Individual and Synergetic Effects of Transit Service Improvement Strategies
Simulation and Validation

West, J; Cats, Oded

DOI
10.1061/JTEPBS.0000095

Publication date
2017

Document Version
Accepted author manuscript

Published in
Journal of Transportation Engineering

INDIVIDUAL AND SYNERGETIC EFFECTS OF TRANSIT SERVICE IMPROVEMENT STRATEGIES – SIMULATION AND VALIDATION

Jens West
Corresponding author
Department of Transport Science, KTH Royal Institute of Technology,
Teknikringen 10, 100 44 Stockholm, Sweden
Email: jens.west@abe.kth.se

Oded Cats
Department of Transport and Planning, Delft University of Technology, the Netherlands
AND
Department of Transport Science, KTH Royal Institute of Technology
Email: o.cats@tudelft.nl

ABSTRACT

Assessment of transit service improvements such as bus lanes, allowing boarding through all doors and headway-based holding control requires detailed simulation capabilities. However, as the usage of models advanced enough to simultaneously analyse physical and operational measures has been limited, their validity has hitherto remained low. This paper assesses the implementation of several bus service improvement measures in a simulation model, BusMezzo. We analyse the impact of isolated and combinations of measures, and validate the model using field experiment data. The model predicted travel time improvements accurately (1-2% difference), while overestimating some of the headway variability effects. The three tested measures 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.

INTRODUCTION

Improving an existing bus service can be a cost and space efficient alternative to new rail or Bus Rapid Transit (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. Improvement strategies are therefore designed to reduce potential delays and sources of uncertainty and typically address both aspects simultaneously.

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 for tram lines 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.

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 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).

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, Schwartz et al. (1982) found that during peak-hour, bus speed increased by 83% and bus reliability increased by 57 percent while traffic speed on the relevant street increased by 10 percent. In contrast, Diab and El-Geneidy (2013) found that while the operation of an exclusive bus lane 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) estimated boarding times of 3.1 seconds per passenger for smart card holders 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). Fernández et al. (2010) showed in a laboratory experiment that boarding time on low-floor buses was only 1.5 seconds with free boarding, and 1.7 seconds with smart cards. However, the same study showed that in real life data from Santiago de Chile, boarding with a combination of smart card ticket verification and free boarding took 2.1 seconds.

A dwell time model is not sufficient in order to observe the full impact of a changed boarding regime, as the severity of bunching problems will be different with different boarding regimes. It is also important to take into consideration that the performance of a transit line is influenced by the other traffic, 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 many have studied the effects of this, starting from Chriqui and Robbillard (1975). However, previous studies usually ignore the fact that the lines might have different vehicle capacity, control and boarding regime, all affecting level of service (West 2011).

In this paper, the impact of three different transit service improvement measures which were implemented during a field experiment in Stockholm are evaluated using 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. Empirical data from the field experiment enabled the validation of the traffic and operational features of the model.

MODELLING TRANSIT OPERATIONS

BACKGROUND

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. Nesheli and Ceder (2015) and Nesheli et al. (2016) implemented a control module in MATSim which allows testing combinations of three different tactics: holding, skipping stops and short turning. However, none of the abovementioned studies has tested model validity by contrasting its predictions with actual observations.

BusMezzo

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. The representation of individual transit vehicles and their properties, traffic conditions, passenger flows and stop activity dynamics makes BusMezzo suitable for studying transit dynamics and the impacts of improvement strategies. The 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). However, the capability of the model to correctly assess the later remained unknown prior to field implementations that could offer empirical data to assess model validity.

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

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 boarding and alighting in Stockholm and Gothenburg was used to calibrate and validate dwell time models in BusMezzo for articulated low-floor buses with three doors (West 2011). Two types of boarding regimes are modelled, boarding only through the front door with ticket inspection by the driver, and free boarding through all doors with no ticket validation. The bus doors in Stockholm and Gothenburg are relatively wide, but the passengers were observed to use them as only one door channel each.

Specification of suitable dwell time functions was based on the data collected and former experience. Previous studies (Dueker et al., 2004) have found a non-linear relationship between the numbers of boarding and alighting passengers and dwell time, but linearity was chosen in these models for simplicity. For boarding through only the front door this simplification is indeed motivated as service time for ticket inspection does not decrease with the number of passengers. For boarding through all doors however, service time per passenger can be assumed to decrease with the number of boarding and alighting passengers. This is roughly modelled by inserting a constant in the linear model; hence for very low numbers of boarding and alighting passengers the dwell time will be slightly overestimated. For high numbers of boarding and alighting passengers, a linear function fits collected data well and we found no significant second-order term. For the overall results, the impact of choosing a linear or a non-linear model is small; the difference in total dwell time between the two types of boarding regimes is substantially larger than the difference between different variants of them. The two main functions are:

$$DT_{Front} = \max(2.4\mathrm{r}_b P_b, 0.94\mathrm{r}_a P_a), \quad (1)$$
$$DT_{All} = 3.3 + 0.86\mathrm{r}_b P_b + 0.49\mathrm{r}_a P_a, \quad (2)$$

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. The crowding factor r based on the findings of Weidmann (1994) is applied in each case,

$$\mathrm{r} = 1 + 0.75\left(\frac{s}{c}\right)^2. \quad (3)$$

where s is the number of on-board standees and c is the standee capacity. For the boarding process, the number of standees is an average of the number before the boarding starts (after the number of alighting passengers has been subtracted) and after its completion. For the alighting process, the number of standees is the number of through standees (i.e., the theoretical number of standees after the alighting process but before the boarding process, as if they were sequential).

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.

GENERALIZED TRAVEL TIME

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.

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 improvement measures which were implemented simultaneously during the field experiment period are:

(1) introduction of bus lanes on some line sections (see figure 1);
(2) continuous operation and control 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).

Line 4 has previously been controlled through scheduled-based dispatching from six time point stops. In the operation and control measure, drivers were instead instructed to keep even headways to the preceding and successive buses by adjusting their speed or holding at stops according to a real-time indicator projected through the bus PC display.

While the initial objective was to test free boarding through all three doors, the implementation reflected a compromise among the stakeholders. The effect of this measure in the field experiment was further diminished by the fact that it was implemented only on one bus line and that it was not widely advertised. Many travellers were hence not aware of the possibility to board through the third door.

In addition, four stops (out of 31) were cancelled in order to increase bus speeds and obtain more balanced stop spacing (see figure 1). The direct dwell time effect of this measure can be directly calculated, as the increase in number of travellers on the other stops was logged. However, case study implementation does not allow detangling the traffic effects of this measure from the introduction of bus lanes. The bus operator estimates that bus trip time saving was approximately 30 seconds per cancelled stop, but a linear regression model of the stop-to-stop travel time shows no significant effect at all related to stop cancellation.

On significant portions of its route, line 4 runs in parallel to ordinary city buses that offer local accessibility. Previous research (West 2011) shows that regularity improvements (e.g., faster boarding and headway control) on one bus line can positively affect other bus lines as well. Other bus lines might in fact have either a positive effect on line 4 (relieving it) or a negative effect (inducing more congestion and bunching). These effects are however not simulated and quantified in this study.

OBSERVED RESULTS

An evaluation study compared AVL and APC records for the field experiment period with records for the corresponding period one year earlier. For a detailed description of the data available and its processing, the reader is referred to Fadaei and Cats (2016). Around 10% of the buses are equipped with APC, which log all boarding and alighting activity, while all buses are equipped with AVL, which records vehicle locations and run time between stops. Compared to before the field experiment, bus speeds for both line directions improved noticeably. During afternoon peak hour, the average inter-stop speed increased from 18.1 to 19.3 km/h for the northbound direction and 16.2 to 17.6 km/h for the southbound direction.

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 were 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.

SIMULATION SETUP

The 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. We thus used the bus simulation model to model the impact of isolated and combination of measures, whereas we verified the scenario with all measures combined using the AVL and APC data collected during the field experiment period. The analysis covers weekday afternoons 15:00 – 18:00. We fitted observed run time data for each inter-stop from before (2013) and after (2014) to a shifted lognormal distribution and estimated the demand 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, observed passenger demand levels remained the same during the before and after periods, but travellers switched from the cancelled stops to adjacent stops. In the direction towards Radiohuset, the number of boarding passengers per bus trip were on average 165 before and 167 after (1% change). In the direction towards Gullmarsplan, the number of boarding passengers were on average 201 before and 196 after (-3% change). The largest change for an individual stop was a drop in alighting passengers from 13 to 9 at Odenplan. All other numbers stayed within +/-3 from before to after (including stops with up to 26-27 boarding or alighting passengers). All the cancelled stops had three or less boarding and four or less alighting passengers on average.

The model simulates traveller arrival at each stop assuming a Poisson generation process. The simulated waiting time is then the time each passenger stays at the stop from his or her own arrival until the next vehicle arrives in the simulation.

SCENARIO DESIGN

The simulation model was used for assessing the impact of each of the main 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. A simulation study of the even-headway control led to a series of field experiments as described in Cats (2014). Following these developments, the field experiment reported in this paper was devised and rolled out. Each time a bus is ready to depart from a time point stop in the simulation model, it triggers the holding control. The simulated bus line is controlled either through scheduled-based dispatching from the six time point stops defined along line 4 or by maintaining even headways to the preceding and successive buses by allowing buses to hold at each stop. The control strategy implementation accounts for the AVL transmission and bus PC display (Cats et al. 2012).

Simulation scenarios were therefore designed for assessing the impact of each measure if introduced independently. Table 1 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 improvement measures could be identified. Furthermore, a number of combinations of the scenarios were analysed to enable studying their interactions.

SIMULATION RESULTS

The total dwell time, total bus trip time, service regularity and total passenger travel time for each scenario are presented in table 2. 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.

By splitting the different measures into multiple simulation scenarios, we 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 does not yield any visible improvement compared to the base case in table 2, service regularity measured in terms of headway variation was improved (see figure 2). Although this improved regularity shortened waiting time for passengers on average by 30 seconds, the headway holding caused an increased in-vehicle travel time that cancelled out the time saving. However, the simulation scenario ("All") which combines headway control with reduced run time and boarding all doors obtained small travel time improvements compared to implementing these measures without headway control. So there are indications of synergy effects between headway control and other measures improving regularity, which is the same result as West (2011) obtained. 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 (see figure 2) 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 time (see figure 3). 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. The removed stops affected 4% of the passengers. For an affected passenger, stop removal increased the walking distance by 100-150 metres, which means that walk time for all passengers on average increased by less than 5 seconds.

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, 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.

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 we estimate that each passenger saved four minutes perceived journey time (15 per cent of the total travel time) in the pilot study.

MODEL VALIDITY

We compared the base scenario (2013) and the field experiment scenario (2014) to AVL data from these periods and the simulation model proved to predict the trip travel time result of the field experiment well, as shown in table 3. The model overestimates travel time by 1-2% in both directions, both for 2013 and 2014, when looking at completed trips. Figure 4 shows that the model predicts bus trajectories accurately. Since inter-stop travel time in the model is based directly on the AVL data in question, the comparison of total trip travel time primarily confirms the validity of the dwell time model (which is calibrated based on boarding and alighting data from stops along the same bus route and similar stops). Hence the results from the analysis of boarding regimes seem robust. The headway control module has been validated in several earlier studies (Cats et al. 2012).

The headway variability depicted in figure 5 is clearly overestimated in the model for the before period, while yielding more accurate outputs for the after period. A possible reason is that drivers in reality adjust their speed between time point stops to achieve more even headways even when this is not part of the strategy endorsed by the operator. Previous studies (Lin and Bertini, Cats et al. 2012) found based on empirical and statistical analysis of vehicle positioning data that drivers adjust their speed along the route to improve transit performance. There is a noticeable difference between the simulated and observed headway variability in the first few stops. In the simulation, buses follow the schedule when dispatching from the terminal, subject to vehicle availability constraints. In reality, however, bus drivers may not perfectly adhere to this dispatching regime, inducing imperfect headways from the start of the trip.

The model simulates traveller arrival at each stop assuming a Poisson generation process and waiting time for each traveller is calculated as the time between his or her arrival and the next simulated vehicle arrival. If waiting time gains instead are calculated from observed vehicle arrivals (but maintaining the hypothesis that traveller arrival is a Poisson process), the sum is roughly half as large. The results of this study 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 due to the overestimation of the difference in headway variations. Hence, we estimate that each passenger saved four minutes of travel time on average during the field experiment period.

CONCLUSION

Simulation models enable to test the impacts of transit improvement strategies prior to their implementation and thus support their design. The individual as well as combined impact of several measures was evaluated in this study using BusMezzo, a dynamic transit operations and assignment model. Vehicle trip time and passenger travel time improvements from each measure were estimated and the model accuracy was validated. The model slightly overestimates travel times by 1-2% when looking at completed trips.

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. The impact of boarding through all doors (6% reduction of bus trip time for the simulated full-scale scenario and 2% from the less successful third-door boarding pilot) can be compared to previous studies where the travel time reduction was calculated using linear regression. For instance, Diab and El-Geneidy (2013) found that boarding from the third door in Montreal decreased bus trip time by 2%.

The three tested measures 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. While the simulation model has been implemented in the past to evaluate investments in large-scale networks (e.g. Cats et al. 2016, Jenelius and Cats 2016), the scalability of the results reported in this study can also be tested in the future using a large-scale case study.

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.

The model validity examination performed in this study demonstrates that the simulation model, BusMezzo, was able to reproduce key phenomena such as vehicle trajectories, bus bunching and dwell time variations for different boarding regimes. Notwithstanding, the results suggest that driver behaviour aspects such as dispatching from the first stop and speed adjustments between stops play an important role that is unexplained by the model. Further empirical investigation will be required to adequately capture these behavioural aspects.

ACKNOWLEDGEMENTS

Part of this work was sponsored by the Stockholm County Council.

REFERENCES

Abdelghany, K.F., Abdelghany, A.F., Mahmassani, H.S. and Abdelfatah, A.S. (2006). Modeling bus priority using intermodal dynamic network assignment-simulation methodology. Journal of Public Transportation, 9 (5), 1-22.

Bates, J., Polak, J., Jones, P. and Cook, A. (2001). The valuation of reliability for personal travel. Transportation Research Part E, 37 (2-3), 191-229.

Bertini, R. and El-Geneidy, A. (2004). Modeling Transit trip time using archived bus dispatch system data. Journal of Transportation Engineering, 130 (1), 56-67.

Cats, O. (2013). Multi-Agent Transit Operations and Assignment Model. In Procedia Computer Science, 19, 809-814.

Cats, O. (2014). Regularity-Driven Bus Operations: Principles, Implementation and Business Models. Transport Policy, 36, 223-230.

Cats, O., Larijani, A.N, Ólafsdóttir, A., Burghout, W., Andreasson, I. and Koutsopoulos, H.N. (2012). Holding Control Strategies: A Simulation-Based Evaluation and Guidelines for Implementation. In Transportation Research Record, 2274, 100-108.

Cats, O., West, J. and Eliasson, J. (2016). A Dynamic Stochastic Model for Evaluating Congestion and Crowding Effects in Transit Systems. Transportation Research Part B, 89, 43-57.

Chang, J., Collura, J., Dion, F. and Rakha, H. (2003). Evaluation of service reliability impacts of traffic signal priority strategies for bus transit. Transportation Research Record, 1841, 23-31.

Cortes, C.E., Pages, L. and Jayakrishnan, R. (2005). Microsimulation of flexible transit system designs in realistic urban networks. Transportation Research Record, 1923, 153-163.

Diab, E.I., El-Geneidy, A. M., 2013. Variation in bus transit service: understanding the impacts of various improvement strategies on transit service reliability. Public Transp. 4 (3), 209–231.

Ding, Y., Chien, S. and Zayas, A. (2001). Simulating bus operations with enhanced corridor simulator. Transportation Research Record, 1731, 104-111.

Dueker, K.J., Kimpel, T.J., Strathman, J.G., Callas, S., 2004. Determinants of bus dwell time. J. Public Transp. 7 (1), 2.

Fadaei, M. and Cats, O. (2016). Evaluating the impacts and benefits of public transport design and operational measures. Transport Policy 48, 105-116.

Fernandez, R. (2010). Modelling public transport stops by microscopic simulation. Transportation Research Part C, 18, 856-868.

Fernández, R., Zegers, P., Weber, G. and Tyler, N. (2010). Influence of Platform Height, Door Width, and Fare Collection on Bus Dwell Time. Transportation Research Record 2143, 59-66.

Furth, P.G. and Muller, T.H.J. Conditional Bus Priority at Signalized Intersections: Better Service with Less Traffic Disruption. In Transportation Research Record: Journal of the Transportation Research Board, No. 1731, TRB, National Research Council, Washington, D.C., 2000, 23–30.

Gao, W., Balmer, M. and Miller, E.J. (2010). Comparisons between MATSim and EMME/2 on the Greater Toronto and Hamilton Area Network. Transportation Research Record, 2197, 118–128.

Jenelius, E. and Cats, O. (2015). The Value of New Public Transport Links for Network Robustness and Redundancy. Transportmetrica A: Transport Science, 11 (9), 819-835.

Kittelson & Associates, Parsons Brinkkerhoff, KFH Group, Texas A&M Transportation Institute, Arup. Transit Capacity and Quality of Service Manual, second ed. Washington, DC: Transit Cooperative Research Program, Report 165, 2013.

Lin, W.H. and Bertini, R. (2004). Modeling schedule recovery processes in transit operations for bus arrival time predictions. Journal of Advanced Transportation, 38 (3), 347-365.

Meignan, D., Simonin, O. and Koukam, A. (2007). Simulation and evaluation of urban bus-networks using a multiagent approach. In Simulation Modeling Practice and Theory, 15 (6), 659-671.

Milkovits, M (2008). Modeling the Factors Affecting Bus Stop Dwell Time - Use of Automatic Passenger Counting, Automatic Fare Counting, and Automatic Vehicle Location Data. Transportation Research Record 2072, 125-130.

Nesheli, M.M. and Ceder, A. (2015). A Robust, Tactic-Based, Real-Time Framework for Public-Transport Transfer Synchronization. Transportation Research Part C: Emerging Technologies, 60, 105-123.

Nesheli, M.M., Ceder, A. and Gonzalez V.A. (2016). Real-time public transport operational tactics using synchronized transfers to eliminate vehicle bunching. IEEE Transactions on Intelligent Transportation Systems, 17(11), 3220-3229.nesh

Neves, J. (2006). The impact of bus lanes on urban traffic environment. Thesis, Porto, Portugal: Department of Civil Engineering, University of Porto.

Osuna, E.E., and Newell, G.F (1972). Control strategies for an idealized public transport system. Transportation Science, 6, 52-72.

Schwartz, S.I., Hollander, A., Louie, C. and Amoruso, R. (1982). Madison Avenue Dual Width Bus Lane Project. Transportation Research Record 854, National Research Council, Washington, D.C., 70-77.

Shalaby, A. (1999). Simulating Performance Impacts of Bus Lanes and Supporting Measures. Journal of Transportation Engineering, September-October, 390-397.

Shalaby, A. and Soberman, R. (1994). Effect of With-Flow Bus Lanes on Bus Travel Times., Transportation Research Record 1433. Transportation Research Board, National Research Council, Washington, D.C., 24-30.

Sundberg, J. and Peterson, B. (2011). Kapacitet i kollektiva trafiksystem - Del 3 - Uppehåll vid hållplats. Trafikplanering meddelande 69, Stockholm: KTH Royal Institute of Technology.

Toledo, T., Cats, O., Burghout, W. and Koutsopoulos, H.N. (2010). Mesoscopic Simulation for Transit Operations. In Transportation Research Part C, 18(6), 896-908.

Turnquist, M.A. (1981). Strategies for Improving Reliability of Bus Transit Service. In Transportation Research Record 818, TRB, National Research Council, Washington, D.C., 7-13.

Wahba, M. and Shalaby, A. (2011). Large-scale application of MILATRAS: case study of the Toronto transit network. Transportation, 38(6), 889–908.

van Oort, N., and R. van Nes (2009). Regularity analysis for optimizing urban transit network design. Public Transport 1 (2), 155-168.

van Oort, N., Wilson, N. H. M. and van Nes, R. (2010). Reliability Improvement in Short Headway Transit Services: Schedule- and Headway-Based Holding Strategies. Transportation Research Record 2143, National Research Council, Washington, D.C., 67-76.

Wardman, M. and Whelan, G. (2011). Twenty years of rail crowding valuation studies: Evidence from lessons from British Experience. In Transport Reviews, 31(3), 379–398.

West, J. (2011). Boarding and bunching: The impact of boarding procedure on bus regularity and performance. Master thesis, Stockholm, Sweden: Transport Science Department, KTH Royal Institute of Technology.

Vuchic, V.R. (1969). Propagation of schedule disturbances in line-haul passenger transportation. Revue de l'UITP, 281-284.

Vuchic, V.R. (1981). Urban Public Transportation Systems and Technology. Prentice Hall. ISBN 978-0139394966.

FIGURES

Fig. 1. Line 4 and the physical measures implemented during the trial period
Fig. 2. Headway coefficient of variation of the headway along the R-G direction
Fig. 3. Average passenger generalized travel cost components under selected scenarios
Fig. 4. Headway coefficient of variation of the headway along the R-G direction

Table 1. Scenario design summary

Scenario	Stops cancelled	Physical road measures	Even-headway control	Free boarding	Construction work on L:a Västerbron
Base 2013					
Reduced run time	X	X			
Headway control			X		
Board all doors				X	
Red. run + board all	X	X		X	
All	X	X	X	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 with the effects of the construction works on Lilla Västerbron for validation purposes

Table 2. Summary simulation scenario results (in minutes)

Scenario	Total dwell time	Total bus trip time	Trip time st. dev.	Pass. general. travel time
Base case	15	61	5	27
Reduced run time	14 (-7%)	56 (-7%)	4	22 (-17%)
Headway control	15 (-0%)	61 (-0%)	5	27 (-0%)
Board all doors	13 (-16%)	57 (-6%)	4	24 (-12%)
Red. run + board all	13 (-18%)	54 (-11%)	3	20 (-26%)
All	12 (-23%)	53 (-13%)	3	20 (-28%)

Table 3. Comparison of observed and simulated trip time statistics (in minutes)

	Direction	2013			2014		
		Trip time	St.dev.	90-perc	Trip time	St.dev.	90-perc
Observed	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
Model	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