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Ex-post assessment of public transportation on-board crowding induced by new urban developments

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ABSTRACT

On-board crowding in public transportation has significant impact on passengers' travel experience. New land-use planning configurations can have wide-ranging crowding effects in the public transportation system. Nevertheless, there is a lack of knowledge on the crowding implications caused by new urban developments. In this study, we propose a method for quantifying the network-wide crowding implications of a new urban development. We apply the method to different kinds of urban developments in terms of type, size, location, proximity to high-capacity public transportation connections as well as socioeconomic characteristics. Size and proximity to a high-capacity connection are highly influential factors in determining the value and the geographical extent of the crowding implications. The analysis proposed in this paper can serve as a tool for the ex-post quantification of the on-board crowding impacts using automated data sources. The insights gained can be utilized in more efficient dimensioning of the supply (service) for newly developed areas as well as for placement of future urban developments accounting for the resulting crowding effects.

1. Introduction

The share of the population living in urban areas exceeds 50% worldwide. By 2045 the global urban population will increase 1.5 times and reach 6 billion, meaning that 7 out of 10 people will live in cities. To accommodate the additional population, 1.2 million km^2 of new built-up urban areas will be added by 2030 (The World Bank, 2023). In the European Union (EU), population projections reveal increasing trends for 60% of all urban regions. In particular, Malta, Ireland and Sweden will experience increases in their urban populations of more than 20% by 2050 (Eurostat, 2021).

In light of these trends, one of the biggest challenges that need to be faced is the provision of adequate and efficient public transportation (PT) to, from, and within new urban areas. Competitive PT is more energy-efficient than private cars, and contributes to reducing greenhouse gas emissions and traffic congestion. However, on-board crowding is considered a key problem in large cities since it negatively affects passengers' travel experience by increasing their stress levels and reducing their overall welfare (Kim et al., 2015). Consequently, on-board crowding can increase passengers' value of time and, therefore, their generalized travel cost (Cats et al., 2015). On-board crowding can also increase travel time variability and passengers' waiting time (Tirachini et al., 2013), thereby affecting route selection (Karatsoli et al., 2024). This can impose additional pressure on the PT system, resulting in longer travel times and higher operational costs, especially during peak hours. Critically, the average operational PT cost can be 60%–100% higher during peak hours than during off-peak periods (Parry & Small, 2009). The abovementioned effects can decrease the attractiveness of PT, consequently restricting the modal split of PT in urban areas.

The urban form (the physical and non-physical characteristics) of a city (and of a new urban development) is strongly related to residents' mobility and, therefore, to the design of PT services (Lee & Bencekri, 2021). For example, dense urban areas are often associated with a higher PT use (Fang, 2015). Each PT mode (e.g., bus, metro, light rail, commuter rail) has an optimum range of operation which is based on the urban form (density) and the characteristics of the associated technology and infrastructure, as described in the next two paragraphs. Therefore, investing in PT infrastructure, especially an expensive one (e.g., metro), should carefully account for the present and future demand and be part of urban and regional strategic planning.

Highly populated new urban developments have a potential for high-capacity PT systems (up to 70,000 passengers/hour) with typically

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higher average speeds, such as the metro, given the high passenger volumes that need to be catered to (Vuchic, 2005). Investments in new metro systems should be accompanied by developments that offer high demand concentration within a walking distance of up to 800m to metro stations (Bivina et al., 2020). In addition, the placement of new metro stations in a newly developed area is of great importance in determining residents' and visitors' mode choices and, therefore, PT demand. The development of high-capacity new metro systems for connecting new suburbs with the city center has proved efficient in many cities worldwide, such as in China (Cho & Kim, 2017), Korea (Lee & Yoon, 2019), and in Canada (Sijpkes & Brown, 1997). In the European context, Stockholm (Cervero, 1995) and London (Levinson, 2008) are notable examples of developing metro systems connecting to new urban developments. The appropriateness of developing metro systems for connecting new urban developments with the rest of the city depends on various criteria such as travel demand, the spatial proximity of the new urban development to the existing city, and the affordability of developing or extending a metro system. The planning of the development of high-capacity PT in conjunction with developing new urban areas has been proven to be more cost-efficient rather than adding such systems following the construction of the new urban development (Lin et al., 2022).

Rail-bound modes with lower capacity characteristics, such as light rail (18,000–20,000 passengers/hour), are usually developed for new urban developments with less population and lower density than those for which metro is most suitable. In the case of light rail, the development in proximity to stations is even more critical than in the case of the metro as people are willing to walk longer to access (egress) for (from) faster PT services (Daniels & Mulley, 2013). The development of Bus Rapid transit (BRT) services has requirements that are on-par with those of light rail services. Its capacity characteristics can range from 5000 passengers/hour (single BRT lane) up to 43,000 passengers/hour (double BRT lane) (Transformative Urban Mobility Initiative (TUMI), 2021). In urban areas, the optimal spacing of BRT stops is at around 450m (Intitute of Transportation and Development Policy (ITDP), 2024). It is important to mention that BRT is more cost-effective while light rail has higher environmental performance (Tirachini et al., 2010), and allows for the provisioning of flexible capacity (Bruun, 2005). Last, developing new bus lines has been proven to be the most cost-effective solution making it the most prevalent mode across many cities around the world (The International Association of Public Transport (UITP), 2024). The requirements in terms of urban form are less evident compared to the other modes. However, good accessibility (such as walking distances within 400m) is required for a successful design. Buses provide lower capacity compared to all other modes (5000 passengers/hour, single bus).

Ex-post evaluation of transport investments can serve a crucial role in informing policy makers on the extent to which project objectives have been met. This fact can assist towards a more holistic evaluation process related to transportation investments, which can serve as a potential reconsideration motive of the abovementioned common planning norms. Nevertheless, ex-post evaluations of transport investments are scarce (Bos & de Swart, 2024; Dixit et al., 2024). There are several reasons for this. First, substantial resources are allocated for the ex-ante planning as well as improvements, thereby not prioritizing funding for ex-post evaluation. Moreover, monitoring the outcomes of a prediction model requires a significant amount of data (e.g., passenger demand data, land-use data, census data, etc.). In most cases, data collection protocols are not introduced at the beginning of the project, therefore making the effects' monitoring (including crowding) difficult to implement (International Transport Forum (ITF), 2017).

In the case of PT, automated data (e.g., Automated Fare Collection (AFC) systems, Automated Passenger Counts (APC)), Automated Vehicle Location (AVL), and General Transit Feed Specification (GTFS)) are cost-efficient sources of a continuous flow of information related to passenger demand and supply (service). Smart card data have also been widely used in exploring the evolution of the urban structure (Y. Zhang et al., 2021) and clustering urban areas based on their attractiveness as activity centers (Cats & Ferranti, 2022). Therefore, they are a unique asset in implementing ex-post evaluations for PT investments related to urban developments. However, commonly, the capacity of PT services connecting to new urban developments is dimensioned based on the expected passenger demand between the newly developed areas utilizing the existing PT system by using a macroscopic assignment model. This approach neglects the effect of the additional passenger demand on the remaining PT network, therefore missing potential additional crowding imposed to already crowded parts of the system (Pyddoke et al., 2017).

In this study, we propose a method, extending the approach proposed by Skoufas et al. (2024), for quantifying network-wide PT implications and capacity needs of newly urban developed areas entirely based on Revealed Preference (RP) data (smart card data). Results can be further investigated and segmented in time and space, further utilizing the capabilities of smart card data. The method is directly reproducible since it relies on individual mobility traces such as smart card data, therefore enhancing its added value. The study contributes to the understanding of induced demand (passengers traveling from/to a newly developed area), the supply component (e.g., is the supply provided adequate to cater to the new mobility needs of a newly developed area?) as well as their linkage to key bottlenecks of the PT network.

We apply the method to various urban developments that took place in Region Stockholm during 2016–2019 by utilizing large-scale panel data in the form of smart card transactions. We select urban developments with diverse characteristics in terms of type (e.g., residential/business/industrial/mixed), size, location (e.g., central/peripheral), proximity to a high-capacity PT connection as well as local socioeconomic characteristics. Our application can assist in the ex-post assessment of PT design associated with urban developments and in relevant policy-making regarding the placement of future urban developments accounting for the resulting crowding effects.

The remainder of this paper is organized as follows. Section 2 presents the proposed method, and Section 3 includes the application of the case study. The key findings of the study are included in Section 4. Section 5 discusses study implications. Last, Section 6 presents the conclusions of the study, and reflects on relevant future research directions.

2. Methodology

In the following, we present the methodological framework for assessing the crowding contributions induced by a new urban development. Our proposed method, illustrated in Fig. 1 has in its core the urban development and accounts for the changes in the PT supply and demand during the corresponding time period. In the following paragraphs, we present in more detail the methodological steps followed in this study.

2.1. Selection of the urban development

The selection of a new urban development is fundamental in our methodology. We account for the local socioeconomic characteristics (e.g., population, number of households, income level), the local PT characteristics (e.g., number of stops, proximity to high-capacity PT connection), size, type (e.g., residential/industrial/business/mixed) as well as the location (e.g., urban/suburban) during the selection process. Last, by filtering the PT stops within the newly developed area we are able to define the set of stops S serving as origins/destinations within the newly developed area (see Fig. 1, Step 1).

2.2. Data processing

Our proposed method utilizes passengers' full travel diaries. In the case of only tap-in PT fare validation systems, tap-out locations, including transfer stations and final destinations, need to be inferred.

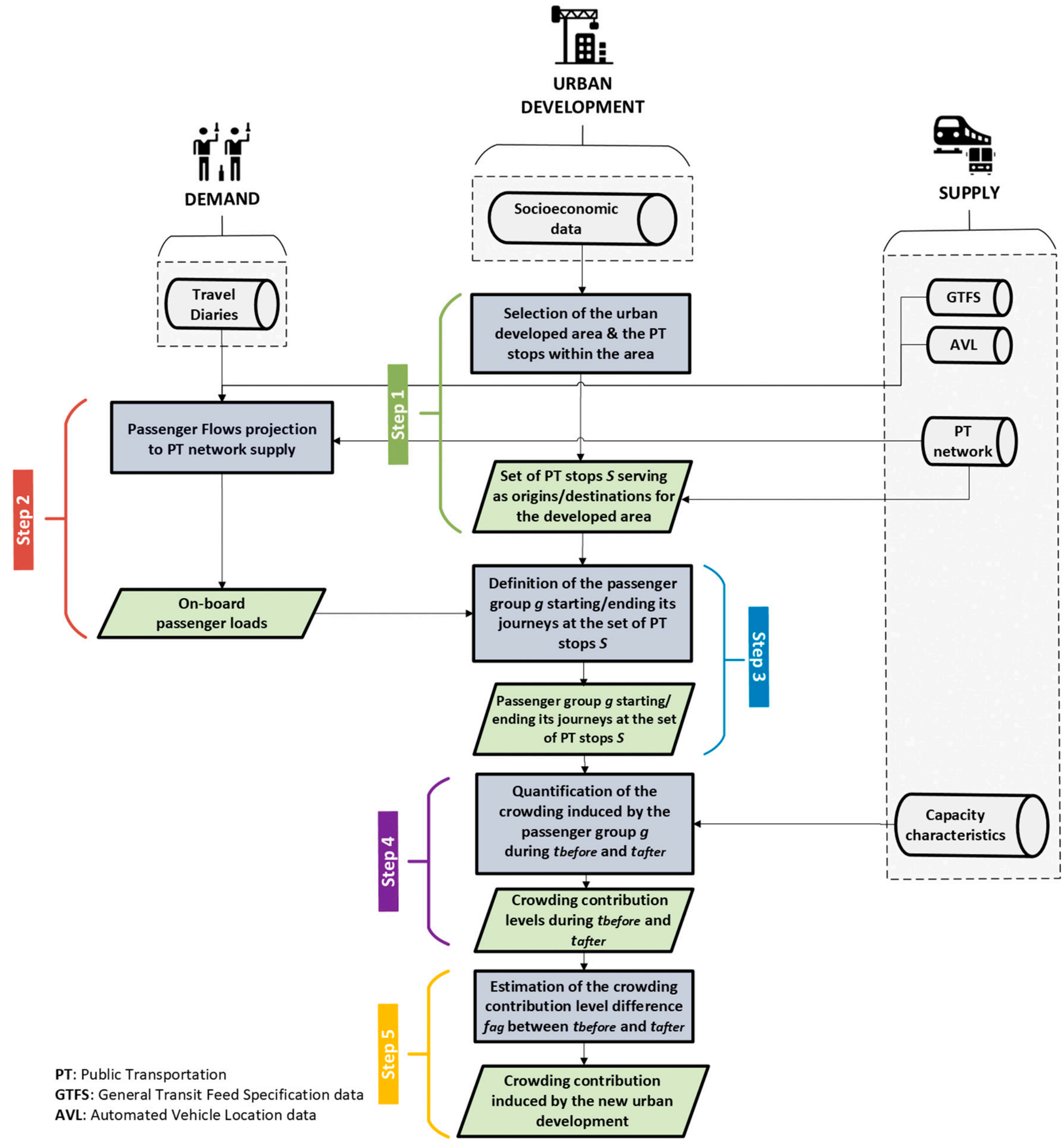

Fig. 1. Methodological framework (elliptic tubes: datasets, rectangles: modules, parallelogram: intermediate databases).

Several methods for inferring tap-out locations have been developed in the relevant literature, accounting for PT systems worldwide (Kholodov et al., 2021; Munizaga & Palma, 2012; Trépanier et al., 2007).

2.2.1. *Passenger flows projection to public transportation network supply*

By utilizing passengers' full travel diaries, the used PT mode, line and vehicle number, departure and arrival times as well as the travel time are known for each passenger journey i by fusing AVL and AFC data. Trips are assigned to the first departure found in AVL after the original tap-in, only for the PT modes where passengers need to tap-in at a platform or a gate. In the case of missing or incomplete vehicle departures in the AVL data, GTFS data can be used since they contain the complete set of departures for all lines in the PT network (see Fig. 1, Step 2).

2.2.2. *Estimation of passenger loads*

When all passenger trips are inferred in the PT network, we estimate passenger loads for each segment of the network traversed by each vehicle departure (run) in the system, by superimposing all individual time-dependent passenger path trajectories, including the passenger loads traveling from/to a new urban development. Furthermore, travel times for each segment are also available. Last, the available seats (seating capacity) across the network segments traversed by each vehicle departure is known as each vehicle departure is associated with the vehicle's characteristics provided by the manufacturer (see Fig. 1, Step 2).

2.2.3. *Definition of passenger group traveling from/to the new urban development*

Passenger loads across all network segments are estimated once each passenger is assigned to a specific vehicle departure. Information for each transaction, including time, location, and subscription type, is included in the smart card data. This feature enables smart card records to be segmented based on various criteria, including temporal, spatial, subscription, or a combination of these (Cats, 2023). For new urban development, we use spatial criteria for defining the passenger group g.

Specifically, we account in the passenger group g only the passengers beginning or ending their journeys in the set of stops S (see Fig. 1, Step 3).

2.3. Measuring crowding contributions induced by a new urban development

Our workflow aims to quantify the crowding contributions induced by a new urban development. Socioeconomic data corresponding to spatial units (e.g., socioeconomic zones) can be used for describing the changes that took place in a given urban development area. We investigate two time periods; one before the beginning of the urban development t_{before} and one at an intermediate stage or the end of the development t_{after} (see Fig. 1, Step 4). The comparison of the two allows for a network-wide comparison and investigation of potential crowding induced by the new urban development (see Fig. 1, Step 5). The proposed metric is based on the load factor of passenger group g, having as origin or destination the set of stops S belonging to the newly developed area. The metric is estimated at the segment level (stop-to-stop). The load factor on segment a and departure i of the passenger group g is the ratio between the load of the group l_{aig}^{before}, l_{aig}^{after} and the seating capacity of the corresponding PT vehicle κ_a^{before}, κ_a^{after}, respectively. The load factor can be expressed as a percentage, where values below 100 % mean that some seats are available and values above 100 % mean that some passengers must stand.

We use Eq. (1) to calculate the crowding contribution f_{ag} induced by passenger group g on segment a as the difference of the average load factors of the passenger group g before and after,

$$f_{ag} = \frac{1}{n_a^{\text{after}}}\sum_{i=1}^{n_a^{\text{after}}}\frac{l_{aig}^{\text{after}}}{\kappa_a^{\text{after}}} - \frac{1}{n_a^{\text{before}}}\sum_{i=1}^{n_a^{\text{before}}}\frac{l_{aig}^{\text{before}}}{\kappa_a^{\text{before}}} \tag{1}$$

where n_a^{before}, n_a^{after} are the number of vehicle departures on segment a across all days in the periods before and after the development.

3. Urban developments and public transportation investments in Region Stockholm

3.1. Overview of the public transportation system and urban development agenda

Region Stockholm has the most extensive multimodal PT network in Sweden, catering to the needs of ca. 2.3 million inhabitants. The network consists of 5549 stations and 700 PT lines, including metro, bus, commuter rail, light rail, and ferries. The ticket system is characterized as tap-in-only, meaning that passengers' tap-out locations need to be inferred. The tap-in location of a passenger trip j is recorded in the AFC data. The inference of the tap-out location is applied by searching for a stop within a defined radius of the tap-in location of the next trip $j+1$. Trip $j+1$ should be made within a specific time window so intermediate activities to be excluded, and it should be facilitated by a matching PT line (Cats et al., 2019).

Prior to the pandemic crisis, ca. 2 million PT journeys were taking place across the Region on a daily basis. Passenger demand has by 2023 partially recovered, reaching ca. 80% of the pre-pandemic levels across all modes. In our study, we analyze demand data from passenger journeys made in autumn (September–November) during 2016 and 2019 to ensure that pandemic-related effects are excluded from our analysis. In total, 60 working days in 2016 and 60 working days in 2019 are selected for the analysis. The selection of several weeks covered by smart card data is considered sufficient to capture changes in passengers' behavioral patterns (Goulet-Langlois et al., 2016). By comparing 3-month data from 2016 and 2019, we are able to examine differences in crowding contributions induced by a new urban development that took place during the corresponding time period.

The population of the City of Stockholm is expected to continue to grow, with an expected population of 1.3 million by 2040, meaning an increase of 15,000 residents per year. This change brings about several challenges in housing developments - 140,000 houses need to be built by 2030 - and in adapting the PT system to keep pace with the demographic and urban developments (Municipality of Stockholm (Stockholms stad), 2018).

The Stockholm Agreement, the result of negotiations among several parties such as the Swedish government, the City of Stockholm, the County Council, and other municipalities of the county, concerns new road and rail infrastructure investments in the Region between 2007 and 2021. The total cost exceeded SEK 100 billion, and it includes several investments for meeting the growing mobility needs in the Region, increasing the number of opportunities across the Region and enabling the urban development of less central areas (City of Stockholm - the City of Stockholm Traffic & Administration, 2012).

Special focus is given to the expansion of the existing rail-based networks for increasing capacity as well as reliability. One characteristic example is the construction of the Stockholm Rail Link (Citybanan) on 2017, a 6km double rail-truck tunnel connecting the northern with the southern parts of Stockholm (see Fig. 2). Last, the agenda of the Stockholm Agreement also includes a plethora of projects in the Region focusing on the expansion of the existing light rail network as well as focusing on the promotion of active transportation modes (i.e., walking, cycling). This aligns with the fact that cities, including Stockholm, are at the forefront of emissions reduction by changing their transportation systems (Gössling et al., 2024).

3.2. Selected urban developments

We select development areas with diverse characteristics (e.g., size, residential/business, central/peripheral, income) in order to examine how the crowding impacts and capacity needs vary for a range of developments. We choose the urban developments of (1) Arenastaden, (2) Barkarbystaden, (3) Campus Albano, (4) Nyboda östra, and (5) Ropsten, given their differences in relation to the aforementioned characteristics. Fig. 2 shows the location of the selected urban developments in relation to the existing PT network (left sub-figure) as well as the set of PT stops S serving as origins or destinations for each urban development (right sub-figures).

For generability and reproducibility purposes, we assign the selected urban developments to more general urban development categories (C) of the urban taxonomy as presented by (Camagni et al., 2002; Rodrigue, 2020):

- **Infilling (C1)**: The development occurs by infilling free spaces within the urban area. Within this category, Brownfield redevelopments highlight the urban expansion opportunities for sites that have lost their economic significance (e.g., old industrial sites, abandoned terminals).
- **Extension (C2)**: It occurs in the immediately adjacent urban edge.
- **Linear development (C3)**: It characterizes developments that follow the main axes of metropolitan transportation infrastructure (e.g., highways, rail infrastructure).
- **Sprawl (C4)**: It characterizes developments that occur at scattered lots without following the existing urban pattern.
- **Large-scale project (C5)**: Characterizes the development of areas with considerable size, independent of the existing built-up area. It concerns constructing a large infrastructure project (e.g., port, airport, industrial zone) and can serve as an incentive for more surrounding developments.

The following paragraphs describe the selected urban developments in more detail in terms of urban form as well as PT characteristics.

(1) Arenastaden: Arenastaden is an infilling development (C1) as it is located within Stockholm's urban area. The urban development plan started in 2009 and was finished in 2020. It is a mix of residential and business areas, including 1500 new apartments, hotels, offices, and

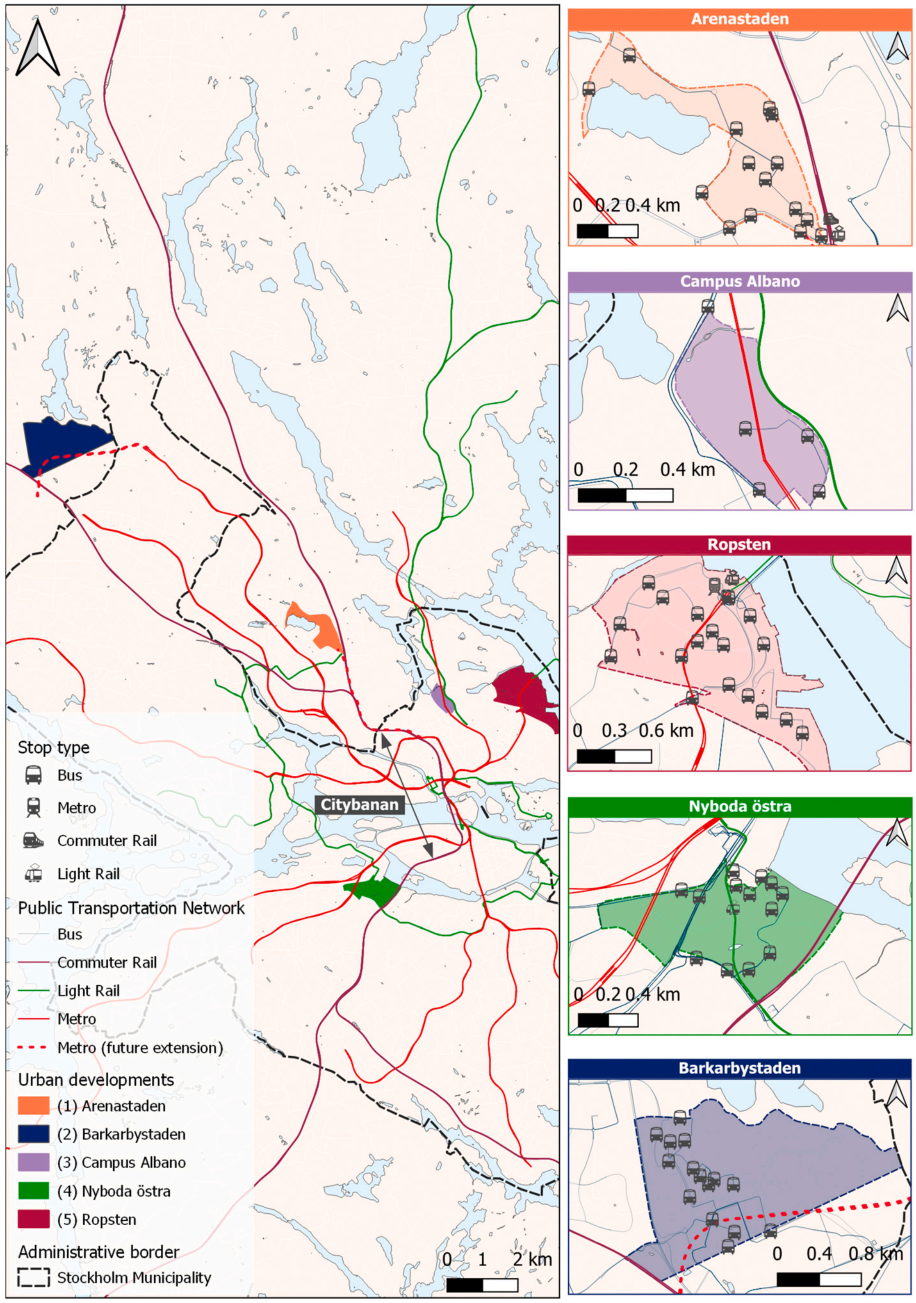

Fig. 2. Selected urban developments in Region Stockholm.

infrastructure. The population density in 2019 is estimated to be 3919 inhabitants/km^2. The area includes a large mall with a retail area of ca. 101,000 sqm and an Arena with a capacity of 50,000–65,000 visitors, as well as office buildings with a total of ca. 30,000 workplaces. There are 15 bus stops located within the area, one commuter rail, and one light rail station (Solna station). Last, the Public Transportation Authority (PTA) is currently planning to expand Stockholm's metro green line to Arenastaden, providing an additional connection to Stockholm's city center (see Fig. 2).

(2) Barkarbystaden: Barkarbystaden is a large-scale extension and linear development (C2/C3) of the adjacent urban area, developed in proximity to the commuter rail and highway network (E18 highway) to enhance its accessibility. By 2035, 14,000 new houses will be built, catering to the housing needs of the ca. 30,000 residents in the area. In terms of population density, Barkarbystaden had 2103 inhabitants/km^2, in 2019. The area hosts a big commercial venue (Barkarby handelsplats) with more than 80 stores, including major commercial actors such as IKEA, with ca. 6000 workplaces in total. The area is connected with Stockholm by combining bus and commuter rail (through Barkarby commuter rail station) or bus and metro (through Akalla metro terminal station). There are 15 bus stops located with the area.

(3) Campus Albano: Campus Albano is a new scientific hub located between KTH Royal Institute of Technology and Stockholm University. It represents an infilling and extension development (C1/C2) in central Stockholm, as the land was not initially used. The area includes 70,000 sqm of new university premises, 1000 newly built student apartments, shops, and restaurants. The construction started in 2016, and the complete plan was inaugurated in 2023. (Municipality of Stockholm (Stockholms stad), 2024). The area is characterized by higher population density, compared to the other case studies. Specifically, the population density is estimated as 9614 inhabitants/km^2 in 2019. The area is connected to the city center by bus. In proximity, there is the multi-

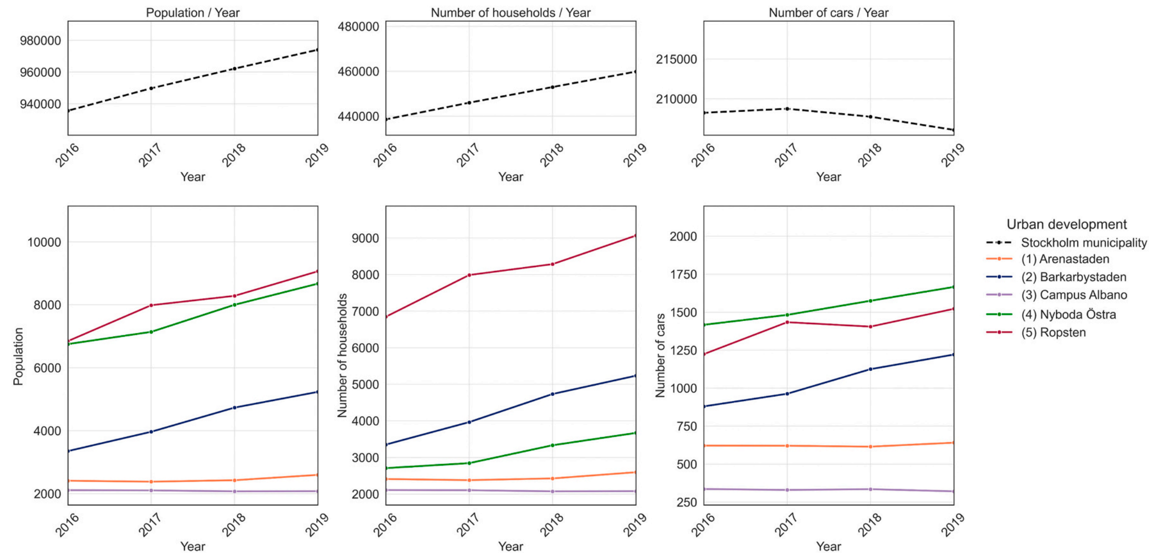

Fig. 3. Evolution of the socioeconomic indicators for each of the selected urban developments.

Table 1
Evolution of socio-economic indicators for each of the selected urban developments.

Urban development	Median income (kSEK)		% of residents with a high standard of living	
	2016	2019	2016	2019
Stockholm municipality	368.4	383.8	14	13
Arenastaden	421.2	447.7	19	17
Barkarbystaden	367.9	369.5	7	3
Campus Albano	354.3	378.5	15	16
Nyboda östra	403.2	415.8	23	19
Ropsten	422.9	455.8	18	12.5

modal PT hub at KTH (Tekniska högskolan), which includes a bus, light rail (towards the north-eastern suburbs), and metro. The area includes five bus stops. The proximity to several university premises, as well as the construction of new ones, makes it an interesting area to explore further as it attracts a significant number of journeys.

(4) Nyboda östra: Nyboda östra is an infilling development (C1) and a good example of a Brownfield redevelopment of a former industrial area into a residential one. The construction started in 2014 and was completed by 2024. By the end of the development, 4000 new apartments will be built, and ca. 10,000 new residents will be residing in the area (Lindgren & Ouertani, 2020). Nyboda östra had the highest population density across all case study areas in 2019 (11,338 inhabitants/km^2). There are 13 bus stops and one light rail stop within the area's boundaries. Additionally, there are two major multi-modal PT hubs in proximity to the urban development: Liljeholmen station, including bus, metro, and light rail, as well as Årstaberg station, including bus, light rail, and commuter rail. The area is connected with the city center of Stockholm with metro and commuter rail by transferring to the aforementioned PT hubs using local bus feeder lines.

(5) Ropsten: Ropsten is a part of the extensive urban development project of Stockholm's Royal Seaport area (Norra Djurgårdsstaden), and it is an extension of Stockholm's urban space as well (C2/C5). The construction started in 2011, and by the end of the development phase (2030), a mix of 12,000 homes will have been constructed alongside businesses and amenities (35,000 new workplaces) and an international port (Municipality of Stockholm (Stockholms stad), 2022). In terms of population density, Ropsten had 5434 inhabitants/km^2 in 2019, characterized as moderate in comparison with the rest of the selected areas. The case study area is connected with Stockholm's city center by metro and buses, and with the Lidingö island to its east by light rail and buses. Overall, it contains twenty bus stops and one multi-modal station (Ropsten station), including metro, light rail, and buses. Next to the Ropsten multi-modal station, there are parking areas for cars, bicycles, and micromobility vehicles, facilitating multi-modal transportation and the 'park and ride' concept in the area.

We obtain the socioeconomic characteristics of the selected urban developments by using open data at the zonal level provided by the Swedish National Statistics Authority (Statistiska Centralbyrån (SCB) (n. d.). Fig. 3 presents the evolution of key socioeconomic attributes (population, number of households, and number of cars) over the analysis period.

The urban developments of (2) Barkarbystaden, (4) Nyboda östra, and (5) Ropsten see a significant increase in their population as well as in the number of households. Specifically, the population increased by 56%, 28%, and 32% for the (2), (4), and (5), respectively, compared to the 4% increase across the entire Stockholm municipality. The developments of (1) Arenastaden and (3) Campus Albano do not see the same increasing pace in any of these variables during the analysis period, given their different development style. Interestingly, the number of cars increases in the residential urban development areas whereas it decreases at the Stockholm municipality level. This last evidence can reflect the results of the Stockholm Agreement related to the promotion of alternative transportation modes instead of private cars.

Socioeconomic indicators are important for characterizing the selected urban developments. We choose the indicators of median income and the share of residents with a high standard of living. The latter refers to the share of people living in households whose economic standard is twice as high as the national median value. Table 1 presents the aforementioned indicators for years 2016 and 2019.

In terms of socio-economic indicators, there is an increase in the median income at the municipality level as well as for all the selected urban developments. Developments that are situated closer to

Stockholm's city center (i.e., Arenastaden, Ropsten, Nyboda östra) are characterized by higher median income levels compared to Barkarbystaden, which is further away from the city center. Campus Albano is a special case since it is centrally located but is characterized by a lower median income level for its surrounding because of its student population.

4. Results

In the following, we present the results of the crowding contribution analysis for our diverse set of urban development. We choose the AM peak (07:00–09:00) since this is the most relevant period for analyzing congestion effects and, therefore, most relevant for policy making. Additionally, results related to how demand and PT supply co-changed during the time period (2016–2019) when the urban developments took place are also presented.

4.1. Differences in passenger demand

Understanding how passenger demand changed in the selected urban developments is important for assessing the crowding contributions. Fig. 4 shows the mean passenger demand traveling from or to each of the selected urban developments as well as across Region Stockholm.

In the level of the entire region, small differences are noted. During the AM peak (07:00–09:00) there is an increase of 1.58%, indicating the overall increase in mobility needs across the Region. However, more notable differences are observed for the selected urban developments. Most notably, there is a dramatic increase of 63.4% in passenger demand from/to the area of (2) Barkarbystaden and an increase of 45.71% in the passengers traveling from or to (1) Arenastaden during the AM peak. Moreover, we observe a moderate increase in the demand of 18.15% (AM peak) related to the urban development in the area of (5) Ropsten. However, in the cases of (3) Campus Albano, a minor increase is noted during the AM peak (<1%) and a slightly negative trend in passenger demand in the case of (4) Nyboda östra (−7.88%).

4.2. Differences in public transportation supply

There are notable differences in the PT supply offered since the local PTA anticipated the overall growth in mobility needs in Region Stockholm during the corresponding time period. Fig. 5 presents the mean relative difference (2016 vs 2019) in provided seating capacity at the network segment level during the AM peak.

Results show that the local PTA has substantially increased the supply (>40% in provided seats) in the north-south axis with the construction of the Stockholm City Line (Citybanan) tunnel in 2017. Additionally, we observe a significant increase in provided supply in the bus network in several corridors in the center of Stockholm. Zooming-in on the selected urban developments, we notice that in all the cases, the local PT supply has increased during the analysis period. In the case of (1) Arenastaden, the increase in the commuter rail supply is accompanied by a substantial increase in the supply of feeder bus lines connecting the area with the multi-modal PT hub of Solna. Similarly, in the case of Barkarbystaden, the substantial increase in the commuter rail supply jointly with the same increase level in the supply of the local bus lines connecting to the nearest PT multi-modal hubs (i.e., Akalla terminal metro station). In the case of (3) Campus Albano, the highest increase in the supply concerns the bus segments connecting the area with nearby PT hubs nearby (e.g., Odenplan). Also, in (4) Nyboda östra, there is an increase in the feeder bus network (up to 20% in provided seats) connecting the area with the closest PT hubs of Liljeholmen and Årstaberg. Last, in (5) Ropsten, the highest increase in the supply includes the segments connecting the area with the city center (e.g., Odenplan, T-Centralen). Regarding the area's connection with the western parts of Stockholm (Lidingö island), the supply in both the bus and the light rail increases substantially.

4.3. Network-wide crowding contributions induced by new urban developments

In this subsection, we present the results of the crowding contributions induced by the different urban developments (in percentage point (pp)), which are the outcome of the interaction between changes in demand and supply discussed in the previous sub-sections (see Eq. (1)).

In the case of the urban development of (1) Arenastaden (see Fig. 6a), the bus network in direct proximity to the urban development is most affected. Specifically, the segments belonging to the feeder bus lines connecting the area to the local multi-modal PT hubs (i.e., Solna, Solna centrum, and Ulriksdal) experience the highest increase in crowding contributions of up to 20pp. Additionally, bus network segments in the

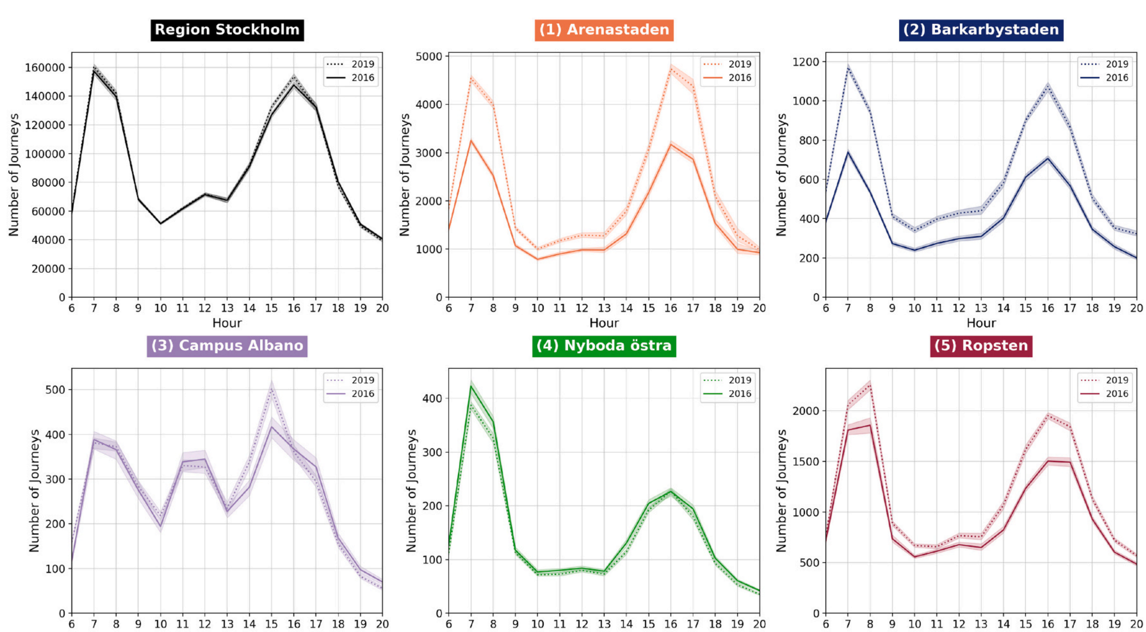

Fig. 4. Mean number of journeys across a workday during 2016 and 2019.

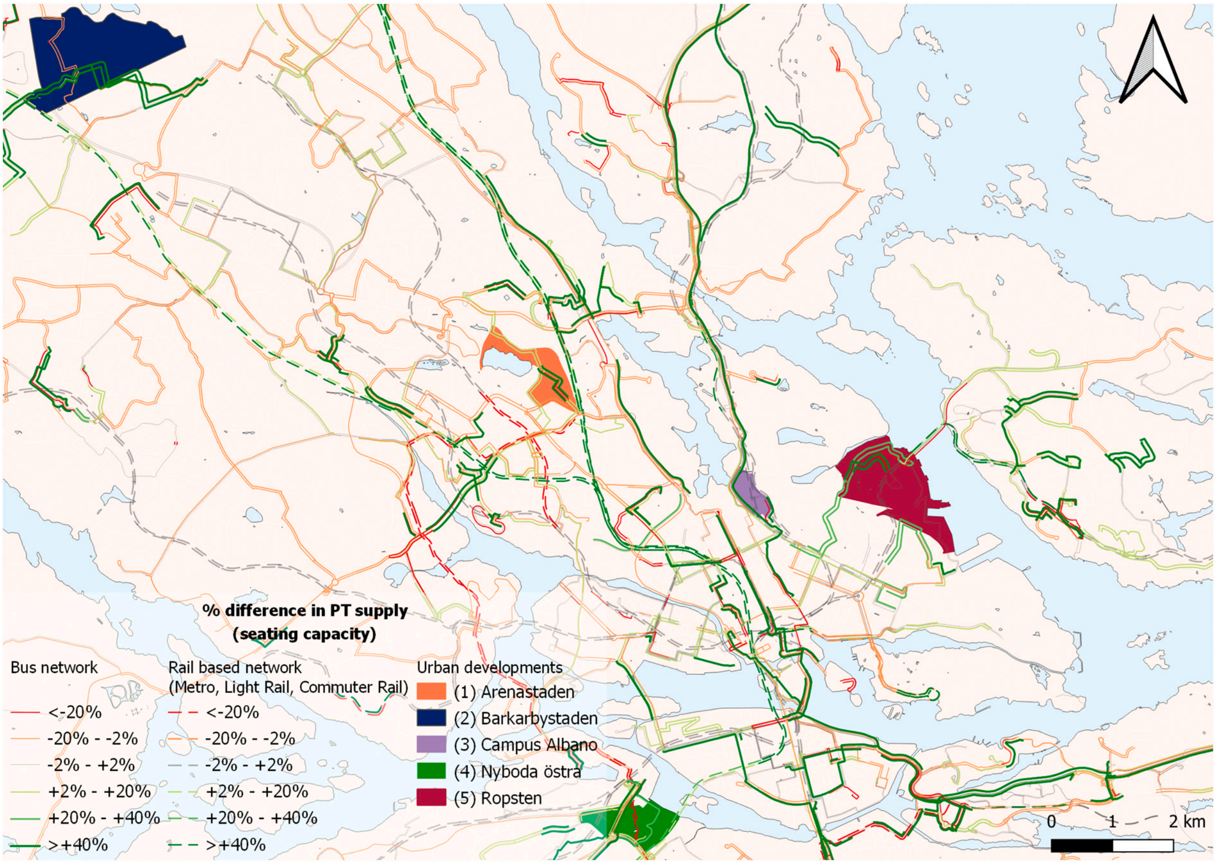

Fig. 5. Relative difference in public transportation supply (service).

southern part of Stockholm (e.g., segments close to the PT hub of Stockholms södra) experience an increase in their crowding contributions of up to 10pp.

The crowding on-board the commuter rail network is notably affected by the urban development. Specifically, the segments connecting the city center and southern Stockholm with Arenastaden (e.g., the multimodal PT hubs of Odenplan, T-Centralen, and Stockholms södra) experience increases in crowding contributions ranging from 10pp up to higher than 30pp. In terms of distance from the area's centroid, these significant crowding contributions occur at relatively long distances of up to ca. 7km. Regarding the metro network, notable increases in crowding contributions of up to 10pp are observed in segments connecting the city center with the hub of Odenplan (e.g., T-Centralen to Odenplan through Rådmansgatan). In the light rail network, some small reductions in the crowding contributions are observed in segments close to the Arenastaden area (e.g., Solna centrum to Solna).

Fig. 6b shows the average differences of the crowding contributions from the urban development on a network-wide level during the AM peak for the (2) Barkarbystaden case. In this case, as in (1) Arenastaden, the feeder bus network connecting the area with local multi-modal PT hubs (e.g., Barkarby, Jacobsberg, Akalla) is substantially affected by the urban development. The commuter rail provides a fast and high-capacity connection between the area and the city of Stockholm. A notable effect (a 10pp increase in the crowding contribution) is observed in the inbound direction of the commuter rail towards the city center and the hubs of Sundbyberg and Odenplan (ca. 10km far from the area).

In the case of (3) Campus Albano, the local bus network (up to ca. 1km from the area's centroid) is primarily affected. Specifically, the segments heading from the closest PT hubs of Odenplan and Tekniska högskolan to the Campus Albano see a crowding contribution increase of up to 10pp and 30pp, respectively. This is expected since this area attracts demand during the morning peak period. The rest of the network, including all the rail-based modes, experiences insignificant changes due to the development of (3) Campus Albano.

Similar to (3) Campus Albano, also in the case of (4) Nyboda östra, important crowding contributions are mainly limited to the local bus network (up to ca. 0.5km from the area's centroid). Specifically, the local feeder bus network is mainly affected by an increase in crowding contributions of up to 5pp. The most affected segments are connectors between the two local PT hubs of Årstaberg (bus, commuter rail, light rail) and Liljeholmen (bus, metro, light rail in proximity). The rest of the PT network does not show any significant changes in terms of crowding contributions.

In the case of the larger-scale development in the (5) Ropsten area, both local and non-local crowding contributions are observed. Fig. 6c presents the network-wide crowding contribution differences induced by the urban development in Ropsten. Results indicate substantial increases in crowding contributions in the bus network (local and non-local). The inbound segments heading towards Stockholm's city center (e.g., segments connecting to the multi-modal PT hubs of Tekniska högskolan and Odenplan as well as to the Vasagatan stop) experience the largest differences in crowding contributions. Similarly, segments towards the seaport (e.g., to Malmvägen stop), as well as segments located on the nearby island of Lidingö (e.g., Kvarnen and Kottla station stops), see a significant increase in crowding contributions. Specifically, these segments experience an increase of on-board crowding contribution of up to 20pp and 40pp. Most increases in crowding contributions are observed within a distance of up to ca. 4.5km from the area's centroid.

Regarding the metro network, an increase of up to 10pp is observed in the segments connecting the area with Stockholm's city center (all metro segments between Ropsten and T-Centralen). The rest of the metro network seems to be unaffected. Many light rail segments indicate a slight decrease of up to –10pp in the crowding contributions (e.g.,

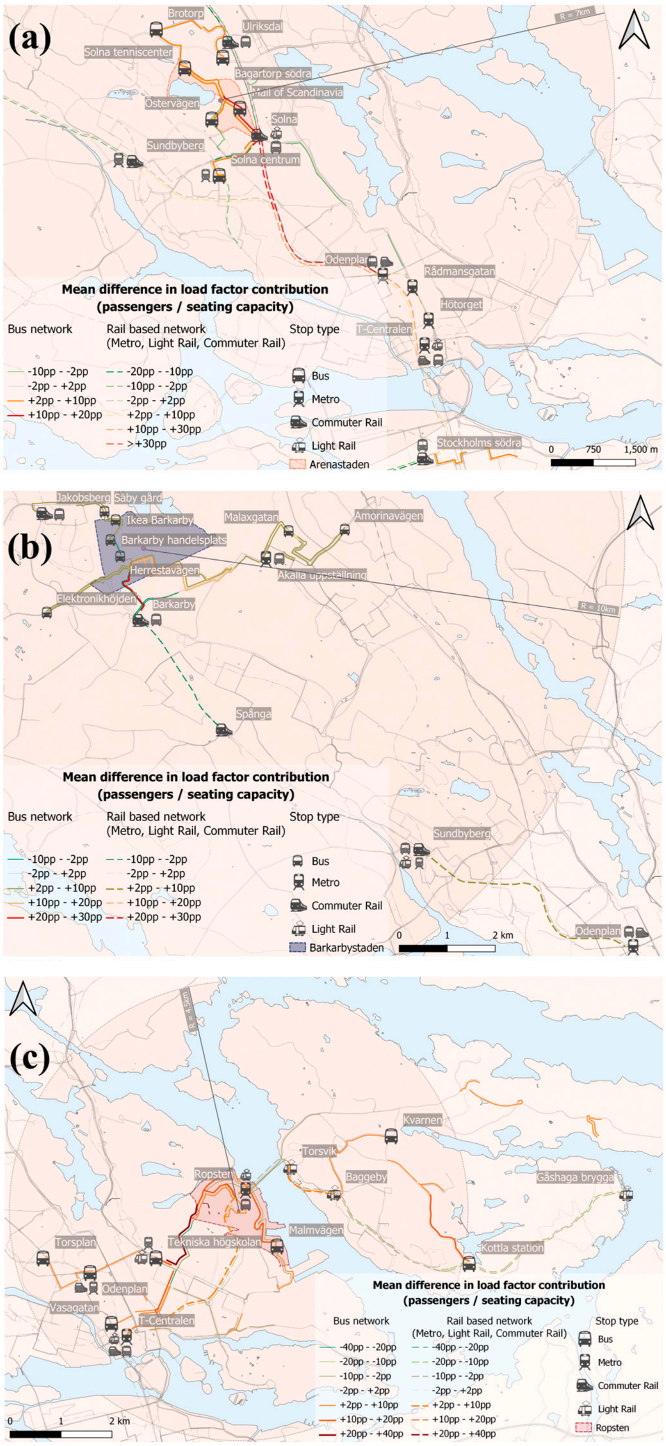

Fig. 6. Network-wide crowding contribution differences induced by the urban developments: (a) Arenastaden, (b) Barkarbystaden, and (c) Ropsten.

segments from Ropsten to Gåshaga brygga in the east). Last, as expected, the commuter rail network is not affected, given its relative remoteness from this urban development.

5. Discussion

Our findings highlight that different categories (C) of urban development result in different crowding effects in the PT network. Characteristics such as the type of urban development (e.g., residential/industrial/mixed), size, location (e.g., central/peripheral), proximity to high-capacity PT modes, the presence of other transportation alternatives as well as the local socioeconomic characteristics are key factors when assessing network-wide PT crowding contributions.

The urban development's category (C) concerning local land use is key in influencing its crowding contributions in the PT network. Promoting mixed-land uses is related to the prevalence of non-motorized trips (Cervero, 1996). For example, infilling, extension, and linear (C1, C2/C3) urban developments with mixed land uses (e.g., residential-business) such as (1) Arenastaden, and (2) Barkarbystaden can have significant crowding contributions to the local PT network (e.g., up to 20pp, see Fig. 6a, b) as well as to the non-local network (e.g., distances higher than 7km) given the important incoming and outgoing passenger flows associated with these areas. In this case, PT supply provision should cater for both types of flows so that PT is a competitive mode. The positive impact of mixed land use on PT ridership is consistent with the literature, such as in the study from Jun et al. (2015). It is important to highlight that mixed land use may offer more opportunities for active transportation as well, thereby significantly restricting car use (Buehler, 2011).

For infilling developments (C1) with a single dominant land use (e.g., (4) Nyboda östra, residential development), the network-wide crowding contributions are limited compared to mixed developments (e.g., up to 5pp) and primarily local (distances up to ca. 1km). In this case, the size of the development is important, as well as the composition of the local modal split. Moreover, extension and large-scale urban developments (C2/C5) with mixed land use (e.g., (5) Ropsten) can result in high network-wide crowding contributions (e.g., up to 40pp, see Fig. 6c) to the local bus network as well as significant non-local crowding contributions (e.g., up to 20pp). Last, more special infilling and extension urban developments (C1/C2), such as a construction of a new university campus (e.g., (3) Campus Albano) can result in primarily local network-wide crowding contributions (distances up to ca. 1km). The existence of universities is found to be positively related to increased PT ridership in the PT network in their vicinity (Choi et al., 2012). It is important to mention that in the case of infilling and extension urban development (C1/C2) (in proximity to PT hubs and the city center), other transport alternatives (e.g., walking, cycling, micromobility) can play an important role in catering to the local mobility needs, especially when young people (e.g., university students) represent a significant portion of the attracted total demand (Ek et al., 2021).

The proximity to a high-capacity mode (e.g., metro, commuter rail) can significantly affect ridership levels and, therefore, network-wide crowding contributions level as well as their spatial extent. In this direction, relevant research reveals that coverage of rail-based modes is associated with a significant increase in PT patronage (Ingvardson & Nielsen, 2018). Our analysis reveals that mixed urban developments with proximity to a high-capacity mode, regardless of their category (C), can have more prominent non-local crowding contributions (e.g., (1) Arenastaden, (2) Barkarbystaden, (5) Ropsten) compared to urban developments without direct access (e.g., (3) Campus Albano). However, strictly residential developments with access to high-capacity modes (e.g., (4) Nyboda östra) may not have prominent contributions to the PT network due to their potential lower passenger demand volumes. Moreover, the presence of micro-mobility options, such as shared bicycles and e-scooters, may affect PT patronage and, therefore, crowding contributions. Specifically, Fishman (2015) mentions that commuting is the most common trip purpose for shared bicycle users, indicating a potential lower PT share for areas with a higher presence of shared bicycle systems. In the same direction, Jayawardhena et al. (2025) report that shared bicycles and e-scooters may complement rail-based PT journeys, but they both tend to compete with buses. These indications may partially explain the lower PT patronage for areas with bus dependence (e.g., (3) Campus Albano, (4) Nyboda östra). However, more systematic analysis involving other modes, such as shared bicycles and e-scooters, is needed to underpin this relation.

The size of a new urban development (e.g., in terms of new residents, provided workplaces, retail areas) directly relates to increased PT patronage and crowding contributions in the PT network (Guerra & Cervero, 2011). For example, developments with a high number of constructed dwelling units (e.g., (2) Barkarbystaden, (5) Ropsten) or a high number of new workplaces (e.g., (1) Arenastaden, (5) Ropsten) or a combination thereof (e.g., (5) Ropsten) exhibit higher levels of crowding contributions compared to relatively smaller urban developments (e.g., (3) Campus Albano, (4) Nyboda östra) regardless of their category (C). Past research suggests that population density is positively associated with PT patronage (Mattson, 2020). While some of the selected urban developments confirm with this finding (e.g., (5) Ropsten), other urban developments with a relatively high population density (e.g., (3) Campus Albano, (4) Nyboda östra) do not align with the anticipated relation between population density and PT use. This finding highlights the complexity of designing PT services in relation to newly developed areas, given the existence of many underlying factors affecting PT demand, as described in this section.

The local socioeconomic characteristics (e.g., number of cars, income level) are important determinants of the local modal split and, therefore, relevant for PT crowding contributions induced by a new urban development. An increase in the population is usually associated with higher use of PT (D. Zhang & Wang, 2014), given the sufficient tuning (increase) of the local PT supply, and thereby higher crowding contributions. In our study, there are examples confirming this anticipation such as the ones of an extension-linear development (C2/C3) (e.g., (2) Barkarbystaden) and an extension-large scale project (C2/C5) (e.g., (5) Ropsten). In these case studies, the significant increase in the population (56% and 32% respectively) was followed by a significant increase in PT use (46% and 18% during the AM peak, respectively). However, in another case study of an infilling development (C1) ((4) Nyboda östra) in terms of population increase (28%), the PT demand followed the opposite trend (decrease of 8% during the AM peak, see Fig. 4).

At this point, it is sensible to involve more socioeconomic characteristics in interpreting this difference, such as income level and the number of cars. Income level is considered as a 'background factor' affecting PT patronage, compared to other factors such as fare price and PT service quality. In addition, income level is a key determinant of car ownership level, and, therefore, it can negatively affect PT demand as a secondary effect (Paulley et al., 2006). In the case of an infilling development (C1) with high income level (e.g., (4) Nyboda östra), private car ownership can follow a similar trend (Lebrand & Theopile, 2022). However, there are cases of urban developments with high-income levels (e.g., (5) Ropsten) where there is high PT use (D. Zhang & Wang, 2014). The latter implies that well-designed PT can make private cars a less attractive mode. Urban developments with lower income levels (e.g., (3) Barkarbystaden) can increase their dependence on the PT (Bondemark et al., 2021; Paulley et al., 2006). Last, the overall economic equality in terms of employment and GDP levels in a city is associated with higher PT patronage and vice versa (Ingvardson & Nielsen, 2018).

It is important to mention that apart from the abovementioned characteristics that can define passenger demand and crowding, crowding per se can impact PT demand due to its inherent discomfort to every passenger. PT planners should consider passengers' propensity to use PT given the new crowding conditions defined by newly developed areas. Metrics such as the *average number of PT journeys per person* before and during/after a new urban development can assist in evaluating how crowding affects PT patronage. In this study, passengers' propensity to use PT did not decrease due to the crowding induced by the selected categories of urban development (the only decrease, a minor one, is observed for the Nyboda östra urban development). Last, in other selected urban developments, this insight may assist in designing PT supply from/to newly developed areas accounting for the effect of crowding when modeling existing (or new) services.

6. Conclusions

Demand predictions of the ex-ante PT planning can sometimes be unreliable, given the differences that have been observed between the original planning and reality. In particular, Nguyen et al. (2020) mention that incorrect demand level can be predicted when on-board crowding is not integrated in the ex-ante demand forecast, given that a higher level of PT on-board crowding can affect its attractiveness and therefore passengers' mode choices. Moreover, Skartland (2023) highlights that different land-use configurations may respond differently to PT planning. In this sense, ex-post evaluation can complement the ex-ante PT planning for new urban developments by calibrating the forecasting model and, therefore, assist in eliminating potential mismatch of new urban development needs and provided PT services. It is, therefore, of utmost importance that ex-post evaluation is included in the political agenda related to PT investments. Several countries, such as the United Kingdom and France, have incorporated the ex-post evaluation in transportation investments by enacting relevant legislation (International Transport Forum (ITF), 2017).

The approach proposed in this study is designed to bridge the abovementioned gaps by serving as an auxiliary tool for PTAs and operators in supporting their ex-ante planning of PT services related to new urban developments. Moreover, the network-wide perspective adopted by the proposed method can assist in identifying non-local, and potentially unexpected and secondary, effects in the system, thereby identifying potential crowding contributions throughout the PT network. In addition, our approach can assist in policy-making related to the placement of new urban developments as well as dimensioning the PT supply tuning as described in the subsequent paragraphs. We apply our method to a diverse set of urban developments that took place in the greater Stockholm area during 2016–2019. In the selection of the urban developments, we deliberately include development categories (C) with diverse characteristics in terms of their type (e.g., residential/business/industrial/mixed), size, location (e.g., central/peripheral), proximity to a high-capacity PT connection as well as local socioeconomic characteristics.

New land-use planning configurations can have a different crowding effect on the PT system. However, ex-post evaluations are usually not carried out to complement the common ex-ante planning. To this end, we propose a method, entirely based on smart card data, able to assess the network-wide crowding contributions as induced by a newly developed area. We account for urban developments with diverse characteristics in terms of type, size, location, proximity to a high-capacity PT connection as well as socioeconomic characteristics. Our results support that the size and the type of newly developed areas are crucial factors towards shaping the network-wide crowding effect. However, socioeconomic characteristics such as income and car ownership level may shape a twofold network-wide crowding effect. Similarly, population density is found to have an inconclusive effect on PT utilization. Capacity provision, and especially proximity to a high-capacity connection, is a key in shaping the demand in newly developed areas as well as defining the geographical extent of the induced crowding effect. However, the existence of supportive transportation modes (e.g., shared bicycles, e-scooters) may complement or compete with PT. Last, concerning the abovementioned insight, our study can guide policy-making related to the placement of future urban developments as well as supply (service) dimensioning for newly developed areas accounting for the resulting crowding effect.

CRediT authorship contribution statement

Anastasios Skoufas: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Matej Cebecauer:** Writing – review & editing, Methodology, Conceptualization. **Wilco Burghout:** Writing – review & editing. **Erik Jenelius:** Writing – review & editing, Supervision, Conceptualization. **Oded**

Cats: Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

None.

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Data availability

The authors do not have permission to share data.

References

Bivina, G. R., Gupta, A., & Parida, M. (2020). Walk accessibility to metro stations: An analysis based on meso- or micro-scale built environment factors. *Sustainable Cities and Society, 55*, Article 102047. https://doi.org/10.1016/j.scs.2020.102047

Bondemark, A., Andersson, H., Wretstrand, A., & Brundell-Freij, K. (2021). Is it expensive to be poor? Public transport in Sweden. *Transportation, 48*(5), 2709–2734. https://doi.org/10.1007/s11116-020-10145-5

Bos, E., & de Swart, L. (2024). Towards a better comparison of ex-post and ex-ante BCA's by decomposing potential causes of difference. *Transport Policy, 151*, 36–45. https://doi.org/10.1016/j.tranpol.2024.02.020

Bruun, E. (2005). Bus rapid transit and light rail comparing operating costs with a parametric cost model. *Transportation Research Record, 1927*, 11–21. https://doi.org/10.3141/1927-02

Buehler, R. (2011). Determinants of transport mode choice: A comparison of Germany and the USA. *Journal of Transport Geography, 19*(4), 644–657. https://doi.org/10.1016/j.jtrangeo.2010.07.005

Camagni, R., Gibelli, M. C., & Rigamonti, P. (2002). Urban mobility and urban form: The social and environmental costs of different patterns of urban expansion. *Ecological Economics, 40*(2), 199–216. https://doi.org/10.1016/S0921-8009(01)00254-3

Cats, O. (2023). Identifying human mobility patterns using smart card data. *Transport Reviews, 44*(1), 213–243. https://doi.org/10.1080/01441647.2023.2251688

Cats, O., & Ferranti, F. (2022). Voting with one's feet: Unraveling urban centers attraction using visiting frequency. *Cities, 127*. https://doi.org/10.1016/j.cities.2022.103773

Cats, O., Rubensson, J., Cebecauer, M., Kholodov, Y., Vermeulen, A., Jenelius, E., & Yusak, S. (2019). *FairAccess - How fair is the fare? Estimating travel patterns and the impactsof fare schemes for different user groups in Stockholm based on smartcard data (tech.rep.)*. https://kth.diva-portal.org/smash/get/diva2:1784265/FULLTEXT01.pdf.

Cats, O., West, J., & Eliasson, J. (2015). *Appraisal of increased public transport capacity: The case of a new metro line to Nacka, Sweden (tech. rep.)*. Stockholm, Sweden: Centre for Transport Studies (CTS). https://www.transportportal.se/swopec/CTS2015-2.pdf.

Cervero, R. (1995). Sustainable new towns: Stockholm's rail-served satellites. *Cities, 12*(1), 41–51. https://doi.org/10.1016/0264-2751(95)91864-C

Cervero, R. (1996). Mixed land-uses and commuting: Evidence from the American Housing Survey. *Transportation Research Part A: Policy and Practice, 30*(5), 361–377. https://doi.org/10.1016/0965-8564(95)00033-X

Cho, S. E., & Kim, S. (2017). Measuring urban diversity of Songjiang New Town: A re-configuration of a Chinese suburb. *Habitat International, 66*, 32–41. https://doi.org/10.1016/j.habitatint.2017.05.009

Choi, J., Lee, Y. J., Kim, T., & Sohn, K. (2012). An analysis of Metro ridership at the station-to-station level in Seoul. *Transportation, 39*(3), 705–722. https://doi.org/10.1007/s11116-011-9368-3

City of Stockholm - the City of Stockholm Traffic & Administration. (2012). Urban mobility strategy (tech. rep.). Stockholm, Sweden https://start.stockholm/globalassets/start/om-stockholms-stad/politik-ochdemokrati/styrdokument/urban-mobility-strategy.pdf.

Daniels, R., & Mulley, C. (2013). Explaining walking distance to public transport: The dominance of public transport supply. *Journal of Transport and Land Use, 6*(2), 5–20. https://doi.org/10.5198/jtlu.v6i2.308

Dixit, M., Cats, O., van Oort, N., Brands, T., & Hoogendoorn, S. (2024). Validation of a multi-modal transit route choice model using smartcard data. *Transportation, 51*(5), 1809–1829. https://doi.org/10.1007/s11116-023-10387-z

Ek, K., Wårell, L., & Andersson, L. (2021). Motives for walking and cycling when commuting – Differences in local contexts and attitudes. *European Transport Research Review, 13*(1). https://doi.org/10.1186/s12544-021-00502-5

Eurostat. (2021). Population projections: Urban growth, rural decline. Retrieved July 5, 2023, from https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20210520-1#:$%5Csim$:text=Between%202019%20and%202050%2C%20the,and%20%2B25.1%25%20respectively).

Fang, K. (2015). Public transport and urban design. https://blogs.worldbank.org/en/transport/public-transport-and-urban-design.

Fishman, E. (2015). Bikeshare: A review of recent literature. *Transport Reviews, 36*. https://doi.org/10.1080/01441647.2015.1033036

Gössling, S., Schweiggart, N., Nieuwenhuijsen, M., McEachan, R. R. C., & Khreis, H. (2024). Urban transport system changes in the UK: In danger of populism? *Cities, 153*, Article 105273. https://doi.org/10.1016/j.cities.2024.105273

Goulet-Langlois, G., Koutsopoulos, H. N., & Zhao, J. (2016). Inferring patterns in the multi-week activity sequences of public transport users. *Transportation Research Part C: Emerging Technologies, 64*, 1–16. https://doi.org/10.1016/j.trc.2015.12.012

Guerra, E., & Cervero, R. (2011). Cost of a ride. *Journal of the American Planning Association, 77*(3), 267–290. https://doi.org/10.1080/01944363.2011.589767

Ingvardson, J. B., & Nielsen, O. A. (2018). How urban density, network topology and socio-economy influence public transport ridership: Empirical evidence from 48 European metropolitan areas. *Journal of Transport Geography, 72*, 50–63. https://doi.org/10.1016/j.jtrangeo.2018.07.002

International Transport Forum(ITF). (2017). *Ex-post assessment of transport investments and policy interventions*. OECD publishing. https://doi.org/10.1787/9789282108154-en

Intitute of Transportation and Development Policy (ITDP). (2024). The BRT standard (tech. rep.). New York, NY, USA https://itdp.org/wp-content/uploads/2024/03/BRT-STANDARD_MAR-2024_ITDP.pdf.

Jayawardhena, M., Delbosc, A., Currie, G., & Rose, G. (2025). When do shared e-scooters complement or compete with public transport? A mixed-method review and comparison with bike sharing. *Journal of Cycling and Micromobility Research, 3*, Article 100057. https://doi.org/10.1016/j.jcmr.2025.100057

Jun, M.-J., Choi, K., Jeong, J.-E., Kwon, K.-H., & Kim, H.-J. (2015). Land use characteristics of subway catchment areas and their influence on subway ridership in Seoul. *Journal of Transport Geography, 48*, 30–40. https://doi.org/10.1016/j.jtrangeo.2015.08.002

Karatsoli, M., Nathanail, E., Basbas, S., & Cats, O. (2024). Crowdedness information and travel decisions of pedestrians and public transport users in the COVID-19 era: A stated preference analysis. *Cities, 149*, Article 104973. https://doi.org/10.1016/j.cities.2024.104973

Kholodov, Y., Jenelius, E., Cats, O., van Oort, N., Mouter, N., Cebecauer, M., & Vermeulen, A. (2021). Public transport fare elasticities from smartcard data: Evidence from a natural experiment. *Transport Policy, 105*, 35–43. https://doi.org/10.1016/j.tranpol.2021.03.001

Kim, K., Hong, S.-P., Ko, S.-J., & Kim, D. (2015). Does crowding affect the path choice of metro passengers? *Transportation Research Part A: Policy and Practice, 77*. https://doi.org/10.1016/j.tra.2015.04.023

Lebrand, M., & Theopile, E. (2022). *Rising incomes, transport demand, and sector decarbonization (tech. rep.)*. World Bank Group. https://documents1.worldbank.org/curated/en/099901304192236433/pdf/IDU0d366435d0a79404645080fe01146ee8b1853.pdf.

Lee, S., & Bencekri, M. (2021). Chapter 17 -urban form and public transport design. In C. Mulley, J. D. B. T. U. F. Nelson, & Accessibility (Eds.), *Urban form and accessibility* (pp. 289–306). Elsevier. https://doi.org/10.1016/B978-0-12-819822-3.00018-3.

Lee, S., & Yoon, H. (2019). Effects of greenbelt cancellation on land value: The case of Wirye New Town, South Korea. *Urban Forestry & Urban Greening, 41*, 55–66. https://doi.org/10.1016/j.ufug.2019.03.001

Levinson, D. (2008). Density and dispersion: The co-development of land use and rail in London. *Journal of Economic Geography, 8*(1), 55–77. https://doi.org/10.1093/jeg/lbm038

Lin, D., Broere, W., & Cui, J. (2022). Underground space utilisation and new town development: Experiences, lessons and implications. *Tunnelling and Underground Space Technology, 119*, Article 104204. https://doi.org/10.1016/j.tust.2021.104204

Lindgren, K., & Ouertani, M. (2020). *Områdesplanering i Årstadal : Hur fastställda visioner och mål påövergripande nivåuttrycks i områdesplanering med exempel påbyggnadsprojekt och parketablering*.

Mattson, J. (2020). Relationships between density, transit, and household expenditures in small urban areas. *Transportation Research Interdisciplinary Perspectives, 8*, Article 100260. https://doi.org/10.1016/j.trip.2020.100260

Municipality of Stockholm (Stockholms stad). (2018). Stockholm City Plan (tech. rep.). Stockholm https://vaxer.stockholm/siteassets/stockholm-vaxer/tema/oversiktsplan-for-stockholm/english_stockholm_city_plan.pdf.

Municipality of Stockholm (Stockholms stad). (2022). The Stockholm Royal Seaport. Retrieved July 7, 2023, from https://international.stockholm.se/city-development/the-royal-seaport/.

Municipality of Stockholm (Stockholms stad). (2024). Albano. Retrieved August 29, 2024, from https://vaxer.stockholm/projekt/norra-djurgarden/albano/.

Munizaga, M. A., & Palma, C. (2012). Estimation of a disaggregate multimodal public transport Origin-Destination matrix from passive smartcard data from Santiago, Chile. *Transportation Research Part C: Emerging Technologies, 24*, 9–18. https://doi.org/10.1016/j.trc.2012.01.007. Cited by: 371.

Nguyen, N. T., Miwa, T., & Morikawa, T. (2020). Demand forecast of public transportation considering positive and negative mass effects. *Transportation Research Part D: Transport and Environment, 85*, Article 102466. https://doi.org/10.1016/j.trd.2020.102466

Parry, I. W. H., & Small, K. A. (2009). Should urban transit subsidies be reduced? *American Economic Review, 99*(3), 700–724. https://doi.org/10.1257/aer.99.3.700

Paulley, N., Balcombe, R., Mackett, R., Titheridge, H., Preston, J., Wardman, M., Shires, J., & White, P. (2006). The demand for public transport: The effects of fares, quality of service, income and car ownership. *Transport Policy, 13*(4), 295–306. https://doi.org/10.1016/j.tranpol.2005.12.004

Pyddoke, R., Norheim, B., & Betanzo, M. F. (2017). *A model for strategic planning of SustainableUrban transport in Scandinavia - a case study of Uppsala, Centre for Transport Studies (CTS)*. https://www.transportportal.se/swopec/CTS2017-7.pdf.

Rodrigue, J.-P. (2020). *The geography of transport systems* (5th ed.). Routledge https://transportgeography.org/?page_id=6295.

Sijpkes, P., & Brown, D. (1997). Montreal's indoor city- 35 years of development. In *7th international conference on underground space 1997*. http://www.fgienr.net/observatoiredelavilleinterieure/documents/ovi_psijpkes_dbrown.pdf.

Skartland, E.-G. (2023). Unfavorable transit planning: Lack of knowledge, lack of collaboration, or political conflicts? A case study of two Norwegian cities aiming to increase transit competitiveness. *Progress in Planning, 167*, Article 100656. https://doi.org/10.1016/j.progress.2022.100656

Skoufas, A., Cebecauer, M., Burghout, W., Jenelius, E., & Cats, O. (2024). Assessing contributions of passenger groups to public transportation crowding. *Journal of Public Transportation, 26*, Article 100110. https://doi.org/10.1016/j.jpubtr.2024.100110

Statistiska Centralbyrån (SCB). (n.d.). Open data for DeSO – demographic statistical areas. Retrieved March 27, 2023, from https://www.scb.se/en/services/open-data-api/open-geodata/deso–demographic-statisticalareas/.

The International Association of Public Transport (UITP). (2024). Bus: The most used mode of public transport around the world. https://www.uitp.org/topics/bus/.

The World Bank. (2023). Urban development / overview. Retrieved July 5, 2023, from https://www.worldbank.org/en/topic/urbandevelopment/overview#1.

Tirachini, A., Hensher, D. A., & Jara-Díaz, S. R. (2010). Comparing operator and users costs of light rail, heavy rail and bus rapid transit over a radial public transport network. *Research in Transportation Economics, 29*(1), 231–242. https://doi.org/10.1016/j.retrec.2010.07.029

Tirachini, A., Hensher, D. A., & Rose, J. M. (2013). Crowding in public transport systems: Effects on users, operation and implications for the estimation of demand. *Transportation Research Part A: Policy and Practice, 53*, 36–52. https://doi.org/10.1016/j.tra.2013.06.005

Transformative Urban Mobility Initiative (TUMI). (2021). Passenger capacity of different transport modes. https://transformative-mobility.org/multimedia/passenger-capacity-of-different-transport-modes/.

Trépanier, M., Tranchant, N., & Chapleau, R. (2007). Individual trip destination estimation in a transit smart card automated fare collection system. *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations, 11*(1), 1–14. https://doi.org/10.1080/15472450601122256. Cited by: 266.

Vuchic, V. (2005). *Urban transit: Operations, planning, and economics*. Wiley.

Zhang, D., & Wang, X. (2014). Transit ridership estimation with network kriging: A case study of second avenue subway, NYC. *Journal of Transport Geography, 41*, 107–115. https://doi.org/10.1016/j.jtrangeo.2014.08.021

Zhang, Y., Marshall, S., Cao, M., Manley, E., & Chen, H. (2021). Discovering the evolution of urban structure using smart card data: The case of London. *Cities, 112*, Article 103157. https://doi.org/10.1016/j.cities.2021.103157