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Evaluating skip-stop policy in urban rail transit systems based on passenger cost

Soumela Peftitsi [a], Erik Jenelius [a], Oded Cats [a,b]

[a] Division of Transport Planning, KTH Royal Institute of Technology, Stockholm, Sweden
[b] Department of Transport and Planning, Delft University of Technology, Delft, the Netherlands

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ABSTRACT

Increasing the operating speed in public transport systems can increase the system capacity, reduce the overall passenger travel time and improve experienced comfort. Skip-stop operation, where subsets of the trains operating on the same tracks skip certain intermediate stops, can accelerate the service and improve passengers' overall travel experience. This paper considers the problem of deciding whether skip-stop operation is beneficial for a given line and which stopping scheme is the most effective. In particular, we investigate whether a simple decision rule for determining the stopping pattern under a skip-stop strategy, derived from the expected weighted time benefits to the passengers, can reliably determine the most suitable skip-stop scheme. To evaluate the impact of alternative stop-skipping strategies, we adopt the existing public transit assignment model BusMezzo, which allows for a realistic representation of passengers' experienced waiting and in-vehicle travel times and the resulting trade-offs between passenger costs and benefits. The decision rule is applied to a set of high-frequency urban rail lines in Stockholm, Sweden. We show that a simple decision rule may not be a robust way of determining a beneficial skip-stop scheme. The results from the case study reveal that the skip-stop operation can have an overall positive impact on passenger generalized travel time but only under certain conditions at the stops along the line.

1. Introduction

Urban rail transit systems around the world face growing travel demand, which is often heterogeneous among stations and often reaches capacity during peak hours. To accommodate the high demand, operators may increase the capacity by using additional transit vehicles, which can be very expensive. Alternatively, increasing the operating speed can increase the capacity at a relatively low cost as a result of shorter cycle times and hence, a larger number of trips that can serve the transit line. Thus, faster operation can improve passengers' travel experience as a result of shorter travel times and reduced on-board crowding. Operational strategies that can increase operating speed, alleviate crowding and service variability have been reviewed by Gkiotsalitis and Cats (2021) and include rescheduling, short-turning (Leffler et al., 2017), vehicle holding (Gkiotsalitis and Cats, 2019), transit priority control strategies (Liang et al., 2022), as well as the design of skip-stop lines (Ibarra-Rojas et al., 2015). Under skip-stop operations, subsets of the trains operating on the same tracks skip certain intermediate stops and serve only a subset of the stops. Consequently, stop-skipping is effective in shortening run times and passenger travel times (Zhou et al., 2020). Moreover, its implementation in real-time can mitigate traffic disturbances and disruptions.

Skip-stop operation was first developed for Chicago urban metro trains in 1948 as a means of increasing the train speed and was maintained for several years (Chicago-L.org, 2021). Since then, this policy was implemented in the metro systems of Philadelphia, New York, and Santiago, Chile (SEPTA, 2022; MTA, 2022; Freyss et al., 2013). A skip-stop policy was introduced in commuter rail traffic in Stockholm, Sweden in 2017. However, due to passengers' dissatisfaction with the lower service frequency at the skipped stops, it switched back to an all-stop operation after a year of operation.

A typical skip-stop policy is the A/B skip-stop operation (Fig. 1). This mode of operation involves two transit lines and three sets of stations. Line A only serves stations A and AB, while line B serves stations B and AB (Vuchic, 1976,2005; Freyss et al., 2013; Lee et al., 2014). Under such a skip-stop policy, a group of passengers is expected to benefit from shorter in-vehicle times, while other passenger groups may experience longer actual and/or perceived travel times due to the need for transfers as well as a lower service frequency at the skipped stops. An early study by Vuchic (1976) discussed the advantages and disadvantages of the

E-mail address: soumela@kth.se (S. Peftitsi).

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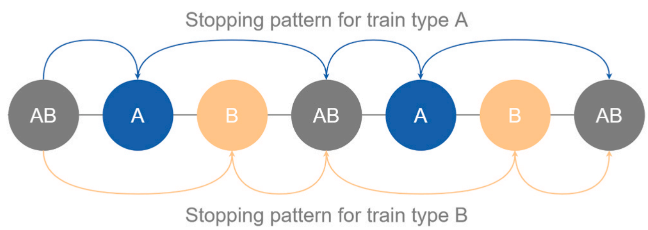


Fig. 1. A/B skip-stop operation.

A/B skip-stop operation, providing a list of considerations for selecting the stops to be skipped. To avoid variability of headways at the AB stops and keep even passenger loading between the transit lines, an equal number of A and B stops, both of low and similar demand, should be skipped. In addition, consecutive A and B stops should be avoided to minimize the number of passengers traveling in the backward traffic direction.

Several studies have focused on finding the optimal stopping patterns at the tactical planning level, where the stopping pattern is fixed and communicated to passengers and drivers well in advance, aiming to minimize passenger travel time (Lee et al., 2014; Huang et al., 2017; Yang et al., 2019), operating cost (Jamili and Pourseyed Aghaee, 2015), or both (Suh et al., 2002; Cao et al., 2014; Chen et al., 2015; Gkiotsalitis, 2019). Gu et al. (2016) explored the skip-stop policy for bus services aiming to minimize passenger, operating, and infrastructure costs. Lee et al. (2014) developed a model that coordinates stopping and skipping stops based on the O-D trips, showing that the implementation of a well-coordinated skip-stop operation in the Seoul metro system in South Korea can potentially reduce passenger total travel time by 20 %. To quantify the effects of the skip-stop operation, Freyss et al. (2013) proposed a continuous approximation approach aiming to find the optimal density of stations rather than the stopping pattern, showing that skip-stop policies are less beneficial in the case of short lines with few stops, low station density, and lines of lower service frequency.

The latter was confirmed by Cao et al. (2014), who showed that the shorter the headway, the lower the costs caused by the skip-stop policy. The stopping patterns that minimize passenger and operating costs were found to be sensitive to the demand level (Chen et al., 2015). Notwithstanding the potential net benefits of skip-stop policies, some passengers may be forced to make a transfer, which burdens them with additional waiting time and a transfer penalty. A study by Salama et al. (2019) focused on producing the optimal stop-skipping pattern so that the number of direct trips is maximized.

In contrast to skip-stop as a tactical planning strategy, dynamic stopping patterns are determined in real-time shortly before the dispatching of the vehicle run from the terminal (Fu et al., 2003; Sáez et al., 2012; Liu et al., 2013). To minimize passenger waiting cost at the skipped stops, Fu et al. (2003) optimized the skip-stop strategy while enforcing that a stop is not allowed to be skipped by two consecutive runs. Liu et al. (2013) determined the dynamic stopping patterns, with the skip-stop operation being applied to every other vehicle departing from the terminal station. Sun and Hickman (2005) investigated dynamic stop-skipping that can also be determined after the vehicle departed from the terminal station, allowing for en-route responses to disruptions. Addressing the dynamic skip-stop problem is a complex problem and requires the communication of the stopping patterns that are determined in real-time to passengers and drivers.

Simulation models have been used in many studies as a tool for determining and evaluating the stopping pattern. Suh et al. (2002) used a simulation model for evaluating the skip-stop operation for the metro system in Seoul, South Korea, considering several alternative stopping patterns based on the number of boarding and alighting passengers at each station. The simulation results showed that the skip-stop policy, despite resulting in longer waiting times, leads to total travel time savings. A simulation-based optimization model for the stop-skipping problem was proposed by Wu et al. (2019). The model considers vehicle overtaking and demand dynamics for minimizing waiting and in-vehicle times as well as operating costs. Farrando et al. (2020) simulated vehicle movements on a mass transit line where stops of low passenger travel demand are skipped, reporting an improvement in line frequency as a consequence of shortened cycle times. Huang et al. (2017) simulated both transit vehicle operations and passengers' boarding and alighting to evaluate the A/B skip-stop policy for both directions of a bus line, showing that it reduces bus bunching and cycle times and helps balance passenger loads. Parbo et al. (2018) selected the stopping patterns that minimize user cost and evaluated them by simulating passengers' behavioral responses.

Several rules for selecting the skipped stops have been adopted in the literature. These rules are often based on passenger volumes per stop or the trade-off between positively and negatively affected passengers if a single stop is skipped. However, the number of passengers affected by skipping a stop does not give insights into the effects on passenger travel time and the cost-benefit relationship. Therefore, this might lead to an overestimation of the expected benefits, since the respective time savings and costs are not directly accounted for. Also, most of the simulation models used in previous studies as an evaluation tool for skip-stop strategies are limited to capturing vehicle movements. Passengers' behavior in response to the skipping operation is usually not considered.

Further, many studies evaluate the stopping patterns based on the trade-off between passenger time savings and costs considering the nominal in-vehicle time savings resulting from dwell time savings and increased operating speed. In crowded conditions inside transit vehicles, however, passengers may perceive in-vehicle time as longer than the nominal. Therefore, the benefits of skip-stop operations may be underestimated when passengers' perception of in-vehicle time is not taken into account. Although several studies have evaluated the effects of skip-stop policies on passengers' total travel time, there is still limited research on assessing this operation concerning on-board crowding.

The objective of this study, motivated by the aforementioned shortcomings, is to propose a methodology based on agent-based transit assignment and simulation for determining when skip-stop operations can be implemented in a transit system. The outcomes are compared to a simple method, based on directly accessible travel and passenger demand information. We investigate to what extent a simple decision rule can be used as a proxy for the full simulation-based framework when deciding the most effective skip-stop scheme. The main contributions of the paper are threefold:

- An agent-based transit assignment model that simulates rolling stock circulation and individual passengers' route choices and models dwell times as a function of boarding, alighting, and on-board passengers is proposed as the methodology for evaluating skip-stop policy. In addition, the methodology simulates passengers' train-carriage boarding decisions and hence captures the distribution of passengers and perceived travel time among individual train carriages.
- A stopping pattern selection rule is proposed where the stopping pattern is determined based on the expectations about the weighted excess waiting time and the weighted saved in-vehicle time as a result of skipping a stop. The effect of on-board crowding on passenger discomfort is considered in estimating the savings in perceived in-vehicle time.
- The impact of alternative stopping patterns on passenger travel time savings is assessed at the tactical planning stage in terms of passenger generalized travel time, including experienced on-board discomfort, thereby providing a more realistic representation of how the skip-stop policy affects passengers' travel experience.

The paper is organized as follows: In Section 2, we present the passenger groups that are affected by the skip-stop policy, propose a decision rule for determining the stopping patterns under this policy and describe the simulation framework used as an evaluation tool. Following this, in Section 3, we describe the real-world case study used to demonstrate the application of the skip-stop decision rule. Finally, Section 4 presents the results of the case study and Section 5 concludes the paper.

2. Methodology

To assess the skip-stop operation as a means of increasing the operating speed and thus, improving passengers' travel experience, we propose a process for determining the stopping pattern and evaluating the benefits of this operation to passengers. The next subsection formulates how different passenger groups are impacted by the skip-stop operation and introduces the main aspects for evaluating the determined stopping pattern. The following subsection then describes the decision rule for selecting the stopping pattern, based on the trade-off between the expected passenger time costs and benefits. Finally, the capabilities of the simulation model used to assess the impacts of the skip-stop operation are presented.

2.1. Impacted passenger groups

We investigate the effects of the A/B skip-stop operation on a single transit line. This model of operations corresponds to dividing the vehicle runs into two separate lines, A and B. Stops are categorized into three sets, stops A, B, and AB. Vehicles that belong to transit line A serve only stops A and AB, while vehicles of line B serve only stops B and AB.

Skipping stops can increase the operating speed which shortens in-vehicle times for a group of passengers as a result of the saved dwell times at stops A and B. However, under this operation, some passengers experience longer waiting times due to lower service frequency at the skipped stops, while others have to make a transfer at an AB stop when their origin and destination are not served by the same line, resulting in additional waiting times at the transfer stop. Thus, the effect of the A/B skip-stop operation is evaluated by taking the trade-off between the time benefits and costs into account.

Passengers who are affected by the skip-stop policy can be categorized into three groups based on the combination of origin and destination stations: *I) passengers experiencing shorter on-board times, II) transferring passengers, and III) passengers waiting longer* (Fig. 2).

Passengers in group *I* travel between AB stops and can take either line A or B, and thereby do not experience additional waiting time. This passenger group may be positively impacted by the skip-stop operation since they can experience shorter in-vehicle time due to saved passenger service time at the skipped stops located between the passenger's origin and destination, and saved time due to increased operating speed when there is no need for braking and accelerating. Skip-stop operation does not affect passengers who are traveling between AB stops when there is no skipped stop located between their origin and destination, since these passengers can take either transit line A or B and do not experience changes in waiting time or in-vehicle time.

The *transferring passengers* are those traveling between an A and a B stop, and hence, need to make a transfer at an AB stop, i.e. a stop that is served by both lines. These passengers experience longer waiting times at their origin as well as at the transfer station since their origin and destination stations are served by only one line operating with a lower frequency. Moreover, passengers' experience is burdened with a transfer penalty. If there is no AB stop located between the passenger's origin and destination, the passenger also needs to transfer to a station either upstream of their origin or downstream of their destination and travel in the backward traffic direction.

Passengers who belong to category *III* have origin or destination station of type A or B, i.e. they travel the following origin-destination (OD) trips, AB-A, A-AB, A-A, AB-B, B-AB, and B-B. These OD trips are served by a single line and are therefore operating with a headway, i.e. time interval between two consecutive train departures from a stop, that becomes twice as long. As a result, these passengers are negatively impacted by the skip-stop operation, since they have to wait longer at their origin.

2.2. Decision rule formulation

To formulate the rule for determining the stopping pattern under the A/B skip-stop operation as a means of improving passengers' travel experience, we consider a single bidirectional transit line of N stops per direction. Lines A and B are assumed to run at equal and high frequencies and depart alternately from the terminal station. Overtaking is not permitted. This assumption is considered reasonable for urban rail systems where vehicles operate on a double track, each of which serves one direction of traffic. Each stop s is classified into type AB, A, or B to indicate the line or lines that serve the station. In other words, a stop of type A is skipped by line B and vice versa, while both lines stop at AB stops. The notation used in the paper is listed in Table 1.

The decision rule requires passenger demand information, represented by an OD demand matrix of average passenger flows q_{ij} between origin station i and destination station j and travel time information,

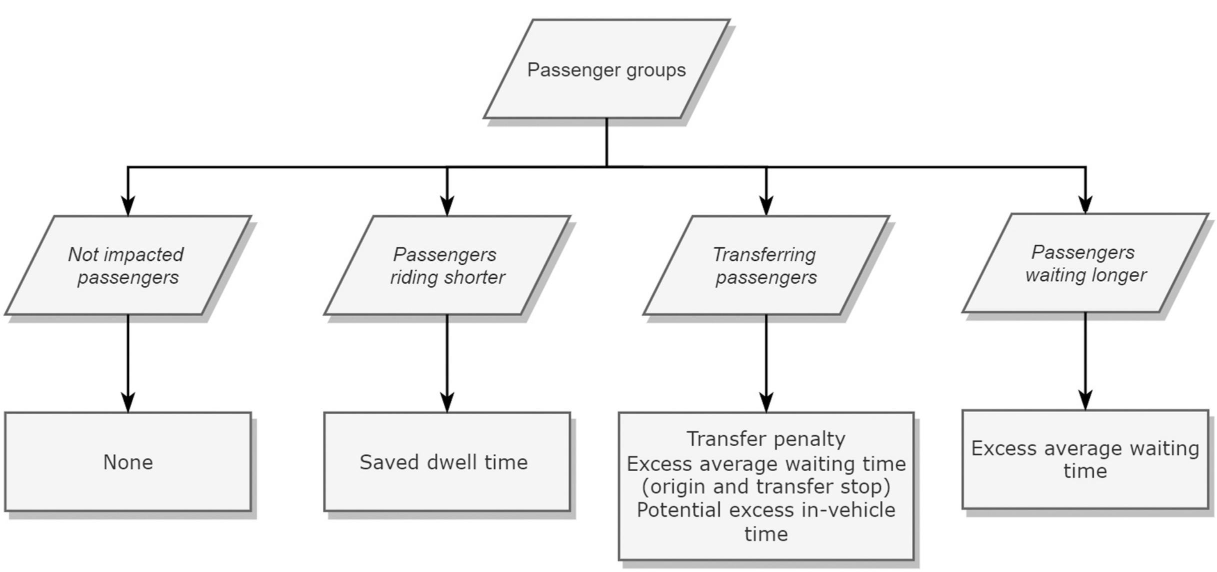


Fig. 2. Impacted passenger groups.

Table 1
Notation.

$i, j, s \in S$	Stop indices, $i, j, s = 1, \ldots, N$, $S = \{A, B, AB\}$
$l \in L$	Transit line, $L = \{A, B\}$
h	Service headway i.e. time interval between two consecutive train departures of transit line l
q_{ij}	Passenger flow between stops i and j
t_{ls}^{dwell}	Average passenger service time of transit line l at stop s
t_s^{lost}	Average lost time per stop s due to vehicle braking and acceleration
t_{ij}^{ivt}	Nominal running time between stops i and j
α_s	Net expected passenger time changes at stop s
β_{ivt}	Passenger in-vehicle time coefficient
β_{wait}	Passenger waiting time coefficient
a_{ls}^{crowd}	Average crowding factor for transit line l at stop s

including the line headway h, running times between consecutive stops t_{ij}^{ivt}, as well as the passenger service time of transit line l at stop s, t_{ls}^{dwell}, and the average lost time due to vehicle braking and accelerating times t_s^{lost}.

The first step of the decision rule is to decide whether each stop is considered a candidate to be skipped or not (Fig. 3). We calculate the trade-off between the expected total passenger time benefits and the total passenger time costs if a single stop s is skipped, denoted by α_s.

Passengers who are expected to be positively affected by skipping stop s are those whose origin i is located upstream of stop s and destination j is located downstream of stop s and hence, they experience shorter in-vehicle time. The saved in-vehicle time is approximated as the average passenger service time t_{ls}^{dwell} at stop s plus the average lost time due to vehicle braking and accelerating times t_s^{lost}. We assume that these passengers are equally distributed between lines A and B, and thus only half of those passengers are affected by skipping stop s, i.e those who are expected to board the line that does not serve stop s. On-board crowding conditions affect how passengers perceive the saved in-vehicle time. Thus, to evaluate the expected time benefits realistically, the saved in-vehicle time is weighted with the in-vehicle time valuation β_{ivt} and a crowding factor a_{ls}^{crowd}. The value of the latter depends on the expected average on-board occupancy at stop s and it varies between sitting and standing passengers (Wardman and Whelan, 2011).

As a consequence of skipping stop s, half of the vehicles do not serve this stop, and thereby, passengers starting or ending their trip at this stop

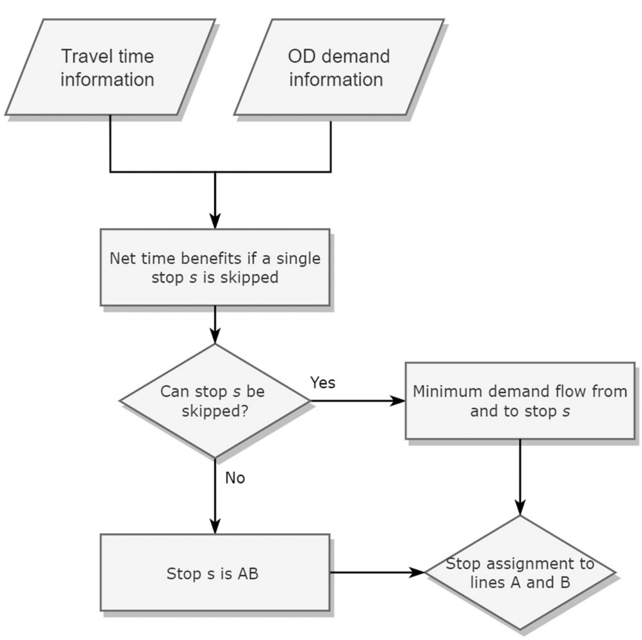


Fig. 3. Stopping pattern decision rule.

are negatively affected and experience longer waiting times. For high-frequency and regular services, such as metro services, the decision rule assumes that passengers arrive randomly at the station and independently of the vehicle departure times, i.e. without consulting the timetable. Under these assumptions, the average waiting time per passenger is equal to half of the headway for systems with high service reliability, and passengers need to wait on average an additional $\frac{h}{4}$ under the skip-stop operation. This approach for estimating the mean waiting time does not account for the heterogeneity of passengers and their trip purpose, service irregularities as well as the transit service type and thus, it might either over- or under-estimate passengers' waiting times, e.g. in case of passengers' arrival relying on real-time vehicle arrival information or in case of service irregularities, respectively.

The expected net time benefits α_s of skipping stop s is given as the trade-off between the expected total passenger perceived in-vehicle time savings as a result of the saved passenger service time t_{ls}^{dwell} and lost time t_s^{lost} at stop s and the expected total passenger costs in waiting time as a result of the additional waiting time $\frac{h}{4}$, as follows:

$$\alpha_s = \sum_{i=1}^{s-1}\sum_{j=s+1}^{N}\frac{q_{ij}}{2}\left(t_{ls}^{dwell}+t_s^{lost}\right)\beta_{ivt}a_{ls}^{crowd} - \left(\sum_{j\in N}q_{sj}+\sum_{i\in N}q_{is}\right)\frac{h}{4}\beta_{wait} \tag{1}$$

If the expected weighted costs are equal to or exceed the expected weighted benefits of skipping stop s (i.e. $\alpha_s \leq 0$), then stop s should not be skipped. Otherwise, if the expected time benefits are larger than the costs (i.e. $\alpha_s > 0$), skipping stop s can potentially lead to a beneficial operation. Note that the set of stops to be skipped may be empty at the end of this procedure.

The next step is to assign the skipped stops to the two lines A and B (Fig. 3). To avoid headway variability at stations served by both lines, we enforce an equal number of stops to be served by lines A and B. The arrangement of skipped stops is selected so that the benefits of the operation are maximized. Under the skip-stop operation, a group of passengers at skipped stops will not be able to reach their destinations without a transfer. Those passengers will thus experience not only longer waiting times at the skipped stops but also lower convenience compared to the all-stop operation. Therefore, based on the OD demand, the skipped stops are assigned to types A and B so that the number of indirect passenger trips (i.e. trips between an A and a B stop) is minimized.

2.3. Public transport simulation approach

To evaluate the effects of the skip-stop strategy, we use BusMezzo, an agent-based transit assignment model (Cats et al., 2010). BusMezzo models the interaction between fleet operations and individual passengers' travel decisions, associated with the effects of crowding. Passenger arrival at the origin stop is modelled as a Poisson random process since it is assumed that passengers do not seek timetable information in high-frequency transit systems. Passengers' travel decisions, including walking, boarding, and alighting decisions, are formulated as discrete choices based on random utility maximization. This allows modelling the resulting demand variations between different vehicle runs or transit lines and passengers' adaptive travel behavior (Cats et al., 2016). Flow-dependent dwell times are modelled as a function of boarding and alighting passengers, including a non-linear effect of on-board crowding.

BusMezzo was recently extended to simulate individual passengers' train-carriage boarding choices and thereby model the distribution of passengers inside transit vehicles (Peftitsi et al., 2021). Capturing individual passengers' perception of in-vehicle time, based on the crowding in the boarded train carriage, the model can be used to provide a more realistic representation of the impact of stop-skipping strategies on the passenger travel experience.

Passenger travel experience is reflected by the generalized travel time, i.e the weighted sum of the experienced travel attributes, including in-vehicle, walking, and waiting times and the number of transfers.

Walking time includes station-to-station walking time as well as within-station walking time at the origin, transfer and destination stations. Based on the time valuations presented by Wardman (2004), waiting and walking times are valued as twice the value of in-vehicle time in uncrowded conditions and the transfer penalty is valued five times the in-vehicle time ($\beta_{inv} = -1$, $\beta_{walk} = \beta_{wait} = 2\beta_{inv} = -2$, $\beta_{transfer} = 5\beta_{inv} = -5$). In crowded conditions, on-board discomfort is reflected as the nominal in-vehicle time weighted with both the in-vehicle time valuation and a crowding factor. The value of the latter depends on the occupancy of the train carriage and whether the passenger has a seat or not (Wardman and Whelan, 2011).

Compared to the all-stop operation, the passenger weighted time costs and savings as a consequence of the A/B skip-stop policy, are computed to assess the overall benefits of the skip-stop operation. In this study, our objective is to evaluate the effectiveness of this operation considering only its benefits to the passengers. Thereby, if the total passenger time cost, due to longer waiting and in-vehicle times, for passenger groups *II* and *III*, is equal to or exceeds the passenger time savings, due to shorter in-vehicle times, for passenger group *I* then the skip-stop operation is not beneficial. Otherwise, the skip-stop operation yields benefits to passengers.

3. Case study

3.1. Description of network and data

The case study consists of seven bi-directional metro lines in Stockholm, Sweden that operate with high-frequency service during the morning rush hour (06:00–09:00 am). In this study, we consider a headway of 2.5 min per line. In total, the metro network is served by 1008 vehicle trips in the morning rush hour. Each bi-directional transit line is simulated in the base case with the average morning peak hour passenger demand of October 2016 as estimated based on smart-card tap-in transactions (Kholodov et al., 2021). Based on empirical incoming and outgoing passenger flows at each station entrance point, for each station-to-station pair we estimated the probability that a passenger starts and ends the trip at a certain platform section at the origin and destination station, respectively.

3.2. Scenarios

To evaluate the effect of the A/B skip-stop operation on passengers' generalized travel time, the case study considers two scenarios:

(1) **All-stop operation**, where the transit vehicles serve all stops along a transit line.
(2) **Skip-stop operation**, where each transit line A and B stops only at their respective predetermined set of stops.

We assess the performance of the decision rule considering two-stop skipping patterns - consisting of one skipped stop each - since the majority of the studied transit lines allow for two candidate skipped stops. In addition, the headway variability at the AB stops due to stop-skipping is minimized if fewer stops are skipped. Transit lines for which the decision rule does not result in candidate skipped stops with expected time benefits are not retained for further consideration in this evaluation. The impact of implementing the skip-stop strategy in a transit line is evaluated in comparison to the all-stop operation. Each studied transit line is simulated for both operation scenarios with the average morning peak hour passenger demand and with demand increased by 20 %, 40 %, 60 %, 80 %, and 100 %. The planned headway is the same in all-stop and skip-stop operations, i.e. the potential positive effect of increasing frequency is not considered in this study.

For each scenario, we conduct 10 simulation runs for a one-hour period. Given significance level and allowed error of 5 %, 10 replications were found to allow statistically significant stability for the average generalized travel time per passenger among the runs.

4. Results

4.1. Performance of the decision rule

To evaluate the proposed decision rule for determining the stopping pattern under the A/B skip-stop strategy, we plot the total expected time benefits α_s of skipping two stops of a transit line against the simulated savings in generalized travel time under the same stopping pattern (Fig. 4).

We observe that there is no clear positive correlation between the expected and simulated benefits of the A/B skip-stop policy. This suggests that the proposed decision rule may not be sufficient for determining the stopping pattern. Therefore, there is a need to understand the reason why there is a discrepancy between the expected and the simulated benefits.

To further investigate the effects of the two-stop skipping pattern on passengers' travel experience, we choose to illustrate the evaluation of the skip-stop operation for a positively impacted transit line (metro line 19) and a negatively impacted line (metro line 14) under increased demand, as highlighted in Fig. 4.

4.2. Metro line 19

A two-stop skipping pattern, shown in Fig. 5(a), has a positive impact on the average generalized travel time of passengers traveling in the southbound direction of metro line 19 in Stockholm, which consists of 35 stops, under increased demand conditions. Fig. 5(b) depicts the expected net time benefits if a single stop of line 19 is skipped as a function of the average number of passengers boarding and alighting at each stop. Based on the proposed decision rule, ten stops of line 19 are candidate skipped stops, yielding time benefits ($\alpha_s > 0$) for the passengers. The implemented two-stop skipping pattern has been determined based on the largest expected time benefits. The two selected skipped stops yield total time benefits equal to 129 pass-hrs. The average nominal in-vehicle time per passenger for this metro line is 10.5 min.

4.2.1. Effect on passengers' travel experience

Fig. 6 (a) shows how the average travel time per passenger, traveling southbound on metro line 19, is affected by the skip-stop operation based on the type of OD trip. Passengers in group *I* are positively affected by the skip-stop operation. Those passengers can board either train type A or B at their origin while benefiting from saved dwell times at the skipped stops. On average, the perceived in-vehicle time per passenger decreases by almost 2 min. A t-test was conducted to determine if the in-vehicle time savings are statistically significant, finding a statistical significance at the 95 % confidence level. Although those passengers do not need to wait longer at their origin, the skip-stop operation might lead to headway variability at the AB stops, which can slightly increase their waiting times.

Under the A/B policy, passengers in group *III* can take only one transit line to travel directly to their destination. Thus, we find that those passengers' weighted waiting time significantly increases by 2.8 min. On average, the waiting time at the passenger's origin station is twice the waiting time under the all-stop operation. However, some of those passengers benefit from a shorter in-vehicle time when the boarded train skips a stop upstream of their destination. On average, each passenger in group *III* experiences in-vehicle time shortened by 1.5 min which represents a decrease of 7 %. For this transit network line, there is no passenger demand between stop types A and B and hence, no passenger belongs to group *II*.

The total passenger time savings as a result of the stop-skipping is shown in Fig. 6(b). The total time benefits for passenger group *I*, which is greater than 300 pass-hrs during one simulation hour, has a large impact on the overall effect of the skip-stop strategy since a large share of

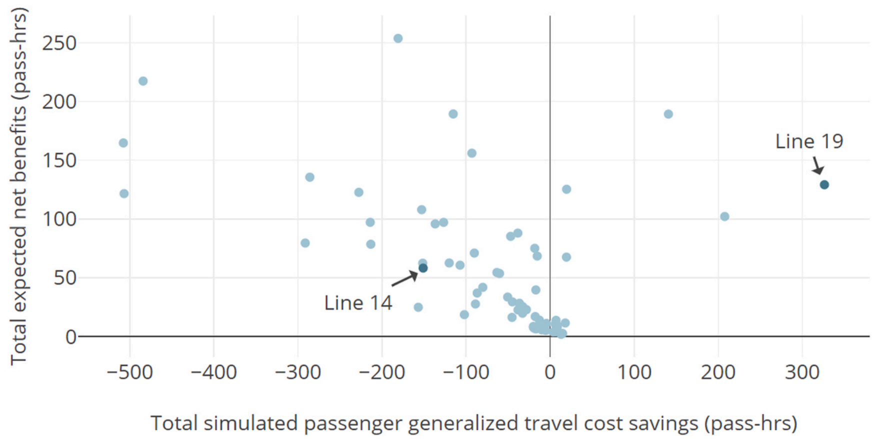


Fig. 4. Total passenger savings in generalized travel time for simulated transit lines as a function of the total expected net time benefits α_s when skipping two stops. Highlighted are metro line 19 (demand 180 %) and metro line 14 (demand 180 %) selected for further analysis.

passengers are positively affected by the stop-skipping.

4.2.2. Sensitivity to demand level

As on-board crowding increases, passengers cannot get a seat, and thus, they experience higher discomfort. Those passengers are expected to benefit most from in-vehicle time savings since they have a greater need to reduce on-board discomfort or minimize the time they spend standing. Therefore, the impact of the skip-stop strategy is expected to be sensitive to demand levels (Fig. 7).

We find that while the positive impact of the skip-stop operation increases with the demand, this effect is bounded with the highest net benefits attained when demand is increased by 80 %. This can be explained by the larger savings in the average in-vehicle time due to the larger number of boarding and alighting passengers at the stops, which leads to longer dwell times spared at the skipped stops. In addition, when the vehicle is crowded, passenger in-vehicle time causes great discomfort and thus, the saved in-vehicle time is also perceived as higher, leading to a higher impact of the skip-stop policy in crowded conditions. However, for further demand increase, even though passengers taking one transit line experience shorter in-vehicle time which is perceived as high in crowding conditions, passengers taking the other transit line experience larger on-board passenger loads due to increased demand and lower frequency at the skipped stop. Therefore, the overall impact on perceived in-vehicle times is reduced in high-crowding conditions.

4.3. Metro line 14

A two-stop skipping pattern, implemented in the southbound direction of metro line 14 in Stockholm as shown in Fig. 8(a), has a negative impact on the average generalized travel time per passenger. On average, the in-vehicle time per passenger traveling on line 14, which consists of 19 stops, is 7 min. Four stops can potentially be skipped, two of which have been selected for the two-stop skipping pattern based on the largest expected net benefits (Fig. 8(b)). The selected two-stop skipping pattern yields total expected benefits of 62 pass-hrs.

4.3.1. Effect on passengers' travel experience

Fig. 9 (a) shows the effect of skip-stop operation on the average travel time per passenger group. On average, compared to the all-stop operation, the skip-stop operation has a negative impact on passengers of group *III* who experience an increase in waiting time equivalent to almost an additional headway, resulting in an overall negative impact on passengers' generalized travel time.

Transferring passengers who belong to group *II* are burdened with additional waiting time both at the origin and transfer stops, experiencing induced waiting time costs equal to 4 min. In addition, those passengers experience a longer ride time by 35 %, i.e., 2.5 min longer than under the all-stop operation. This can be explained by the decision of some of the passengers to transfer at a station either upstream of their origin or downstream of their destination and as a result, they travel in the reverse traffic direction which adds to their in-vehicle time. On average, the skip-stop operation increases the generalized travel time per passenger in group *II* by 7 min which represents a relative increase of 68 %.

Passengers of group *I* are better off due to shorter nominal in-vehicle time thanks to saved dwell times at the skipped stops. Nevertheless, we find that for metro line 14, the higher discomfort experienced by those passengers due to longer perceived in-vehicle time surpasses the nominal in-vehicle time savings. However, the in-vehicle time cost per passenger in group *I* accounts for less than 17 % of the average in-vehicle time costs for passengers that belong to group *II*. Experienced discomfort on-board the trains is expected to increase with the unevenness of the passenger distribution among individual train carriages (Peftitsi et al., 2021). We find that the skip-stop operation has a negative impact on passenger distribution, resulting in increased on-board crowding unevenness for heavily loaded trains (Fig. 9(b)). In this study, the unevenness of crowding is expressed as the ratio of the difference in passenger load between the most and the least loaded carriage to the total passenger load in the train. Unevenness thus takes values ranging between 0 and 1, with larger values indicating greater unevenness of the passenger distribution.

As a conclusion, the effect of the A/B skip-stop policy depends on how passengers, traveling between each OD pair, are distributed inside the transit vehicle and the impact of the stopping pattern on this distribution. In particular, the popular entrance points for the busiest stations along the studied direction of line 14 are all located at the south part of the station platform. Passengers at the busy stations of line 14 are unevenly distributed towards the carriage located closer to the popular access points (cf. Peftitsi et al. (2020)). Skipping stops might result in variations in on-board load among lines A and B, which amplifies the effects of on-board crowding unevenness on passengers' perception of in-vehicle time.

Line 14 differs from line 19 presented in Section 4.2 in its station infrastructure characteristics and passenger flow distribution. In particular, the popular access points of the stations along line 19 include both southern and northern parts of the station platforms and hence on-board passenger loads are more evenly distributed among train carriages compared to line 14. Therefore, any variation in loads between lines A and B under the skip-stop operation does not have a large effect on passengers' discomfort when passengers are on average evenly distributed among the train carriages.

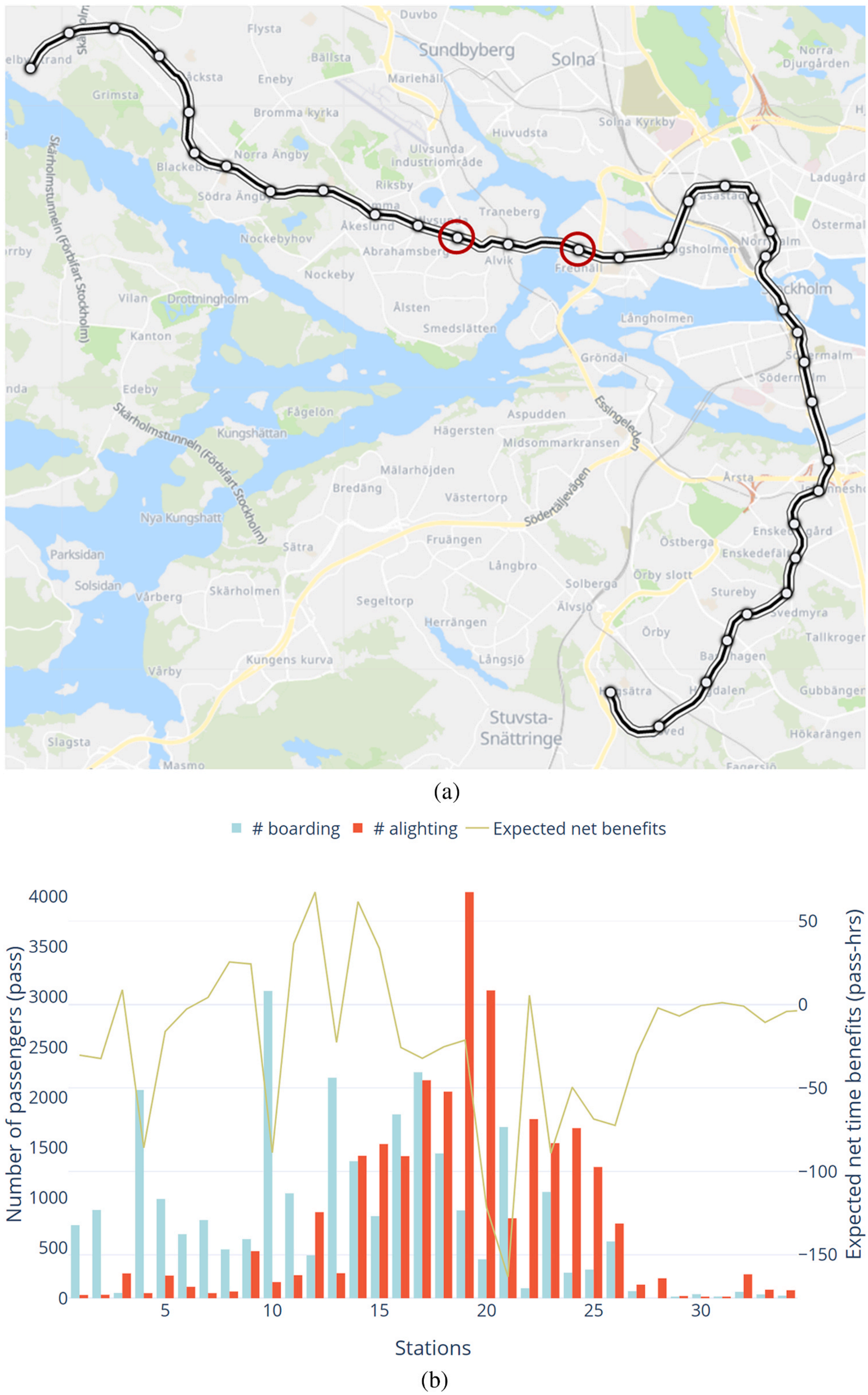


Fig. 5. (a) Map of metro line 19. Encircled are the skipped stops (Stora mossen and Kristineberg) in the southbound direction (MapSource: Moovitapp).; (b) Metro line 19 average boardings and alightings and expected net time benefits per skipped stop under increased demand (180 %).

4.3.2. Sensitivity to demand level

Investigating the sensitivity of the skip-stop operation to demand level, we find that on average, passengers traveling southbound on metro line 14 experience costs in generalized travel time, which increase with the demand (Fig. 10).

In low crowding conditions, passengers benefit from savings in in-vehicle time as a result of the saved dwell times at the skipped stops. As demand grows, passengers experience longer perceived in-vehicle time, when compared to the all-stop operation. This can be explained by the greater discomfort passengers experience in high crowding conditions, which is in turn exacerbated by the uneven distribution of passengers among individual train carriages. However, for even higher

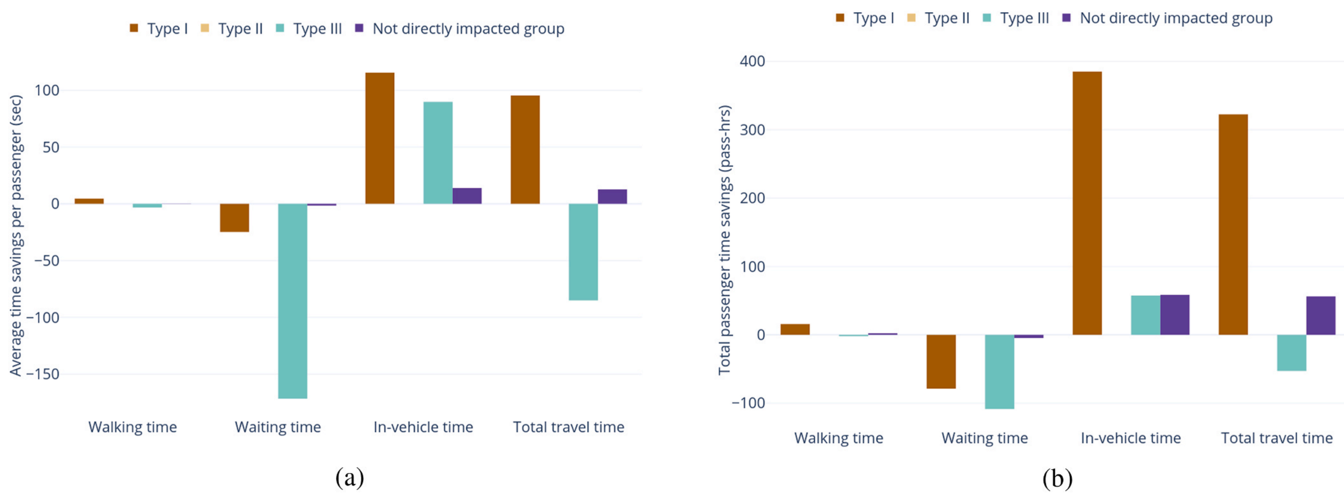


Fig. 6. Effect of skip-stop operation on (a) average time savings per passenger in seconds; (b) total passenger time savings in passenger-hours; for the southbound direction of metro line 19 under increased demand (180 %).

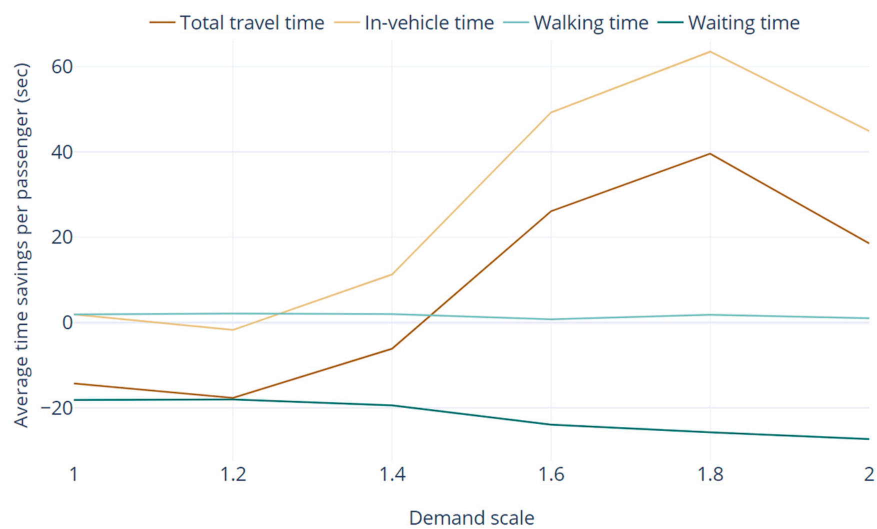


Fig. 7. Sensitivity of the skip-stop operation on metro line 19 to demand. The horizontal axis shows demand relative to the baseline level.

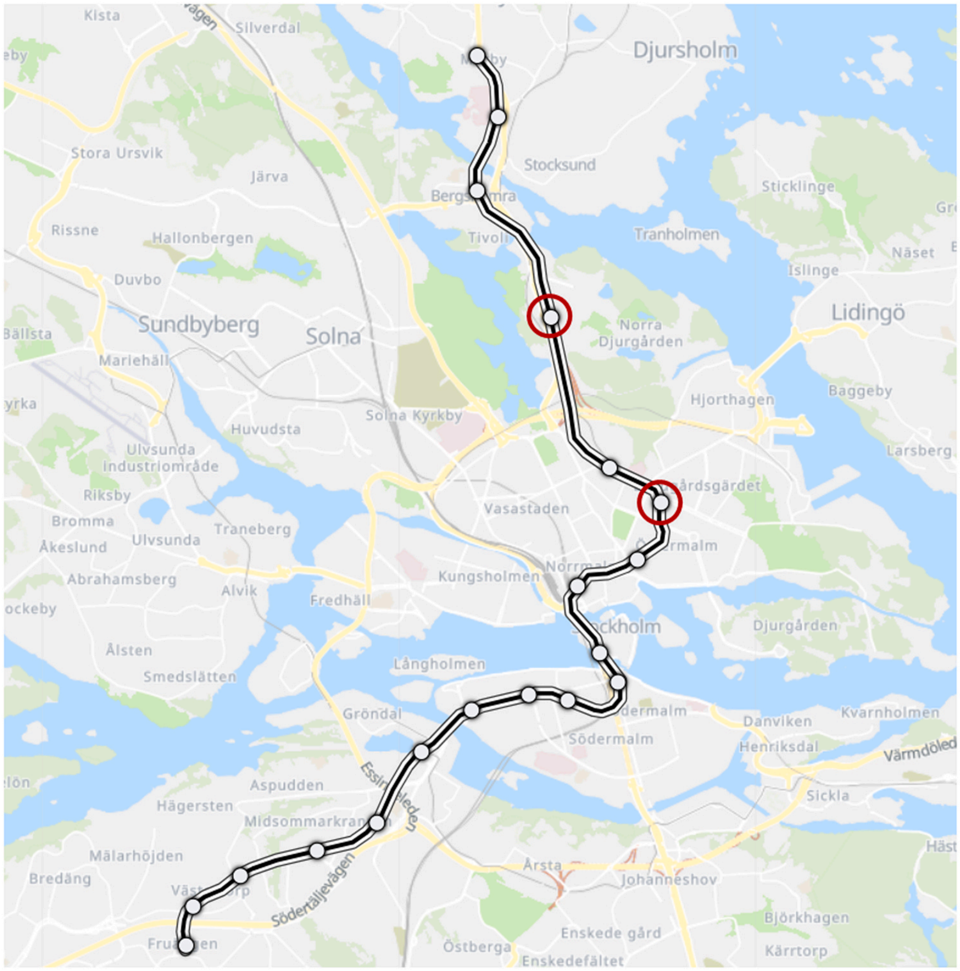
demand conditions (200 % demand), the skip-stop policy results in lower costs in passengers' perceived in-vehicle time. This is explained by the more even distribution of passengers when the capacity of the train carriages is almost reached, which reduces the impact of crowding unevenness on passenger discomfort.

5. Discussion and conclusion

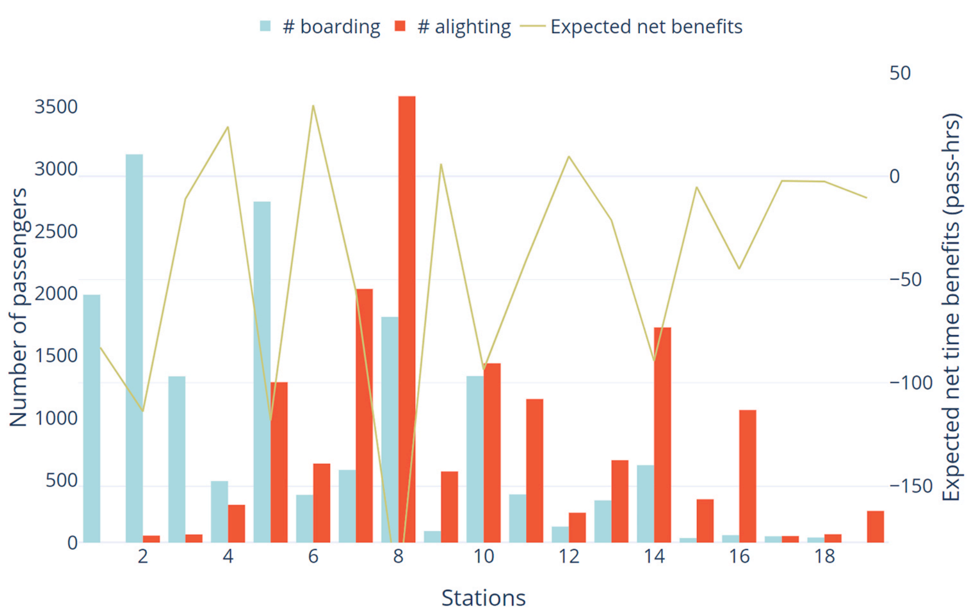
This study contributes to the assessment of the skip-stop policy as a means of accelerating transit services and improving passengers' overall travel experience. For assessing savings in passenger generalized travel time under the skip-stop policy, we introduced an agent-based transit operations and assignment simulation methodology that captures individual passengers' route choices and passenger load distribution inside trains, and models dwell times as a function of boarding, alighting, and on-board passengers. This simulation model allows us to study stop-skipping from the perspectives of different impacted passenger groups. We also formulated a simple decision rule that requires only easily accessible supply and demand data for determining the stopping pattern considering the expected passenger net weighted time benefits and compared the output of the two approaches.

We applied the proposed decision rule to seven bi-directional metro lines in Stockholm, Sweden simulated in the morning peak hour to investigate the performance of the decision rule when two stops are skipped. We found a limited correlation between the expected time benefits of the stopping pattern determined by the proposed decision rule and the simulated benefits of the same pattern.

This discrepancy between the decision rule and the simulated evaluation is attributed to passenger flow dynamics, which are accounted for in the simulation model but not in the decision rule. In particular, the transit assignment model emulates the passenger distribution inside transit vehicles, which critically affects crowding discomfort and passengers' perception of in-vehicle times. This allows simulation-based assessment to account for passengers' generalized travel time based on crowding discomfort in individual train carriages. In contrast, the decision rule simplifies the effect of crowding discomfort and does not account for the effect of passenger load distribution among individual train carriages on the perception of in-vehicle times, which might result in the undervaluation of the expected time benefits of the skip-stop operation. Moreover, the decision rule evaluates the expected stop-skipping effects during the peak hour demand conditions, while the simulation framework, which simulates individual passenger's travel decisions, allows modelling the resulting demand variations between transit lines and vehicle runs as well as capturing the effect of individual

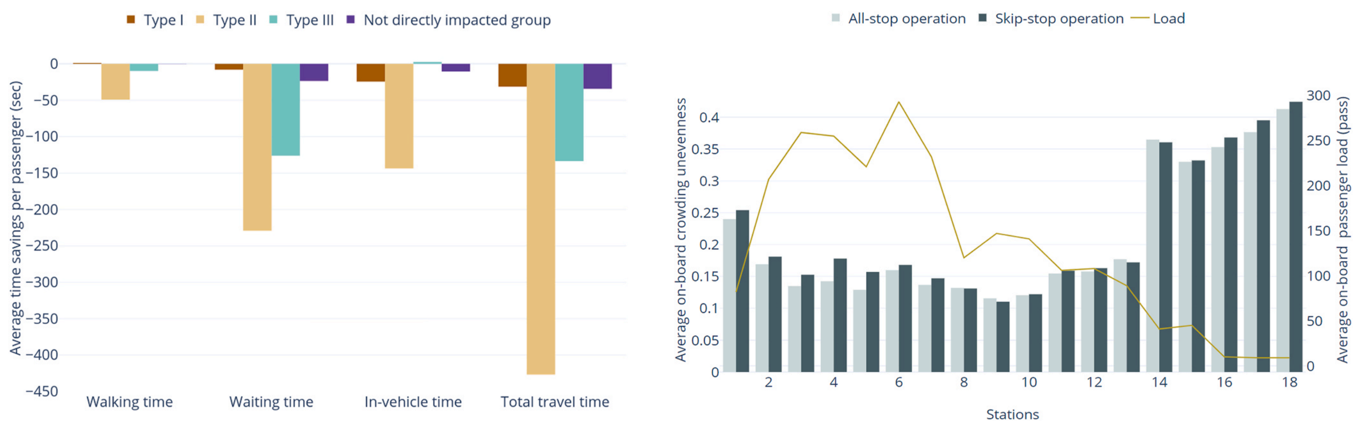


(a)



(b)

Fig. 8. (a) Map of metro line 14. Encircled are the skipped stops (Universitetet and Stadion) in the southbound direction (MapSource: Moovitapp).; (b) Metro line 14 average boardings and alightings and expected net time benefits per skipped stop under increased demand (180 %).



(a) (b)

Fig. 9. (a) Effect of skip-stop operation on average time savings per passenger in seconds for the southbound direction of metro line 14 under increased demand (180 %).; (b) Average on-board crowding unevenness upon train departure from a stop under all-stop and skip-stop operation in increased demand conditions (180 %). The unevenness of crowding is given as the ratio of the difference in passenger load between the most and the least loaded carriage to the total passenger load in the train. It takes values between 0 and 1; larger values correspond to a greater unevenness of the on-board passenger load distribution.

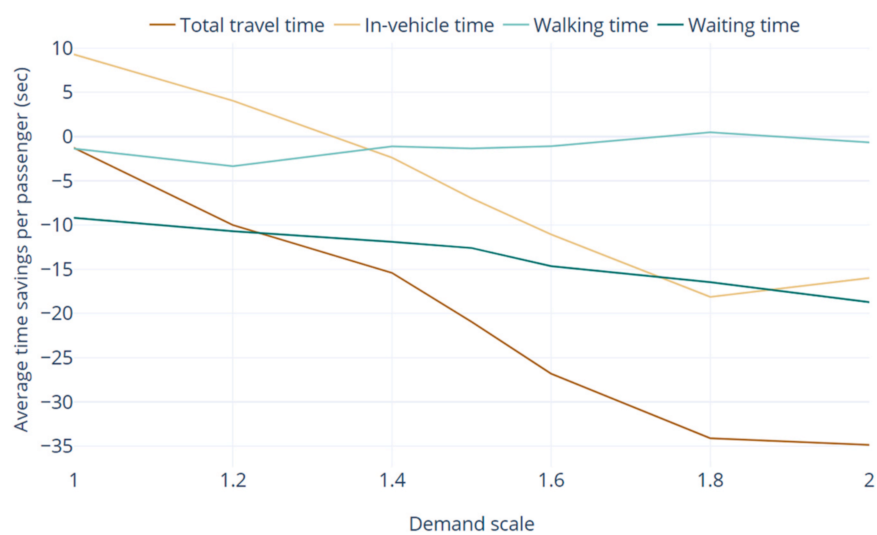


Fig. 10. Sensitivity of the skip-stop operation on metro line 14 to demand level. The horizontal axis shows demand relative to the baseline level.

passengers' trip choice on the overall expected benefits of the skip-stop operation.

In addition, the simple decision rule does not account for costs inflicted on induced transfers, since the decision is made for a single candidate stop, estimating the trade-off between the expected time benefits and the costs of skipping a single stop. However, the passengers that are forced to make a transfer under stop-skipping experience induced time costs related to a transfer penalty and longer waiting time at their origin and transfer stops. Consequently, the expected time costs under the skip-stop operation are likely to be an underestimation. Conversely, the simulation model accounts for passenger transfer decisions and thus, the waiting and in-vehicle time costs are estimated based on the selected transfer stop.

This suggests that the decision rule may not be a robust way of determining stopping patterns that can yield time benefits to the passengers. Thus, simulation models that emulate transit performance and passenger behavioral decisions should be used as an evaluation tool for these patterns. To avoid undervaluation of the expected benefits, future research may extend the decision rule to include the impact of the expected on-board crowding unevenness on passengers' perceived in-vehicle time savings.

Skip-stop operation in urban rail transit is subject to scheduling constraints, i.e. trains operating on a single track must keep a minimum distance from the preceding train. Therefore, the number of skipped stops and the arrangements of skipped stops might affect the planned schedule, leading to headway variability, which might lead to longer passenger travel times. As a result, there is a need to coordinate the stopping pattern and the timetable to minimize the negative effects of the skip-stop operation. In this study, the decision rule has been applied only for determining two-stop skipping patterns to minimize the headway variability. Such simplification might limit the validity of the stop-skipping effects.

Considering the trade-off between time costs and benefits, the skip-stop strategy can lead to savings in overall passenger generalized travel time. The benefits of such operation increase with the demand, since dwell times increase with the number of boardings and alightings. In addition, these savings have a higher value for passengers in crowded conditions due to the greater level of discomfort. However, very specific conditions at the stops along the transit line make the skip-stop operation beneficial for passengers. The effects of such operation depend on the distribution of passengers among individual train carriages along the line, which directly influences passengers' experienced discomfort and perception of in-vehicle times.

The simulation model adopted in this study models the dwell times as a function of boarding, alighting, and on-board passengers. However, the effect of uneven passenger load distributions on dwell times is not captured. The distribution of passenger loads among the train carriages as well as across the station platform is expected to affect train dwell times since a more even passenger distribution leads to shorter boarding and alighting times. We can therefore expect dwell time savings as a result of the stop-skipping as an underestimation when passengers are considered to be evenly distributed among train carriages. Future research should evaluate the effects of the distribution of passengers along train platforms and across train carriages on dwell times as part of the assessment of tactical planning decisions.

Skip-stop operation has been successfully implemented in only a few public transport systems around the world. For instance, passengers in Stockholm, Sweden opposed the skip-stop policy that was implemented for commuter rail traffic in 2017 because of their dissatisfaction caused by the lower service frequency at the skipped stops (Cederblad, 2018). The decision rule proposed in this paper for choosing the stopping pattern can support the implementation of such a strategy in practice. Since this decision rule is not a standalone robust way of evaluating the benefits of stop-skipping, simulation techniques that are capable of emulating passenger train-carriage choices can further support the practical implementation of this strategy.

The simple decision rule proposed in this study is based on easily accessible travel and passenger information and can be used as a guide for public transport operators for supporting decision-making before implementing a skip-stop strategy. Simulating passengers' behavioral response to the skip-stop operation, we evaluate the overall impact of alternative stop-skipping strategies on savings in passenger generalized travel times. There is a behavioral relation between crowding and perceived in-vehicle time in public transport and thereby, it is important to evaluate how passengers would perceive the benefits of any control strategy under different demand conditions.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Soumela Peftitsi reports financial support was provided by Swedish Transport Administration.

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