Measuring train crowding unevenness: A Stockholm metro case study

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ABSTRACT
We propose a methodology for quantifying the unevenness of the crowding distribution among the cars of rail transit vehicle. The proposed train crowding unevenness metric is defined as the total experienced crowding, normalized between 0 and 1 across all possible distributions of the same total train load. The methodology is demonstrated for the metro network in Stockholm, Sweden based on automated car load data. Train crowding unevenness is found to be lower at departure from inner city metro stations and especially during the highest peak of the morning rush hour; this finding suggests that the uneven distribution of passengers in the train is critically affected by the total passenger load inside the vehicle. Investigating this interaction, we found that train crowding evenness increases with the on-board passenger load. Certain metro stops are exceptions to the aforementioned finding which could be explained by the existence of a popular or a single station access point that leads to skewed distribution of passengers on the platform prior the arrival of the train. These insights may be used by transit planners and operators to increase the understanding of how passengers are distributed in the train along the metro line and eventually increase the capacity utilization of the trains through investments in infrastructure or operational interventions and thereby reduce the experienced on-board crowding level.

1. Introduction

The increasing mobility in many cities leads to higher congestion levels at many public transport stations and inside the transit vehicles, especially during peak periods. There is a general need to improve the performance of the public transport system and the level of service.

On-board crowding levels increase when passengers are not uniformly distributed on the platform and eventually inside the vehicle. Passenger loads can be highly unevenly distributed along platforms and between the cars of trains 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 operating costs, as well as a higher experienced crowding discomfort. Some studies aim at reducing the skewness of the passenger distribution in the train by determining the optimal train stop location along a platform (Sohn 2013) or by means of providing real-time crowding information (Zhang et al. 2017).

There is a number of indicators used in the literature to measure perceived the

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Table 1. Notation

i	Train car index, $i = 1, \ldots, I$
j	Train trip index
s	Station index $s = 1, \ldots, S$
κ	Total train car capacity
TCU_js	Train j crowding unevenness metric at station s
$w_{js}^{observed}$	Observed total experienced crowding in train j at station s
w_{js}^{min}	Minimum total experienced crowding in train j at station s
w_{js}^{max}	Maximum total experienced crowding in train j at station s
q_{ijs}	Train car load at departure
$\beta(q)$	In-vehicle time multiplier for $0 \leq q \leq \kappa$

crowding level on-board the vehicle. Hensher et al. (2011) estimated the crowding disutility as a function of the proportion of sitting passengers and the number of standing passengers. The number of standing passengers per m^2 and the seat occupancy, which are interacted with the in-vehicle time, are used by Tirachini et al. (2014) to represent the disutility of crowding. A review of the range of the objective and subjective on-board crowding indicators is provided by Li and Hensher (2013). Although these measures provide a quantitative metric of perceived crowding , they do not capture the crowding unevenness in the train. A better understanding and a more accurate representation of train crowding would help to design a more attractive public transport system. In this study, a framework is proposed for quantifying the crowding unevenness on-board the train utilizing passenger load data of each car. Applying the proposed train crowding unevenness metric, the propagation of train crowding unevenness is investigated and the performance of the metro system in Stockholm, Sweden is evaluated.

The remainder of the paper is structured as follows. The methodology proposed to quantify the train crowding unevenness is provided in section 2. A case study for the Stockholm metro network is described in Section 3. The performance of the network is presented in Section 4. Section 5 draws conclusions, assesses the limitations of the study and outlines follow-up work.

2. Methodology

This section presents the framework for quantifying the unevenness of crowding on-board a multi-car train and evaluating the performance of the system. The proposed framework requires the utilization of data that can capture the on-board passenger load of each car. The notation used in this section is summarized in Table 1.

Passenger loads q_{ijs} for each train run j, station s and car i describe the utilization of each train car and may be obtained through the car weighing devices which modern trains are often equipped with or sensors installed at the vehicle doors. The passenger load data of each car upon departure from the station is used to characterize the in-vehicle crowding.

Each of the elements included in the estimation of train crowding unevenness metric, denoted by TCU_{js}, consists of the multiplication of the passenger load of each car i after train j departs from stop s and the respective in-vehicle multiplier, $\beta(q_{ijs})$, which is a monotonically increasing function reflecting the perceived in-vehicle time. An alternative measure of this function can be obtained as a special linear case by using $\beta(q_{ijs}) = q_{ijs}$. This captures the crowding experienced by each passenger in terms of number of passengers, but without adding any valuation as to how this crowding is perceived.

The actual total experienced crowding, denoted by $w_{js}^{observed}$, is the in-vehicle time multipliers summed over all passengers in the train.

$$w_{js}^{observed} = \sum_{i \in I} \Big[q_{ijs} \cdot \beta(q_{ijs}) \Big] \tag{1}$$

The minimum total experienced crowding, w_{js}^{min}, corresponding to the case that the same total number of passengers are evenly distributed among the train cars, is given by

$$w_{js}^{min} = \sum_{i \in I} q_{ijs} \cdot \beta\left(\frac{\sum_{i \in I} q_{ijs}}{|I|} \right) \tag{2}$$

The maximum total experienced crowding, w_{js}^{max}, corresponding to the case that the same total number of passengers is as unevenly distributed as possible among the train cars, is given by

$$w_{js}^{max} = \left\lfloor \frac{\sum_{i \in I} q_{ijs}}{\kappa} \right\rfloor \cdot \kappa \cdot \beta(\kappa) + \left(\sum_{i \in I} q_{ijs} - \kappa \cdot \left\lfloor \frac{\sum_{i \in I} q_{ijs}}{\kappa} \right\rfloor \right) \cdot \beta\left(\sum_{i \in I} q_{ijs} - \kappa \cdot \left\lfloor \frac{\sum_{i \in I} q_{ijs}}{\kappa} \right\rfloor \right) \tag{3}$$

In this situation, all passengers are located in the same car until it reaches capacity; the remaining passengers are located in another car, and so on until no passengers remain.

The train crowding unevenness metric after the train j departs from station s, denoted as TCU_{js}, is the normalized unevenness out of the possible range and resembles the Gini coefficient, measuring how far the passenger distribution in the train deviates from a totally equal distribution.

$$TCU_{js} = \frac{w_{js}^{observed} - w_{js}^{min}}{w_{js}^{max} - w_{js}^{min}} \tag{4}$$

Train crowding unevenness metric TCU_{js} takes the value 0 in case of perfect evenness in the train - on-board crowding is minimal given the overall passenger load level, i.e. passengers are equally distributed over all train cars and the value 1 in case of perfect unevenness - on-board crowding is maximal given the overall passenger load level, i.e. passengers are filling cars in succession.

A numerical example

Let us consider a 3-car train with equally utilized cars. The car load q_{ijs} is assumed to be 150 passengers, while the car capacity, κ, is 300 passengers. The in-vehicle time multiplier in this study is given as a linear case by using $\beta(q_{ijs}) = q_{ijs}$. The actual total experienced crowding $w_{js}^{observed}$ in the train is equal to the minimum total experienced crowding w_{js}^{min} that is estimated to be experienced as 67500 $pass^2$. This implies that for the case of fully even load distribution, the train crowding unevenness index is 0.

Considering the case where the passenger load is 200, 100 and 0 in the 3 different cars of the train, the actual total experienced crowding is 50000 $pass^2$, while the minimum experienced load is 30000 $pass^2$. In the most uneven load distribution, the

Figure 1. A map of the metro network in Stockholm, Sweden. Map source: AB Storstockholms Lokaltrafik

passengers fill one car until it fully reaches its capacity and hence, the maximum total experienced crowding w_{js}^{max} is estimated to be equal to 90000 $pass^2$. The normalized train crowding unevenness is then 0.33.

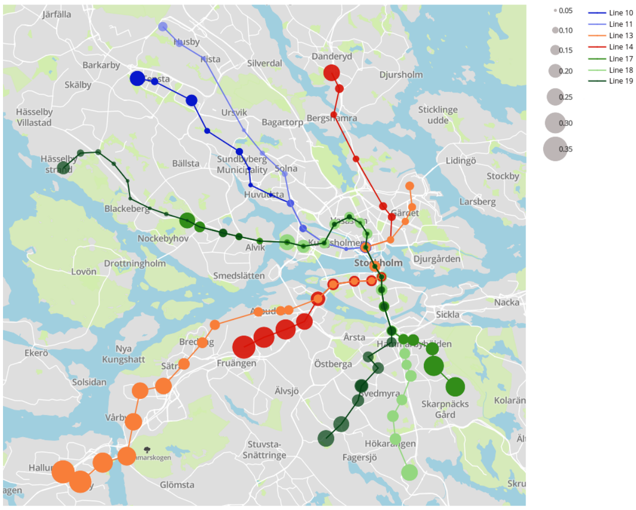
3. Case study

The proposed methodology is applied to a case study for the metro network in Stockholm (Fig. 1). The Stockholm metro network consists of 7 lines, all of which use the T-centralen hub.

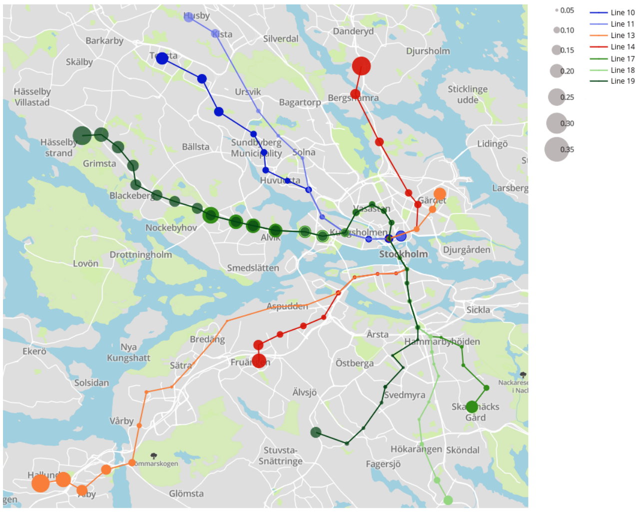
In order to apply the proposed framework, data about the passenger load in individual cars of the train is required. Passenger load data for each car unit is available for each train trip, operating by the 3-car metro trains, upon departure from each station during the morning rush period (6:00 am - 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. According to the train manufacturer, the design capacity of a car unit is 126 seated passengers and 288 standees.

4. Results

Train crowding unevenness metric TCU_{js} is estimated for all the train trips operating during the morning peak period in October 2016, serving either the total length or shorter segments of each metro line in Stockholm. Figures 2(a) and 2(b) demonstrate the average train crowding unevenness upon departure from a station of the train trips serving the southbound and northbound direction, respectively. On average, train trips departing from the inner city stations exhibit the lowest TCU_{js}, i.e. the most uniform



(a)



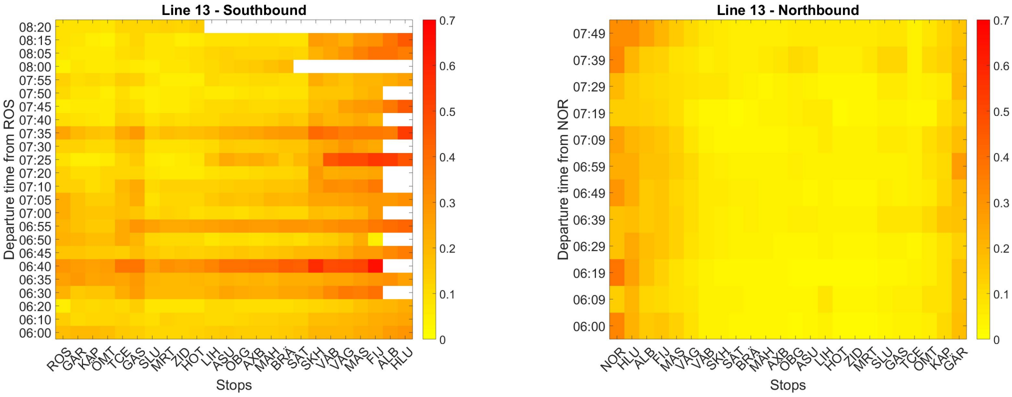
(b)

Figure 2. Performance of Stockholm metro network (morning peak period) (a) Southbound direction; (b) Northbound direction. The bubble size increases with the train crowding unevenness metric.

crowding distribution between individual train cars. Train crowding is observed to be more uneven when departing from the terminal stations, located close to the starting/ending points of the metro lines. Trains heading south are found to be on average less uniformly loaded. For demonstration purposes, the performance of lines 13 and 14, which exhibit large unevenness on board the trains operating on the southbound direction, is presented in this section.

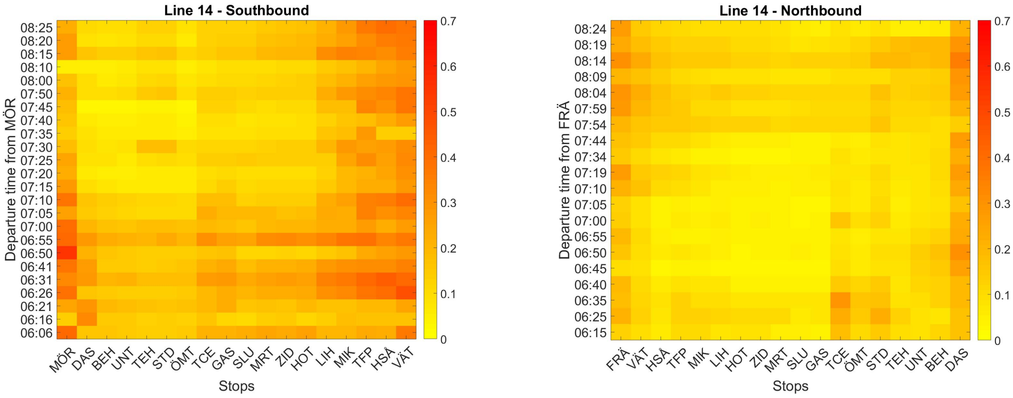
4.1. Train crowding unevenness variation over time

Figures 3 and 4 present the average train crowding unevenness for the train trips, showing the variation of crowding unevenness with time during the morning peak period. Train trips operating on a shorter part of the metro line, serving some of the stations of the line are included in the analysis; uncolored cells represent missing data



(a) (b)

Figure 3. Average train crowding unevenness for train trips departing from a station of metro line 13 (a) Southbound; (b) Northbound.



(a) (b)

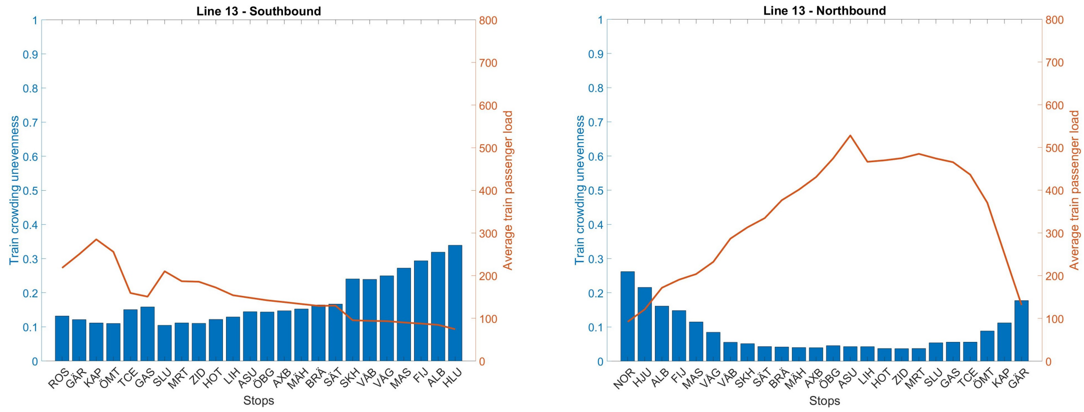
Figure 4. Average train crowding unevenness for train trips departing from a station of metro line 14 (a) Southbound; (b) Northbound.

for a train trip.

Trains serving the stops on the southbound direction of the red metro lines, shown in figures 3(a) and 4(a), are found to exhibit the most uneven passenger distribution in the morning peak hour of the analysis period, being on average, equal to 0.18, while the most uniform distribution of crowding is observed between 07:30 and 08:30 am. On the other hand, trains serving the north direction of line 13 are among the most uniformly loaded in the morning peak hour (Figure 3(b)). Crowding unevenness metric is found to be on average equal to 0.08 in trains serving the aforementioned metro line.

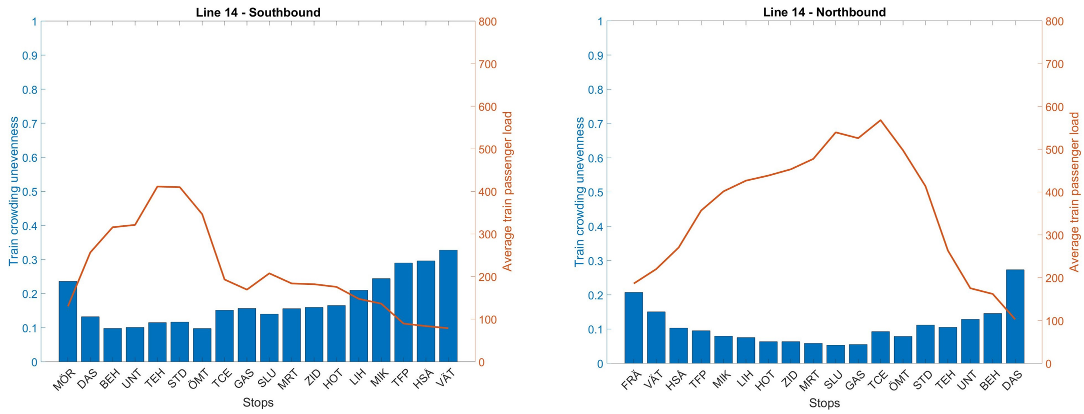
4.2. Effect of on-board passenger load

On average, train crowding unevenness along each metro line and over time is found to be lower at departure from inner city stations between 07:30 and 08:30 am, when the metro system experiences the highest demand. This suggests that crowding unevenness in the train is affected by the total number of passengers being on-board the vehicle upon departure. To investigate the effect of the total on-board passenger load on the



(a) (b)

Figure 5. Performance of metro line 13 (a) Southbound; (b) Northbound.



(a) (b)

Figure 6. Performance of metro line 14 (a) Southbound; (b) Northbound.

train crowding unevenness after the train departs from a station, the propagation of train crowding unevenness along the metro lines and the relation between the average TCU_{js} after the train departs from a metro station and the average total on-board passenger load for all metro lines are presented in figures 5 and 6. It is observed that on average, for larger total passenger load in the train, the TCU_{js} takes lower values, which implies that that passengers are more uniformly distributed between different cars of the train.

The train crowding unevenness in the train trips of the red metro line 13 is observed to be lower for larger average on-board total passenger load (Fig. 5). Trains heading north are quiet evenly loaded at the inner city stations, where the average TCU_{js} is lower than 0.05 (Fig. 5(b), 6(b)). Although the average on-board load in the trains, heading north and dwelling at Liljeholmen (LIH) is observed to decrease sharply, i.e. there is a large number of alighting passengers, the distribution of passengers in the train remains quiet uniform. The almost equal number of passengers alighting from each train car could possibly explain this finding, implying that alighting passengers are eventually evenly distributed on the northbound platform at LIH.

Figure 6 presents how the average train crowding unevenness propagates along the red metro line 14 in the morning rush hour. Although trains at T-centralen (TCE), heading north, have the largest average passenger load, they do not have the most uniform passenger distribution as it could be expected (Fig. 6(b)). The highly uneven distribution of passengers on the platform prior to boarding due to the existence of a popular access point at TCE might explain the average TCU_{js} value.

The large number of alighting passengers at the southbound platform at TCE for both red metro lines leads to an increase of the train crowding unevenness metric due to the fact that most of the on-board passengers alight from a certain train car (Fig. 5(a), 6(a)).

5. Conclusions

We present a methodology that utilizes automated car passenger load data to quantify the crowding unevenness on-board the train and evaluate the performance of the system. The train crowding unevenness metric is defined as the total experienced crowding, normalized between 0 and 1 across all possible distributions of the same total train load. An application of the proposed methodology is carried out for the Stockholm metro network, including both directions of 7 metro lines. For demonstration purposes, the analysis results of the red metro lines has been discussed in this paper. For this case study, car load data, involving the trips over a one-month period is utilized.

It is found that on-board passenger load is on average less uniform upon departure from stations located close to the terminal points of the line, while trains are more evenly loaded at the inner city metro stations, especially between 07:30 and 08:30 am, when the highest travel demand is usually observed. This finding suggests that the train crowding unevenness is affected by the total passenger load in the vehicle. For this reason, the interaction between on-board train passenger load and the train crowding unevenness has been investigated at each station of the metro lines in Stockholm. We find that the train crowding unevenness increases with the decrease of on-board passenger load. However, the passenger distribution in the train is found to be skewed even for an increase in the total on-board load at departure from specific stations. This is presumably due to the presence of a single access point that leads to skewed distribution of passengers on the platform prior the arrival of the train.

The proposed train crowding unevenness metric has been demonstrated for the metro network in Stockholm; however, the methodology is general and could be applied to any other train system without any limitations. The study is useful for metro operators to understand the uneven passenger distribution across the train and increase the utilization of the train capacity, thereby reducing the operating costs through infrastructure investments or operational changes. Infrastructure interventions, such as re-planning of the station layout and rearrangement of the location of entrances, or operational interventions, such as implementation of real-time information system informing passengers about the crowding level across the platform and in the arriving train, could reduce unevenness of train crowding and hence, reduce the vehicle requirements and increase passenger experienced comfort on-board the train.

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