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Evaluating transit preferential measures - priority lanes, boarding and control strategies

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Abstract Assessment of bus service improvements such as bus lanes, allowing boarding through all doors and headway-based holding control ideally requires a simulation model that combines features of both classical analytical models and microscopic simulation. However, as the usage of such models has been limited, their validity has hitherto remained low. BusMezzo, a dynamic transit operations and assignment model, was developed to enable the analysis and evaluation of transit performance and level of service under various system conditions. This paper describes two case studies where assessment of bus service improvements in BusMezzo was tested and validated. The model was shown to predict travel time improvements well, while overestimating some of the headway variability effects. It turned out that the preferential measures had a positive system impact and that there are synergetic effects.

Keywords: Transit Assignment · Simulation · Validation · Reliability · Boarding

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1 Introduction and background

Improving an existing bus service can be a cost and space efficient alternative to new rail or BRT investments (BHLS 2011). Many of the BRT concepts (e.g., bus lanes, boarding through all doors and frequent services) can be introduced partially or fully even if infrastructure for completely traffic separated public transport is not available.

The two most important determinants of service performance are speed and reliability (Bates et al. 2010). These service attributes determine the average and variability of passenger travel time, respectively. Preferential measures are therefore designed to reduce potential delays and sources of uncertainty and typically address both aspects simultaneously. In the context of general traffic operations, simulation models asserted themselves as the primary tool for evaluation at the operational level. Due to the nature of transit systems in terms of size, complexity and dynamics – in particular with the implementation of Advanced Public Transport Systems - it is unrealistic to apply global analytical models to solve transit management problems. Transit simulations may serve several interests (Meignan et al. 2007): observation of network dynamics and design; evaluation and control of dynamic processes, and; evaluation of network performance under alternative designs. Transit simulation models may therefore be instrumental in testing the implications of various operational measures prior to their implementation.

Most of the previous transit simulation studies were conducted by adjusting traffic simulation models that do not represent transit operations or enhancing existing simulation models by extending their capabilities for specific applications (Abdelghany et al. 2006, Ding et al. 2001, Chang et al. 2003, Cortes et al. 2005). Fernandez (2010) developed a stop design and performance simulation model where the operations of the immediate stop area under different vehicle and passenger arrival patterns are analysed. Microscopic transit simulation models were also proposed by Morgan (2002) and Lee et al. (2005) for the purpose of evaluating transit signal priority strategies.

In all of the abovementioned studies, passenger and vehicle arrival processes were represented for a given line segment without considering their inter-dependency along the route. This prohibits the analysis of operational measures that may have effects that extend beyond a single segment and may even influence other lines. Whilst MILATRAS (Wahba and Shalaby 2011) and MATSim (Gao et al. 2010) offer transit assignment simulation models, they lack transit operations modelling capabilities such as vehicle scheduling, control strategies and crowding effects. BusMezzo, a multi-agent transit operations and assignment simulation model was validated for its supply representation in a small case study in Tel Aviv (Toledo et al. 2010) and was applied for studying control strategies in Stockholm (Cats et al. 2012).

In this paper, the impact of three different transit service improvement measures which were implemented during a field experiment in Stockholm are evaluated using BusMezzo simulation. The detailed simulation model enables comparing the effects of the three measures in a way that would be difficult solely by analysing empirical data from the field experiment. As the usage of such detailed models has been limited, their validity has hitherto been low. The capabilities of the simulation model, which is described in chapter 3, are demonstrated in a case study described in chapter 4 and for the real world field experiment described in chapter 5. Empirical data from the field experiment enabled the validation of the traffic and operational features of the model. Conclusions from both case studies are drawn in chapter 6.

2 Transit preferential measures

Transit travel times consist of running times between stops and dwell times at stops. Turnquist (1981) analysed four strategies for improving transit service reliability; vehicle-holding strategies, reducing the number of stops made by each bus, signal preemption, and provision of exclusive right-of-way, while van Oort and van Nes (2009) performed a case study analysis of the relationship between transit network design and regularity using a limited simulation tool (simulating arrival and departure time of individual vehicles, but lacking representation of passengers or operations control). In both cases a main conclusion was that achieving even headways between consecutive vehicles is a key factor in attaining a high level of service.

Introduction of dedicated bus lanes has been studied extensively and with good results, theoretically (Vuchic 1981), empirically (e.g., Schwartz et al. 1982 and Shalaby and Soberman 1994) and with the aid of simulation models (e.g., Shalaby 1999). These findings suggest that replacing mixed traffic lanes with dedicated bus lanes effectively reduce bus travel time and variability, while in some cases only with a minor negative effect on car travel times. For example, ~~(e.g., ~~Schwartz et al. (1982) found that during peak-hour, bus speed ~~was ~~increased by 83% and bus reliability ~~was ~~increased by 57 percent while traffic speed on the ~~particular ~~relevant street ~~was ~~increased by 10 percent.~~).~~ In contrast, Diab and El-Geneidy (2013) found that while the operation of an exclusive bus lane ~~shortened ~~had a modest effect on reducing bus running time ~~(~~by 2.7%~~)~~, travel time variability increased ~~(~~by 0.5%~~)~~ due to the effect of right turning vehicles. Their study analysed empirically a mix of measures to improve transit performance in Montreal using automated vehicle location (AVL) and automated passenger counts (APC) data with a focus on reliability. Neves (2006) offers a good overview of the advances in the dedicated bus lanes domain.

Dwell times account for a sizeable share of the total travel time. Bertini and El-Geneidy (2004) estimated that the total time lost due to serving stops is 33% of the total travel time for urban services, of which half is attributed to passenger service time per-se. Furthermore, dwell time is an important source of unreliability as it causes high variability with a coefficient of variation in the range of 0.6 to 0.8 (TCQSM, 2013). The effects of for instance changing the boarding procedure are not limited to trip travel time but also influence service regularity. The relationship between a change in the boarding procedure and passenger travel time is therefore not straightforward for high frequency bus services. Vuchic (1969) developed a deterministic model to show that even the smallest disturbances inevitably lead to bunching. According to Vuchic, the most effective way to deal with bunching is to reduce boarding times. Diab and El-Geneidy (2013) found that the introduction of a new fare collection system increased bus running time by 3.8% and increased running time variation by 0.7 %.

Expressing dwell time as a function of different parameters such as door configuration, vehicle design and crowding level has been the target for numerous studies (e.g. Weidmann 1994 and Tirachini 2013). The fare payment system also affects the service time. A study in Chicago (Milkovits 2008) ~~found~~estimated boarding times of 3.1 seconds per passenger for smart card holderss and 4.2 for swipe cards on low-floor buses. Dwell time is generally assumed to be shorter and more reliable when boarding is allowed through all doors than when only allowed through the front door (Sundberg and Peterson 1989). In a laboratory experiment by Fernández et al. (2010) the boarding time was only 1.5 seconds with free boarding, and 1.7 with smart cards on low-floor buses. However, real life data showed that boarding with a combination of smart card ticket verification and free boarding took 2.1 seconds and alighting 1.3 seconds.

One of the common practices aimed to improve service reliability is holding control strategies (Osuna and Newell 1972). Van Oort et al. (2010) used a simulation model to analyse a real line and several hypothetical lines and found that with two holding points schedule-based holding outperformed headway-based holding in terms of additional travel time. However, they assumed a slow schedule and little travelling across the holding points. Based on simulation and empirical results, Cats et al. (2012) concluded ~~(e.g., Cats et al. 2012) to suggest~~ that a control strategy that regulates departures from all stops on the basis of the headways of the preceding bus and the following bus can improve service performance considerably from both passenger and operator perspectives. Conditional priority at traffic lights was studied in an experiment by Furth and Muller (2000).

3 Modelling transit operations

BusMezzo, a dynamic transit operations and assignment model, was developed to enable the analysis and evaluation of transit performance and level of service under various system conditions (Cats 2013). The model represents the interactions between traffic dynamics, transit operations and traveller decisions. BusMezzo was implemented within a mesoscopic traffic simulation model and the different sources of transit operations uncertainty including traffic conditions, dwell times and service disruptions are modelled explicitly. BusMezzo represents vehicle schedules and hence the potential propagation of delays from previous trips.

Individual vehicles and travellers are modelled in BusMezzo, but not their second-by-second movements. The dynamic path choice model considers each traveller as an adaptive decision maker for which progress in the transit system consists of successive decisions that are based on the respective path alternatives and their anticipated downstream attributes. Travel decisions are modelled within the framework of discrete random utility models. The simulation analysis in BusMezzo enables to assess the impact of individual operational measures on performance and passenger travel experience as well as the magnitude of unrealized potential improvements.

Dwell time at stops can take different functional forms. In order to analyse different boarding regimes, adequate dwell time modelling is essential. Video recording of bus boarding and alighting in Stockholm and Gothenburg was used to calibrate and validate dwell time models in BusMezzo (West 2011). Specification of suitable dwell time functions was based on the data collected and former experience. The two main functions are:

– $DT_{Front} = MAX(2.4P_b, 0.94P_a)$ and
– $DT_{All} = 3.3 + 0.86P_b + 0.49P_a$

where P_b and P_a are the vehicle and stop specific number of boarding and alighting passengers respectively. DT_{Front} denotes the dwell time in case boarding is possible only from the front door whereas DT_{All} denotes the dwell time when allowing free boarding through all doors. A crowding factor based on the findings of Weidmann (1994) is applied in each case.

Each stop could be defined as a potential time point stop implying that the holding strategy under consideration determines the departure time based on the dynamic system conditions. In order to analyse the impacts of holding strategies on transit performance, it is necessary to model dynamically the interactions between passenger activity, transit operations and traffic dynamics. An evaluation of different holding criteria (e.g., only with respect to the preceding vehicle or to both the preceding and the succeeding vehicle) and number and location of time point stops was previously conducted using BusMezzo (Cats et al. 2012). The holding strategies were implemented in the model.

Passenger travel experience in the assignment model is measured as perceived journey time where waiting time is weighted twice as high as uncrowded in-vehicle time. Capacity constraints are enforced so that passengers that are left behind have to wait for the next vehicle. Vehicle specific on-board crowding affects boarding and alighting time as well as traveller journey time perception. Crowded in-vehicle time is weighted higher than uncrowded in-vehicle time according to the multipliers suggested in a meta-analysis performed by Wardman and Whelan 2011.

4 Case study: Synthetic bus corridor

In Stockholm buses are normally boarded only through the front door, and alighted through the other doors, but allowing boarding through all doors on the high-frequency lines has been suggested by many stakeholders. The impact of the two different boarding procedures on dwell time was mentioned in the previous chapters. However, to capture the full effect of changing to boarding through all doors is it important to be able to quantify the bunching problems in situations with different boarding procedures and demand (West 2011). It is also important to take into consideration that the performance of one transit line is influenced by the whole traffic network, including other transit lines (van Oort and van Nes 2009). Different services in terms of frequencies may co-exist and operate along the same corridor and this has been studied by many starting from Chriqui and Robbillard (1975) but usually ignoring the fact that the lines might have different vehicle capacity, control and boarding regime, all affecting level of service. Studying the impact of interaction between boarding regime and holding strategy is therefore interesting in the case of mixed-frequency on a common corridor.

In order to study this, a generic case was set up in the simulation environment, where different boarding procedure and holding strategy scenarios were assessed. This case resembles the real world case described in the next chapter to a large extent, but allows drawing more general conclusions. It provided motivation for conducting the real world field experiment and pinpointed the potential benefits.

The case study network consists of two bus lines partially overlapping along a common corridor (Figure 1). Line A is a high-frequency line with a planned headway of 4 minutes whereas line B has a planned headway of 8 minutes. On the shared section, both lines use the same stops. Passengers that board along the shared corridor and have their destination on the corridor are assumed to be indifferent towards the two lines and thus board the first arriving vehicle. A synthetic OD-matrix was created to emulate typical peak hour boarding patterns and passenger loads on busy inner-city bus lines. An implicit way of modelling traffic conditions was chosen in the case study, with run time distributions based on real bus line data from bus line 1 in Stockholm, where the run time between each stop was found to follow the log-normal distribution, with individual parameters for each link (Cats et al. 2012).

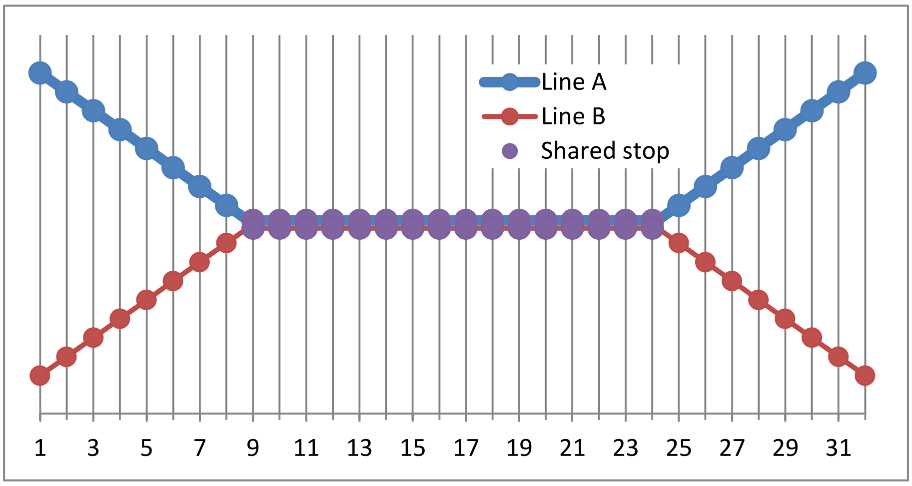

Fig. 1 Simulated transit network

4.1 Boarding and holding control scenarios

The studied scenarios are summarized in table 1. Scenario 0 is the base scenario, where boarding is allowed only through the front door. In scenario 1, the type of boarding procedure is changed only for the high-frequency line, line A. Line B keeps the front door boarding procedure, to emulate a situation where a high quality service line is introduced, which possibly conflicts with existing public transport. In scenario 2, boarding is allowed through all doors for both lines. In these scenarios, a traditional schedule based holding strategy is implemented. The schedule was recalculated for the scenarios where boarding was allowed through all doors, otherwise most of the reduced dwell time would have appeared mostly as increased holding time.

To study how the regularity can be improved by other means than by allowing boarding through all doors, a state-of-the-art headway-based holding strategy was implemented on the high-frequency line. In these scenarios, the buses are not held with respect to a fixed schedule, but with respect to the headway both to the preceding and the subsequent vehicle (Cats et al. 2012). Test simulations showed that headway-based holding improved neither regularity nor travel times for line B, the low-frequency line.

When the high-quality, high-frequency line and the less frequent line with boarding only through the front door are operating on the common line segment, persistent bunching might be the result. The bus with boarding through only the front door can be assumed to be consistently slower, so a vehicle with boarding through all doors will sooner or later catch up, and thereafter they will run together. However, as will be showed in the results, this issue was not dominant.

Table 1 Scenario description

Scenario	Holding strategy Line A	Holding strategy Line B	Boarding procedure Line A	Boarding procedure Line B
0	Schedule	Schedule	Front door	Front door
0H	Headway	Schedule	Front door	Front door
1	Schedule	Schedule	Free	Front door
1H	Headway	Schedule	Free	Front door
2	Schedule	Schedule	Free	Free
2H	Headway	Schedule	Free	Free

4.2 Simulation results

In table 2, statistics of the bus run time distribution are reported. The 85th percentile run time, which is the base for scheduled vehicle circulation, decreases by 26 per cent from scenario 0 to scenario 2H for line A. For line B the decrease is 24 per cent. Scenario 1 is notable, with line B having a very small deviation from the mean.

Table 2 Run time comparison (in minutes)

	Line A			**Line B**		
Scenario	**Mean run time**	**St D**	**85-perc**	**Mean run time**	**St D**	**85-perc**
0	44	8	50	45	7	50
0H	41	8	47	43	6	45
1	35	4	38	42	2	42
1H	35	5	38	39	5	42
2	38	5	39	40	5	42
2H	34	4	37	37	4	38

Average passenger travel time for line A is depicted in table 3. For line A, passenger travel time decreases significantly compared to the base scenario in all scenarios except scenario 0H. The ride time decreases significantly only in scenario 2H. The dwell time and waiting time decrease is significant in all scenarios except for 0H.

Table 3 Average passenger travel time change for line A compared with the base case (scenario 0); green fields represent results significant on the 95 % level and yellow on the 90 % level

Scenario	Ride time	Dwell time	Waiting time	Holding time	Total time
0	230.4	253.5	191.5	27.8	703.2
0H	-4%	-11%	-12%	22%	-8%
1	-7%	-29%	-22%	-49%	-21%
1H	-5%	-33%	-22%	-21%	-20%
2	-6%	-33%	-21%	49%	-18%
2H	-16%	-39%	-23%	-29%	-27%

When it comes to holding time, random variation in ride times has a large impact on both setting the schedule and on the simulation itself. This is why the significance levels are lower, even for substantial differences in holding time. It can be argued that either scenario 2 has a schedule with an excessive amount of slack or that scenario 0 has an insufficient amount of slack. These problems are hard to avoid when setting schedules both in reality and in simulations, but become obsolete when applying the headway-based holding strategy. However, the difference in total travel time between scenarios 2 and 2H cannot be explained by the reduced holding time, as the difference between them in ride time and dwell time is also significant.

Figure 2 shows how the headway variation for line A increases along the journey. In all scenarios large externally caused delays are experienced between stop 9 and stop 10 and at some other random links. The effect of the changed boarding procedure is that delays do not propagate to downstream links to the same extent. The schedule-based holding seems to be unsuccessful in some cases, most notably at stop 17 in scenario 1.

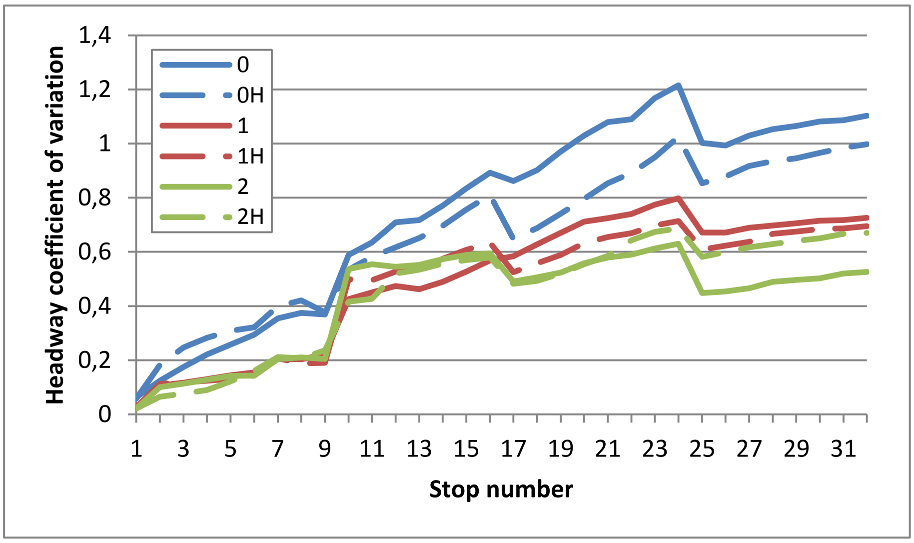

Fig. 2 Headway variation for line A

Figure 3 shows how the vehicle run time variation (of which selected statistics are presented in table 3) is shifted to lower values of the run time distribution (i.e., a greater number of run times are substantially shorter than the mode) in the scenarios with headway-based holding. In the scenarios with schedule-based holding, the run time variation is almost entirely towards longer run times than the mode. The shortest run times in terms of average, median and 85th percentile are all in scenario 2H.

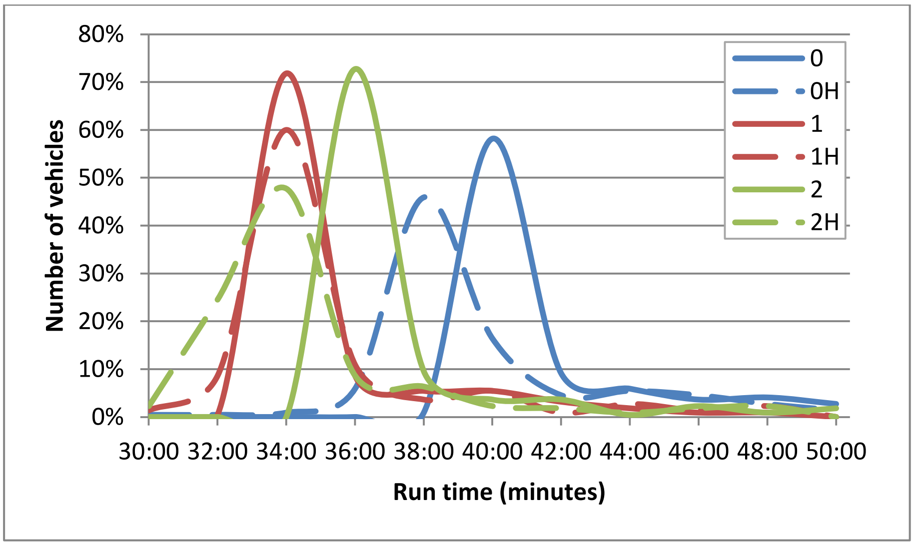

Fig. 3 Vehicle run time histogram for line A

In summary the results show that in a high-demand system with overlapping bus lines, free boarding through all doors can decrease average passenger travel time and vehicle circulation time by 20 - 25 per cent. At the same time obtaining better regularity implies less crowded buses. As a result, the average number of passengers who were left behind due to overcrowding decreased by 0.5 passenger per bus and stop. Furthermore, the implementation of these measures is not only beneficial for the line where it was introduced, but also positively affects the other line.

The results of this case study suggest that allowing passengers to board through all doors can in combination with a regularity-driven holding strategy potentially yield large benefits in Stockholm trunk bus network. This is further explored in the following section, using simulation and empirical data.

5 Case study: Real-world high-demand trunk line

Line 4 is the busiest and most frequent bus line in Stockholm, with more than 60,000 boarding passengers per day and 4-5 minutes headways during large parts of the day. The line traverses all major districts of Stockholm inner-city and connects major transfer stations to metro, commuter train, local trains and bus terminals. It is the most important line out of the four high-capacity trunk bus lines which operate in Stockholm inner-city and constitute the backbone of its bus network. These lines are marked differently and are actively branded as the blue lines which are designed to offer a high level of service. Boarding is allowed only through the front door, where tickets are inspected but not sold. The line alternates between dedicated bus lanes and regular city streets without grade separation. However, due to traffic conditions, the average commercial speed (origin to destination, including stop dwell time) of buses on trunk line 4 was merely 13 km/h during the rush hour in 2013. Additionally, delays and poor regularity persistently causes passengers to experience unpredictable waiting and travel times.

In order to improve the level-of-service on this cardinal bus line, a field experiment was initiated by Stockholm Municipality, Stockholm County and the bus operator, Keolis. The experiment included the implementation of a range of physical and operational measures on line 4 and took place in the spring of 2014, from March 17 to June 19. The most important of the preferential measures which were implemented simultaneously during the field experiment period are:

(1) introducing bus lanes on some line sections;

(2) continuously operating and controlling based on regularity (even-headway control and control centre operations) and;

(3) boarding from the third door (an on-board conductor validated the ticket upon boarding).

While the initial objective was to test free boarding through all four doors, the implementation reflected a compromise among the stakeholders.

In addition, four stops were cancelled in order to increase bus speeds and obtain more balanced stop spacing. On significant portions of its route, line 4 runs in parallel to ordinary city buses that offer local accessibility. The set-up analysed and discussed in Section 4 is hence prevalent along its route.

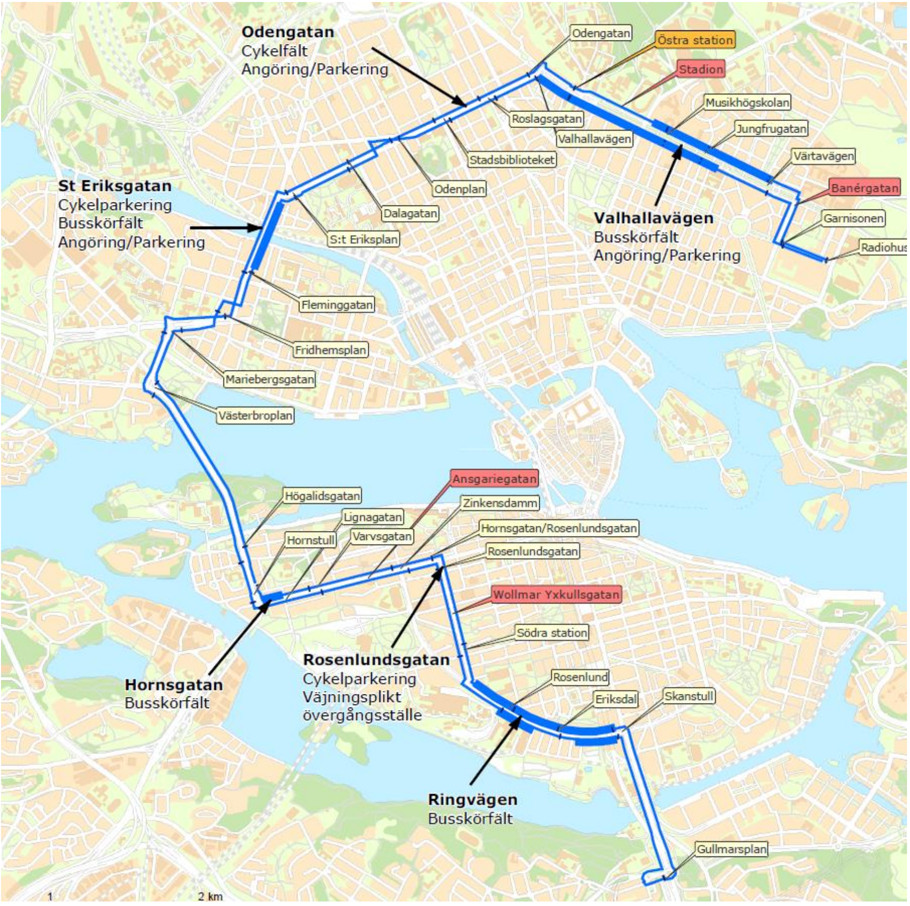

Fig. 5 Physical measures that were implemented during the trial period (cancelled stops in red and new bus lanes in bold blue, other measures included removed parking lots and changes in bike lanes)

5.1 Empirical results

There is a modest but clear increase in bus speeds along both line directions with the average speed increasing by 6-9%. The average speed increased from 18.1 and 16.2 to 19.3 and 17.6 km/h for the northbound and southbound directions, respectively.

In total, the average complete trip time from the first stop to the last one during the afternoon peak period decreased by five minutes during the field experiment. Hence, the average complete trip cycle time during this period became ten minutes shorter. Moreover, fewer trips are exceedingly long and headway variability, measured in terms of the coefficient of variation, decreased by 28%. These improvements could potentially help the operator to cut the fleet size by two buses, from 27 to 25 buses. This calculation is based on maintaining the current planned headway. Alternatively, the same fleet could be used for offering a higher frequency.

5.2 Simulation study

This pilot study constituted a perfect opportunity to evaluate the joint impacts of these measures. However, their simultaneous introduction does not allow drawing conclusions on their isolated effects and marginal contributions to overall change in performance. The bus simulation model was thus used to model the impact of isolated and combination of measures, whereas the scenario with all measures combined can be verified using empirical data collected during the field experiment period. Running time distribution for each inter-stop section was based on before and after empirical data and fitted to a shifted log-normal distribution. Demand estimation was done for before and after cases based on iterative proportional fitting of the empirically logged total boarding and alighting margins per stop which were obtained from APC. Overall passenger demand levels remained the same during the study period.

5.3 Scenario design

The simulation model was used for assessing the impact of each of the main preferential measures on the overall performance. The physical measures - additional bus lanes and stop cancellation - were assessed as a whole through their impact on bus running time. In addition, the operational measures included two distinct interventions - allowing boarding from the third door and even-headway holding control. Both measures are expected to influence dwell times, passenger volumes and service reliability. Simulation scenarios were therefore designed for assessing the impact of each measure if introduced independently. Table 4 summarizes the scenario design and indicates the different measures that were considered in each scenario.

The simulation model enables the assessment of the potential benefits of truly allowing boarding from all doors without ticket inspection. In order to reflect the field experiment adequately in the 2014 scenario, the dwell time function was modified to reflect the actual implementation. Ticket inspection is estimated to increase boarding time by one second per passenger compared to boarding without ticket inspection and the number of door channels available for boarding/alighting has a diminishing effect on total service time (doubling the number of door channels decreases service time by 40%).

The impact of the construction works that occurred on the bridge, Lilla Västerbron, in one direction 2013 and in the other direction 2014 was also analysed. By removing this effect from the construction work in the simulation model, the effect of the preferential measures could be identified. Furthermore, a number of combinations of the scenarios were analysed to enable studying their interactions.

Table 4 Scenario design summary

	Stops cancelled	Physical road measures	Even-headway control	Free boarding	Construction work on L:a Västerbron
Base 2013					
Reduced run time	X	X			
H:way control			X		
Board all doors				X	
Scenario 2014	X	X	X	X*	X**

*) The 2014 scenario was simulated both with the boarding regime that was used during the field experiment and with free boarding through all doors
**) The 2014 scenario was simulated both with the effects of the construction works on Lilla Västerbron (for validation purposes) and without them

5.4 Simulation results

The total dwell time, total bus trip time, service regularity and total passenger travel time for each scenario are presented in table 5. Dwell time is important in itself but is also a key determinant of regularity and therefore of both passenger waiting time and in-vehicle travel time. Total trip time and its variability are the most important determinants of fleet size and hence the operational costs associated with provisioning a given service frequency.

Table 5 Summary simulation scenario results

	Total dwell time	Total bus trip time	Trip time st. dev.	Pass. general. travel cost
Base case	15 min	61 min	5 min	27 min
Red. run time	14 min (-7%)	56 min (-7%)	4 min	22 min (-17%)
H:way control	15 min (-0%)	61 min (-0%)	5 min	27 min (-0%)
Board all doors	13 min (-16%)	57 min (-6%)	4 min	24 min (-12%)
All	12 min (-23%)	53 min (-13%)	3 min	20 min (-28%)

By splitting the different measures into multiple simulation scenarios, it could be concluded that of the saved vehicle travel time minutes five were because of the street measures (bus lanes) and removed stops, while free boarding through all doors would have decreased it by four minutes. Together with the street measures and removed stops this would save eight minutes average trip travel time.

While the headway control ~~is~~does not ~~giving~~yield any visible improvement compared to the base case in Table 5, service regularity measured in terms of headway variation has significantly improved. Moreover, ~~tests~~simulation scenarios ~~with~~which combin~~ing~~ed headway control with either reduced run time or boarding all doors (which are not shown in the table) ~~gave~~obtained small improvements compared to these measures alone. So there ~~are appears to be~~are indications of synergy effects between headway control and other measures improving regularity, which is the same result as the one in the first case study. When combining all measures, however, the effect is lower than the sum of their marginal contributions.

For trunk line 4 the planned headway upon departure in the afternoon peak period is 4-5 minutes. However, the actual headway between consecutive trips varies considerably from one bus to the other. In the extremes, this leads to the bunching phenomenon where buses run in platoons which has negative implications on passengers waiting times, capacity utilization and operational reliability. Improving service regularity was therefore one of the main objectives of the pilot study. The after period shows a significant improvement in service regularity and fewer incidents of bus bunching.

The simulation model enables the analysis of individual passenger travel experience and the respective travel time components and on-board crowding. According to simulation results, every traveller on line 4 saved seven minutes generalized travel cost (perceived journey time) in the field experiment (compared to the before period), which is 20% of their total generalized travel cost (see figure 6). The average crowding multiplier decreased from 1.22 in the before period to 1.17 in the after period. This means that on average the load was a bit above seat capacity in both periods, but due to better regularity in the after period, fewer passengers were forced to stand or sit in an overcrowded bus.

Waiting time decreased the most in relative terms due to better regularity, by 35% (one and a half minute or three minutes expressed as equivalent in-vehicle time) with all measures combined. Total in-vehicle riding time decreased by two minutes, even though the time passengers spent in vehicles that were holding increased by 20 seconds due to the headway based holding strategy. Out of almost six minutes of observed travel time savings ~~observed~~, one minute is attributed to the changes in boarding regime, whereas physical street measures and removed stops account for a reduction of almost five minutes. Headway based holding did not have a significant effect on average travel time. Free boarding through all doors would decrease total perceived journey time by 12% (three minutes per passenger) when compared to front door boarding.

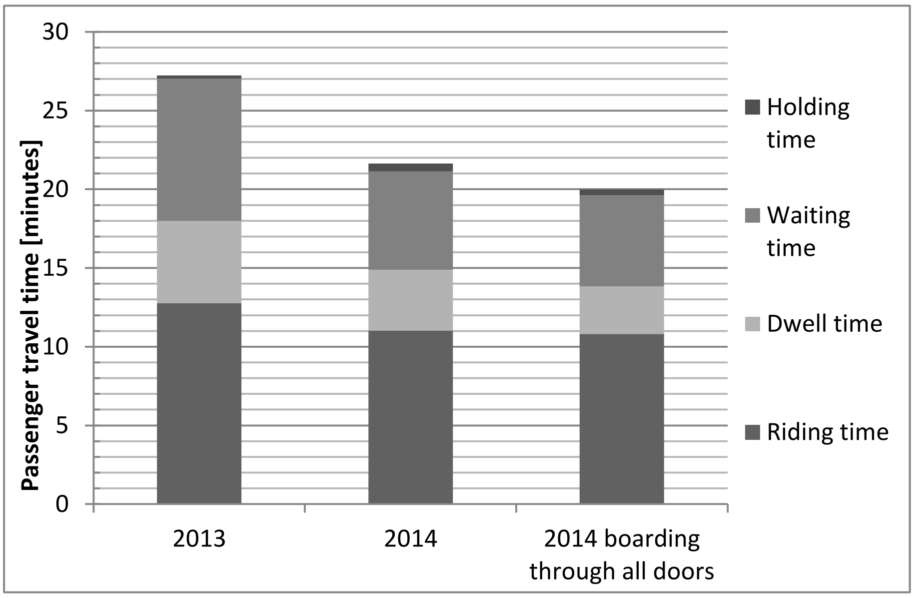

Fig. 6 Average passenger generalized travel cost components under selected scenarios

In summary, the pilot study improved the level-of-service while at the same time obtaining greater operational certainty, leading to substantial passenger time savings and operational benefits. The simulation results suggest that improved regularity and fewer bunching led to a 25 per cent reduction in passenger waiting times. In addition, improved regularity resulted with a more even passenger loads. Approximately half of the regularity improvements are attributed to the headway-based holding. However, the potential benefits from changing the boarding regime have hardly materialized in the field experiment.

Based on a comprehensive analysis of empirical and simulation data it was estimated that each passenger saved four minutes perceived journey time (15 per cent of the total travel time) in the pilot study.

5.5 Model validity

The base scenario (2013) and the field experiment period scenario (2014) were compared to empirical data and the simulation model proved to predict the trip travel time result of the field experiment well, while overestimating some of the headway variability effects. The simulation data includes dwell time at first and last stop which the AVL system does not record, which explains why the average trip travel time in table 6 is approximately one minute longer for the simulation. The headway variability depicted in figure 7 is clearly overestimated in the model for the before period, while the after period more accurate. These results suggest that the simulated gains in dwell time and riding times are robust while the simulated waiting time gains are overestimated by a factor of two. Hence, it is estimated that each passenger saved four minutes of travel time on average during the field experiment period.

Table 6 Comparison of empirical and simulated trip time statistics [in minutes]

		2013			2014		
		Trip time	St.dev	90-perc	Trip time	St.dev	90-perc
Empirical	To Gullmarsplan	63.3	6.3	71.0	58.7	5.1	64.7
	To Radiohuset	56.4	3.6	60.8	53.0	3.4	57.2
Simulation	To Gullmarsplan	64.1	6.4	72.8	59.0	3.9	64.1
	To Radiohuset	57.5	3.4	62.4	54.2	3.5	58.6

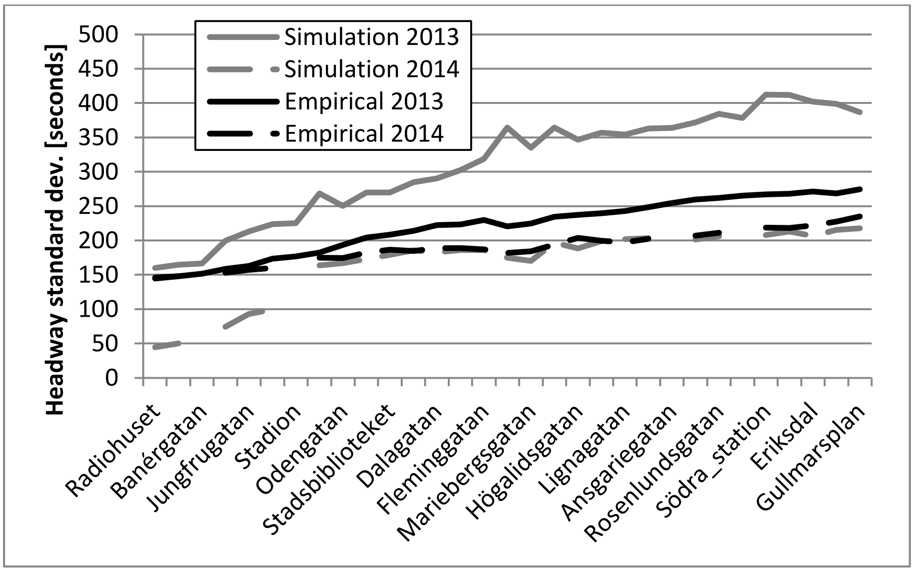

Fig. 7 Standard deviation of the headway along the R-G direction

6 Conclusions

Simulation models enable to test the impacts of transit preferential measures prior to their implementation and thus support their design. The individual as well as combined impact of several preferential measures was evaluated in this study using BusMezzo, a dynamic transit operations and assignment model, in two case studies. The bus corridor case study with heterogeneous bus operations demonstrated the potential of combining boarding through all doors and headway-based holding in improving passenger travel time and regularity. These findings were further elaborated in the field experiment case study where vehicle trip time and passenger travel time improvements from each preferential measure were estimated and validated.

Our findings indicate that all three tested measures (boarding through all doors, headway-based holding and bus lanes) had an overall positive impact on service performance and that they exercised negative synergy effects with their combined effect being smaller than the sum of their marginal contributions, except for headway-based holding which exercised positive synergy effects with the two other measures. It is therefore advisable to simulate alternative measures prior to their implementation to assess their impacts and refine their design. These measures are relatively cheap compared to investments in new transit infrastructure and large societal gains can therefore be achieved by their implementation.

Following its experience with the headway-based control during the field experiment, the bus operator has decided to continue using it for service operations and control. Cats (2014) outlined recommendations for alternative incentive schemes and business models that could be deployed to promote regularity-driven operations.

Allowing free boarding through all doors can be beneficial for the operator, even when accounting for the increased fare evasion, if ridership increases as an effect. Allowing free boarding through all doors makes it possible to either use larger vehicles or to increase frequency while maintaining regularity. The conclusion is that it could be economically beneficial for the operator to allow free boarding through all doors on line 4 in Stockholm and on comparable bus lines elsewhere.

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