Policies for On-board Crowding in Public Transportation – A Literature Review

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Abstract

Crowding in public transportation is increasingly perceived as a problem in large cities. Public transport authorities strive to develop policies that manage demand and reduce crowding in the best way. This paper reviews studies of policy instruments aimed at crowding and demand management of public transportation, mainly quantitative studies. The most observed policies are adjustments of fare (including differentiation), frequency, capacity, bus size and in some cases road tolls. The reviewed studies either implicitly represent crowding by the willingness to pay for less crowding or by reduction of occupancy levels. We subdivide papers into studies that model transport scenarios and studies that observe passenger demand, often real-world cases. We use social welfare optimization as reference point for analysis of the study contributions. Studies that observe passenger demand present results limited to the effects on overall demand and generally not in terms of social welfare. Some studies report on price differentiating policies that succeed in reducing peak demand, reductions ranging from 1.2 to 10 percent. Most modelling studies find it optimal for occupancy to decrease, however, some studies find that higher occupancy rates are welfare optimal. Few of the reviewed studies present the costs and benefits directly associated with decreasing occupancy. Few studies present both spatio-temporal distributions of occupancy and include a policy for the reduction of crowding. This suggests that a clearer picture of the severity of on-board crowding, together with a policy to manage crowding would be useful.

Keywords
Crowding, on-board crowding, occupancy, public transport, policy

JEL Codes
R40, R48

1. Introduction

The costs of transport has increased in large cities at a fast rate this last decade around the world. Congestion increases travel cost due to the increased usage of roads and railway networks. Crowding on-board public transportation vehicles increases the number of full vehicles circulating, increases passenger waiting time and travel time variability (Tirachini, Hensher & Rose 2013). This imposes a high strain on the public transport system, especially in peak periods, resulting in higher operating costs and longer travel time. According to Parry & Small (2009) average operating costs in public transit can be between 60 to 100 percent higher in peak periods compared to the off-peak periods. The reason being higher vehicle costs, higher unit labour costs, for buses these costs are even higher on congested roads. Economists now find that crowding externalities need to be accounted for in the design process of public transport systems. Ceder (2007) stresses that operators need to adjust public transit services based on analysis of demand and crowding, not from rules of thumb for occupancy, such as the maximum number of standees and headway policies. The most intuitive strategy to reduce crowding is to increase frequency, this is however associated with high costs. Today, metropolitan cities such as Melbourne, Sydney, Singapore, Washington and London have implemented price differentiating policies in their public transport system or parts of it, as an attempt to reduce peak occupancy (Tirachini, Sun, Erath, & Chakirov 2016; de Palma, Lindsey & Monchambert 2017). This leads to question which policy tools are available to manage on-board crowdedness and how well the policies manage crowding. Are the policies evaluated from a social welfare perspective?

This study reviews the literature on policy tools that manages crowding. Policy tools are defined as policies or management strategies that intend to reduce or alleviate on-board crowding or reduce negative externalities from crowding in public transportation, directly or indirectly. They can for example be operational, economic, engineering or design oriented. The altering of exogenous variables in demand models are considered as policies in this review. The literature is presented by policy, data, effect on crowding/occupancy and evaluations of policies are reported from a social welfare perspective. Additionally, this review identifies gaps in the literature on policies for crowding.

1.1 Method

The method to find relevant and current literature began with a broad search on crowding and public transport, in English, using Google scholar, without restrictions on publication year, geographical area or language. The following strings of search were used; “crowding AND public transit OR public transport*”, “policy AND crowding AND public transport* OR public transit”. The searches were repeated with different synonyms for crowding, such as “on-board crowding”, “in-vehicle crowding”, “over crowdedness” and with keywords such as “delay” and “demand” in the place of “crowding”. Regular Google searches in English were performed using similar strings of search just mentioned. A Google scholar search with restriction on publication year 2017 was done to identify the most recent publications on the subject. Additionally, the snowball method was used by identifying references in known studies to find relevant articles. This process was repeated until no more relevant articles could be found. The initial studies used for this method were Perry & Small 2009; Zhang, Jenelius & Kottenhoff 2016; Cats 2014.

This paper is structured as follows. Section 2 presents a conceptual framework for the analysis of different policy instruments. Section 3 reviews how crowding affects passengers, section 4 reviews how crowding is measured, section 5 identifies crowding policies, section 6 reviews data. Furthermore, section 7 reviews the policy effects on crowding and welfare effects; observational studies (7.1) and modelling studies (7.2). Section 8 concludes the literature review and discusses optimal policy (8.1).

2. Conceptual Framework

We propose a welfare economic conceptual framework for the analysis of the efficiency of different policy instruments and for analysis of the study contributions. There are three important reasons for this choice.

1. The first is that public transportation networks in large cities are a part of a larger transport system, including roads and railway networks. Policy instruments directed to one area of the transport system, as means to reduce an externality problem such as; on-board crowding, road congestion, parking space scarcity, emissions of greenhouse gases, can affect another externality in an unintended way. Several policies may be required for the desired effect and a full set of effects from the various policies need to be reported.

2. Public transport is associated with the market imperfection that higher frequency and lower fare is associated with larger welfare effects, than compared to a fare equal to marginal cost.

3. Creating models representing these complex relationships requires a large set of functions, valuations and elasticities of demand. Such models are costly for public transport authorities to implement and maintain as the estimation of these

relationships require data on the trips, passenger counts, vehicle location, car flows, vehicle speed etc.

The phenomenon in focus here – crowding – is of course closely connected to occupancy in public transport vehicles. Quantification of the prevalence and changes in crowding requires data on occupancy and a precise definition of crowding. We therefore review definitions, the data used and calculated effects of policies on occupancy and crowding. Already at the outset of the work with this paper the goal was to find studies that had identified and analysed effects of policies to handle crowding. We were particularly interested in finding studies that calculated welfare effects of policies. After a thorough examination of the identified papers it was found that they could be sorted in two categories; 1) studies that primarily observe the levels of occupancy and how these levels are affected by policies and 2) studies that optimize the use of policy instruments and attempt to evaluate the welfare of policies. Observational studies primarily report on occupancy levels before and after a policy has been implemented. Some use stated choice experiments and some use ridership data. Modelling studies have a social welfare perspective, typically present a demand function and optimize variables such as fare, frequency, capacity, bus size, road tolls and seat provision etc. to maximize social welfare. As these different approaches are fundamentally different, we choose to separate the presentation of the studies in this paper according to the two categories: 1) observational studies, and, 2) modelling studies.

3. How crowding affects passengers

Crowding has been shown to cause negative effects on passengers' travel experience in several ways, it increases the levels of stress and reduces the overall welfare of passengers (Kim, Hong, Ko, & Kim (2015). High crowding levels not only cause passenger discomfort and disrupts service reliability it can increase passenger travel time because of increased boarding and alighting times and result in denied boarding for passengers (Sanchez-Martinez, Paget-Seekings, Southwick, & Attanucci 2018). How passengers value crowding can depend on various factors such as travel purpose, travel duration, culture and other context specific factors. Tirachini et al. (2016) identify that passengers in the Singapore metro are willing to travel in the opposite direction to receive a seat and then re-board in the intendent direction. They conclude that not accounting for the disutility experienced by standing passengers in crowded conditions will lead to systematic underinvestment of public transport capacity upgrades. Ignoring the disutility of crowding will also lead to underestimation of benefits from peak-spreading strategies, such as time-differentiated pricing and real time information of crowding (Tirachini et al. 2016).

4. How crowding is measured

4.1 Review of crowding definitions

Most studies acknowledge the problems associated with crowding. Observational studies use a variety of expressions for “crowding”, such as “overcrowding, passenger load, passenger demand”, while studies that have a social welfare perspective typically only use the term “crowding” or “occupancy”. Very few studies with a policy towards crowding clearly define crowding, that is, they do not specify at what point the level of occupancy causes crowding. One study stand outs and presents a threshold of crowding as a function and graphical representation for the crowding level that creates disutility for passengers (de Palma, Kilani and Proost 2015).

4.1 Different types of crowding measures

There are two dimensions of crowding; density (an objective measure) and passengers’ subjective perception of crowding. Although perceived crowding is related to passenger density, they are not identical. The subjective perception of crowding is highly influenced by individual preferences, expectations, previous experience, and culture. In the field of psychology, the perceived crowding level is about the invasiveness of personal space. The term crowding is therefore more complex than a density measure (Evans & Wener 2007). Current research usually captures one dimension or the other.

Stated preference studies

In stated preference (SP) studies there are two main methods to measure crowding, by the load factor and by the number of passengers per square meter. The load factor is determined by the number of passengers divided by the number of seats (or seating and standing capacity). A pronounced threshold level of crowding based on vehicle capacity is required to determine crowding when using the load factor. Different vehicles can have varying amounts of standing space, which means that the same load factor can imply different levels of crowding depending on vehicle type. The number of passengers per square metre does not exhibit this problem. Monetary values per time unit or per trip are other valuation methods of these measures. When crowding is studied in relation to comfort and service, a standing multiplier is most used for valuation of crowding (Whelan & Jonson 2004). When the cost of crowding is computed in economic literature, the cost is often assumed to be linear, based on empirical evidence (Hörcher et al. 2018 a; Wardman & Whelan 2011). This might, however, not be completely accurate. Sanchez-Martinez et al. (2018) point out that crowding can increase with the duration of the trip; passengers might tolerate a short part of the trip under crowded conditions, although, perhaps not the entire trip.

Revealed preference studies

Revealed preference (RP) studies on crowing valuations have begun to appear in the literature due to the increasing availability of smart card data. Smart card data is frequently used to model travel behaviour, model spatio-temporal patterns and consequently improve public transport planning (Chu 2008; Luo et al. 2018). Standing density and seating capacity are measures used in RP crowding valuation, typically with route choice analysis. Such studies have found that people reroute when it is crowded and avoid crowding itself (Kim et al. 2015; Yap et al. 2018). Frequent travellers seem to adapt their route due to crowding more than infrequent travellers do (Yap et al. 2018). Crowding valuations from RP studies have found lower values than SP studies, indicating that stated choice results of crowding might be overestimated (Hörcher et al. 2017; Yap et al. 2018). It is worth noting that RP studies of crowding valuation are less common than SP studies. One of the main reasons is likely that data required for route choice analysis, complete origin-destination (OD) matrixes are rare. The reason being, few public transport systems in the world require both tap-ins and tap-outs, which directly generates OD-matrixes. It is however possible to infer missing tap-outs with various OD-estimation methods[1].

Review of crowding measures

This review finds that less than half of the studies with a crowding policy present a measure of threshold level of crowding. Among the observational studies, one study presents a crowding threshold; 270 passengers per metro carriage, set at the median metro passenger load in Stockholm (Zhang et al. 2016). A few observational studies present occupancy levels, such as passenger density per square metre (Batarce, Munoz & de Dios Ortuazar 2016; Haywood & Koning 2015) and one presents peak hour demand (Sarkar & Jain 2016). A few observational studies have a valuation of crowding such as a crowding multiplier, a crowding cost, an overcrowding penalty in pence per minute (Whelan & Johnson 2004), the social value of time (Batarce, Munoz & de Dioz Ortuzar 2016) and a travel time multiplier (Kroes et al. 2014). One observational study has a threshold level for passenger flow to be maintained at a metro station in Beijing (Xu, Liu & Jiang 2016). Among the modelling studies, two present a crowding measure; occupancy as a crowding threshold level (de Palma et al. 2015) and aggregate crowding per capita (Parry & Small 2009). There are modelling studies that calculate a crowding value such as crowding cost functions, multiplier for parameter values in estimations and/ or value of travel time savings (VTTS) in terms of crowding. Half of the modelling studies present occupancy measures, such as peak occupancy over capacity (Börjesson et al. 2017;

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[1] Trip-chaining (Wang, Attanucci & Wilson 2011), passenger-to-train assignment (Zhu, Koutsopoulos & Wilson 2017), fusing smart card data and bus GPS trajectories (Tu et al. 2018) to mention a few.

Hörcher & Graham 2018), density of standing passengers per square metre (Tirachini, Hensher & Rose 2014), number of users on a train (de Palma et al. 2017) and bus boarding passengers (persons/vehicle) in peak (Asplund & Pyddoke 2020).

It is worth noting that there are studies that present crowding definitions and that measure the levels of spatio-temporal crowding, they do not however typically present solutions or policies to manage crowding and are therefore not included in this review. These studies rather model the spatio-temporal patterns for travel behaviour analysis, transit modelling and aim to improve system management (Chakirov & Erath 2011; Chu & Chapleau 2008; Luo et al. 2018; Sun & Jin 2018).

5. Identified crowding policies

The following list of policies in Table 1 have been identified in the literature as possible strategies to reduce crowding. Policies in bold are reviewed in this present study, the remaining policies have only been mentioned in the literature and are therefore not reviewed.

Table 1. Identified policies

Policy category	Policy
Economic	**Price differentiation**
	Ticket type provision
	Internalize cost (impose tax = marginal cost of crowding)
Operational	**Increase capacity**
	Increase frequency
	Regularity driven service
	Short turning
Infrastructure/ Engineering	**Extend PT network**
	Metro line automatization/ increase frequency
	Exclusive bus lanes
	Design of access points at stations
Information	**Real-time information (RTI)**
	Information about expected crowding levels
Route choice behaviour modelling	**Passenger control (reduce access to station entries, platforms, staircases etc.)**
Design	**Seat provision**
	Vehicle design
	Air quality
	Cleanliness
	Noise reduction
Service	Delay management
Other	**Staggered school-start**

This review presents 26 studies, most of them are economic studies, one is a literature review and one is an engineering study. Table 2 gives an overview of all studies reviewed, crowding policy, case study and location. The most common policy identified is price differentiation. A few studies approach the problem of crowding more indirectly, for example by using reliability improvement measures, such as bus holding strategies to avoid bus bunching, optimize the seat provision of public transportation vehicles, or propose passenger control strategies that reduces the access of passengers to the station entry or platform. Other solutions that may alleviate crowding are the supply of better services, reliability improvements, reduction of delays and improvement of the quality of communication to passengers (Li & Hensher 2013). Less mentioned solutions are improving air quality, air circulation, cleanliness, prohibiting loud conversations and music in public transport (Li & Hensher 2013).

Table 2. Overview of studies

Author(s), (year)	Policy	Case	Location
Asplund & Pyddoke (2020)	Optimize fare and frequency	Ex ante	Uppsala, Sweden
Batarce, Munoz & de Dios Ortuzar (2016)	Increase bus capacity and frequency	Ex ante	Santiago, Chile
Berrebi, Watkins & Laval (2015)	Regularity driven services	No	-
Börjesson, Fung & Proost (2017)	Optimize fare, frequency, bus size, no of bus lanes and car tolls	Ex ante	Stockholm, Sweden
Cats (2014)	Regularity driven services	Ex post	Stockholm, Sweden
Cats, Larijani, Koutsopoulos & Burghout (2011)	Regularity driven services	Ex post	Stockholm, Sweden
Currie (2010)	Price differentiation	Ex post	Melbourne, Australia
de Palma, Kilani & Proost (2015)	Optimize fare, share of seats and schedule	Ex ante	Paris, France
de Palma, Lindsey & Monchambert (2017)	Optimize fare and capacity	Ex ante	Paris, France
Douglas, Henn & Sloan (2011)	Price differentiation	Ex ante	Sydney, Australia
Halvorsen, Koutsopoulos, Lau, Au & Zhao (2016)	Price differentiation	Ex post	Hong Kong
Haywood & Koning (2015)	Automatization of metro line	Ex ante	Paris, France
Haywood, Koning & Prud'homme (2018)	Optimize crowding level subject to fare	Ex ante	Paris, France
Hörcher & Graham (2018)	Optimize frequency, capacity and occupancy rate	No	-
Hörcher, Graham & Anderson (2018 a)	Optimize fare regimes	No	-
Hörcher, Graham & Anderson (2018 b)	Optimize seat capacity	No	-
Horn af Rantzien & Rude (2014)	Price differentiation	Ex ante	Stockholm, Sweden
Kroes, Kouwenhoven, Debrincat & Pauget (2014)	Extension of mass transit railway line	Ex ante	Paris, France
Liu & Charles (2013)	Price differentiation	Yes	Various locations
Ljungberg (2007)	Staggered school start	Ex ante	Linkoping, Sweden
Parry & Small (2009)	Optimize fare subsidy	Ex ante	Washington DC, Los Angeles & London
Sarkar & Jain (2016)	Price differentiation	Ex ante	New Delhi, India
Tirachini, Hensher & Rose (2014)	Optimize frequency, seat capacity, subsidy, no of bus doors	No	Sydney, Australia
Whelan & Johnson (2004)	Price differentiation	Yes	England
Xu, Liu & Jiang (2016)	Passenger control	Ex ante	Beijing, China
Zhang, Jenelius & Kottenhoff (2016)	Real-time information (on metro platforms)	Ex post	Stockholm, Sweden

Number of policies according to study type

Among the 15 observational studies price differentiation is the most common policy (Table 3). The second most common policy is regularity-driven operations.

Table 3. Observational studies

Policy	Number of studies
Price differentiation	7
Regularity-driven operations	3
Real-time information	1
Capacity and frequency	1
Engineering	1
Infrastructure	1
Passenger control	1

The 11 modelling studies usually have a social welfare perspective, present a demand function and optimize variables such as fare, frequency, capacity, bus size and road toll to maximize social welfare (Table 4). The most common variables included are fare, frequency and capacity. Note that these policies are the demand function variables in economic models and usually not tested policies.

Table 4. Modelling studies

Policy	Number of studies
Fare, frequency, capacity, bus size, road price etc.	3
Fare & frequency	2
Fare & capacity	2
Fare, seat provision, schedule	1
Fare, seat provision, occupancy	1
Fare & occupancy	1
Fare	1

6. Review of Data

Early research on crowding in public transport began in the 1970s, investigating crowding and how various factors such as employment levels, GDP, fare and time-table reliability affects demand. Until recent years crowding research almost exclusively used stated preference data because of the convenient data collection methods and because of the difficulty of observing revealed preferences. More recently, passenger loads deduced from smart card transactions have become available, which has opened new possibilities to model transit systems, predict demand and to some extent estimate crowding. Public transit agencies have started to show interest in travel demand management (TDM), originally used to control automobile traffic. The possibility to optimize vehicle capacity by using automated data collection measures and using data to reduce crowding was suggested already in 1984 by Buneman. In this review we find that half of the observational studies use data that originates from passenger data, the other half use survey data. A few observational studies combine survey data with route choice observations or with passenger count at selected stations (Table 5). Four out of 11 modelling studies, to some degree use real passenger data, the remaining studies use survey data or no data and instead display numerical examples for optimizations (Table 6). This suggests that although the availability of smart card data has increased, it is not yet widespread that studies on crowding policies use quantified levels of crowding from real passenger data, such as smart card transactions or automatic passenger count data.

7. Review of policy effects on crowding/occupancy and welfare effects

7.1 Observational studies

Half of the observational studies have policies that have been applied in the real world, usually reporting on crowding levels before and after the policy implementation. None of the observational studies present quantified levels of crowding from passenger data. Price differentiation is as mentioned the most common policy among observational studies. The most effective price differentiating strategy is to increase price in the peak and decrease price in the off-peak period. Most studies with a price differentiation policy compute quantified effects on occupancy. See Table 5 for effects on crowding for observational studies.

Price differentiation reduces occupancy

Based on the literature review by Liu and Charles (2013), it seems to be possible to shift demand through peak pricing if peak/off-peak fare differentials are significant. Free or discounted off-peak pricing is more appreciated by passengers. However, increased peak fares are more effective in shifting the time people travel. In the morning passengers are more willing to change their travel time to before the peak rather than after. Passengers traveling long distances are more sensitive to peak pricing strategies. Currie (2010) finds that peak demand is reduced by 1.2 to 1.5 percent when a zero-fare before morning peak is implemented in Melbourne, Australia. Results are computed using a combination of survey results and weekly ticket validations. Halvorsen, Koutsopoulos, Lau, Au & Zhao (2016) observe that 3 percent of morning peak travellers shift to pre-peak hour (07:15-08:15) due to a 25 percent lower fare at pre-peak hour in Hong Kong[2]. Douglas, Henn & Sloan (2011) implement a policy

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[2] Users of adult fare cards are eligible for the fare discount, which is valid at 29 stations in Hong Kong (44 percent of all trips).

of 30 percent peak fare increase and a 30 percent off-peak fare decrease. This results in 10 percent reduced peak train loads in Sydney, Australia, based on barrier exit data. Sarkar & Jain (2016) model passenger demand in New Delhi, India and implement a 20 percent peak fare increase and a 20 percent off-peak fare decrease. Peak occupancy is reduced by 9 percent and off-peak occupancy is increased by 14 percent in the demand model. Whelan & Johnson (2004) implement peak fare pricing up to a 30 percent increase in peak and a 30 percent decrease in off-peak on passenger count data from England. They observe reduced levels of peak loading, ranging from 3 to 11 percentage points. Reducing seat provision by 30 percent increases peak loading by 36 percentage point in the hierarchical demand model. Horn af Rantzien & Rude (2014) estimate peak fare elasticity and off-peak fare elasticity. They find that peak period elasticities are between [-0.20, -0.14] and off-peak period elasticities are between [-0.31, -0.16], depending on the regression model, adjusted or final. They also test price differentiation, increasing price in peak and decreasing price in off-peak, which lowers demand in peak, increases demand in off-peak, overall demand is slightly lower than at the base. This policy is profit maximizing, welfare effects from redistributing passenger from peak to off-peak are not presented. There are five studies among the reviewed papers that present price elasticities. Apart from Horn af Rantzien & Rude, there is only one other study that estimates own price elasticities, Batarce et al. (2016) estimate bus passenger density elasticity of demand and find values ranging between [-0.69, -0.12], depending on the passenger density (standing/m^2).

Regularity-driven services

Three observational studies implicitly affect occupancy levels by improving regularity in bus traffic, using holding strategies, where the buses hold at certain stops, or by regularity-driven services; buses keep a certain distance to each other instead of following a timetable. These policies are successful in reducing the share of bunched buses and significantly improve regularity of public bus transportation networks (Cats 2014; Cats, Larijani, Koutsopoulos and Burghout 2011; Berrebi, Watkins & Laval 2015). Two of the studies use operation simulation models and apply the study on real-world cases that turned out successfully in terms of traffic flow and improved reliability (Cats 2014; Cats, Larijani, Koutsopoulos and Burghout 2011). These studies do not present quantified levels of occupancy as result of the strategies, nor do they present welfare effects. One study on real-time information makes passengers switch metro carriages, from crowded ones to less occupied ones. The level of occupancy decreases by 4.3 percentage points in the most crowded metro car in Stockholm, Sweden (Zhang et al. 2016).

Passenger control

One study presents a method of capacity-oriented controls of passengers at subway stations in Beijing, such as closing subway gates, only leaving one or a few gates open, controlling and reducing passengers' access to staircases, escalators or platforms. A simulation-based algorithm based on queuing network theory and route choice behaviour is developed. The algorithm solves passenger flow with a case study from Beijing, using OD matrixes that are randomly generated from AFC data. They find a threshold of 120 passenger at the specific subway station; if the inbound number of passengers is controlled and kept below 120, passenger flow is maintained because the inflow is held lower than outflow of passengers. The bottleneck problem is therefore avoided, and crowding is alleviated (Xu, Liu & Jiang 2016).

Table 5. Observational studies – policy effects on crowding/occupancy

Policy category	Author(s), (year)	Policy	Effect on crowding/occupancy
Price differentiation	Liu & Charles (2013)	Price differentiation	Demand can be shifted if fare differentials are significant.
	Currie (2010)	Zero-fare before morning peak	Peak demand is reduced 1.2% to 1.5%, total demand increases.
	Halvorsen et al. (2016)	Lower off-peak fare	Peak demand is shifted, 3% of morning peak travellers shift to pre-peak hour.
	Douglas et al. (2011)	Increase peak fare 30% and decrease off-peak fare 30%.	Peak train load is reduced 10%.
	Sarkar & Jain (2016)	Increase peak fare 20% and decrease off-peak fare 20%.	Peak occupancy is reduced 9% and off-peak occupancy is increased 14%.
	Whelan & Johnson (2004)	Increase peak fare 30%. Decrease off-peak fare 30%. Increase peak fare 30% and decrease off-peak fare 30%. Reduce seat provision 30%.	Peak loading is reduced 11% points. Peak loading is reduced 3% points. Peak loading is reduced 9% points. Peak loading increases 36% points.
	Horn af Rantzien & Rude (2014)	Increase monthly pass 1%	Reduces peak demand by 0.14 and off-peak demand by 0.16.
RTI	Zhang et al. (2016)	Real-time information on metro platforms	Occupancy in crowded subway cars is reduced 4.3% points. Occupancy in less crowded subway cars increases 4.1% points.
Regularity-driven operations	Cats (2014)	Regularity driven bus operations	Headway variability is reduced, implied that crowding would reduce.
	Cats et al. (2011)	Bus holding strategy (regularity driven vs schedule-based)	Improved service reliability, passenger time travel savings and reduced operating costs.
	Berrebi et al. (2015)	Holding control strategy	Reduces the share of bunched buses and shortens waiting time for passengers. Unknown effect on passenger loads.
Operational	Batarce et al. (2016)	Increase bus capacity Increase frequency	Passenger-density is reduced 1.2% points. Passenger-density is reduced 1.1% points.
Line automatization	Haywood & Koning (2015)	Automatization of metro line	Passenger density is reduced 20%.
Infrastructure	Kroes et al. (2014)	Extension of mass transit railway line	Number of passengers is reduced by 10.6%.
Passenger control	Xu et al. (2016)	Passenger control	The bottleneck problem is avoided at the subway station, passenger flow is improved, and crowding is alleviated.

Line expansion, frequency and capacity increase

There are three observational studies that present welfare effects based on time multipliers and willingness to pay or CBA's (no optimization). Line automatization of metro one in Paris increases frequency by 20 percent during peak, which increases the average speed during rush hour by 15 percent. Assuming constant demand during peak, this policy reduces in-vehicle time and thus decreases average passenger density by 20 percent according to survey data. Welfare benefits from reducing passenger density by 20 percent in peak hours would amount to €12.4 M per year (Haywood & Koning 2015). An expansion of a commuter train line in Paris, would according to Kroes et al. (2014) relieve the number of passengers on two main existing commuter train lines by 10.6 percent, equivalent of 1,239 h reduced perceived travel time. This has been transformed into a monetary benefit equivalent of €23 M per year, or €480 M over a 30-year period (8 percent discount rate). The investment cost of the extended network is €3.1 to €3.5 billion. Batarce et al. (2014) finds that increasing bus capacity reduces mean passenger density by 1.2 percentage points compared to the baseline in Santiago, Chile, overall demand increases by 8 percent. Increasing bus frequency reduces mean passenger density by 1.1 percentage points compared to the baseline and reduces waiting time. Marginal user benefits are negative for both policies, total net benefits are however positive, 0.61 for increasing capacity and 1.43 for increasing frequency.

7.2 Modelling studies

Just as the observational studies, none of the reviewed modelling studies present quantified levels of crowding. Many studies however present occupancy levels that originate from passenger data, sometimes peak occupancy levels. Whether peak occupancy implies crowding or not, is not confirmed by the reviewed studies. Nearly all modelling studies present elasticities of demand from previous empirical studies. Only one study computes elasticities; demand elasticities of frequency and demand elasticities of vehicle size from numerical examples (Hörcher & Graham 2018). See Table 6 for an overview of effects on crowding and welfare effects for modelling studies.

Increasing fare and frequency in optimum reduces occupancy

Börjesson et al. (2017) model optimal pricing, bus frequency, bus size and the number of bus lanes for a corridor that depends on the presence of congestion pricing for cars. They find that in optimum, peak frequency increases, off-peak frequency decreases, peak bus fare increases, off-peak car toll increases, and larger buses should be used, compared to the baseline. For all mentioned policy instruments peak occupancy decreases, except for increased car toll pricing, which increases peak occupancy. Authors assume that passengers are evenly distributed across buses during peak and off-peak periods, on-board crowding is therefore underestimated in the model. Peak occupancy levels decreases the most from using large buses. The largest welfare benefits come from decreasing frequency in off-peak periods and from using larger buses.

Tirachini et al. (2014) optimize bus frequency, seat provision, fare subsidy, bus size and road toll, from transport demand data from a corridor in north Sydney, Australia. In optimum, they find that bus frequency should increase, seat provision should increase, and subsidies decrease (fare increase) and maximize the number of doors. The density of standing passengers is reduced in optimum. Results from maximizing social welfare in the travel demand models show that, with the given OD matrix, and given that crowding causes passenger disutility, optimal solutions are the following; a large bus (12 meters), more frequent buses (25-26.1 vehicles/hour), a large increase in the bus fare, the maximum number of seats given the bus size (39 for 12 m buses). Additionally, the optimal number of doors given the bus size should be maximized (3 doors for 12 m buses) because this reduces boarding and alighting times and subsequentially crowding. Boarding from all doors is more efficient than only boarding from the front door.

Increasing fare and using time differentiated fares reduces occupancy

de Palma et al. (2017) evaluate three fare regimes and show that when applying a uniform fare, the equilibrium user cost of trips is higher than in the zero-fare regime. The user cost in social optimum is slightly lower than in the uniform fare. The occupancy level is reduced by 12.3 percent with the uniform fare regime, compared to the zero-fare regime. In social optimum the occupancy levels are reduced nearly as much as the uniform fare regime (11.5 percent). Welfare gains are highest in social optimum when applying time differentiated fares. Haywood et al. (2018) find that a fare increase is optimal to minimize welfare losses when considering the economic cost of congestion in the Paris metro. Optimal fare increases by 43 percent, and occupancy measured in terms of peak patronage decreases by 9 percent.

Table 6. Modelling studies – policy effects on crowding/occupancy and welfare effects

Author(s), (year)	Policy	Effect(s)
Asplund & Pyddoke (2020)	Decrease fare and frequency in optimum	Peak occupancy increases. Positive welfare effects.
Börjesson et al. (2017)	Increase peak frequency, decrease off-peak frequency, increase peak bus fare, increase off-peak car toll, use larger buses.	Peak occupancy is reduced for all policies except increased car toll. All policies generate welfare.
de Palma et al. (2015)	Optimize fare, share of seats and schedule	Optimal solution to minimize costs from crowding is to charge higher peak fares and adjust capacity.
de Palma et al. (2017)	Zero-fare Uniform fare Peak fare (social optimum)	Baseline Total occupancy is reduced 12.3% Total occupancy is reduced 11.5% Welfare gains are highest in social optimum when applying time differentiated fares.
Haywood et al. (2018)	Increase peak fare by 43%	Peak occupancy is reduced 9%. Welfare losses are minimized.
Hörcher & Graham (2018)	Optimize frequency, capacity and occupancy rate (test with different market sizes; demand imbalances)	Crowding may be an optimal outcome of optimal second-best capacity when demand fluctuates. Peak and off-peak subsidies should be equal in optimum.
Hörcher et al. (2018 a)	1) Single-ticket fare, 2) Mixed regime; single-ticket and season ticket fares.	The regime single-ticket fare reduces crowding and is welfare maximizing. The mixed regime is profit maximizing and causes higher occupancy than the single-ticket regime. Offering season passes increases occupancy levels.
Hörcher et al. (2018 b)	Optimize seat capacity	Could lower excessive demand.
Ljungberg (2007)	Staggered school start	Staggered school start could lower demand.
Parry & Small (2009)	Increase fare subsidy in optimum	Occupancy increases, social welfare increases.
Tirachini et al. (2014)	Increase bus frequency, increase seat provision, lower subsidy and maximize no. of bus doors in optimum.	Occupancy measured as density of standing passengers is reduced.

Decreasing fare and frequency increases occupancy in optimum

Parry & Small (2009) optimize fare subsidies in London, Washington and Los Angeles. To maximize social welfare, optimal fare subsidies should increase, that is, fares should be lowered, which increases occupancy levels. The other way around, increasing fares would decrease occupancy. Asplund & Pyddoke (2020) also find that fares should be lowered in optimum, causing occupancy to increase in a mid-size town in Sweden. They evaluate four regimes: (1) fare, (2) frequency, (3) fare and frequency, (4) fare, frequency, while keeping generalized cost constant. In optimum, fare and frequency should be reduced, causing peak occupancy to increase compared to the baseline. Positive welfare effects are generated in all four regimes in optimum. Welfare effects are highest in regime (3), where both fare and frequency is reduced. Peak occupancy increases the least in regime (1), lower fare. Hörcher & Graham (2018) investigate how public transport supply is affected by demand imbalances. They optimize frequency, capacity and the rate of occupancy using a demand model on a numerical example. Peak and off-peak subsidies should be equal in optimum. They also find that crowding may be an optimal outcome of optimal second-best capacity when demand fluctuates, which means that crowding is not necessarily a sign of incorrect supply level.

Ticket-type provision

Hörcher, Graham & Anderson (2018 a) evaluate three different provisions of ticket-options; (1) single-ticket fare, (2) single-ticket and season tickets, (3) single-tickets, season tickets and endogenous capacity. They optimize the ticket-option provision with frequency and find that the only regime that reduces occupancy and that is welfare maximizing is the single-ticket fare. Additionally, provision of both single-tickets and season tickets, the mixed regime, is profit maximizing. Offering season tickets increases occupancy levels. Season tickets do improve social welfare if single-ticket prices are not so low that market share of season tickets drops to zero.

Seat provision

Hörcher, Graham & Anderson (2018 b) optimize seat provision based on the marginal cost of travelling, which includes the cost of crowding, in terms of lost travel time. The model finds optimal seat capacity and how large the occupancy externality should be such that welfare is maximized. The results suggest that optimal seat capacity should drop to zero and all passengers should stand when demand increases, contrary to Tirachini et al. (2014) who found that seat provision should increase in optimum. de Palma et al. (2015) optimize fare, seat provision and train arrival time using a stochastic choice model. Authors find that trains with high crowding should charge higher prices, or trains with the best arrival times should charge higher prices. Alternatively, the operator can adjust the number of seats to manipulate passengers' choices. Increasing the number of seats generates benefit in terms of comfort but reduces standing capacity. Reducing the number of seats increases standing capacity but reduces comfort. This is the only study among the modelling studies that does not present any welfare effects.

Staggered school-start might reduce occupancy

Ljungberg (2007) investigates factors such as bus routes, bus size, fare, school start in a mid-size town in Sweden and conduct CBA's to evaluate the various policies, one at a time. Welfare optimization is done for bus fare and bus size. Ljungberg (2007) finds that a half an hour staggered school-start could reduce bus transport costs and reduce demand; welfare effects are not presented for this policy. Straighter bus line reduces average travel time, increasing frequency reduces waiting time and using smaller buses increases the net social welfare but increases the need for subsidization. The author suggest that the demand variation in peak and off-peak periods can be solved by price differentiation. Zero-fare in off-peak could be welfare improving, the effects on occupancy are however not presented.

8. Conclusion

The aim of this literature review is to identify available policies for crowding on-board public transport vehicles, and to review how well the policies manage crowding from a social welfare perspective. We review 26 studies and subdivide them according to study type: modelling studies and observational studies. In the category observational studies, the most frequent policy is price differentiation. The most frequent policies analysed with modelling studies are fare, frequency and capacity. Among all papers reviewed, we find that most studies use survey data, and fewer use real ridership data. A couple studies use numerical example data. Few studies present a definition of crowding and most acknowledge the negative externalities from crowding (passenger discomfort, disrupted service reliability, increased travel time). Many studies measure occupancy in terms of passenger demand, passenger density, passenger loads etc. Less than half of the reviewed studies present a crowding measure. As for the reader, it is unclear when occupancy becomes severe enough to be considered crowded. Worth noting, is that, there are engineering studies that present spatio-temporal levels of crowding, for the purpose of travel behaviour analysis and transit modelling (Chakirov & Erath 2011; Chu & Chapleau 2008; Luo et al. 2018; Sun & Jin 2018). These studies generally do not propose policies for crowding and are therefore not reviewed and included. Policy instrument towards crowding seem to be left for transport economists to evaluate, while sometimes lacking passenger data. This suggests there might be a problem with the availability of data. Since we

do not have insight of ongoing studies and as the use of smart card data and demand management has increased, such studies could potentially currently be ongoing.
Among the observational studies, we find that price differentiation could be an effective measure to reduce peak occupancy, since it shifts passengers from peak to off-peak. Observed levels of reduced occupancy range from 1.1 to 10 percent. Studies with regularity-driven policies are successful in terms of improved traffic flow and reliability, usually reducing headway variability. Quantified effects on crowding or occupancy are not presented. Real-time information is shown in one study to affect passengers' choice of metro cars, shifting passengers from occupied metro cars to less occupied ones. Welfare effects are typically not presented for observational studies. There are however three observational studies with welfare effects. The first implements line automatization in the Paris metro, the second presents a case of hypothetically extending a commuter train line in Paris and the third increases bus frequency and bus capacity in Santiago, Chile. The welfare effects are computed by using time multipliers and willingness to pay from survey values, which are then converted into perceived travel time and monetary benefits. Line automatization of the Paris metro generates the highest monetary benefits from reduced occupancy among these three studies.

Most modelling studies find it welfare improving for frequency, fare and capacity to increase, leading to lower peak occupancy. Other policies such as increasing peak frequency, reducing off-peak frequency, increasing peak fare, using larger buses, maximizing the number of doors on buses, reduces peak occupancy and provides welfare benefits. There are two studies that find opposing results; that in optimum, the fare and frequency should decrease, resulting in higher levels of occupancy for social welfare to be maximized. Varying results on optimal fare and frequency requires public transit authorities to use a flexible fare system allowing for differentiated charging of trips, if reduced occupancy and maximized social welfare are the main goals. The size of the public transport network and local differences also needs to be considered when choosing a fare system. One of the contradictory studies with increased fare and frequency was conducted, in Washington DC, Los Angeles and London, that is large cities, and the other in a mid-size town in Sweden, Uppsala. Providing single tickets is found to reduce occupancy levels and is welfare improving compared to offering season tickets. Season tickets are often heavily discounted for everyday commuters who also use the public transit system the most, often at peak times and heavily occupied links, yet they are still commonly provided by public transit authorities.

Results for optimal seat capacity are found to differ, Tirachini et al. (2014) find that seat provision should increase for reduced occupancy and maximal social welfare, while de Palma et al. (2015) find that the optimal seat capacity should drop to zero for more standing capacity when occupancy increases. The decision on seat capacity will depend on the value of seated conditions versus standing conditions when it is crowded. Two studies in total present elasticities of demand, one observational study and one modelling study. Price elasticities seem to be low compared to previous studies. The remaining modelling studies all present price elasticities originating from previous empirical studies.

8.1 Discussion

Optimal policy to use will depend on the levels of crowding, the severeness of the external effects of crowding. It will also depend on the current level of fare, frequency, capacity and if previous measures already have been taken. Before public transport vehicles have reached maximum capacity, it is possible to increase the vehicle capacity and it is possible to increase frequency. If operators already have provided maximum capacity per vehicle and maximum frequency that the network can sub stand and the crowding problem remains, other methods, such as price differentiation and real-time information are available. To be considered when choosing a crowding policy is also the mode of transportations in the transport system and other transport and environmental policies in effect. Public transport policies should be synchronized with road policies, in fact the entire transportation network should be considered for the intended effect.

The decision to include the valuation of crowding for investment decisions and public transport planning is crucial. If public transport authorities do not include the value of crowding, the negative effects of crowding will persist or increase and suboptimal solutions will be reached, considering urbanization and population growth. Including the correct seating valuation is important because if authorities use valuations that are too low, the operators will reduce the number of seats to create more standing capacity or provide larger vehicles with more capacity rather than increasing frequency. Distinguishing between seated and standing valuation in crowded conditions is also important. If passengers experience high disutility from standing, perhaps increasing capacity of standing space at the expense of seating capacity may not be ideal. If authorities want the crowding valuation to reflect the complete cost of crowding, closest to what passengers' experience, the valuation should have some reference both in an objective density measure, such as ridership data and from surveys of passengers' subjective perception of crowding, and evaluate both seating and standing discomfort of crowding.

The location where the public transportation agency operates also affects optimal policy. We have seen that in mid-size towns in Sweden it could be optimal to lower the fare and frequency, suggesting crowding may not have become severe enough yet. In Stockholm regularity-driven services has reduced bus bunching, and real-time information has affected metro passengers to change metro car to a less crowded ones. In large metropolitan cities such as London, Sydney and Melbourne the situation is more critical, where the news reports that passengers are denied boarding in peak hours. In large cities in Asia occupancy levels are extremely high, to the extent that, as mentioned in Beijing, engineers have found a solution to control passenger access to the station or turnstiles, to maintain a certain flow and avoid bottlenecks.

Appendix 1

Table 7. Complete overview of studies in alphabetical order

Author(s), (year)	Policy	Method	Data	Case	Location
Asplund & Pyddoke (2020)	Optimize fare and frequency	Demand model	APC (N = 15.7 M) & survey	Ex ante	Uppsala, Sweden
Batarce, Munoz & de Dios Ortuzar (2016)	Increase bus capacity and frequency	ML & CBA	Survey (N = 3380) & route choice observations	Ex ante	Santiago, Chile
Berrebi, Watkins & Laval (2015)	Regularity driven services	Dispatching policy	Numerical example	No	-
Börjesson, Fung & Proost (2017)	Optimize fare, frequency, bus size, no of bus lanes and car tolls	Demand model & CBA	RP travel data	Ex ante	Stockholm, Sweden
Cats (2014)	Regularity driven services	Transit operations simulation	APC & AVL	Ex post	Stockholm, Sweden
Cats, Larijani, Koutsopoulos & Burghout (2011)	Regularity driven services	Transit operations simulation	APC & AVL	Ex post	Stockholm, Sweden
Currie (2010)	Price differentiation	Financial calculus (NPV)	Survey (N=901) & weekly ticket validations	Ex post	Melbourne, Australia
de Palma, Kilani & Proost (2015)	Optimize fare, share of seats and schedule	Stochastic choice model	None	Ex ante	Paris, France
de Palma, Lindsey & Monchambert (2017)	Optimize fare and capacity	Microeconomic model	RP & SP (origin unknown)	Ex ante	Paris, France
Douglas, Henn & Sloan (2011)	Price differentiation	Logistic regression	Rail exit (N=786)	Ex ante	Sydney, Australia
Halvorsen, Koutsopoulos, Lau, Au & Zhao (2016)	Price differentiation	Descriptive analysis	AFC (N=400 k)	Ex post	Hong Kong
Haywood & Koning (2015)	Automatization & frequency increase	CBA	Survey (N=668)	Ex ante	Paris, France
Haywood, Koning & Prud'homme (2018)	Optimize crowding level subject to fare	Demand model	Metro survey	Ex ante	Paris, France
Hörcher & Graham (2018)	Optimize frequency, capacity and occupancy rate	Demand model	None	No	-
Hörcher, Graham & Anderson (2018 a)	Optimize fare regimes	Demand model	None	No	-
Hörcher, Graham & Anderson (2018 b)	Optimize seat capacity	Demand model	SCD (metro)	No	-
Horn af Rantzien & Rude (2014)	Price differentiation	Linear regression	APC (N=120 k)	Ex ante	Stockholm, Sweden
Kroes, Kouwenhoven, Debrincat & Pauget (2014)	Extension of mass transit railway line	Discrete choice analysis	Survey & metro station observations	Ex ante	Paris, France
Liu & Charles (2013)	Price differentiation	Literature review	-	-	Various locations
Ljungberg (2007)	Staggered school start, fare, bus size, route	Demand models and CBA	Passenger & survey	Ex ante	Linkoping, Sweden
Parry & Small (2009)	Optimize fare subsidy	Microeconomic model	Rail data, national statistics	Ex ante	Washington DC, Los Angeles and London

Sarkar & Jain (2016)	Price differentiation	Elasticity model	Passenger demand (N = 416 k; origin unknown)	Ex ante	New Delhi, India
Tirachini, Hensher & Rose (2014)	Optimize frequency, seat capacity, subsidy, no of doors (bus)	MNL & demand models	Survey (N = 1,932)	No	-
Whelan & Johnson (2004)	Price differentiation	Demand model (hierarchical)	APC	Yes	England
Xu, Liu & Jiang (2016)	Passenger control	Demand model (simulation)	AFC data (N=39,803)	Ex ante	Beijing, China
Zhang, Jenelius & Kottenhoff (2016)	Real-time information (on metro platforms)	Linear regression	Survey, train load & video	Ex post	Stockholm, Sweden

Appendix 2

Abbreviations:

AFC – Automatic Fare Collection

APC – Automatic Passenger Count

AVL – Automatic Vehicle Location

CBA – Cost Benefit Analysis

NPV – Net Present Value

OD-matrix – Origin destination model to understand traveller’s true origin and destination

RP – Revealed Preferences

RTI – Real Time Information

SP – Stated Preferences

VTTS – Value of travel time savings

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