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Determinants of passengers' metro car choice revealed through automated data sources: A Stockholm metro case study

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Abstract The paper proposes a methodology based on multiple automated data sources for evaluating the effects of station layout, arriving traveller flows, and platform and on-board crowding on the distribution of boarding passengers in individual cars of a metro train. The methodology is applied to a case study for a sequence of stations in the Stockholm metro network. While train car loads are generally skewed towards the leading cars, results indicate that a crowded arriving train is associated with increasing boarding shares in the middle and rear cars. Moreover, higher platform crowding is found to have a positive significant effect on the boarding share in the middle car. We find that the boarding car distribution is also affected by the locations of entrances and the distribution of entering traveller flows. The insights may be used by transit planners and operators to increase the understanding of how passengers behave under crowding conditions and identify the factors that affect travelers' metro car choice.

Keywords Public transport · Crowding · Load data · Boarding decision · Passenger distribution · Metro

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1 Introduction

As travel demand increases in many cities, overcrowding at public transport stations during peak hours is recognized as a major issue. Crowding on platforms has implications for dwell times and passengers waiting times and reduces reliability (Lam et al. 1999). The effect is non-linear; the larger the passenger load on the platform, the longer the boarding and alighting times per passenger.

Congestion on platforms also has a critical impact on crowding within vehicles (Leurent 2011). On-board crowding is associated with many negative consequences, such as discomfort and stress attributed to crowding, unexpected delays, low probability of getting a seat and the risk of failing to board a train (Tirachini et al. 2013). Haywood et al. (2017) showed that not getting a seat, shorter distances to other passengers and less efficient use of time during the journey cause a higher disutility of on-board crowding perceived by passengers.

Studies show that passenger loads can be highly unevenly distributed along platforms and between the cars of trains and metros even during peak hours (TRB 2014; Zhang et al. 2017). This implies that train cars are not equally utilized, which leads to higher vehicle requirements and higher operating cost, as well as higher experienced crowding discomfort. Some studies aim to reduce the skewness of the passenger distribution in the train by determining the optimal train stop location along a platform (Sohn 2013) or providing real-time crowding information (Zhang et al. 2017).

Some studies have examined passengers' behavior during the processes of boarding and alighting, and the potential impact on dwell times and the service level for passengers (Qi et al. 2008; Krstanoski 2014). Pel et al. (2014) analyzed passengers' behavioral response to in-vehicle crowding conditions, considering the average load factor (i.e., the ratio of the average on-board passenger load to the seating capacity) as on-board discomfort indicator. Metro passengers have been shown to choose an alternative path in order to avoid delay due to on-board crowding, but also to avoid crowding itself (Kim et al. 2015).

The skewed distribution of passengers waiting on the platform is highly related to the physical structure of the platform and the position of access points (Szplett and Wirasinghe 1984). The distance between the platform entrance and the waiting position, the capacity of each waiting position, and the exit location at the destination station, are some of the factors that affect the distribution of passengers on the platform (Liu et al. 2016). Kim et al. (2014) conducted a survey at heavily congested metro stations, studying passengers motivation for choosing a specific metro car to board. They results showed that 77% of the respondents reported choosing a specific car intentionally; among these, 70% stated that their motivation was to minimize walking distance at the destination station, 17% sought to minimize walking distance at the origin station, and 13% stated that they sought to maximize comfort during the trip.

Notwithstanding the insights gained by stated preference studies, travel behavior in practice may differ from the surveyed and hence it is desirable to

use actual observations to investigate how metro passengers make their travel decisions. To the best of our knowledge, no studies have examined passenger's car boarding choice based on a combination of several automatically collected data sources.

This paper proposes a framework based on automated data sources for investigating the effects of on-board and on-platform crowding as well as incoming traveller flows at each platform access point on passengers' choice among different cars of a metro train. The methodology utilizes ridership data and station entering traveller flows as input to systematically examine how passengers respond to crowding in different metro cars and in their decision to board a specific metro car. The framework is applied to a sequence of stations in the Stockholm metro network where passenger loads are highly skewed between cars.

The remainder of the paper is structured as follows. Section 2 describes the proposed methodology and the data required in this study. In section 3 the Stockholm metro network, for which on-board crowding in each car unit is analyzed, is introduced. The main analysis results are given in section 4 and section 5 draws conclusions and outlines follow-up work.

2 Methodology

In the following, we evaluate passengers' boarding car choice based on the crowding in individual cars of the metro train approaching the station, the physical infrastructure of the station, and platform crowding. The notation used is summarized in Table 1.

Table 1 Notation

i	Metro train car, $i = 1, \ldots, N$
j	Train trip
s, t	Metro station $s, t = 1, \ldots, S$
k	Platform access point, $k = \{south, middle, north\}$
χ_{js}	Ratio of boarding to alighting passengers
$q_{ijs}^{onboard}$	Metro car passenger load at departure
$q_{js}^{onboard}$	Total train passenger load at departure
q_{ijs}^{board}	Passengers boarding car i
q_{ijs}^{alight}	Passengers alighting car i
q_{jst}^{travel}	Station-to-station demand for each pair of stations s, t
q_{js}^{wait}	Passengers waiting on platform
q_{jsk}^{arrive}	Arriving flow at southbound platform access location k
p_{ijs}^{board}	Share of passengers boarding car i
p_{jsk}^{arrive}	Share of passengers arriving at southbound platform access location k
γ^{seat}	Seated capacity per metro train

2.1 Data requirements

The analysis of passenger boarding car choice is based on three types of automated data sources:

Train passenger loads

Passenger loads $q_{ijs}^{onboard}$ for each train run j, station s and car i are used to estimate on-board congestion. Such data may be obtained based on the weight of each car upon departure from each station. Passenger load data are used to compute the crowding level in each car as well as the load difference between consecutive stations.

Station entering passenger flows

Smart card tap-ins q_{jsk}^{arrive} provide information about the entering traveller flow at each access point k of each station s during the time interval relevant for each vehicle trip j. In this study, this data source is used to estimate the share of incoming passengers at each access point.

Station-level OD matrix

Aggregate travel demand data q_{jst}^{travel} describe the average station-to-station demand for each pair of stations s, t during the time interval relevant for train run j. This origin-destination demand data can be derived from Automatic Fare Collection systems or from transit assignment models. This aggregated travel demand is used to estimate the average ratio between boarding and alighting passengers at each station.

Station layout

In addition to the passenger-oriented data, the physical structure of the station, including the layout of the station platforms and the location of access points, is also required.

Figure 1 summarizes the types of information that are obtained through the combined data sources.

2.2 Data processing

Boarding car distribution

Ridership data are used to estimate the distribution of passengers between the cars of each metro train. The passenger load difference in each car $i = 1, \ldots, N$, after train j departs from station s, denoted by Δq_{ijs}, is defined as

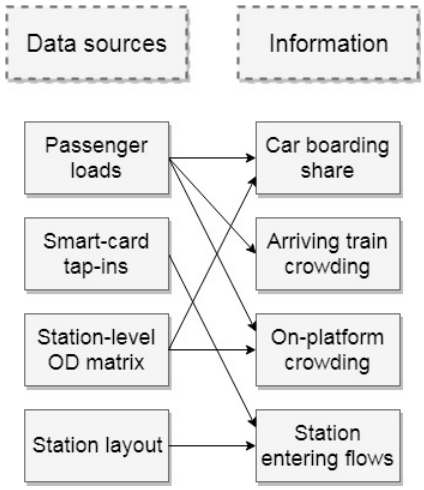

Fig. 1 Information obtained from the data sources.

the difference in load between two consecutive stations, $s-1$ and s, $q_{ij,s-1}^{onboard}$ and $q_{ijs}^{onboard}$, respectively,

$$\Delta q_{ijs} = q_{ijs}^{onboard} - q_{ij,s-1}^{onboard} \tag{1}$$

The study focuses on analyzing passengers' boarding decision and hence, observations with negative load difference are not included in the analysis.

The average number of boarding and alighting passengers at station s, obtained from the aggregate OD matrix, is used to estimate the number of passengers boarding each car i on trip j upon departure from station s. The ratio of the average number of boarding to alighting passengers, denoted by χ_{js}, is computed as

$$\chi_{js} = \frac{\sum_{t=s+1}^{S} q_{jst}^{travel}}{\sum_{t=1}^{s-1} q_{jts}^{travel}} \tag{2}$$

Assuming that the ratio applies to each metro car, the estimated number of passengers boarding car i on train trip j is then

$$q_{ijs}^{board} = \frac{\chi_{js}}{\chi_{js}-1} \Delta q_{ijs} \tag{3}$$

The share of passengers boarding car i, denoted by p_{ijs}^{board}, is

$$p_{ijs}^{board} = \frac{q_{ijs}^{board}}{\sum_{i=1}^{N} q_{ijs}^{board}} \tag{4}$$

Platform entry point distribution

The paper investigates the impact of the distribution of incoming passengers between the entry points of the metro station on passengers' boarding car choice. The share of incoming passengers at platform entry location k is computed from the station entering flows,

$$p_{jsk}^{arrive} = \frac{q_{jsk}^{arrive}}{\sum_{k=1}^{K} q_{jsk}^{arrive}} \tag{5}$$

Waiting passengers

Assuming that there are no passengers who are denied from boarding the train or choose not to board, the number of waiting passengers on the platform prior train departure j is assumed to be equal to the total number of passengers boarding train j, is computed from the passenger load data and aggregate OD demand data,

$$q_{js}^{wait} = \sum_{i=1}^{N} q_{ijs}^{board} \tag{6}$$

2.3 Boarding car share model

Stepwise regression with backward elimination approach is used to identify predictor variables that have a significant impact on the share of passengers boarding each train car. The procedure starts with all the candidate predictors in the model. Considering a 5% level of significance, the least significant variable (the one with the largest p-value) is excluded and the model is refitted iteratively. After termination, the remaining predictors have p-values smaller than 0.05.

3 Stockholm Case Study

3.1 Study area

Key stations and segments of the Stockholm metro network are significantly crowded during the morning peak. On average, more than 268,000 passengers board Stockholm metro trains during the morning peak period (6:00–9:00) (SL 2016). A full-length metro train in Stockholm consists of three cars (front, middle and rear). According to the train manufacturer, the design capacity of a car unit is 126 seated passengers and 288 standees.

The southbound segment of metro line 14 between Mörby centrum and Tekniska högskolan is selected for this study. The segment serves five metro stations, namely the terminus Mörby centrum (MÖR), Danderyds sjukhus (DAS), Bergshamra (BEH), Universitetet (UNT), and Tekniska högskolan

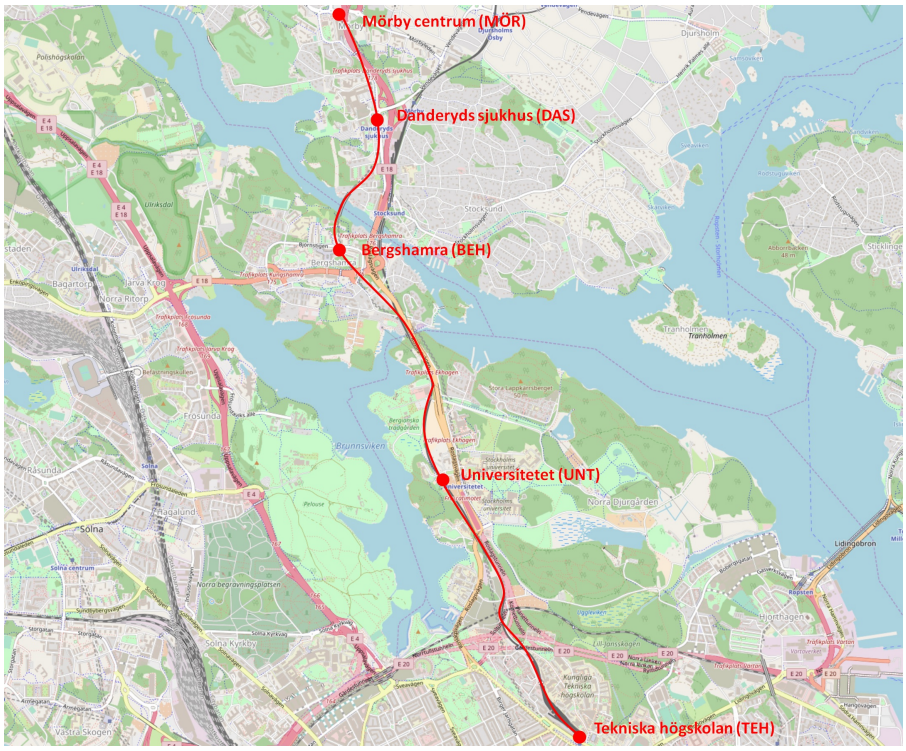

Fig. 2 Map of the studied segment of Stockholm metro network. Map source: OpenStreetMap

(TEH) (Fig. 2). Two stations after TEH, the line joins a corridor shared with another line and serves 14 additional stations. During the morning peak hour, the planned headway for metro line 14 is 5 minutes.

3.2 Data

In order to apply the analysis framework in Section 2, several sets of data regarding passenger loads, pedestrian flows, travel demand and station infrastructure, are used.

Passenger load data for each car unit are available for each southbound train trip at departure from each station during the morning rush period (6:00–9:00 am) on working days in October 2016. The number of passengers in each car is estimated based on an average weight of 78 kg per passenger including luggage. In total, 1185 train load observations for different train runs and stations are available during the analysis period. Of the 1185 observations, 948 observations are randomly selected as the training set, while the remaining 237 are used as a test data set. Observations with a negative passenger load difference in at least one metro car are not used.

Total incoming passenger counts at each entrance point of the station, aggregated every 15 minutes, are available from smart card transactions for the morning peak hour for the same analysis period (6:00 am – 9:00 am on working days in October 2016). Since metro users in Stockholm do not have to tap the smart card when they exit metro stations, information about users' exit station is not available.

Aggregate origin-destination travel demand data for the morning peak period at the station-to-station level for the metro line are produced in the traffic assignment model Visum, based on the official planning zonal OD matrix. These data are used to estimate the proportion of boarding to alighting passengers at each metro station.

Infrastructure characteristics, namely the layout of the platforms that serve the metro trains heading south, specifying the entrance/exit locations are

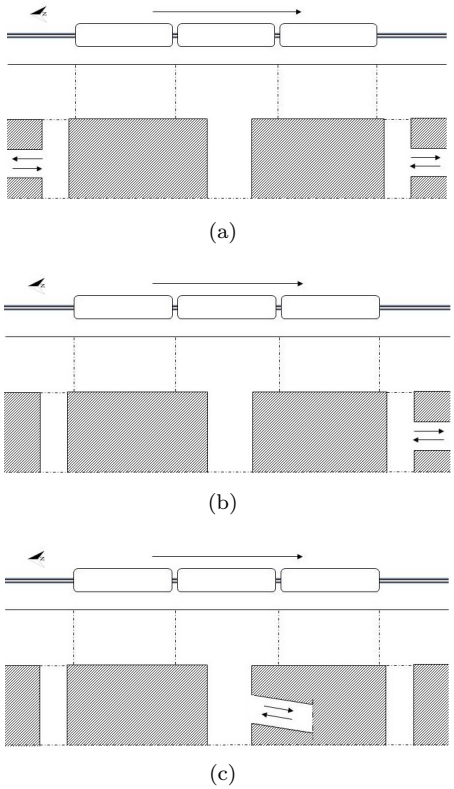

Fig. 3 Layouts of the southbound platforms of the Mörby centrum–Tekniska högskolan corridor: (a) Danderyds sjukhus (DAS), Bergshamra (BEH), Tekniska högskolan (TEH); (b) Universitetet (UNT); (c) Mörby centrum (MÖR). The metro train, heading south, is represented by rounded rectangles, indicating individual car units. The double arrows indicate the platform access points and the gray shaded parts indicate the non-walkable areas.

available for the five selected metro stations (Fig. 3). The train stop location on the platform is assumed to be known.

3.3 On-board passenger load profile

The average crowding level across the analysis period in each of the three metro cars is illustrated in Fig. 4. On average, between DAS and TEH the front train car exhibits the largest passenger load in the morning rush hour, in particular from 7:30 am to 8:30 am. The south entrances of these four stations are located close to popular bus terminals and the main campuses of KTH Royal Institute of Technology (Tekniska högskolan) and Stockholm University (Universitetet), thus yielding a skewed distribution of passengers on-board the train. However, at MÖR, which has only one entrance located close to the middle of the platform, the middle train car tends to be the car with slightly higher crowding level.

4 Results

4.1 Impact of on-board crowding

To evaluate the impact of on-board crowding in the arriving train on the passenger boarding distribution between cars, the share of boarding passengers in each metro car is plotted against the total arriving train passenger load in Fig. 5. The arriving train load at station s is equal to the train passenger load at departure from station $s-1$, $q_{j,s-1}^{onboard}$. It can be observed that the boarding share in the front car decreases with the passenger load in the arriving train. Conversely, for the middle and rear cars, the share of boarding passengers seems to increase for larger passenger loads.

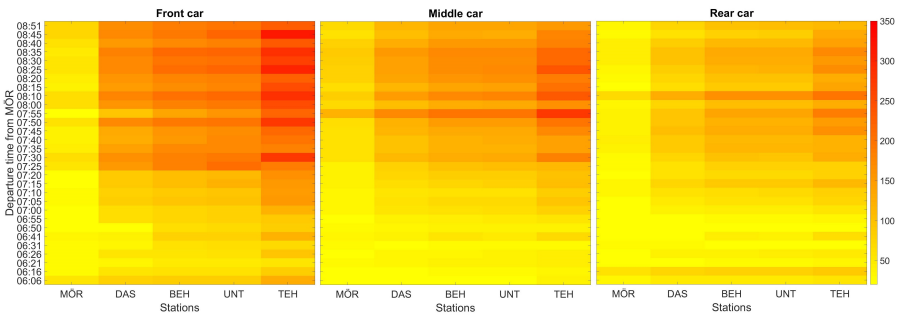

Fig. 4 Average metro car load for train trips departing from each station. *Left*: Front car. *Middle*: Middle car. *Right*: Rear car.

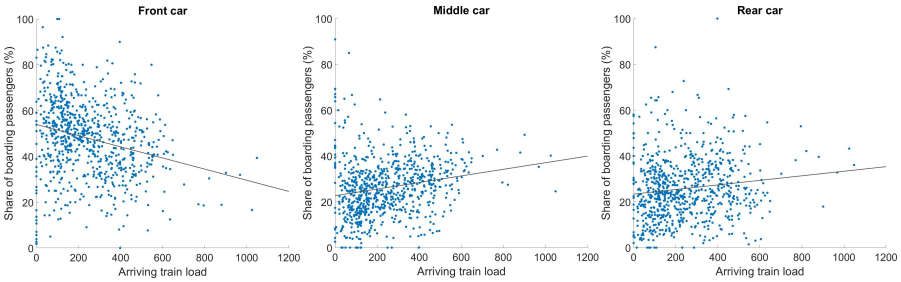

Fig. 5 Share of boarding passengers (%) in individual metro cars as a function of the arriving train passenger load.

4.2 Impact of station layout and entering traveller flows

A hypothesis is that the passenger car boarding distribution can be partly affected by the physical infrastructure of the platform and the access point locations as well as the incoming passenger counts at each platform entrance (Szplett and Wirasinghe 1984). Fig. 6 and 7 show the share of passengers boarding each metro car as a function of the share of incoming passenger counts at the south and middle access point of the southbound platform, respectively. MÖR is the only station of the considered segment that has a single access point at the middle of the platform; hence, the share of incoming passengers at the middle platform entrance is either 100% for the observations at this station, or 0% for the observations at the other stations. It is shown that for larger proportions of passengers entering the southern platform entrance, the boarding share increases in the front car and decreases in the middle and rear cars. As can be expected, the existence of an access point at the middle of the platform leads to increasing boarding share for the middle car.

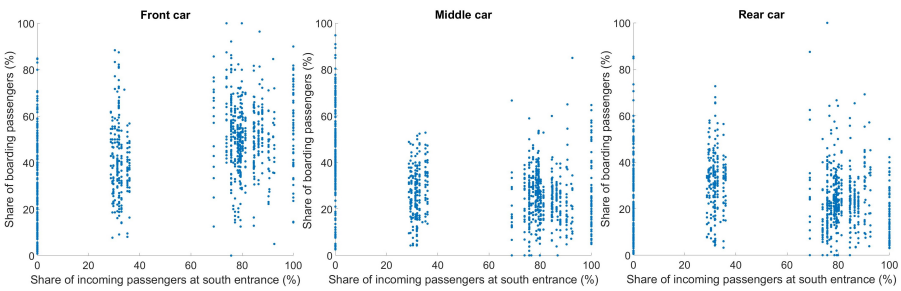

Fig. 6 Share of boarding passengers (%) in individual metro cars as a function of the share of incoming passenger counts at the south platform entrance.

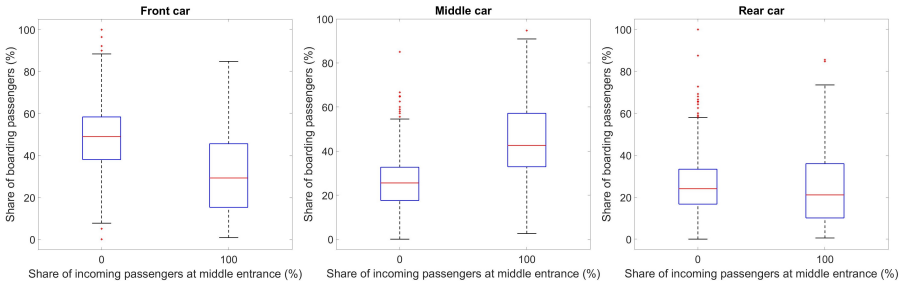

Fig. 7 Boxplots representing the share of boarding passengers (%) in individual metro cars as a function of the share of incoming passenger counts at the middle platform entrance.

4.3 Impact of platform crowding

According to Leurent (2011), crowding on the platform, indicated by the number of waiting passengers, critically affects on-board crowding. Figure 8 indicates the boarding share of each metro car as a function of the number of passengers waiting on the platform prior train departure. It can be observed that for the middle car, the boarding share increases with the number of passengers waiting on the platform. For the front and rear cars, the boarding share decreases with the platform crowding.

4.4 Multiple regression analysis

To evaluate the impact of on-board and on-platform crowding as well as the share of entering travellers at the south and middle platform access points on the boarding share of each train car i ($i = 1, 2, 3$), regression models

$$p_{ijs}^{board} = \alpha_i + \beta_{1,i} * q_{j,s-1}^{onboard} + \beta_{2,i} * p_{js,south}^{arrive} + \beta_{3,i} * p_{js,middle}^{arrive} + \beta_{4,i} * q_{js}^{wait} + \varepsilon_{ijs} \tag{7}$$

are estimated using the backward elimination approach.

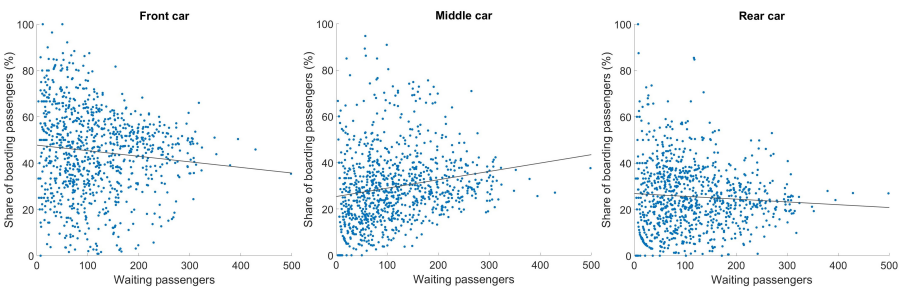

Fig. 8 Share of boarding passengers (%) in individual metro cars as a function of the number of passengers waiting on the platform.

Table 2 Regression results for the share of passengers boarding each metro car for models I and II.

	I		II	
	Front car			
Variable	**Estimate**	**t-statistic**	**Estimate**	**t-statistic**
Intercept	43.8%	21.56	43.7%	21.55
$q_{j,s-1}^{onboard}$	-0.03%	-7.95	-0.03%	-8.36
$p_{js,south}^{arrive}$ (%)	0.183%	7.43	0.178%	7.38
$p_{js,middle}^{arrive}$ (%)	-0.118%	-4.78	-0.126%	-5.42
q_{js}^{wait}	-0.007%	-1.02	-	-
Observations	948		948	
R^2	0.257		0.257	
	Middle car			
Variable	**Estimate**	**t-statistic**	**Estimate**	**t-statistic**
Intercept	22.3%	12.89	19.9%	19.87
$q_{j,s-1}^{onboard}$	0.017%	5.82	0.018%	6.12
$p_{js,south}^{arrive}$ (%)	-0.0363%	-1.73	-	-
$p_{js,middle}^{arrive}$ (%)	0.198%	9.47	0.226%	16.58
q_{js}^{wait}	0.015%	2.51	0.012%	2.19
Observations	948		948	
R^2	0.266		0.263	
	Rear car			
Variable	**Estimate**	**t-statistic**	**Estimate**	**t-statistic**
Intercept	33.9%	18.91	33.7%	18.86
$q_{j,s-1}^{onboard}$	0.011%	3.42	0.01%	3.22
$p_{js,south}^{arrive}$ (%)	-0.147%	-6.76	-0.153%	-7.20
$p_{js,middle}^{arrive}$ (%)	-0.0806%	-3.71	-0.0897%	-4.38
q_{js}^{wait}	-0.007%	-1.27	-	-
Observations	948		948	
R^2	0.069		0.068	

Analysis results for Model I, presented in Table 2, show that the arriving train passenger load is statistically significant for all train cars at the 5% level. The share of incoming flow at the south entry location is found to have a highly statistically significant impact on the share of passengers boarding the front and rear cars, while the boarding share of the middle car is not significantly affected at the 5% level. For each car, the arriving pedestrian flow at the middle platform entrance is significant at the 5% level. Model results indicate that the number of passengers waiting on the platform prior train departure j does not have a significant effect for front and rear cars (p-value > 0.05).

Insignificant predictors are excluded through backward elimination, and the final regression model (model II) for each metro car i ($i = 1, 2, 3$) is

$$\begin{aligned} p_{1,js}^{board} &= \alpha_i + \beta_{1,1} * q_{j,s-1}^{onboard} + \beta_{2,1} * p_{js,south}^{arrive} + \beta_{3,1} * p_{js,middle}^{arrive} + \varepsilon_{1,js} \\ p_{2,js}^{board} &= \alpha_i + \beta_{1,2} * q_{j,s-1}^{onboard} + \beta_{2,2} * p_{js,middle}^{arrive} + \beta_{3,2} * q_{js}^{wait} + \varepsilon_{2,js} \\ p_{3,js}^{board} &= \alpha_i + \beta_{1,3} * q_{j,s-1}^{onboard} + \beta_{2,3} * p_{js,south}^{arrive} + \beta_{3,3} * p_{js,middle}^{arrive} + \varepsilon_{3,js} \end{aligned} \tag{8}$$

The regression model II yields the estimation results summarized in Table 2. The remaining variables have a measurable statistically significant effect on the car boarding share at the 5% level.

Model II results indicate that an increase of arriving train load by 1 unit, if the other predictors remain constant, is associated with a 0.03% points decrease in the boarding share of the front car. The share of travellers entering

the south entry point has a positive marginal effect, 0.178% points per passenger share %, on the boarding share in the front car which is closer to the south platform access point. The arriving flow at the middle platform entrance is found to increase the boarding share of the middle car by 0.226% points per passenger share %. The estimated impact of the crowded platform variable on the boarding share of the middle car is obtained as 0.012% points, indicating that for larger number of waiting passengers on the platform, passengers tend to walk to the middle of the platform. Although the coefficient corresponding to the crowded platform variable seems to be low, the impact of the variable is high; holding the remaining predictors constant, the share of passengers boarding the middle car increases by 1.2% points for every additional 100 passengers waiting on the platform.

The residuals of the regression models are analyzed for violations of the regression analysis assumptions and found to be normally distributed. Two alternative models are also evaluated. The seated capacity of the metro train, denoted by γ^{seat}, is used to classify each metro train into one of two categories: crowded and not crowded. In the first alternative model, the crowded train variable CT_{js}, defined as

$$CT_{js} = \begin{cases} q_{j,s-1}^{onboard}, & \text{for } q_{j,s-1}^{onboard} \geq \gamma^{seat} = 378 \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

is used as independent variable instead of the arriving train passenger load $q_{j,s-1}^{onboard}$.

The second alternative model specification considers the crowded train indicator CI_{js} as a binary variable, taking value 1 for crowded and 0 for not crowded arriving train.

$$CI_{js} = \begin{cases} 1, & \text{for } q_{j,s-1}^{onboard} \geq \gamma^{seat} = 378 \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

Both alternative models are found to have lower explanatory power than Model II.

The test data set (237 observations) is used to estimate the root mean square errors (RMSE) of the linear regression models as a measure to examine if the selected model has the best performance. We find that model II has the lowest deviation between the predicted and observed values compared to the alternative regression models. For Model II, it is found that the average size of the residual (RMSE) is equal to 0.168, 0.134 and 0.136 for the front, middle and rear car, respectively, indicating that the model is better in predicting the boarding share in the middle and rear cars. The RMSE from the historical mean forecasts is also estimated for each metro car and compared to the RMSE for the regression model II. It is found that the ratio of the RMSE's for Model II and the historical mean model is less than one, indicating that Model II provides superior forecasts.

5 Conclusion

We propose a methodology based on a combination of multiple automated data sources to evaluate the effects of on-board and on-platform crowding, as well as entering traveller flow at each platform access point, on the distribution of passengers across the metro train. The methodology is applied to a case study for the Stockholm metro system. Three automatically collected data sources, metro car passenger loads, smart card tap-in data and aggregate station-to-station travel demand, are fused to evaluate the effect of potential variables on the load imbalance between the cars of the train.

On average, train car loads at the studied stations are highly skewed towards the leading cars. Analysis results show that crowding on-board the arriving train has a statistically significant positive impact on the boarding share of the middle and rear cars, which are shown to generally be the less crowded cars. The shares of incoming passengers at the south and middle platform access points are found to increase the share of boarding passengers in the front and middle car, respectively. These findings suggest that the share of incoming passengers at an access point positively affects the boarding share of the closest car, implying that passengers aim to minimize the walking distance at the origin station.

Platform congestion, given by the number of waiting passengers prior train departure, is observed to have a statistically significant positive impact on the boarding share of the middle train car, showing that passengers choose to wait at the middle section of the platform aiming to minimize discomfort and as a result, the passenger distribution between cars tends to be less uneven at higher on-platform crowding.

The study is limited to identify factors that affect the car boarding choice related to passengers' origin location, since smart-card tap-outs are not available for metro users in Stockholm. Data about passengers' destination stop, in-vehicle travel time as well as the walking distance of each passenger will presumably explain some of the variability in car boarding choice.

This study may be useful for metro operators for increasing the understanding of the uneven passenger distribution across the train. The study results could be generalized by studying other metro transit locations with different demand level and characteristics. In a future work, the estimated outgoing traveller flow at individual platform access points could be used to analyze the alighting share of individual cars and examine other factors related to passengers' destination stop that affect passenger car choice.

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