664**	0.168	0.167	0.102	0.059
I feel secure on board busses and trains	0.143	0.105	0.129	**0.857**	0.158	0.117	0.054
I feel secure at stations and bus stops	0.166	0.105	0.096	**0.656**	0.151	0.126	0.102
I am not afraid of traffic accidents when using PT	0.142	0.102	0.179	**0.468**	0.194	0.180	0.056
Travelling with PT is comfortable	0.352	0.154	0.139	0.148	**0.594**	0.142	0.137
The busses and trains are modern	0.221	0.235	0.122	0.126	**0.531**	0.136	0.050
The busses and trains are clean	0.121	0.228	0.156	0.207	**0.501**	0.106	0.078
I normally get a seat when I travel with PT	0.194	0.023	0.083	0.147	**0.405**	0.091	0.168
PT is beneficial to society	0.193	0.077	0.085	0.129	0.115	**0.770**	0.052
PT is good for the environment	0.155	0.050	0.063	0.132	0.111	**0.674**	0.089
More people will travel with PT in the future	0.248	0.108	0.062	0.113	0.124	**0.462**	0.174
PT fares are reasonable	0.192	0.100	0.078	0.087	0.133	0.088	**0.814**
PT gives value for money	0.266	0.108	0.090	0.107	0.178	0.207	**0.767**
Eigenvalue	8.236	1.862	1.532	1.301	1.186	1.022	0.973
Cronbach's alpha	0.847	0.699	0.772	0.759	0.746	0.714	0.857

Table 6.3; Rotated factor analysis.

Factor F1 “accessibility” contains items related to service frequency, travel time, waiting time, and ease and attractiveness of using the public transport system. Factor F2 “information” is related to the quality of information en-route when using public transport, and when planning a trip. Factor F3 “staff” incorporates the statements related to the helpfulness of the staff. F4 “safety” is associated with safety and security of the public transport system. F5 “comfort” is related to the comfort and cleanliness of public transport vehicles. F6 “norms” includes statements related to psychological beliefs about the environmental and societal importance of public transport as well as the perceived importance in the future. Factor F7 “costs” includes the last two statements related to the costs and perceived value for money of the public transport system.

6.4.3 Model estimation results

The structural equation models were estimated using the WLSMV estimator due to the violation of normally distributed data for all constructs according to the Kolmogorov-Smirnov test, and because it provides the best option when modelling categorical or ordered data (Brown, 2006). As the data still had missing entries for some variables, pairwise deletion was used in the estimation. While still assuming that data is missing completely at random (MCAR) it was preferred over listwise deletion in order to use as much data as was available.

The path diagram of the general model structure of Model I illustrated in Figure 6.2 was evaluated for all six cities. The initial model included all seven identified service quality dimensions from the factor analysis. However, three factors were not significantly related to overall satisfaction and recommendation to others, namely information, staff behaviour and safety. Hence, these were removed. It was tested to estimate one full model using data from all cities, but as the datasets for each city showed differences in terms of significant factors influencing satisfaction, recommendation and public transport use separate models were evaluated for each city. Furthermore, several model estimations were performed to test the differences across different years and user groups. Specifically, separate models based on data samples for each year were estimated to test possible structural variations over time. Similarly, car users and non-car users were estimated separately to capture structural differences across these users. While the results did show statistically significant differences in terms of parameter estimates no differences to general findings, ranking of most important parameters nor model fit were identified. Hence, it was decided to continue using a general model formulation which was estimated on six datasets, namely for each city separately, but including data for all years and all respondents. However, mean differences across years and between car users and non-car users were taken into account by adding dummy variables.

The final models for each city showed goodness-of-fit measures in terms of RMSEA equal to 0.028-0.033 which is consistent with the recommended maximum of 0.050 (Hu and

Bentler, 1999), and CFI equal to 0.963-0.977 which is above the recommended minimum value of 0.900 (Browne and Cudeck, 1992).

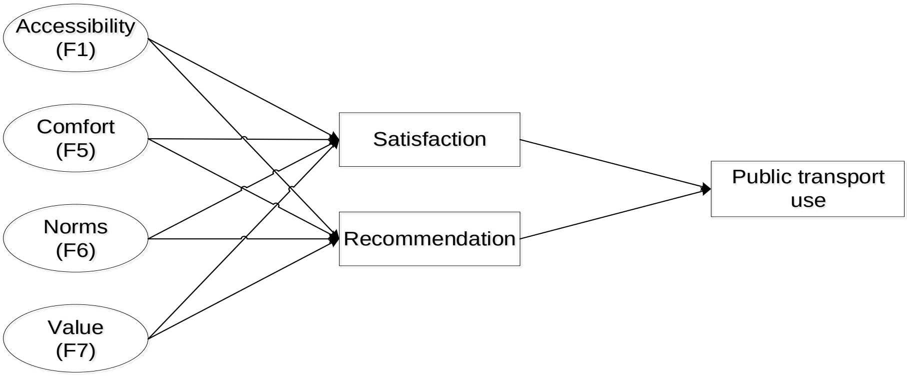

Figure 6.2; Path model for Model I relating the factors, overall satisfaction, recommendation to others and travel use frequency (solid black lines denote positive relationships).

6.4.3.1 *The relation between public transport satisfaction, recommendation and travel use*

The main results in terms of parameter estimates for the main relationships between service factors, overall satisfaction, willingness to recommend public transport to others and public transport use are shown in Figure 6.3 where each column represents a parameter estimate, significant at the 95% level. Detailed results for these relationships are shown in Tables 6.4-6.6 which includes the influence of respondents' socio-economic characteristics. Estimates of the measurement equations of the service quality constructs and the influence of socio-economic characteristics are shown in Table 6.10-Table 6.17 in Appendix I. Note that the control variables taking into account mean differences across years are not reported due to space constraints.

It can be seen that accessibility measures are the most important characteristics for achieving high level of satisfaction with public transport whereas the perceived value of the public transport system and the importance to society and the environment were also positively significant. Only for Stockholm was comfort a marginally important issue for overall satisfaction. While also the parameter estimates were significantly different across cities, the general finding of three main drivers for satisfaction was consistent across all six cities, hence suggesting similar respondent preferences across all cities. Similar findings were seen from the impact on whether respondents recommend public transport to others. As expected, accessibility measures were most important followed by costs and norms in terms of societal and environmental measures, similarly as for overall satisfaction. Again, comfort was marginally important for respondents in the Stockholm survey.

The frequency of use was positively related to overall satisfaction and willingness to recommend to others with the latter having the largest influence, except for Vienna where they were equally related. This confirms the importance of peer acceptance in affecting travel use with public transport also found in other studies (Bamberg et al., 2007; Chen and Chao, 2011).

When taking into account the characteristics of the respondents several findings can be highlighted. Firstly, in several cities males use public transport less than females which is consistent with findings using the Danish National Travel Survey (Christiansen, 2015). Hence, this finding is seen across several cities. Secondly, the use frequency decreases with age. Respondents under 24 years of age and students are the most frequent users which is probably because of the lack of other travel alternatives. For respondents in the middle age categories public transport use is lower, probably due to different travel patterns often requiring more independence, e.g. travelling with children. Moreover, the elderly travels the least which is possibly related to a generally fewer number of trips. This could also be the reason why the retired respondents and those categorised with other occupations, e.g. unemployed respondents, travel less, both generally and with public transport. On the other hand students travelled more with public transport which is consistent with previous findings (Taylor et al., 2009).

6.4.3.2 The relation between factors and socio-economic variables

The identified seven service quality dimensions of public transport satisfaction from the survey were significantly related to respondents' characteristics, cf. Tables 6.11-6.17 in Appendix I. Satisfaction with accessibility was higher for elderly and retired respondents across most cities. This could be due to these passenger groups focusing less on minimising travel times which is also reflected in lower value of time.

Satisfaction with information is higher for students and lower for respondents in the middle age groups. Satisfaction with staff is highest for retired and elderly, and lowest for the youngest travellers up to 24 years of age. Safety is also perceived more positively for the elderly, students and males. Males and respondents belonging to the older age categories perceive comfort as less satisfying, and full time workers seem to be less satisfied than all other occupation groups. This could again be related to a larger focus on minimising travel time. The perceived importance of public transport to society and the environment is emphasised more with age of the respondents. Finally, males are more positive towards public transport's value whereas respondents categorised with other occupations are negative. This could be an income effect which could not be taken into account directly as it was not part of the data. The value of public transport is also seen to be positively related with age.

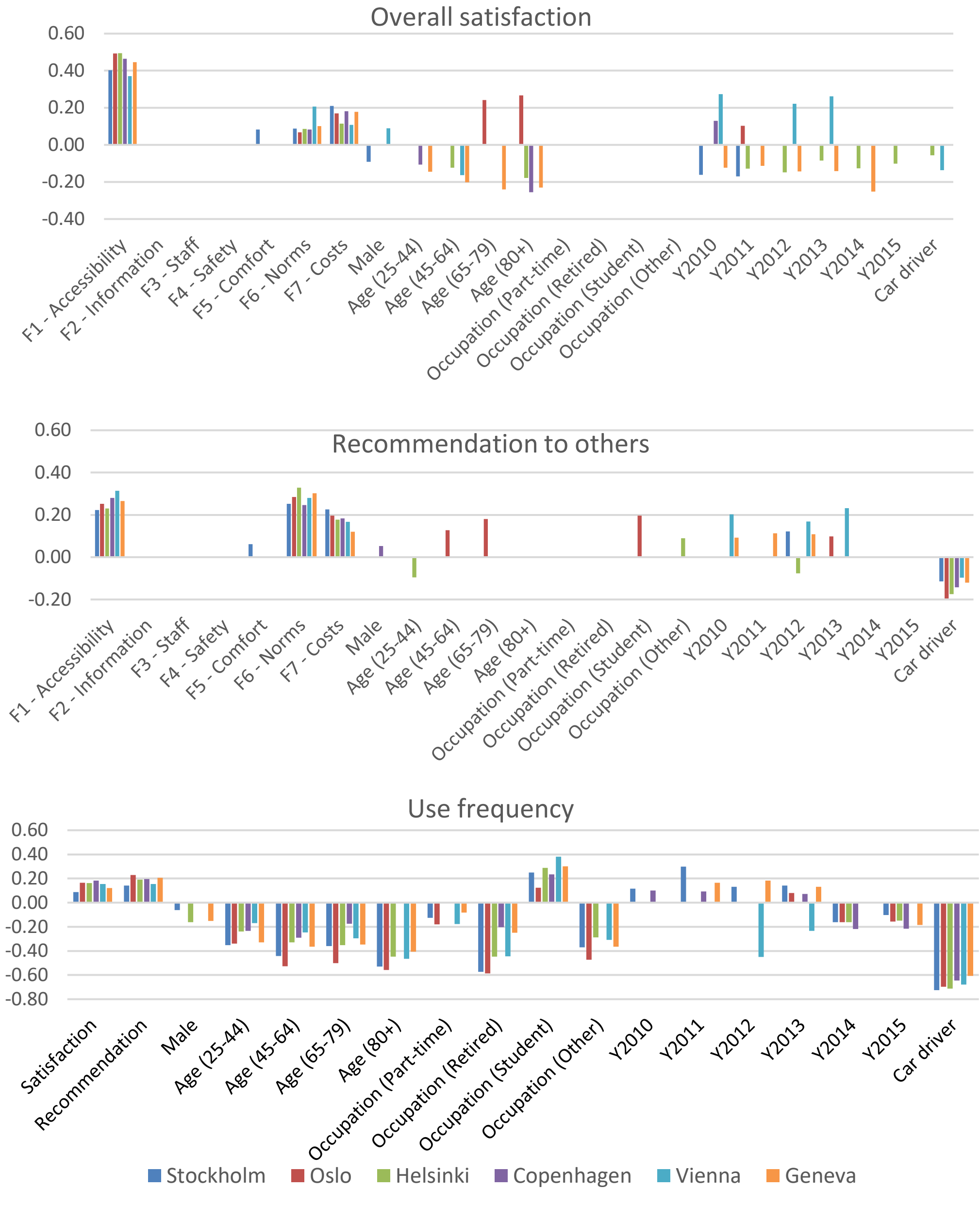

Figure 6.3; Main parameter estimates for Model I relating the service quality dimensions to general satisfaction (top left) and recommendation to others (top right), and relating overall satisfaction and recommendation to others to frequency of use (bottom).

Overall satisfaction	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
F1 – Accessibility	0.40**	0.49**	0.49**	0.46**	0.37**	0.45**
F5 – Comfort	0.08**	-	-	-	-	-
F6 – Norms	0.09**	0.07**	0.09**	0.08**	0.21**	0.10**
F7 – Costs	0.21**	0.17**	0.11**	0.18**	0.11**	0.18**
Male	-0.09**	-	-	-	0.09*	-
Age 25-44	-	-	-	-0.11*	-	-0.15*
Age 45-64	-	-	-0.12**	-	-0.16*	-0.20**
Age 65-79	-	0.24**	-	-	-	-0.24**
Age 80+	-	0.27**	-0.18*	-0.26**	-	-0.23*
Car driver	-	-	-0.06**	-	-0.14**	-

*Table 6.4; Parameter estimates of the structural equations linking the factors to overall satisfaction and socio-economic characteristics in Model I. * p<0.05, ** p<0.01.*

Recommendation to others	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
F1 – Accessibility	0.22**	0.25**	0.23**	0.28**	0.31**	0.27**
F5 – Comfort	0.06**	-	-	-	-	-
F6 – Norms	0.25**	0.29**	0.33**	0.25**	0.28**	0.30**
F7 – Costs	0.23**	0.20**	0.18**	0.18**	0.17**	0.12**
Male	-	-	-	0.05*	-	-
Age 25-44	-	-	-0.10**	-	-	-
Age 45-64	-	0.13**	-	-	-	-
Age 65-79	-	0.18**	-	-	-	-
Occupation, student	-	0.20**	-	-	-	-
Occupation, other	-	-	0.09**	-	-	-
Car driver	-0.11**	-0.20**	-0.18**	-0.14**	-0.10**	-0.12**

*Table 6.5; Parameter estimates of the structural equations linking the factors to willingness to recommend public transport to others and socio-economic characteristics in Model I. * p<0.05, ** p<0.01.*

Frequency of use	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
Satisfaction	0.09**	0.17**	0.16**	0.18**	0.15**	0.12**
Recommendation	0.14**	0.23**	0.19**	0.20**	0.15**	0.21**
Male	-0.06**	-	-0.16**	-	-	-0.15**
Age 25-44	-0.35**	-0.34**	-0.24**	-0.23**	-0.17*	-0.33**
Age 45-64	-0.44**	-0.53**	-0.33**	-0.29**	-0.25**	-0.36**
Age 65-79	-0.36**	-0.50**	-0.35**	-0.18**	-0.30**	-0.35**
Age 80+	-0.53**	-0.56**	-0.45**	-	-0.47**	-0.41**
Occupation, part time	-0.13**	-0.18**	-	-	-0.18**	-0.08*
Occupation, retired	-0.57**	-0.59**	-0.45**	-0.20**	-0.44**	-0.25**
Occupation, student	0.25**	0.12*	0.29**	0.23**	0.38**	0.30**
Occupation, other	-0.37**	-0.47**	-0.29**	-	-0.31**	-0.36**
Car driver	-0.73**	-0.70**	-0.71**	-0.65**	-0.68**	-0.61**

*Table 6.6; Parameter estimates of the structural equations linking satisfaction and willingness to recommend public transport to others to public transport use and socio-economic characteristics in Model I. * p<0.05, ** p<0.01.*

Generally, higher satisfaction on all factors were negatively related to using a car for usual trips. This could be because the car fulfils complex travel patterns, but it also suggests a reinforcing loop where car drivers remembers public transport as being worse than it actually is as found in Pedersen et al. (2011). However, it was not possible to investigate this specifically in this study.

6.4.3.3 The cyclical process between satisfaction and travel use

The hypothesis of a cyclical loop between travel satisfaction and travel use frequency was investigated by formulating Model II as illustrated in Figure 6.4.

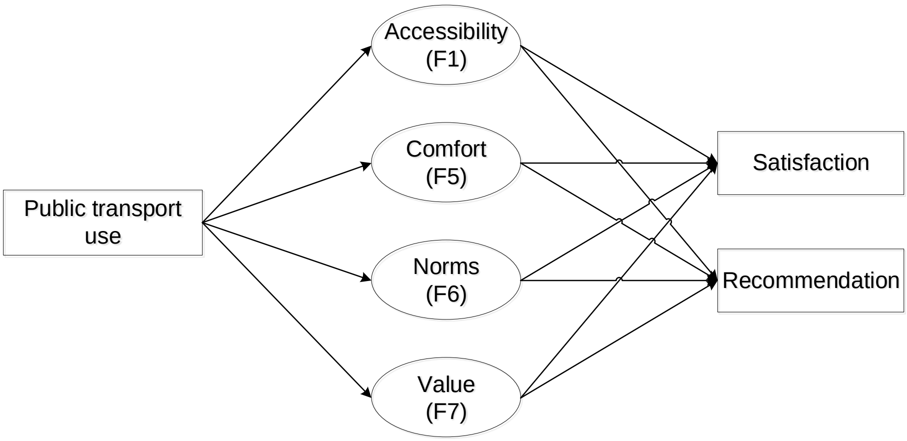

Figure 6.4; Path model for Model II relating public transport use, service quality dimensions, overall satisfaction and recommendation to others (solid black lines denote positive relationships).

The goodness-of-fit measures proved a good fit with RMSEA at 0.030-0.034 and CFI at 0.960-0.976 for the six city-specific path models. Hence, similar fit as compared to the traditional model and well within the acceptance of a good fit (Browne and Cudeck, 1992; Hu and Bentler, 1999).

An overview of the parameter estimates of Model II are shown in Figure 6.5 while detailed results are shown in Table 6.7-Table 6.9. Detailed results in terms of estimates of the measurements equations of the seven service dimension constructs and the influence of respondents' socio-economic characteristics are shown in Table 6.18-Table 6.25 in Appendix II. Note that in this model individual service factors are directly related to all three observed variables of travel use, overall satisfaction and recommendation.

Public transport use was mostly influenced by satisfaction with accessibility measures followed by measures related to the perceived importance to society and the environment of the public transport system and its perceived costs, similarly as in Model I. Perceived safety also showed significance across all cities consistent with much previous literature highlighting the importance of safety and security (Fellesson and Friman, 2012; Lierop et al., 2017). The factors related to information, staff behaviour and comfort also influenced public transport use of respondents from some of the included cities, however at a smaller relative magnitude.

Overall satisfaction with public transport and willingness to recommend it to others showed similar results where measures related to accessibility were most important to respondents followed by perceived costs and societal importance. In addition, generally car drivers were significantly less satisfied and willing to recommend public transport.

The influence of respondents' socio-economic characteristics on satisfaction with individual service characteristics showed that satisfaction with all service attributes, except information, increased with age of the respondent, cf. Table 6.8. Nevertheless, despite of this public transport use was smaller for these age groups as compared to younger respondents.

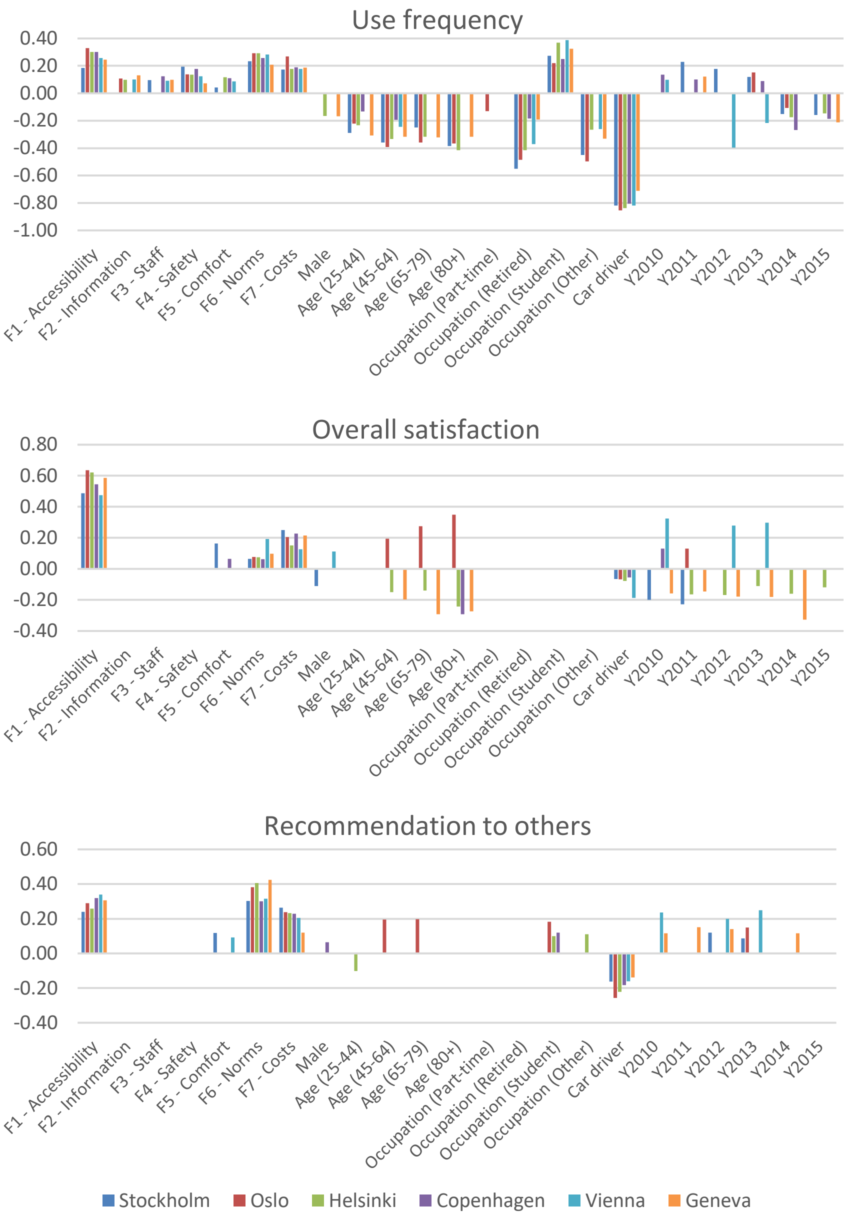

Figure 6.5; Main parameter estimates for Model II relating public transport use to factors (above) and factors to overall satisfaction (middle) and willingness to recommend to others (bottom).

Frequency of use	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
F1 – Accessibility	0.18**	0.33**	0.30**	0.30**	0.26**	0.25**
F2 – Information	-	0.11**	0.10**	-	0.10**	0.13**
F3 – Staff behaviour	0.10**	-	-	0.13**	0.09**	0.10**
F4 – Safety	0.20**	0.14**	0.14**	0.18**	0.12**	0.07**
F5 – Comfort	0.04*	-	0.12**	0.11**	0.09**	-
F6 – Norms	0.23**	0.29**	0.29**	0.26**	0.28**	0.21**
F7 – Costs	0.17**	0.27**	0.18**	0.19**	0.18**	0.19**
Male	-	-	-0.17**	-	-	-0.17**
Age 25-44	-0.29**	-0.22**	-0.23**	-0.13*	-	-0.31**
Age 45-64	-0.36**	-0.39**	-0.33**	-0.19**	-0.25**	-0.32**
Age 65-79	-0.25**	-0.36**	-0.32**	-	-	-0.32**
Age 80+	-0.38**	-0.37**	-0.42**	-	-	-0.32**
Occupation, part time	-	-0.13*	-	-	-	-
Occupation, retired	-0.55**	-0.49**	-0.41**	-0.18**	-0.37**	-0.19*
Occupation, student	0.27**	0.22**	0.37**	0.25**	0.39**	0.32**
Occupation, other	-0.45**	-0.50**	-0.27**	-	-0.26**	-0.33**
Car driver	-0.82**	-0.86**	-0.84**	-0.80**	-0.82**	-0.71**

*Table 6.7; Parameter estimates of the structural equations linking satisfaction and willingness to recommend public transport to others to public transport use and socio-economic characteristics in Model II. * p<0.05, ** p<0.01.*

Overall satisfaction	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
F1 – Accessibility	0.49**	0.64**	0.62**	0.54**	0.47**	0.59**
F5 – Comfort	0.16**	-	-	0.06**	-	-
F6 – Norms	0.07**	0.08**	0.08**	0.06**	0.19**	0.10**
F7 – Costs	0.25**	0.20**	0.15**	0.23**	0.13**	0.22**
Male	-0.11**	-	-	-	0.11*	-
Age 45-64	-	0.19**	-0.15**	-	-	-0.20*
Age 65-79	-	0.28**	-0.14*	-	-	-0.29**
Age 80+	-	0.35**	-0.24*	-0.29**	-	-0.27*
Car driver	-0.07*	-0.07**	-0.08**	-0.06*	-0.19**	-

*Table 6.8; Parameter estimates of the structural equations linking the factors to overall satisfaction and socio-economic characteristics in Model II. * p<0.05, ** p<0.01.*

Recommendation to others	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
F1 – Accessibility	0.24**	0.29**	0.26**	0.32**	0.34**	0.31**
F5 – Comfort	0.12**	-	-	-	0.09*	-
F6 – Norms	0.30**	0.38**	0.41**	0.30**	0.32**	0.43**
F7 – Costs	0.26**	0.24**	0.23**	0.23**	0.21**	0.12**
Male	-	-	-	0.06*	-	-
Age 25-44	-	-	-0.10*	-	-	-
Age 45-64	-	0.20**	-	-	-	-
Age 65-79	-	0.20*	-	-	-	-
Occupation, student	-	0.18**	0.10*	0.12*	-	-
Occupation, other	-	-	0.11**	-	-	-
Car driver	-0.16**	-0.26**	-0.22**	-0.18**	-0.16**	-0.14**

*Table 6.9; Parameter estimates of the structural equations linking the factors to willingness to recommend public transport to others and socio-economic characteristics in Model II. * p<0.05, ** p<0.01.*

6.5 DISCUSSION

This study investigated the relationship between satisfaction with various service elements of public transport, overall satisfaction levels, willingness to recommend transit to others, and travel use frequency by use of a large-scale satisfaction survey across six European cities. The cross-sectional comparison across cities showed consistently that characteristics related to accessibility and speed of the public transport system were most important for passengers followed by costs and personal norms in terms of perceived societal and environmental importance of public transport. While the two most important determinants are in line with other studies highlighting the importance of accessibility and speed when designing attractive public transport systems (Lierop et al., 2017; Mouwen, 2015), it is noteworthy that respondents' personal beliefs regarding the societal and environmental importance of public transport is a significant contributor to increased satisfaction and travel use frequency. Hence, when public transport is perceived as more than just a travel option satisfaction is higher and use frequency increases. This could be due to the increased focus on the importance of sustainable transport in solving mobility issues in metropolitan areas, and is in line with previous research finding evidence of a positive relationship between perceived fairness, travel satisfaction and frequency of use (Kaplan et al., 2014a).

This study also found significantly lower satisfaction with public transport for younger respondents despite more frequent use. Younger users can often be described as captive users as they do not have other travel alternatives, e.g. due to lower car ownership. Hence, their use of public transport is more by need rather than an actual choice. As satisfaction for these user groups are lower it points towards a fundamental problem where public transport has not succeeded in creating an attractive system for its main users. It is therefore important that public transport becomes a more satisfying choice of transport if it is to be attractive for generations to come.

6.6 Conclusions and implications

The present study has important implications for policy and practice. The findings confirm the importance of prioritising accessibility measures in terms of travel speed, ease of access and service frequency, and ensuring reasonable costs and a high perceived value when designing public transport systems. But the results also showed that respondents' perceived societal and environmental importance of public transport were significant sources for overall satisfaction and use frequency of the public transport system. This finding suggests the importance of also focusing on public transport as being environmentally sustainable when improving the perceived attractiveness of public transport. Hence, public transport agencies could consider these issues in their branding to both attract more passengers, but also to keep existing passengers more satisfied.

Furthermore, younger passengers and students were systematically less satisfied despite using public transport more frequently. This suggests a structural problem with public transport as travel habits formed in early life shapes travel behaviour throughout life. Hence, public transport should focus on the specific needs of young travellers to ensure a high level of satisfaction among these groups of travellers. This require a constant focus on efficient operations ensuring fast and reliable public transport, and, as suggested by this study, a stronger focus on sustainability.

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APPENDIX I

This appendix includes the detailed results from Model I relating the service quality dimensions to overall satisfaction, willingness to recommend to others and use frequency as described in section 6.4.3 of the paper. Table 6.10 shows the estimates of the measurement equations of the latent constructs of service quality dimensions for all six cities while Table 6.11-Table 6.17 show the influence of background variables on the seven service quality dimensions. Note that binary variables for each year was also included to take into account variations across years, but these are not reported.

	Stockholm	**Oslo**	**Helsinki**	**Copenhagen**	**Vienna**	**Geneva**
Public transport (PT) is good for work/school trips	1.000	1.000	1.000	1.000	1.000	1.000
PT is good for shopping, leisure etc.	1.047	0.979	1.039	0.927	0.941	0.940
PT is good for trips in the city centre	0.967	0.984	0.734	0.874	0.707	1.042
PT is good for trips outside the city centre	1.016	0.921	1.023	0.892	1.016	0.871
Nearest stop is close to where I live	0.666	0.694	0.667	0.676	0.715	0.598
Travel time on public transport is reasonable	1.125	1.048	1.080	1.167	1.152	1.054
Waiting time is short at transfers	1.040	0.979	1.032	1.101	1.099	0.990
I am satisfied with the number of departures	1.027	0.955	1.075	1.052	1.155	1.039
PT mostly runs on schedule	1.039	0.987	0.931	1.047	1.111	0.948
Transfers are easy	1.115	1.092	1.140	1.219	1.224	1.114
It is easy to get the information needed before a trip	1.000	1.000	1.000	1.000	1.000	1.000
The information is good when problems occur	0.970	0.935	0.942	1.108	0.982	1.032
The information is good in stops and terminals	1.014	0.985	0.956	1.109	1.084	1.076
The staff answers my questions correctly	1.000	1.000	1.000	1.000	1.000	1.000
The staff behaves nicely and correctly	0.990	1.025	1.102	1.008	0.984	1.013
I feel secure at stations and bus stops	1.000	1.000	1.000	1.000	1.000	1.000
I feel secure on board busses and trains	1.090	1.136	1.022	1.088	1.064	1.132
I am not afraid of traffic accidents when using PT	0.907	0.952	0.919	0.906	0.846	0.987
Travelling with PT is comfortable	1.000	1.000	1.000	1.000	1.000	1.000
The busses and trains are modern	0.812	0.899	0.741	0.894	0.857	0.843
The busses and trains are clean	0.769	0.872	0.684	0.756	0.812	0.797
I normally get a seat when I travel with PT	0.664	0.713	0.614	0.764	0.724	0.703
More people will travel with PT in the future	1.000	1.000	1.000	1.000	1.000	1.000
PT is good for the environment	1.071	1.206	1.159	1.089	0.987	0.973
PT is beneficial to society	1.221	1.286	1.231	1.285	1.224	1.117
PT gives value for money	1.000	1.000	1.000	1.000	1.000	1.000
PT fares are reasonable	0.909	0.799	0.795	0.802	0.890	0.833

Table 6.10; Estimates of the measurement equations of the latent constructs of Model I. All estimates are significant at the 99% level.

F1 – Accessibility	**Stockholm**	**Oslo**	**Helsinki**	**Copenhagen**	**Vienna**	**Geneva**
Male	-	-	-	-	-	-0.07*
Age 25-44	-	-	-	-	-	-
Age 45-64	0.12*	-	-0.09*	-	-	-
Age 65-79	0.45**	-	-	-	-	0.22*
Age 80+	0.71**	0.26*	0.20*	0.23*	-	0.39**
Occupation, part time	-	-	0.10*	0.13**	-	-
Occupation, retired	-	0.21**	0.19**	0.20**	0.28**	-
Occupation, student	-	-	0.14**	-	-	-
Occupation, other	-0.13*	-	0.09*	0.19**	-	0.18**
Car driver	-0.34**	-0.42**	-0.40**	-0.59**	-0.46**	-0.38**

*Table 6.11; Parameter estimates for factor 1 “accessibility” in Model I. * p<0.05** p<0.01.*

F2 – Information	**Stockholm**	**Oslo**	**Helsinki**	**Copenhagen**	**Vienna**	**Geneva**
Male	-	-	-	0.09**	-	-0.07*
Age 25-44	-	-	-0.22**	-	-	-0.18*
Age 45-64	-	-0.18**	-0.31**	-0.17**	-0.32**	-0.29**
Age 65-79	-	-	-0.18**	-0.21**	-0.40**	-
Age 80+	0.44**	0.32*	-	-	-0.47**	-
Occupation, part time	-	-	0.12*	-	-	-
Occupation, retired	-	-	-	-	-	-
Occupation, student	0.14*	-	0.11*	-	-	-
Occupation, other	-	-	-	-	-	0.18**
Car driver	-	-0.12**	-0.14**	-0.15**	-0.24**	-0.12**

*Table 6.12; Parameter estimates for factor 2 “information” in Model I. * p<0.05** p<0.01.*

F3 – Staff behavior	**Stockholm**	**Oslo**	**Helsinki**	**Copenhagen**	**Vienna**	**Geneva**
Male	-	-	0.14**	0.09**	-	-0.15**
Age 25-44	0.17**	-	-	0.18**	-	-
Age 45-64	0.34**	0.22**	0.16**	0.29**	-	-
Age 65-79	0.72**	0.39**	0.26**	0.51**	0.25*	-
Age 80+	1.29**	0.95**	0.47**	0.73**	0.51**	0.53**
Occupation, part time	0.13*	-	-	-	-	-
Occupation, retired	-	0.14*	0.12**	-	-	-
Occupation, student	0.18**	-	-	-	-	-
Occupation, other	-	-	-	-	-	0.13*
Car driver	-0.13**	-0.07*	-0.12**	-0.22**	-0.20**	-0.11**

*Table 6.13; Parameter estimates for factor 3 “staff behaviour” in Model I. * p<0.05** p<0.01.*

F4 – Safety	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
Male	0.28**	0.30**	0.39**	0.40**	0.34**	0.25**
Age 25-44	-	-	-0.10*	-	0.26**	-
Age 45-64	-	-	-	-	0.24**	-
Age 65-79	0.49**	0.24**	0.20**	0.28**	0.24*	0.22*
Age 80+	0.97**	0.76**	0.52**	0.43**	-	0.33**
Occupation, part time	-	-	-	-	-	-
Occupation, retired	-0.33**	-	-	-0.10*	-	-
Occupation, student	-	0.19**	0.20**	-	0.27**	0.33**
Occupation, other	-0.29**	-0.16*	-	-	-	-
Car driver	-0.21**	-0.13**	-0.17**	-0.28**	-0.22**	-0.15**

*Table 6.14; Parameter estimates for factor 4 "safety" in Model I. * p<0.05** p<0.01.*

F5 – Comfort	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
Male	-	0.08**	0.06**	0.10**	-	-
Age 25-44	-	-	-0.09*	-	-	-
Age 45-64	0.19**	0.12*	-	0.13*	-	-
Age 65-79	0.44**	0.29**	0.16**	0.34**	-	0.23*
Age 80+	0.87**	0.78**	0.52**	0.49**	-	0.54**
Occupation, part time	0.12*	0.19**	0.14**	-	-	-
Occupation, retired	0.11*	0.28**	0.19**	0.12*	0.20*	-
Occupation, student	0.19**	0.21**	-	-	-	0.21**
Occupation, other	-	-	0.10*	-	-	0.27**
Car driver	-0.16**	-0.14**	-0.24**	-0.24**	-0.28**	-0.11**

*Table 6.15; Parameter estimates for factor 5 "comfort" in Model I. * p<0.05** p<0.01.*

F6 – Norms	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
Male	0.06*	-	-0.15**	0.15**	0.18**	-
Age 25-44	0.22**	0.27**	0.13**	0.13*	-	0.21**
Age 45-64	0.31**	0.16*	-	0.26**	0.21*	0.25**
Age 65-79	0.52**	0.36**	0.17**	0.24**	-	0.47**
Age 80+	0.58**	0.54**	-	0.28**	-	0.49**
Occupation, part time	-	-	-	-	0.15*	-
Occupation, retired	-0.16**	-	-	-	-	-
Occupation, student	-	-	-	0.13*	-	-
Occupation, other	-0.18**	-0.21*	-	-	-	-
Car driver	-0.28**	-0.27**	-0.33**	-0.37**	-0.28**	-0.26**

*Table 6.16; Parameter estimates for factor 6 "norms" in Model I. * p<0.05** p<0.01.*

F7 – Costs	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
Male	0.09**	0.11**	0.08**	0.12**	0.11*	0.09**
Age 25-44	0.39**	0.29**	0.12**	0.22**	0.16*	0.18**
Age 45-64	0.55**	0.30**	0.28**	0.32**	-	0.32**
Age 65-79	0.98**	0.68**	0.36**	0.61**	0.40**	0.54**
Age 80+	1.17**	0.97**	0.66**	1.03**	0.39*	0.73**
Occupation, part time	-0.09*	-	-	-	-	-
Occupation, retired	-0.15**	0.14**	-	-	0.14*	-
Occupation, student	-	-	-	-	-	-
Occupation, other	-0.22**	-	-0.13**	-	-0.24**	-0.12*
Car driver	-0.18**	-0.29**	-0.27**	-0.32**	-0.19**	-0.20**

*Table 6.17; Parameter estimates for factor 7 "costs" in Model I. * p<0.05** p<0.01.*

APPENDIX II

This appendix includes detailed results for Model II of the cyclical relationship between public transport use and satisfaction from section 6.4.3.3 of the paper. Table 6.18 shows the estimates of the measurement equations of the latent constructs of service quality dimensions for all six cities while Table 6.19-Table 6.25 show the influence of background variables on the seven service quality dimensions. Note that binary variables for each year was also included to take into account variations across years, but these are not reported.

	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
Public transport (PT) is good for work/school trips	1.000	1.000	1.000	1.000	1.000	1.000
PT is good for shopping, leisure etc.	1.046	0.978	1.038	0.926	0.941	0.940
PT is good for trips in the city centre	0.966	0.983	0.734	0.873	0.707	1.042
PT is good for trips outside the city centre	1.016	0.920	1.022	0.890	1.015	0.870
Nearest stop is close to where I live	0.666	0.694	0.667	0.676	0.715	0.597
Travel time on public transport is reasonable	1.125	1.047	1.079	1.166	1.151	1.054
Waiting time is short at transfers	1.040	0.978	1.031	1.099	1.098	0.989
I am satisfied with the number of departures	1.027	0.954	1.074	1.051	1.155	1.037
PT mostly runs on schedule	1.039	0.985	0.930	1.045	1.111	0.946
Transfers are easy	1.115	1.091	1.140	1.217	1.223	1.113
It is easy to get the information needed before a trip	1.000	1.000	1.000	1.000	1.000	1.000
The information is good when problems occur	0.970	0.935	0.942	1.107	0.982	1.031
The information is good in stops and terminals	1.014	0.984	0.956	1.108	1.084	1.076
The staff answers my questions correctly	1.000	1.000	1.000	1.000	1.000	1.000
The staff behaves nicely and correctly	0.990	1.025	1.102	1.008	0.984	1.013
I feel secure at stations and bus stops	1.000	1.000	1.000	1.000	1.000	1.000
I feel secure on board busses and trains	1.090	1.136	1.022	1.088	1.064	1.132
I am not afraid of traffic accidents when using PT	0.907	0.952	0.920	0.906	0.846	0.987
Travelling with PT is comfortable	1.000	1.000	1.000	1.000	1.000	1.000
The busses and trains are modern	0.813	0.899	0.741	0.894	0.857	0.844
The busses and trains are clean	0.769	0.872	0.684	0.756	0.812	0.797
I normally get a seat when I travel with PT	0.665	0.713	0.614	0.764	0.724	0.702
More people will travel with PT in the future	1.000	1.000	1.000	1.000	1.000	1.000
PT is good for the environment	1.070	1.208	1.160	1.089	0.987	0.975
PT is beneficial to society	1.221	1.288	1.232	1.285	1.224	1.119
PT gives value for money	1.000	1.000	1.000	1.000	1.000	1.000
PT fares are reasonable	0.908	0.799	0.795	0.802	0.890	0.833

Table 6.18; Estimates of the measurement equations of the latent constructs for Model II. All estimates are significant at the 99% level.

F1 – Accessibility	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
Male	-	-	0.06**	-	-	-
Age 25-44	0.14*	-	-	-	-	-
Age 45-64	0.18**	-	-	-	-	-
Age 65-79	0.50**	0.18*	0.17**	-	-	0.30**
Age 80+	0.79**	0.38**	0.32**	0.24*	-	0.46**
Occupation, part time	-	0.12**	0.10*	0.13**	-	-
Occupation, retired	-	0.37**	0.31**	0.25**	0.37**	0.13*
Occupation, student	-	-	-	-	-	-
Occupation, other	-	0.16*	0.17**	0.19**	-	0.26**
Car driver	-0.19**	-0.13**	-0.14**	-0.34**	-0.25**	-0.21**

*Table 6.19; Parameter estimates for factor 1 “accessibility” in Model II. * p<0.05** p<0.01.*

F2 – Information	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
Male	-	-	-	0.09**	-	-
Age 25-44	-	-	-0.19**	-	-	-
Age 45-64	-	-0.14*	-0.28**	-0.17**	-0.30**	-0.25**
Age 65-79	-	-	-0.15*	-0.21**	-0.41**	-
Age 80+	0.44**	0.36**	-	-	-0.48**	-
Occupation, part time	-	-	0.12*	-	-	-
Occupation, retired	-	-	-	-	0.18*	-
Occupation, student	0.14*	-	-	-	-	-
Occupation, other	-	-	0.09*	-	-	0.19**
Car driver	-	-	-0.06*	-0.15**	-0.16**	-

*Table 6.20; Parameter estimates for factor 2 “information” in Model II. * p<0.05** p<0.01.*

F3 – Staff behavior	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
Male	-	-	0.14**	0.09**	-	-0.14**
Age 25-44	0.20**	-	-	0.20**	-	-
Age 45-64	0.38**	0.22**	0.16**	0.31**	-	-
Age 65-79	0.75**	0.39**	0.25**	0.52**	0.25*	0.22*
Age 80+	1.33**	0.95**	0.47**	0.73**	0.50**	0.56**
Occupation, part time	0.13*	-	-	-	-	-
Occupation, retired	-	0.15*	0.12**	-	0.18*	-
Occupation, student	0.15*	-	-	-	-	-
Occupation, other	-	-	-	-	-	0.15**
Car driver	-	-	-0.12**	-0.12**	-0.13**	-

*Table 6.21; Parameter estimates for factor 3 “staff behaviour” in Model II. * p<0.05** p<0.01.*

F4 – Safety	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
Male	0.28**	0.30**	0.41**	0.40**	0.34**	0.25**
Age 25-44	-	-	-	-	0.26**	-
Age 45-64	-	-	-	0.12*	0.27**	-
Age 65-79	0.53**	0.29**	0.24**	0.28**	0.24*	0.25*
Age 80+	1.04**	0.81**	0.57**	0.43**	-	0.36**
Occupation, part time	-	-	-	-	-	-
Occupation, retired	-0.22**	-	0.08*	-	-	-
Occupation, student	-	0.16**	0.15**	-	0.22*	0.28**
Occupation, other	-0.20**	-	-	-	-	-
Car driver	-	-	-0.05*	-0.14**	-0.12**	-0.09**

*Table 6.22; Parameter estimates for factor 4 "safety" in Model II. * p<0.05** p<0.01.*

F5 – Comfort	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
Male	-	0.08*	0.08**	0.10**	-	-
Age 25-44	-	-	-	-	-	-
Age 45-64	0.21**	0.12*	-	0.15*	-	-
Age 65-79	0.46**	0.29**	0.20**	0.34**	-	0.23*
Age 80+	0.88**	0.78**	0.57**	0.49**	-	0.54**
Occupation, part time	0.12*	0.19**	0.14**	-	-	-
Occupation, retired	0.14*	0.28**	0.24**	0.14**	0.23**	-
Occupation, student	0.17**	0.21**	-	-	-	0.21**
Occupation, other	-	-	0.13**	-	-	0.26**
Car driver	-0.13**	-0.14**	-0.14**	-0.15**	-0.21**	-0.11**

*Table 6.23; Parameter estimates for factor 5 "comfort" in Model II. * p<0.05** p<0.01.*

F6 – Norms	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
Male	0.06*	-	-0.10**	0.15**	0.18**	-
Age 25-44	0.28**	0.34**	0.21**	0.16**	-	0.27**
Age 45-64	0.39**	0.27**	0.15**	0.31**	0.27**	0.32**
Age 65-79	0.58**	0.46**	0.26**	0.24**	-	0.54**
Age 80+	0.67**	0.65**	0.30**	0.28**	-	0.55**
Occupation, part time	-	-	-	-	0.15*	-
Occupation, retired	-	-	0.11*	0.12*	-	-
Occupation, student	-	-	-	-	-	-
Occupation, other	-	-	0.09*	-	-	-
Car driver	-0.09**	-	-0.09**	-0.17**	-	-0.12**

*Table 6.24; Parameter estimates for factor 6 "norms" in Model II. * p<0.05** p<0.01.*

F7 – Costs	Stockholm	Oslo	Helsinki	Copenhagen	Vienna	Geneva
Male	0.09**	0.11**	0.11**	0.12**	0.10*	0.13**
Age 25-44	0.44**	0.35**	0.16**	0.24**	-	0.23**
Age 45-64	0.62**	0.39**	0.33**	0.36**	0.20*	0.38**
Age 65-79	1.03**	0.77**	0.42**	0.60**	0.40**	0.60**
Age 80+	1.24**	1.07**	0.73**	1.02**	0.38*	0.79**
Occupation, part time	-0.10*	-	-	-	-	-
Occupation, retired	-	0.28**	0.10*	0.11*	0.21**	-
Occupation, student	-	-	-	-0.15**	-	-
Occupation, other	-0.15**	-	-0.08*	-	-0.18**	-
Car driver	-	-0.06*	-0.12**	-0.16**	-	-0.07*

*Table 6.25; Parameter estimates for factor 7 "costs" in Model II. * p<0.05** p<0.01.*

7 THE ROLE OF SATISFYING EXISTENCE, RELATEDNESS AND GROWTH NEEDS IN COMMUTER MODAL USE FREQUENCY

Ingvardson, J. B., Kaplan, S., Nielsen, O. A., Di Ciommo, F., de Abreu e Silva, J., Shiftan, Y., 2017, *The Role of Satisfying Existence, Relatedness and Growth Needs in Commuter Modal Use Frequency*. Re-submitted after first round of review to *Transportation*, September 20, 2017.

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Based on conference paper:

Ingvardson, J. B., Kaplan, S., Nielsen, O. A., Di Ciommo, F., de Abreu e Silva, J., Shiftan, Y., 2017, *The Commuting Habit Loop: The Role of Satisfying Existence, Relatedness and Growth Needs in Modal Choice*. Proceedings of the Transportation Research Board (TRB) 96th Annual Meeting, Washington D.C., USA, January 8-12, 2017.

ABSTRACT

Understanding the motivators of travel mode choice is essential to design effective transport policies for promoting and maintaining sustainable travel trends. This study focuses on enhancing the framework for representing travel mode choice by incorporating the ERG model of human needs and the Theory of Planned Behaviour in a coherent framework. The proposed approach reveals the socio-ecological motivators for travel mode choice and their association with travel satisfaction and higher frequency of travel mode choice. A large-scale survey of commuters in the Greater Copenhagen Area and structural equation modelling validates empirically the proposed framework. The Greater Copenhagen area represents a region where transit, bicycle and car each have large modal shares, hence enabling to validate the approach in a multi-modal environment. The results confirm the hypothesis that travel mode choices are a decision process which are based on satisfying functional, relatedness and growth needs. Higher satisfaction relates to higher travel mode use frequency, which in the study area is greater for bicycle and car compared to transit. Higher bicycle satisfaction relates positively to cycling self-concepts and self-efficacy and negatively to car self-concepts. Greater car use satisfaction increases with car self-concepts and transit use difficulties, and decreases with functional difficulties in car use and better cycling self-efficacy. Higher transit satisfaction mainly relates to experiencing difficulties with other modes.

Keywords: Mode choice, travel satisfaction, multimodal transport, ERG model of human needs, Theory of Planned Behaviour

7.1 INTRODUCTION

Travel mode choice is an everyday exercise of people whether commuting to work or visiting friends or family. For recurrent trips it is characterised by routine behaviour and based on previous experiences (Carrus et al., 2008; McFadden, 2001). In contrast to making a deliberate mode choice travellers build up travel habits where the choice becomes default based on an expectation of obtaining desired results or goals (Gärling and Axhausen, 2003; Aarts et al., 1997). Understanding the underlying motivators of recurrent travel choices is essential for designing effective transport policies and interventions, as recurrent travel choices relate to long-term lifestyle choices, formed in early life-stages, and transferred across generations in a travel socialization process (Chang and Lai, 2015; Haustein et al., 2009; Sigurdardottir et al., 2013).

Much research has been devoted to transport mode choice due to its importance in travel demand models. Traditionally it has been modelled by deploying utility theory where the travel mode with the highest utility is chosen by the traveller (McFadden, 2001). The utility is a function of characteristics associated with each mode such as travel time and travel cost. However, as individual weekly travel patterns tend to be repetitive mode choice is to a large extent influenced by psychological factors such as attitudes, social norms, lifestyle and travel habits (Haustein et al., 2009; Van Acker et al., 2010). Recent research efforts have focused on such aspects by using psychological theories to capture the human psychology in transport mode choice decisions. Maslow's theory of human needs (Maslow, 1943) was used in Alfonzo (2005) to analyse how various factors influenced the decision-making process for walking trips. And Winters and Tucker (2004) proposed a tool for analysing level-of-service of multiple transport modes equally based on a hierarchy of transportation user needs. The approach was further developed in Perone et al. (2005) by using the ERG (existence, relatedness and growth) theory of human needs (Alderfer, 1969). Other studies have addressed the issue of mode choice using the Theory of Planned Behaviour (Ajzen, 1991), e.g. by analysing mode-switching potential of day trip travellers (Anable, 2005), mode switching of car and motorcycle users towards public transport (Chen and Chao, 2011), and by investigating the role of social climate on transit use (Salvá et al., 2015). Nevertheless, understanding the underlying motivators of recurrent travel choices and its conceptualization in the context of well-being remains a challenge (Abou-Zeid et al., 2012). And specifically there has been a lack of research analysing social travel and incorporating other evaluation frameworks for measuring travel satisfaction (De Vos et al., 2013).

Simultaneously, several studies have focused on how to measure satisfaction (De Vos et al., 2015). While many studies focused on the importance of various attributes in ensuring an attractive public transport system with high satisfaction among users, see a review in Lierop et al. (2017), the direct evaluation of such attributes might not give the full picture of how the system performs in terms of the needs of users. A recent and widely adopted alternative framework is the Satisfaction with Travel Scale (STS, Ettema et al. (2011)), which measures satisfaction in terms of subjective well-being (SWB, Kahneman et al. (1997)). The SWB is comprised of two components, namely affective (feelings) and cognitive (judgement of satisfaction) well-being. In a travel satisfaction context the affective component of STS is related to the experienced feelings of the traveller during the trip and the cognitive component is how the traveller would evaluate the trip (De Vos et al., 2016). The affective component is measured using six scales distinguishing between positive deactivation (e.g. relaxed) and negative activation (e.g. stressed) and between positive activation (e.g. tired) and negative deactivation (e.g. alert), respectively. The cognitive component is a three-fold evaluation of the general quality of the trip (Ettema et al., 2011). While the measure does take into account feelings and emotions related to trip making it does not take into account how well the travel mode satisfies the needs of the traveller.

The main contribution of this present study is a further development of the concept of a cyclical process between travel mode choice and travel satisfaction as proposed by De Vos et al. (2016). This work enhances the framework by proposing a joint decision-making framework incorporating the Theory of Planned Behaviour (TPB, Ajzen (1991)) and the ERG theory of human needs (ERG, Alderfer (1969)). This study presents also a large-scale survey analysed with structural equation models (SEM) to validate empirically the framework for multi-modal weekly commuting in Denmark.

The general framework is based on people choosing a travel mode that gives them the highest level of satisfaction. However, instead of measuring satisfaction using STS we propose to embed a unifying framework of the TPB and ERG theory as the link between travel satisfaction and mode choice. Hence, travel mode choice relies on the sense of well-being, which is motivated by satisfying the three types of human needs: existence, relatedness, and personal growth needs of self-esteem and self-actualization. This view also agrees with previous studies suggesting that travel behaviour is governed by a holistic experience comprising perceptions, emotions, past experiences, attitudes, and social climate (Abou-Zeid et al., 2012; Susilo and Cats, 2014). While the importance of enhancing the instrumental value of travel services in terms of travel time, accessibility, reliability and other level-of-service aspects is uncontested (de Oña et al., 2016a), studies show that children and adults associate travel choices with relatedness and personal growth, which are part of essential human needs (Alderfer, 1969; Maslow, 1943). Adolescents associate car-use with gaining travel independence and increasing spatial opportunities, self-image through financial status, prestige, and cool feeling, and role as future care-givers (Sigurdardottir et al., 2014). Transit use is correlated with self-esteem and respect for others through perceived spatial equity, price and travel mode fairness (Kaplan et al., 2014a), and with 'relational value' through social climate appreciation (Salvá et al., 2015). And Perone et al. (2005) provided evidence that transit use is associated with functional and psychological needs of relatedness and growth. Cycling enhances multi-dimensional self-esteem comprising of physical, competencies, growth, self-identity and life-values self-concepts (Spotswood et al., 2015). Bicycle lessons are beneficial in increasing cycling competencies, enlarging the activity space, increasing the activity participation and travel independence, and improving the feelings of self-esteem, self-confidence and empowerment (van der Kloof et al., 2014). Last, the transport system is perceived as essential for gaining safety and security in health, employment and social stability, in particular among low-income households, and failing to achieve these needs may result in physical, social, geographical, and economic social exclusion (Lucas, 2012). Thus, as suggested by Taniguchi et al. (2014) and Mateo-Babiano (2016), it is equally important to look at the travel experience from the perspective of meeting a wide spectrum of human needs.

The remainder of the paper presents the proposed framework and mathematical model followed by their empirical validation, namely the questionnaire design, the sample and the model estimates. Last, we discuss the results and offer policy implications.

7.2 METHODOLOGY

7.2.1 Behavioural framework

The hypothesised behavioural framework outlined in Figure 7.1 was built to better explain decision-making of travel mode choices. It is based on a general feedback mechanism between mode choice and satisfaction similar to the framework proposed in De Vos et al. (2016). When performing a mode choice the traveller is rewarded in terms of an experienced level of satisfaction. The satisfaction is memorised and to some extent influences future mode choices (Gärling and Axhausen, 2003). The framework accommodates both single- and multiple-mode commuting routine.

For measuring satisfaction this present study proposes a decision-making framework incorporating Alderfer's ERG theory of human needs (Alderfer, 1969) and the TPB (Ajzen, 1991). The ERG theory is based on a threefold conceptualisation of human needs: (i) *existence* (i.e., functional needs), (ii) *relatedness* (i.e., sense of belonging and togetherness), and (iii) *growth* (i.e., self-actualization, fulfilment of inner potential and life opportunities). The ERG theory was developed from Maslow's hierarchical theory of motivation (Maslow, 1943), but has the advantage of assuming that each of the three domains can be satisfied independently. The TPB theory links behavioural intentions to attitudes, subjective norms and perceived behavioural control, and it is compatible with the theory of needs. The attitudes from the TPB overlap with the human growth needs, and social norms overlap with the relatedness needs as both cover relations to significant others that are important for personal preferences. Specifically, attitudes form an integral part of individuals' self-concepts and help define their identity, so that acting upon our attitudes contributes to integrity as a life value, a sense of self-actualization, and increased self-esteem. Norms are collections of rules defined by society and significant others, so the choice to act upon or in contrary to social norms links to both the feeling of togetherness and belonging as well as increased self-esteem and self-actualization. Acting according to attitudes and norms answer the individuals' relatedness and growth needs and induces a sense of well-being. The perceived behavioural control complement the ERG theory by adding self-efficacy expectations (Bandura, 1977), namely perceived functional and psychological barriers to act and have an influence on the level of satisfaction. Intentions are included in the form of realised intentions, namely actual mode choice and use. Lastly, the framework is influenced by individual socio-economic and commute characteristics. This is in accordance with the socio-ecological model (McLeroy et al., 1988), which states that people's attitudes, norms and perceived difficulties, as well as the positive feelings associated with the satisfaction of needs, are influenced by the socio-ecological system including the physical, institutional, and socio-cultural environments.

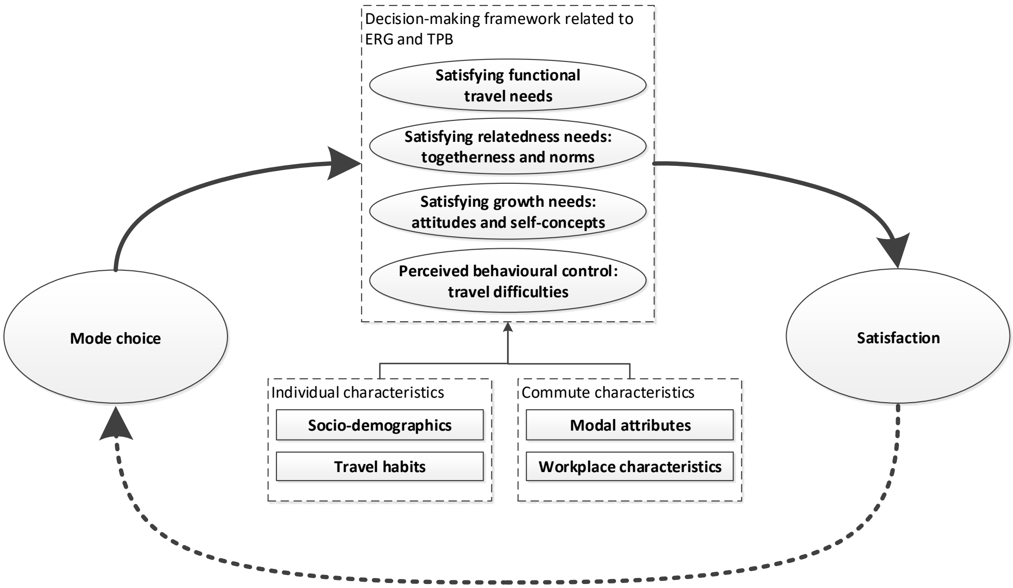

Figure 7.1; Behavioural framework

The proposed framework led to the following research hypothesis. Generally, mode use frequency and satisfaction are positively correlated to not only basic functional needs, but also higher-order togetherness and self-actualisation needs. Hence, satisfaction and mode usage do not only depend on traditional attributes of the transport system, but also on how well the transport mode is perceived to satisfy higher order needs. Particularly, bicycle and car use are hypothesised to be positively related to togetherness and growth needs and negatively correlated to perceived travel difficulties. Public transport use is hypothesised to mostly being positively correlated with basic functional needs.

7.2.2 Survey design and administration

An on-line survey was tailored to the behavioural framework. The survey consisted of four parts: (i) general travel habits and commute characteristics; (ii) ERG statements; (iii) TPB statements; (iv) individual characteristics. ERG and TPB statements were tailored to the commute mode choice context.

Respondents were asked about their travel trends as the frequency of travelling by each mode (i.e., car, bicycle, transit) and whether they travelled with others in their commute. The frequency was measured on a Likert scale ranging from rarely to daily, with 2-3 times monthly, once weekly, and 2-3 times weekly as intermediate points. The travel habits were elicited independently per mode to allow for multimodality over time (Cherchi and Cirillo, 2014; Schlich and Axhausen, 2003). Respondents were also asked to rate the level of satisfaction they associate with commuting by each mode on a 5-point Likert scale from very dissatisfied to very satisfied.

The statements measuring ERG and TPB dimensions were defined based on a literature review of the most important attributes for travel satisfaction (de Oña and de Oña, 2015; De Vos et al., 2016; Lierop et al., 2017; Susilo and Cats, 2014). The identified attributes were combined with statements on the perceived mode-specific travel difficulties. A total of 50 statements were phrased, namely fifteen on existence needs, ten on togetherness needs, eleven on growth needs, and fourteen on mode-specific travel difficulties. Each statements were measured using the 5-point Likert scale ranging from strongly disagree to strongly agree.

Existence need items investigated functional needs when travelling such as health, safety, time and monetary savings, reliability and multi-tasking during travel. They included travel time and costs, avoiding travel hassles such as congestion, parking, and transfers, being able to carry personal belongings, and being able to work or have privacy during the trip.

Relatedness need items investigated the ability to form or enhance interpersonal relationships, feeling part of a group, and conforming with social norms. Interpersonal relationships are formed or enhanced during commuting by spending quality time travelling together with family, friends, and colleagues, and helping others by giving a ride to significant others. Feeling part of a group or community was expressed as participating in bike-to-work campaigns or exercising with friends. Conforming to norms was related to individual perceptions regarding the behaviour of people in the social circle of the individual in terms of their commute mode choice.

Growth need items related to developing self-concepts associated with physical ability, competencies (e.g., self-efficacy, overcoming challenges), self-identity related to environmental sustainability and fitness, social self-concept (e.g., social status, prestige), self-actualisation and self-esteem derived from a general optimism, and feeling of life satisfaction.

The perceived behavioural control in the commute mode context was expressed as the perceived ease associated with using the mode. Travel difficulties are mode specific by definition: for transit, they are its perceived accessibility, speed, price, crowding and reliability; for cycling, they are weather, hilliness, travel distance and traffic safety; for car use, they are travel expenses, driving stress, perceived difficulties to find parking, traffic safety and traffic congestion.

Individual characteristics included socio-economic information and past travel experiences. The commute characteristics comprise the perceived time and cost associated with the modal choice and situational attributes, namely the home-work distance, parking availability, transit availability at the workplace, and bicycle facilities.

The questionnaire was distributed on-line to commuters in the Greater Copenhagen Area in June 2016. Respondents were recruited through 6,000 firms that are all the firms with more than five employees registered in the list of the Danish Bureau of Statistics as located in the region. The selection criterion of at least five employees served to indicate firms that have office location, require commuting and are of sufficient size to participate in the Danish bike-to work campaign. University networks and the social media further distributed the questionnaire, which allowed reaching a large and heterogeneous group of commuters at modest costs.

7.2.3 Mathematical model

The questionnaire items and the observed individual characteristics led to the formulation of a structural equation model (SEM) to test the hypothesised behavioural framework. SEM allows accommodating measurement errors when the explanatory and the dependent variables are latent multi-dimensional constructs, and modelling simultaneously endogenous latent constructs, their relationship with exogenous observed variables, and their correlation pattern.

The model contained four sets of equations: measurement equations (eq. 1) linking the measurement indicators (questionnaire items) to the latent ERG and TPB constructs; structural equations (eq. 2) associating the latent attitudinal constructs with individual socioeconomic characteristics; structural equations (eq. 3) relating the explanatory and the mediator latent constructs; structural equations (eq. 4) linking the latent mediators to the dependent variable.

$$I_{rn} = Z^*_{ln} \cdot \alpha_r + \nu_{rn} \quad \text{and} \quad \nu_n \sim N(0, \Sigma_\nu) \quad \text{for} \quad r = 1, \dots, R \tag{1}$$

$$Z^*_{ln} = S_{ln} \cdot \beta_l + \omega_{ln} \quad \text{and} \quad \omega_n \sim N(0, \Sigma_\omega) \quad \text{for} \quad l = 1, \dots, L \tag{2}$$

$$Z^*_l = Z_i \cdot \beta_i + \varphi_l \quad \text{and} \quad \varphi_l \sim N(0, \Sigma_\varphi) \quad \text{for} \quad l = 1, \dots, L \quad , i = 1, \dots, K \tag{3}$$

$$Y_{in} = Z^*_{ln} \cdot \beta_z + \xi_{in} \quad \text{and} \quad \xi_n \sim N(0, \Sigma_\xi) \quad \text{for} \quad i = 1, \dots, I \tag{4}$$

where I_{rn} is the value of an indicator r of the latent construct Z^*_{ln} as perceived by respondent n, Z^*_{ln} is the value of latent construct l for respondent n, S_{ln} is a vector of M respondents' observed individual characteristics, and Y_{in} is a vector of travel users' satisfaction levels. Error terms are expressed as elements ω_{ln}, v_{rn}, ξ_{in} of the vectors following a normal distribution with respective covariance matrix Σ_ω, Σ_v, Σ_ξ, while parameters to be estimated are α_r, β_l, β_i, and β_z. Considering R indicators translates into writing R measurement equations and estimating an $(R \times 1)$ vector α of parameters (i.e., one parameter is estimated for each equation), while considering L latent constructs translates into writing L structural equations and estimating an $(M \times L)$ matrix of β parameters (i.e., M parameters are estimated for each equation).

The vector α of parameters of the measurement equations and the vector β's of parameters of the structural equations were estimated using Mean- and Variance-adjusted Weighted Least Squares (WLSMV) (Muthén and Muthén, 2017). The goodness-of-fit was measured using the relative CFI (comparable Fit Index) and the absolute Root Mean Square of Approximation (RMSEA).

7.3 Results

7.3.1 Sample characteristics

The survey yielded 1,481 complete responses (92.7% of the survey entries), which is an adequate sample size considering the often used rule of thumb minimum criterion of 1000 observations, or ten responses per indicator (Nunnally et al., 1967). Table 7.1 describes the sample socio-economic characteristics and the study area in general taken from the Danish national travel survey.

The sample characteristics are in line with the survey aim and scope to target commuters in the Greater Copenhagen Area. The sample is gender balanced and includes adults in the working age, most of the respondents are full-time employees and either reside or work in the study area. The commuting destination indicates the existence of both radial and local commuting patterns, in line with the mono-centric metropolitan structure. The car ownership is in line with the one in the region according to the Danish Bureau of Statistics, and the same applies to the distribution of commuting distance with an average commute of 20 km, and 38.7% of the sample commuting up to 10 km each way.

The sample corresponds to the Danish national travel survey apart from education, income and workplace location, which is reasonable considering that the employees were recruited through companies rather than directly.

Figure 7.2 illustrates the travel frequency and satisfaction with each of the three modes and shows their correspondence. The level of satisfaction is generally high and similar for the car and the bicycle as commute modes, compared to transit for which only less than 40% are satisfied or very satisfied. The modal shares of car, bicycle and transit at least 4-5 times a week or daily are respectively 42%, 31% and 17%, in line with the modal shares of 45%, 32% and 18% in the region according to the Danish National Travel Survey.

Variable	Categories				
Gender	Male 44.6 (46.7)	Female 55.4 (53.3)			
Age	18-30 13.0 (30.7)	30-45 37.2 (26.0)	46-65 47.2 (41.4)	> 65 2.6 (2.0)	
Car accessibility	Yes 68.4 (78.4)	No 31.6 (21.6)			
Family status	Single no children 14.3 (15.9)	Couple no children 31.3 (29.9)	Single with children 4.7 (3.7)	Couple with children 44.0 (34.5)	Other 5.7 (16.0)
Employment status	Full time 87.6 (74.0)	Part time 7.6 (26.0)	Other 4.9		
Monthly income ($)	0-3000 6.0 (32.8)	3000-4500 15.6 (15.7)	4500-6000 35.0 (14.5)	6000-7500 23.0 (12.0)	> 7500 20.3 (25.1)
Education level	High-School 7.2 (11.7)	Tertiary 23.3 (38.3)	Bachelor 22.4 (29.6)	Graduate 47.2 (20.4)	
Commute origin	Copenhagen 40.0 (36.8)	Suburbs 34.5 (32.6)	Rural 25.5 (30.6)		
Commute destination	Copenhagen 51.3 (43.4)	Suburbs 44.5 (32.1)	Rural 4.2 (24.5)		
Commute distance	0-5 km 17.3 (13.5)	5-10 km 21.4 (16.2)	10-20 km 25.5 (17.4)	20-30 km 13.8 (17.8)	> 30 km 22.1 (35.1)

Table 7.1; Sample Characteristics

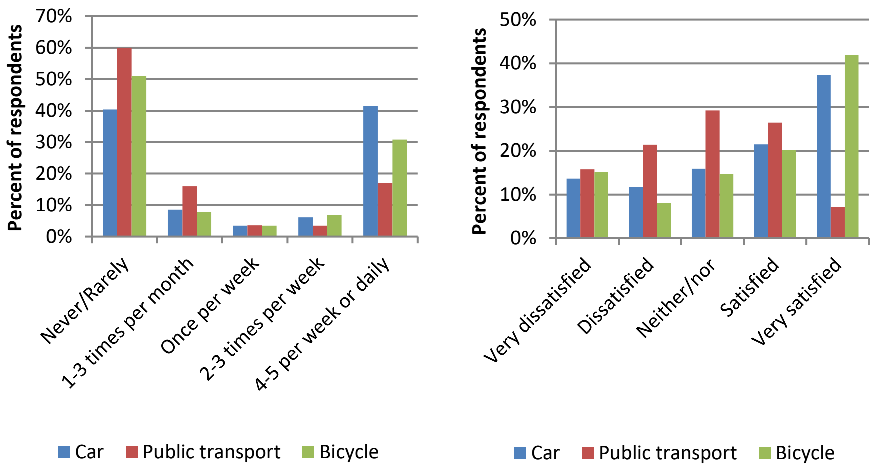

Figure 7.2; Frequency of use (left) and level of satisfaction (right) with car, transit and bicycle for the commute trip.

7.3.2 Factor analysis

The existence, relatedness and growth needs and the travel difficulties were obtained via exploratory factor analysis (EFA). This was chosen due to the flexibility of EFA as compared to confirmatory factor analysis (CFA) as it was possible to analyse the structure between survey items where some were mode-specific, e.g. items related to growth needs and travel difficulties, and some were a combination of mode-specific and generic, e.g. items related to existence needs and relatedness needs. Instead of estimating a large number of factors a priori, the EFA was effectively used to reduce the number of factors for the subsequent SEM.

The survey data showed good internal consistency with Cronbach's alpha = 0.792, and good sampling adequacy with Kaiser-Meyer-Olkin (KMO) = 0.884 measured on all survey statements related to ERG and TPB with no single items having a measure of sampling adequacy of less than 0.70. The determinant of the Spearman correlations matrix equal to 7.4E-12 established the existence of correlations without multi-collinearity, and the Bartlett's test for sphericity rejected the null hypothesis of an identity correlations matrix. Principal axis factoring with orthogonal Varimax rotation generated the seven factors in Table 7.2 where the dominant items marked in bold were defined as those with an absolute value greater than 0.30 (Kline, 1994). The internal consistency for each factor was good as the Cronbach's alpha's were all above 0.70 (Miller, 1995).

	Factors						
Item	F1 (8.596)	F2 (5.525)	F3 (3.443)	F4 (3.272)	F5 (2.117)	F6 (1.928)	F7 (1.583)
It is important for me to get exercise	**0.528**	0.103	0.313	-0.134	0.069	0.420	-0.041
It is important for me to get fresh air	**0.512**	0.131	0.308	-0.121	0.103	0.411	-0.057
I feel mentally strengthened when I bicycle	**0.878**	0.052	0.134	-0.106	-0.052	0.155	0.000
I feel on top and with good energy when I bicycle	**0.894**	0.079	0.112	-0.081	-0.045	0.161	-0.023
I enjoy challenging myself physically when I bike	**0.736**	0.153	0.027	0.036	-0.007	0.115	0.013
I feel good about myself when I bike	**0.853**	0.052	0.104	-0.140	-0.034	0.186	-0.005
I feel good about contributing to the environment when I bike	**0.657**	0.089	0.211	-0.193	0.049	0.092	-0.016
It is important for me to travel with my colleagues	0.002	**0.776**	0.095	0.067	0.024	-0.087	-0.045
It is important for me to spend quality time together med other people	-0.014	**0.753**	0.080	0.062	0.046	-0.130	-0.038
It is important for me to bring/collect others on the way	0.015	**0.483**	-0.113	-0.002	0.087	-0.061	-0.013
It is important for me to exercise with friends	0.104	**0.852**	0.047	0.059	0.036	0.046	0.065
It is important for me to talk about a shared hobby with people that are important to me	0.049	**0.857**	0.066	0.109	0.022	-0.004	0.054
It is important for me to participate in joint activities at work, e.g. Bike to work campaigns	0.238	**0.684**	0.127	0.012	0.011	0.124	0.020
It is important for me to be part of a bicycle culture	0.209	**0.774**	0.095	0.043	-0.001	0.100	0.050
It is important for me to save money	0.169	0.088	**0.397**	-0.019	0.269	0.091	0.125
It is important for me to avoid driving stress	0.079	0.115	**0.473**	-0.022	0.123	-0.054	-0.122
It is important for me to avoid road congestion	0.121	0.099	**0.465**	-0.037	0.286	0.104	-0.084
It is important for me to avoid worrying about parking	0.042	0.048	**0.509**	0.029	0.253	0.088	0.004
I believe it is important not to contribute to congestion	0.297	0.133	**0.362**	-0.105	0.068	-0.008	-0.092
Transit is inaccessible to me	-0.092	0.084	**-0.332**	0.053	0.164	-0.180	0.235
Driving a car is too expensive	0.102	0.010	**0.523**	-0.143	-0.113	0.104	0.021
Searching for parking takes too long	0.045	0.000	**0.643**	-0.078	-0.083	0.121	0.001
Driving a car is too stressful	0.145	-0.025	**0.763**	-0.251	-0.157	0.006	-0.019
Driving a car is too dangerous	0.051	0.096	**0.602**	-0.175	-0.124	-0.120	-0.012
Driving a car is too unreliable (congestion)	0.070	-0.008	**0.657**	-0.207	-0.131	-0.033	-0.002
I live life to the fullest when I drive my car (e.g. By listening to music)	-0.063	0.093	-0.237	**0.673**	0.157	-0.148	0.078
Driving a car is a cool way to travel	-0.125	0.061	-0.135	**0.829**	0.082	-0.114	0.064
Driving a car makes me feel optimistic and high-on-life	-0.105	0.092	-0.114	**0.877**	0.077	-0.098	0.057
Driving a car makes me feel that I get the most out of every situation	-0.156	0.098	-0.267	**0.758**	0.139	-0.174	0.096
I feel more independent when I drive a car	-0.119	0.037	-0.241	**0.610**	0.128	-0.236	0.109
It is important for me to arrive safely	0.016	0.073	0.081	0.060	**0.531**	-0.102	-0.061
It is important for me to carry my things	-0.022	0.012	-0.050	0.134	**0.568**	-0.122	-0.021

It is important for me to save time	-0.019	0.019	-0.152	0.000	**0.496**	-0.123	0.111
It is important for me to go wherever and whenever I want	0.002	0.038	-0.171	0.117	**0.477**	0.066	0.194
It is important for me to have privacy during my transport	-0.099	0.152	0.051	0.265	**0.309**	-0.171	0.060
It is important for me to avoid congestion in transit	0.068	0.022	0.172	0.110	**0.506**	0.156	0.340
It is important for me to avoid having to change transport mode / line	-0.023	0.035	0.037	0.088	**0.565**	0.059	0.272
It is important for me to arrive on time	0.008	-0.006	0.038	0.012	**0.574**	-0.016	0.067
Biking is difficult because of the weather (R)	0.156	-0.030	0.076	-0.202	-0.073	**0.548**	-0.113
Biking is difficult because of the terrain (R)	0.231	-0.104	0.064	-0.210	-0.059	**0.681**	-0.082
Biking is difficult because of the distance (R)	0.222	0.006	0.155	-0.113	-0.059	**0.688**	-0.022
Biking is dangerous due to other traffic (R)	0.208	-0.013	-0.167	-0.124	-0.069	**0.448**	-0.170
Transit is too slow	-0.035	-0.007	-0.394	0.031	0.177	-0.164	**0.559**
Transit is too expensive	0.009	0.040	0.018	0.012	0.090	-0.023	**0.575**
Transit is too crowded	-0.019	-0.046	0.058	0.129	0.146	-0.090	**0.731**
Transit is unreliable	-0.039	0.002	-0.159	0.131	0.150	-0.145	**0.645**
Cronbach's alpha	0.916	0.890	0.818	0.905	0.746	0.756	0.756

Table 7.2; Rotated Factor Matrix. Note: (R) – Reversed coding in the case of negatively-phrased items; ***bold*** *– highest factor loading for each item. Eigenvalues in parenthesis.*

Factor F1 "positive cycling self-concepts" is associated with the ability of commuting by bicycle to satisfy growth needs of self-efficacy, self-actualization, optimism and self-esteem. Factor F2 "travel togetherness" incorporates all survey statements related to relatedness needs, including joint travel, shared travel experiences, helping others and participating in joint activities related to the social milieu and work environment. Factor F3 "car use functional difficulties" includes statements related to the preference for avoiding difficulties associated with car use and are related to negative driving experience such as difficulties to find parking, congestion, driving stress, etc. Factor F4 "positive car self-concepts" incorporates statements associated with the ability of commuting by car to satisfy growth needs of self-efficacy, travel independence, optimism and social status. Factor F5 "satisfying functional needs" relates to general functional needs such as arriving safely on time, saving time and being able to travel when needed without worrying about transfers. Factor F6 "cycling self-efficacy" gathers statements related to coping with challenges while cycling, i.e. reversed travel difficulties, such as the weather conditions, hilly terrain, distance and traffic. Factor F7 "functional difficulties in transit" includes the four items related to transit being slow, expensive, crowded and unreliable.

7.3.3 Model estimation results

The model was estimated using the standard WLSMV estimator in MPlus, due to the violation of normally distributed data for all items according to the Shapiro-Wilk test, and because it provides the best option when modelling ordered data such as 5-point Likert data (Brown, 2006). The tested model revealed goodness-of-fit measures in terms of

RMSEA equal to 0.050, which is consistent with the recommended maximum (Hu and Bentler, 1999). In addition, the CFI equal to 0.903 was above the recommended minimum value of 0.90 (Browne and Cudeck, 1992).

Table 7.3 through Table 7.5 show the parameters estimates and critical ratios (C.R.) as the ratio of parameter estimate and standard error: Table 7.3 shows the measurement equations, Table 7.4 presents the structural equations linking the latent ERG and TPB constructs to socio-economic characteristics, and Table 7.5 shows the structural equations relating the travel satisfaction to the ERG and TPB constructs. Figure 7.3 shows the path diagram of the model structure.

Positive cycling self-concepts (F1)	*est.*	*C.R.*
It is important for me to get exercise	1.000	-
It is important for me to get fresh air	1.000	75.09
I feel mentally strengthened when I bicycle	1.241	56.95
I feel on top and with good energy when I bicycle	1.284	56.51
I enjoy challenging myself physically when I bike	1.072	50.35
I feel good about myself when I bike	1.248	55.53
I feel good about contributing to the environment when I bike	0.942	40.19
Travel togetherness (F2)	*est.*	*C.R.*
It is important for me to travel with my colleagues	1.000	-
It is important for me to spend quality time together med other people	0.993	95.35
It is important for me to bring/collect others on the way	0.746	44.03
It is important for me to exercise with friends	1.079	107.49
It is important for me to talk about a shared hobby with people that are important to me	1.080	88.80
It is important for me to participate in joint activities at work, e.g. Bike to work campaigns	1.009	88.70
It is important for me to be part of a bicycle culture	1.055	96.40
Car use functional difficulties (F3)	*est.*	*C.R.*
It is important for me to save money	1.000	-
It is important for me to avoid driving stress	1.383	11.50
It is important for me to avoid road congestion	1.370	12.07
It is important for me to avoid worrying about parking	1.254	11.89
I believe it is important not to contribute to congestion	1.441	12.19
Transit is inaccessible to me	-0.286	-3.34
Driving a car is too expensive	1.247	10.90
Searching for parking takes too long	1.408	11.07
Driving a car is too stressful	2.431	12.93
Driving a car is too dangerous	1.908	12.74
Driving a car is too unreliable (congestion)	1.886	12.66
Positive car self-concepts (F4)	*est.*	*C.R.*
I live life to the fullest when I drive my car (e.g. By listening to music)	1.000	-
Driving a car is a cool way to travel	1.215	58.20
Driving a car makes me feel optimistic and high-on-life	1.282	57.08
Driving a car makes me feel that I get the most out of every situation	1.154	56.56
I feel more independent when I drive a car	0.951	40.99

Satisfying functional needs (F5)	*est.*	*C.R.*
It is important for me to arrive safely	1.000	-
It is important for me to carry my things	1.122	21.65
It is important for me to save time	0.952	17.33
It is important for me to go wherever and whenever I want	1.088	18.89
It is important for me to have privacy during my transport	0.736	13.24
It is important for me to avoid congestion in transit	1.287	21.40
It is important for me to avoid having to change transport mode / line	1.353	21.59
It is important for me to arrive on time	1.131	20.06
Cycling self-efficacy (F6)	*est.*	*C.R.*
Biking is difficult because of the weather (R)	1.000	-
Biking is difficult because of the terrain (R)	1.388	23.51
Biking is difficult because of the distance (R)	1.096	22.22
Biking is dangerous due to other traffic (R)	0.924	20.45
Functional difficulties in transit (F7)	*est.*	*C.R.*
Transit is too slow	1.000	-
Transit is too expensive	0.982	23.72
Transit is too crowded	1.281	27.77
Transit is unreliable	1.170	26.96

Table 7.3; Estimates of the Measurement Equations of the latent Constructs

Positive cycling self-concepts (F1)	*est.*	*C.R.*
Male	-0.107	-2.43
Car availability	0.156	2.84
Home location: Copenhagen suburbs	0.104	2.13
Bicycle travel time greater than 30 min	0.260	5.32
Travel togetherness (F2)	*est.*	*C.R.*
Age 45-65	-0.180	-1.88
Education: vocational	-0.326	-2.58
Education: Tertiary	-0.374	-2.70
Education: Bachelor	-0.357	-3.03
Education: Graduate	-0.548	-4.96
Workplace location: Copenhagen city	-0.314	-3.21
Car use functional difficulties (F3)	*est.*	*C.R.*
Male	-0.070	-1.55
Car availability	-0.124	-2.33
Positive car self-concepts (F4)	*est.*	*C.R.*
Age 30-45	-0.298	-3.69
Age 45-65	-0.346	-4.23
Car availability	0.121	2.01
Education: Bachelor	-0.211	-2.00
Education: Tertiary	-0.399	-4.09
Student	-0.288	-1.87
Workplace location: Copenhagen suburbs	-0.206	-2.55
Satisfying functional needs (F5)	*est.*	*C.R.*
Male	-0.224	-4.10
Age 45-65	-0.191	-2.25
Cycling self-efficacy (F6)	*est.*	*C.R.*
Male	0.200	4.55
Income: high	0.159	3.01
Travelling with children	0.124	1.52
Monthly travel costs less than 500 DKK	0.342	3.16
Travel time: less than 10 min	0.459	4.59
Travel time: 10-50 min	0.374	6.49
Functional difficulties in transit (F7)	*est.*	*C.R.*
Age 30-45	-0.427	-4.45
Age 45-65	-0.436	-4.48
Age higher than 65	-0.834	-4.21

Table 7.4; Estimates of the Structural Equations Linking the ERG and TPB Constructs to the Socio-Economic Characteristics

	Direct effect		Total effect	
Positive cycling self-concepts (F1)	*est.*	*C.R.*	*est.*	*C.R.*
Perceived transit use frequency	-0.098	-3.58	-0.129	-4.27
Perceived bicycle use frequency	0.214	6.36	0.396	12.89
Perceived car use frequency	-	-	-0.262	-10.85
Travel togetherness (F2)	*est.*	*C.R.*	*est.*	*C.R.*
Perceived bicycle use frequency	0.105	2.31	0.105	2.31
Car use functional difficulties (F3)	*est.*	*C.R.*	*est.*	*C.R.*
Perceived transit use frequency	0.097	3.23	0.097	3.23
Perceived bicycle use frequency	0.129	3.65	0.129	3.65
Perceived car use frequency	-0.492	-13.19	-0.492	-13.19
Positive car self-concepts (F4)	*est.*	*C.R.*	*est.*	*C.R.*
Perceived bicycle use frequency	-0.127	-3.32	-0.127	-3.32
Perceived car use frequency	0.367	8.59	0.367	8.59
Satisfying functional needs (F5)	*est.*	*C.R.*	*est.*	*C.R.*
Perceived transit use frequency	-0.068	-1.86	-0.097	-2.66
Perceived car use frequency	0.123	2.43	0.346	8.01
Perceived bicycle use frequency	-	-	-0.033	-3.12
Cycling self-efficacy (F6)	*est.*	*C.R.*	*est.*	*C.R.*
Perceived transit use frequency	-0.189	-7.02	-0.189	-7.02
Perceived bicycle use frequency	0.350	10.97	0.350	10.97
Perceived car use frequency	-0.292	-7.57	-0.292	-7.57
Functional difficulties in transit (F7)	*est.*	*C.R.*	*est.*	*C.R.*
Perceived transit use frequency	-0.075	-2.00	-0.075	-2.00
Perceived car use frequency	0.323	6.99	0.323	6.99
Car satisfaction	*est.*	*C.R.*	*est.*	*C.R.*
Car use functional difficulties (F3)	-0.311	-10.37	-0.311	-10.37
Positive car self-concepts (F4)	0.232	8.89	0.232	8.89
Cycling self-efficacy (F6)	-0.065	-1.79	-0.065	-1.79
Functional difficulties in transit (F7)	0.139	5.08	0.139	5.08
Perceived bicycle use frequency	-	-	-0.092	-4.65
Perceived transit use frequency	-	-	-0.028	-2.00
Perceived car use frequency	-	-	0.302	10.36
Transit satisfaction	*est.*	*C.R.*	*est.*	*C.R.*
Car use functional difficulties (F3)	0.127	3.58	0.127	3.58
Satisfying functional needs (F5)	-0.052	-1.53	-0.052	-1.53
Cycling self-efficacy (F6)	0.063	1.70	0.063	1.70
Functional difficulties in transit (F7)	-0.274	-6.68	-0.295	-7.92
Perceived bicycle use frequency	-	-	0.040	2.76
Perceived transit use frequency	-	-	0.026	1.78
Perceived car use frequency	-	-	-0.187	-6.39
Bicycle satisfaction	*est.*	*C.R.*	*est.*	*C.R.*
Positive cycling self-concepts (F1)	0.366	12.38	0.366	12.38
Positive car self-concepts (F4)	-0.101	-3.72	-0.101	-3.72
Cycling self-efficacy (F6)	0.232	6.90	0.354	11.45
Perceived bicycle use frequency	-	-	0.239	11.17
Perceived transit use frequency	-	-	-0.091	-5.98
Perceived car use frequency	-	-	-0.201	-9.36

Correlation patterns				
Car satisfaction - transit satisfaction	0.107	3.94	-	-
Car satisfaction - bicycle satisfaction	0.117	4.11	-	-
Transit satisfaction - bicycle satisfaction	0.125	4.40	-	-

Table 7.5; Estimates of the Structural Equations Relating the Travel Satisfaction with the Latent ERG and TPB Constructs and Travel Mode Use

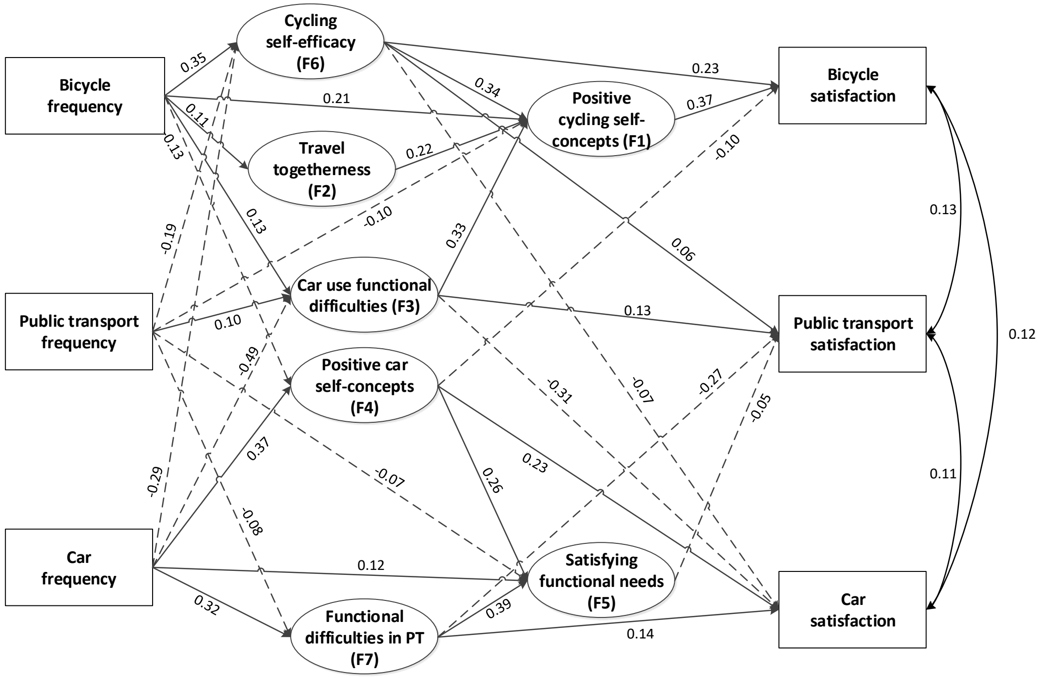

Figure 7.3; Model structure of the cyclical process relating mode use to satisfaction via the seven factors of ERG and TPB constructs (solid lines denote positive relationship, dashed lines denote negative relationship).

7.4 Discussion

7.4.1 The relation between the ERG and TPB constructs and respondents' characteristics

The model results show that the ERG and TPB constructs are significantly related to demographics, home and workplace locations and commute characteristics, cf. Table 7.4.

Cycling self-concepts are stronger for women, while cycling self-efficacy is stronger for men, indicating gender differences in satisfying growth needs. For women, cycling satisfies mainly self-identity of being sportive and environmentally sustainable, optimism, and self-esteem, while for men cycling satisfies physical challenges, namely self-efficacy and developing competencies. Cycling self-concepts are stronger for people cycling half an hour or more in their commuting trip, suggesting reciprocity between the development of cycling self-concepts and the cycling amount. Cycling self-efficacy is stronger for people travelling with children, possibly due to the need to serve as role models, and people with local travel patterns, as indicated by the low travel costs and time.

Positive car self-concepts relate positively to car availability and young age, and negatively to higher education, students and the workplace being in Copenhagen suburbs rather than city centre and rural locations. The results indicate a match between lifestyle and the development of car-related self-concepts, namely young people and people with high car availability who work in suburban locations, where there is higher car accessibility and no perceived problems with parking or congestion, develop stronger car self-concepts. Functional difficulties are perceived as stronger by women and people with low car availability, indicating again a reciprocity effect, namely people who see functional difficulties in driving have lesser tendency to own a car and vice versa. Satisfying functional travel needs such as multi-tasking, safety, and privacy, is associated positively with women and is perceived as more important at both younger and third age, indicating a shift in the travel preferences with the shift in lifestyle induced by the various life-cycle stages. The results are compatible with the findings of Sigurdardottir et al. (2013) and Sigurdardottir et al. (2014).

Travel togetherness is more important at younger ages, for people working in city centre locations, and seems to diminish with education length. This points towards needs being determined by lifestyles where young travellers preferring to travel together with friends and young families with their children.

The perceptions regarding the functional difficulties related to transit diminishes with age, with young people showing the greatest dislike for transit.

7.4.2 The relation between the travel use, ERG and TPB constructs and travel satisfaction

The general model structure was chosen based on the hypothesised research framework, namely that travel use is evaluated based on the ERG and TPB constructs resulting in a level of satisfaction with each mode. The flexibility of the ERG theory allowed for independence within needs satisfaction. Hence, several formulations were tested with different mutual relationships between the ERG and TPB constructs. The final model structure which yielded the best fit, confirmed the hypothesis that satisfaction from using the various transport modes is strongly and significantly related to the perceived existence, relatedness and growth needs, as well as the perceived difficulties and barriers associated with travel, cf. Figure 7.3. Thus, the model structure confirms the research hypothesis that travel satisfaction is related not only to functional needs, but also to relatedness and growth needs. Furthermore, that needs satisfaction varies across modes, which is mostly evident when comparing positive self-concepts for bicycle (F1) and car

(F4). Despite being similar concepts of higher-order needs the model results suggest that travel self-efficacy (negative travel difficulties) lead to development of positive self-concepts for bicyclists whereas this is not the case for car and public transport users.

The specific results show that higher bicycle satisfaction is linked positively to cycling self-concepts and self-efficacy, and negatively to car self-concepts. Higher cycling frequency and lower car and transit use frequency are associated with increased perception of cycling self-efficacy and travel togetherness. The two factors have equal role as mediators between cycling frequency and cycling self-concepts, namely higher cycling frequency leads to better feelings of self-efficacy and togetherness which motivate a better feeling of self-actualization and self-esteem leading in turn to higher satisfaction. The hierarchy agrees with Maslow's pyramid of needs where growth needs are higher-order than relatedness and functional needs. Nevertheless, in agreement with the ERG model, the relatedness needs are satisfied in parallel to the functional needs and the two are almost equally important in developing cycling self-concepts.

Greater car satisfaction associates positively with car self-concepts and transit use difficulties, and negatively with functional difficulties in car use and cycling self-efficacy. Positive car self-concepts are related positively to car use and negatively to cycling frequency. The functional difficulties in car use are associated with higher transit and cycling frequency and lower car use, while difficulties in transit use are associated with higher car use and lower transit use.

Greater transit satisfaction correlates positively with greater difficulties in car use and negatively with difficulties in transit use and the ability to satisfy travel needs by car. The importance of these factors shows that the car, rather than the bicycle, is the main competitor of transit, and that the use of transit derives by existence or functional needs. Greater transit satisfaction links to lower perceived cycling self-efficacy, meaning that transit satisfaction is greater for people who feel less comfortable in using the bicycle or the car.

The correlation patterns across the satisfaction from the three modes show positive correlations, meaning that higher satisfaction from a certain mode translates into higher general satisfaction also from the other modes. Namely, people whose needs are satisfied feel satisfied with the transport system in general, and dissatisfaction from one mode translates into a system-wide dissatisfaction.

7.4.3 Limitations

While the current study provides important insights regarding need satisfaction in modal choice, the data source used in this study is not without limitations. Firstly, this study uses cross-sectional data, which is an efficient method to investigate the assumptions of the relationship between need satisfaction and travel use. However, such data cannot by definition be used to model change. For such purpose panel data is needed as a further research direction. Secondly, the current study focuses on commute trips. This was chosen because commute trips constitute 37% of all trips in the Greater Copenhagen Area, larger than any other trip purpose. Further research could investigate the consistency of results across other travel purposes and population groups. Thirdly, our data does not include joint trips because commuting trips are mostly done individually. Nevertheless, when considering leisure travel purposes joint travel needs to be considered.

7.5 CONCLUSIONS

This study proposes a unifying framework of measuring travel satisfaction in modal choice by using a needs-oriented approach based on the TPB and ERG theories. The results confirm the hypothesis of travel mode frequency being related to satisfaction through a cyclical process while being subject to need satisfaction and travel difficulties. Specifically, the results confirm the hypothesis regarding the importance of satisfying higher-order needs of togetherness, self-efficacy and positive self-concepts in travel mode choice, in addition to the functional needs (travel time and cost) considered in the traditional approach. The findings are in line with recent studies, e.g. Abou-Zeid et al. (2012), Kaplan et al. (2014), van der Kloof et al. (2014), Salvá et al. (2015), Spears et al. (2013), and Spotswood et al. (2015). Moreover, we found that satisfaction with travelling by car is motivated by functional difficulties with other modes, ease of using car and self-concepts. Such concepts are more pronounced for young travellers with higher car accessibility and working in rural areas, hence highlighting the influences of socio-demographics on travel behaviour. Bicycle satisfaction is motivated by mainly higher-order needs of travel togetherness, cycling self-efficacy and cycling self-concepts. Gender differences were observed as males put more emphasis on cycling self-efficacy in terms of developing cycling competences where women emphasised self-concepts, e.g. self-esteem and being environmental friendly. Satisfaction with public transport is motivated mainly by functional difficulties with other modes.

The findings show that non-monetary rewards as increased sense of self-efficacy, togetherness, and positive self-concepts are strong motivators of satisfaction, possibly even more than monetary rewards. Hence, encouraging their development in relation to sustainable modes and relevant branding may result in successful long-term shift towards sustainable travel. The results show that, at least in Denmark, the main competitor of the car is the bicycle as commute travel mode, not only because of the mode share but mainly because both are related to the formation of positive self-concepts that lead to higher self-esteem. This advantage of the bicycle is an important consideration in the decision to integrate bicycle and transit use and in promoting bicycle infrastructure. Nevertheless, habits are reinforced by recurrent experience and reward and thus difficult to break (Chen and Chao, 2011; Aarts et al., 1997). Therefore, emphasis should be on long-term policies and promotion of sustainable travel from an early age.

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8 CONCLUSIONS

This PhD study presents several new insights into what creates an attractive public transport system as seen from both the passengers' and the societal point of view. The contributions range within the wide spectrum of public transport planning focusing on the differences in attractiveness across public transport modes. The analyses cover both the attractiveness as perceived by passengers in terms of travel satisfaction, and that of the society in terms of traffic impacts associated with implementing these systems. Hence, this dissertation together with the six associated papers contribute to the state-of-art within three main research areas of public transport planning: i) potential impacts of improvements to public transport operations, ii) larger effects of public transport systems, and iii) determinants of travel satisfaction.

8.1 IMPROVEMENTS TO PUBLIC TRANSPORT OPERATIONS

The findings of paper 1 (chapter 2) and paper 2 (chapter 3) both highlight the importance of coherent planning of public transport systems in order to optimise operations for the benefit of the travellers. This includes the overall planning of public transport timetables to minimise passenger waiting times, and the specific implementation of new on-street public transport systems such as BRT and LRT.

The main contribution of paper 1 (chapter 2) is an evaluation of various service elements related to BRT and LRT operations. As these systems comprise many service components, the focus is on assessing the effects of individual components as well as coherent systems as experienced by the passengers. Hence, the study analyses the effects of various APTS elements such as pre-board fare collection to optimise the boarding process, and holding strategies to reduce bunching of vehicles. On the infrastructure side it includes fully segregated running ways and signal prioritisation to increase travel speed by minimising delays caused by congestion. A specific contribution from the study is an extension and application of a mesoscopic simulation model originally developed in Ingvardson and Jensen (2012a). The model simulates public transport operations in great detail which allows a thorough evaluation of each of the service elements. The feedback loop between the mesoscopic simulation model and the public transport assignment model allows modelling changes to passenger flows in the transport network resulting from improvements to the bus operations. The results of the study highlights the importance of not only focusing on infrastructure elements when upgrading public transport. While implementation of segregated infrastructure ensures increased travel speeds, service planning elements are more important for providing a reliable service with less bunching of vehicles. Finally, the results shows larger effects when combining infrastructure and service planning elements in coherent systems than when implemented individually. This suggests the existence of synergy effects, hence highlighting the importance of coherent planning of both infrastructure and service planning elements when improving on-street public transport systems.

The contribution of the second study (chapter 3) is the development of a general framework for estimating passenger waiting times which incorporates the arrival patterns of passengers explicitly. As arrival behaviour can be either random or non-random, e.g. due to timing the arrival according to the timetable, this study proposes to model passenger waiting times by a mixture distribution consisting of two components, namely a uniform distribution and a beta distribution. Hence, the two distinct travel behaviour types are explicitly modelled and evaluated. The approach is validated using a large-scale Automated Fare Collection (AFC) system from the Greater Copenhagen Area covering trip legs in metro, suburban and regional trains across headway times of 2-60 minutes. The results shows that a large share of passengers time their arrival to stations even at short service headways, e.g. 43% at 5-minute headways and 52% at 10-minute headways. This highlights the importance of providing real and accurate timetables to allow passengers to time their arrival at the station in order to actively minimise their waiting times. By not providing accurate departure times, e.g. if using frequency-based timetables, passengers are forced to arrive randomly, thereby prolonging their waiting time. Considering that passengers value waiting time relatively higher than other travel time components further emphasises the importance. Another significant contribution of the framework is the possibility to incorporate the approach in transport assignment models by explicitly modelling the actual arrival behaviour of passengers instead of assuming fixed hidden waiting times based on service frequency. Specifically, the mixture distribution is very flexible as it allows for two important aspects, namely i) different shares between the uniform and beta components, i.e. random and non-random arrivals, and ii) different parameters of the beta component, i.e. the degree of timeliness of passenger arrivals. Hence, the approach can be adapted specifically to the given setting, e.g. specific service headway times.

8.2 LARGE-SCALE EFFECTS OF PUBLIC TRANSPORT SYSTEMS

The focus of chapters 4 and 5 is new insights into the larger scale impacts of public transport systems. The focus of both studies is to compare effects across public transport modes in order to evaluate effects related to the rail factor as previous studies have debated whether rail-based modes are more attractive than their bus-based counterparts even at similar service levels. While this has been found to be the case in multiple studies (Axhausen et al., 2001; Fosgerau et al., 2007; Nielsen, 2000), others find that the differences are due to different service characteristics, e.g. travel time and reliability (Ben-Akiva and Morikawa, 2002; Tørset, 2005).

The first study (chapter 4) contributes to existing research by comparing the overall effects of less expensive BRT and LRT systems to more expensive metro and heavy rail systems. The sample of reviewed systems contains 86 public transport systems from cities from around the world. The comparison is two-fold by analysing i) the traffic impacts in terms of travel time reductions, ridership increases, and modal shifts, and ii) the strategic effects in terms of effects on property values and urban development. Firstly, the review identifies notable effects from implementing BRT systems with respect to travel times and ridership. However, effects vary considerably across studies due to specifically the coherence of implementation, e.g. degree of segregated infrastructure and other BRT elements, and the competition with other modes, e.g. attractiveness of remaining public transport system, level of road congestion and car use restrictions. In terms of modal shifts from car traffic the results reveal large differences across projects as some have notable influence whereas others have very limited effects. However, large effects are observed across all modes, hence suggesting the importance of planning attractive systems optimally rather than focusing on the public transport mode itself. Secondly, the review analyses the strategic effects across studies finding evidence of large increases to property values after implementing both BRT, LRT, metro and heavy rail systems. However, the effects vary notably across projects. Even within the same city similar systems can result in different effects, hence highlighting the influence of local conditions as well as differences in assessment methods across the reviewed studies. A statistical comparison shows no significant differences across public transport modes. However, findings suggest negative externalities from the BRT in close vicinity of stations resulting in less or even negative effects on urban development and property values. Hence, BRT systems have the risk of leading to unattractive urban areas as BRT take up more urban space. In summary, the review suggests that effects are not limited to expensive rail-based public transport modes. Instead, it is important to focus on coherent planning ensuring improved service levels and attractiveness rather than just relying on obtaining effects due to implementing expensive LRT or metro systems. However, as negative externalities are difficult to avoid in close proximity of high-capacity BRT systems it is a greater challenge to implement these systems while simultaneously ensuring attractive station environments within dense urban areas.

The second study (chapter 5) contributes to the research by analysing the determinants of public transport ridership across 48 European metropolitan areas. Focus of the study is to compare the influence of different public transport modes, network density and network topology. The initial literature review of 36 previous studies identifies the most important determinants of ridership within socio-economic, land use, built environment and transport characteristics to be used in the subsequent analyses. The dataset constructed from the review includes population and employment densities, public transport coverage in terms of metro, suburban rail and LRT, network characteristics in terms of the number of terminals and cycles (*cyclomaticity*), and economic characteristics in terms of per capita GDP, GINI coefficient, car ownership, and unemployment rate. The initial results confirm the general hypothesis of positive relationships between ridership on the one hand and service coverage and employment density on the other hand. Due to the relatively small sample size of 48 cities and the number of explanatory variables a factor analysis and subsequent regression is performed to obtain a higher degree of freedom. The factor analysis reveals four factors in the dataset, namely i) metro coverage, network connectivity and urban density, ii) suburban rail coverage, iii) economic inequality, and iv) light rail coverage. The results of the regression analysis show increased public transport ridership in cities with dense urban structures and dense public transport coverage whereas economic inequality is associated with significantly lower ridership. While the results do not estimate the absolute significance of network connectivity indicators, the results suggest stronger correlation from the number of terminals, hence highlighting the importance of transfer possibilities. Finally, a significant contribution from the study is the importance of defining urban areas to ensure comparability across cities.

8.3 Determinants of travel satisfaction

The contribution of chapters 6 and 7 is new insights into the influence of psychological factors on travel behaviour with special emphasis on how attitudes and social norms influence satisfaction and travel use frequency.

The first study (chapter 6) investigates the main determinants of public transport satisfaction and their relationship with travel use frequency and willingness to recommend public transport to others. By this, the study contributes to the research by specifically analysing the influence of social norms in travel use. The study deployed a large-scale satisfaction survey from six European cities ensuring not only a large sample, but also a validation of the results across travel cultures. The main contribution of the study was a two-fold implication for policy and practice. Firstly, the findings confirmed the importance of prioritising accessibility measures in terms of travel speed, ease of access and service frequency while ensuring reasonable costs and a high perceived value of the system. In addition, higher perceived societal and environmental importance of public transport was associated with higher satisfaction and travel use frequency in public transport. These results were consistent across respondents from the six cities, thereby emphasising the results and their validity. This highlights the importance of psychological beliefs in travel satisfaction and behaviour, and suggests that agencies could focus more on these aspects in their branding of the system. Secondly, younger passengers and students were systematically less satisfied despite using public transport more frequently, hence highlighting a structural problem within public transport as travel habits formed in early life tend to shape travel behaviour throughout life (Schwanen et al., 2012). It is therefore important to focus on delivering satisfactory service to younger users in order to retain these passengers throughout life.

The second study (chapter 7) investigates the influence of psychological factors on travel satisfaction in greater detail by proposing a unifying framework for representing travel mode use frequency. The decision-making framework incorporates the Theory of Planned Behaviour (TPB, (Ajzen, 1991)) and the ERG theory of human needs (ERG, (Alderfer, 1969)). By this, satisfaction is measured and evaluated based on the sense of well-being and need satisfaction rather than solely using traditional service characteristics. The framework includes four groups of factors, namely i) *existence needs*, i.e. functional needs, ii) *relatedness needs* including social norms, iii) *growth needs* including attitudes and self-concepts, and iv) *travel difficulties*. The framework is evaluated through a case study in Copenhagen based on 1,481 respondents from a tailor-made questionnaire. The results confirm the hypothesis that travel mode use frequency is related to travel satisfaction through a cyclical process while being subject to need satisfaction and travel difficulties. This is the case for travel satisfaction with bicycle and car which is mainly motivated by higher-order needs of travel togetherness, self-efficacy and positive self-concepts. Also functional needs are important, including travel time and costs, which are considered in the traditional approach. On the other hand, public transport satisfaction is mainly motivated by functional difficulties with other modes. This could suggest that public transport is seen as a pure transport solution among the respondents of the survey. However, as the survey did not explicitly cover higher-order needs related to public transport satisfaction adequately, the actual implications for public transport are not fully unambiguous. But the general results in terms of the importance of higher-order, non-monetary aspects such as positive self-concepts and togetherness might be generally valid, especially considering the results of chapter 6, which highlighted the importance of environmental and social aspects.

8.4 Policy implications

The conclusions of this dissertation spans widely across the topic of improving public transport systems to attract more passengers. But three conclusions are worth highlighting for their implications for policy and practice.

Firstly, the results show that large impacts can be obtained by cost-effective BRT systems in metropolitan areas if they are implemented as thorough and coherent systems. However, the flexibility of the concept comprising many design elements is a threat towards inefficient implementation. On an operational level, coherent planning is crucial to ensure optimal effects for passengers in terms of travel speed and reliability. On a more societal level, it is important to minimise externalities, which are often associated with high-capacity BRT systems, to ensure attractive city areas and large strategic effects. Such impacts are easier to obtain from rail-based modes, especially metro systems, due to less externalities at similar travel speeds, high comfort, and generally high attractiveness.

Secondly, the findings related to passenger waiting times highlight the importance of providing real and accurate timetables to passengers. A large share of passengers actively make an effort to reduce their waiting times at their first encounter with the public transport system, even when headway times are as short as 5 minutes. It is therefore important that public transport agencies and operators provide accurate timetables to passengers instead of frequency-based timetables which is commonly used, e.g. by the Copenhagen metro. By this, waiting times can be reduced, thus creating a more attractive public transport system. The proposed method for estimating waiting times also has practical value in transport models for better representing the travel behaviour of passengers, thus ensuring more accurate estimations of passenger effects of improvements to public transport services.

Thirdly, the findings of this dissertation suggest the importance of aspects other than traditional service characteristics in influencing travel satisfaction and travel use frequency. For travel behaviour in general satisfaction is motivated also by higher-order needs, e.g. positive self-concepts, by users of cars and bicycles. Hence, if transport systems provide a sense of well-being and are consistent with the personal belief of the user they will be perceived as more attractive. The study did not specifically investigate this for public transport users. However, for public transport social norms and perceived societal and environmental importance of public transport are highlighted as being strongly associated with both satisfaction and use frequency across six European cities. Hence, public transport could exploit such aspects, e.g. by branding the system to attract more passengers.

8.5 Future research

While this dissertation has made a considerable contribution to the literature and knowledge regarding how to ensure attractive public transport systems, much more research can be dedicated to this important research area. Each of the six papers include study limitations and possible future research paths within each research domain, however two main topics are worth highlighting on a general level.

Firstly, the general topic of improving public transport timetables for the benefit of passengers is a research theme that could deserve more focus. Extensive research has focused on developing timetables with the purpose of minimising transfer times en-route. Considering that 55% of public transport trips in the Greater Copenhagen Area only involve one trip leg more research could be dedicated to minimising first waiting time. While this dissertation contributed significantly to this topic, future research could continue this path by analysing the influence of various timetable types where headways are not constant, e.g. stations with skip-stop services, Also, studies could analyse the influence of real-time information, which is readily available for more and more passengers through online travel planners. This has the potential to increase the amount of passengers that actively minimises their waiting time by arriving timely at stations and stops. Hence, the influence on arrival behaviour is a highly relevant research path.

Secondly, research within travel satisfaction and mode choice could investigate further the importance of satisfying higher-order needs. The proposed method for evaluating travel satisfaction on the basis of need satisfaction, as proposed in chapter 7, can be extended further to address more specifically the needs of public transport users. A specific issue is also the direction of causality which requires panel data to analyse properly. This will allow for evaluating the influence on mode choice and general travel habits, especially in relation to choice users, which are important to attract into the public transport system considering the potential for reducing congestion and negative externalities of the transport sector.

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Public transport systems are essential for ensuring mobility in the dense and increasingly congested metropolitan areas.

This thesis investigates factors that can contribute to make public transport systems more attractive for passengers and the society. Firstly, the analyses address public transport operations in terms of analysing improvements to on-street public transport systems and the influence of service frequency on passenger waiting times. Secondly, large-scale traffic and strategic impacts are analysed including the effects of dense public transport networks on ridership and property values based on literature and data collected for 48 European metropolitan areas. Finally, the thesis covers the main determinants of passengers' travel satisfaction taking into account traditional service quality elements, but also how well the transport system satisfies the needs of the passengers.

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