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

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ABSTRACT

15   Assessment of transit service improvements such as bus lanes, allowing boarding through all

16   doors and headway-based holding control requires detailed simulation capabilities. However, as

17   the usage of models advanced enough to simultaneously analyse physical and operational

18   measures has been limited, their validity has hitherto remained low. This paper assesses the

19   implementation of several bus service improvement measures in a simulation model, BusMezzo.

20   We analyse the impact of isolated and combinations of measures, and validate the model using

21   field experiment data. The model predicted travel time improvements accurately (1-2%

22   difference), while overestimating some of the headway variability effects. The three tested

23   measures exercised negative synergy effects with their combined effect being smaller than the

24   sum of their marginal contributions, except for headway-based holding which exercised positive

25   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

51   improve service performance considerably from both passenger and operator perspectives.

52   Conditional priority at traffic lights was studied in an experiment by Furth and Muller (2000).

53   Introduction of dedicated bus lanes has been studied extensively and with good results,

54   theoretically (Vuchic 1981), empirically (e.g., Schwartz et al. 1982 and Shalaby and Soberman

55   1994) and with the aid of simulation models (e.g., Shalaby 1999). These findings suggest that

56   replacing mixed traffic lanes with dedicated bus lanes effectively reduce bus travel time and

57   variability, while in some cases only with a minor negative effect on car travel times. For

58   example, Schwartz et al. (1982) found that during peak-hour, bus speed increased by 83% and

59   bus reliability increased by 57 percent while traffic speed on the relevant street increased by 10

60   percent. In contrast, Diab and El-Geneidy (2013) found that while the operation of an exclusive

61   bus lane had a modest effect on reducing bus running time by 2.7%, travel time variability

62   increased by 0.5% due to the effect of right turning vehicles. Their study analysed empirically a

63   mix of measures to improve transit performance in Montreal using automated vehicle location

64   (AVL) and automated passenger counts (APC) data with a focus on reliability. Neves (2006)

65   offers a good overview of the advances in the dedicated bus lanes domain.

66   Dwell times account for a sizeable share of the total travel time. Bertini and El-Geneidy (2004)

67   estimated that the total time lost due to serving stops is 33% of the total travel time for urban

68   services, of which half is attributed to passenger service time per-se. Furthermore, dwell time is

69   an important source of unreliability as it causes high variability with a coefficient of variation in

70   the range of 0.6 to 0.8 (TCQSM, 2013). The effects of for instance changing the boarding

71   procedure are not limited to trip travel time but also influence service regularity. The

72   relationship between a change in the boarding procedure and passenger travel time is therefore

73   not straightforward for high frequency bus services. Vuchic (1969) developed a deterministic

74   model to show that even the smallest disturbances inevitably lead to bunching. According to

75   Vuchic, the most effective way to deal with bunching is to reduce boarding times. Diab and El-

76 Geneidy (2013) found that the introduction of a new fare collection system increased bus

77 running time by 3.8% and increased running time variation by 0.7 %.

78 Expressing dwell time as a function of different parameters such as door configuration, vehicle

79 design and crowding level has been the target for numerous studies (e.g. Weidmann 1994 and

80 Tirachini 2013). The fare payment system also affects the service time. A study in Chicago

81 (Milkovits 2008) estimated boarding times of 3.1 seconds per passenger for smart card holders

82 and 4.2 for swipe cards on low-floor buses. Dwell time is generally assumed to be shorter and

83 more reliable when boarding is allowed through all doors than when only allowed through the

84 front door (Sundberg and Peterson 1989). Fernández et al. (2010) showed in a laboratory

85 experiment that boarding time on low-floor buses was only 1.5 seconds with free boarding, and

86 1.7 seconds with smart cards. However, the same study showed that in real life data from

87 Santiago de Chile, boarding with a combination of smart card ticket verification and free

88 boarding took 2.1 seconds.

89 A dwell time model is not sufficient in order to observe the full impact of a changed boarding

90 regime, as the severity of bunching problems will be different with different boarding regimes. It

91 is also important to take into consideration that the performance of a transit line is influenced by

92 the other traffic, including other transit lines (van Oort and van Nes 2009). Different services in

93 terms of frequencies may co-exist and operate along the same corridor and many have studied

94 the effects of this, starting from Chriqui and Robbillard (1975). However, previous studies

95 usually ignore the fact that the lines might have different vehicle capacity, control and boarding

96 regime, all affecting level of service (West 2011).

97 In this paper, the impact of three different transit service improvement measures which were

98 implemented during a field experiment in Stockholm are evaluated using simulation. The

99 detailed simulation model enables comparing the effects of the three measures in a way that

100 would be difficult solely by analysing empirical data from the field experiment. As the usage of

101 such detailed models has been limited, their validity has hitherto been low. Empirical data from

102 the field experiment enabled the validation of the traffic and operational features of the model.

MODELLING TRANSIT OPERATIONS
103

BACKGROUND
104

105 In the context of general traffic operations, simulation models asserted themselves as the

106 primary tool for evaluation at the operational level. Due to the nature of transit systems in terms

107 of size, complexity and dynamics – in particular with the implementation of Advanced Public

108 Transport Systems - it is unrealistic to apply global analytical models to solve transit

109 management problems. Transit simulations may serve several interests (Meignan et al. 2007):

110 observation of network dynamics and design; evaluation and control of dynamic processes, and;

111 evaluation of network performance under alternative designs. Transit simulation models may

112 therefore be instrumental in testing the implications of various operational measures prior to

113 their implementation.

114 Most of the previous transit simulation studies were conducted by adjusting traffic simulation

115 models that do not represent transit operations or enhancing existing simulation models by

116 extending their capabilities for specific applications (Abdelghany et al. 2006, Ding et al. 2001,

117 Chang et al. 2003, Cortes et al. 2005). Fernandez (2010) developed a stop design and

118 performance simulation model where the operations of the immediate stop area under different

119 vehicle and passenger arrival patterns are analysed. Microscopic transit simulation models were

120 also proposed by Morgan (2002) and Lee et al. (2005) for the purpose of evaluating transit

121 signal priority strategies.

122 In all of the abovementioned studies, passenger and vehicle arrival processes were represented

123 for a given line segment without considering their inter-dependency along the route. This

124 prohibits the analysis of operational measures that may have effects that extend beyond a single

125   segment and may even influence other lines. Whilst MILATRAS (Wahba and Shalaby 2011) and

126   MATSim (Gao et al. 2010) offer transit assignment simulation models, they lack transit

127   operations modelling capabilities such as vehicle scheduling, control strategies and crowding

128   effects. Nesheli and Ceder (2015) and Nesheli et al. (2016) implemented a control module in

129   MATSim which allows testing combinations of three different tactics: holding, skipping stops and

130   short turning. However, none of the abovementioned studies has tested model validity by

131   contrasting its predictions with actual observations.

BusMezzo

133   BusMezzo, a dynamic transit operations and assignment model, was developed to enable the

134   analysis and evaluation of transit performance and level of service under various system

135   conditions (Cats 2013). The model represents the interactions between traffic dynamics, transit

136   operations and traveller decisions. BusMezzo was implemented within a mesoscopic traffic

137   simulation model and the different sources of transit operations uncertainty including traffic

138   conditions, dwell times and service disruptions are modelled explicitly. BusMezzo represents

139   vehicle schedules and hence the potential propagation of delays from previous trips. The

140   representation of individual transit vehicles and their properties, traffic conditions, passenger

141   flows and stop activity dynamics makes BusMezzo suitable for studying transit dynamics and

142   the impacts of improvement strategies. The model was validated for its supply representation in

143   a small case study in Tel Aviv (Toledo et al. 2010) and was applied for studying control

144   strategies in Stockholm (Cats et al. 2012). However, the capability of the model to correctly

145   assess the later remained unknown prior to field implementations that could offer empirical

146   data to assess model validity.

147   Individual vehicles and travellers are modelled in BusMezzo, but not their second-by-second

148   movements. The dynamic path choice model considers each traveller as an adaptive decision

149   maker for which progress in the transit system consists of successive decisions that are based on

150   the respective path alternatives and their anticipated downstream attributes. Travel decisions

151   are modelled within the framework of discrete random utility models. The simulation analysis in

152   BusMezzo enables to assess the impact of individual operational measures on performance and

153   passenger travel experience as well as the magnitude of unrealized potential improvements.

154   DWELL TIME

155   Dwell time at stops can take different functional forms. In order to analyse different boarding

156   regimes, adequate dwell time modelling is essential. Video recording of boarding and alighting in

157   Stockholm and Gothenburg was used to calibrate and validate dwell time models in BusMezzo

158   for articulated low-floor buses with three doors (West 2011). Two types of boarding regimes are

159   modelled, boarding only through the front door with ticket inspection by the driver, and free

160   boarding through all doors with no ticket validation. The bus doors in Stockholm and

161   Gothenburg are relatively wide, but the passengers were observed to use them as only one door

162   channel each.

163   Specification of suitable dwell time functions was based on the data collected and former

164   experience. Previous studies (Dueker et al., 2004) have found a non-linear relationship between

165   the numbers of boarding and alighting passengers and dwell time, but linearity was chosen in

166   these models for simplicity. For boarding through only the front door this simplification is

167   indeed motivated as service time for ticket inspection does not decrease with the number of

168   passengers. For boarding through all doors however, service time per passenger can be assumed

169   to decrease with the number of boarding and alighting passengers. This is roughly modelled by

170   inserting a constant in the linear model; hence for very low numbers of boarding and alighting

171   passengers the dwell time will be slightly overestimated. For high numbers of boarding and

172   alighting passengers, a linear function fits collected data well and we found no significant

173   second-order term. For the overall results, the impact of choosing a linear or a non-linear model

174   is small; the difference in total dwell time between the two types of boarding regimes is

175   substantially larger than the difference between different variants of them. The two main

176   functions are:

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

177   where P_b and P_a are the vehicle and stop specific number of boarding and alighting passengers

178   respectively. DT_{Front} denotes the dwell time in case boarding is possible only from the front

179   door whereas DT_{All} denotes the dwell time when allowing free boarding through all doors. The

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

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

181   where s is the number of on-board standees and c is the standee capacity. For the boarding

182   process, the number of standees is an average of the number before the boarding starts (after

183   the number of alighting passengers has been subtracted) and after its completion. For the

184   alighting process, the number of standees is the number of through standees (i.e., the theoretical

185   number of standees after the alighting process but before the boarding process, as if they were

186   sequential).

187   Each stop could be defined as a potential time point stop implying that the holding strategy

188   under consideration determines the departure time based on the dynamic system conditions. In

189   order to analyse the impacts of holding strategies on transit performance, it is necessary to

190   model dynamically the interactions between passenger activity, transit operations and traffic

191   dynamics. An evaluation of different holding criteria (e.g., only with respect to the preceding

192   vehicle or to both the preceding and the succeeding vehicle) and number and location of time

193   point stops was previously conducted using BusMezzo (Cats et al. 2012). The holding strategies

194   were implemented in the model.

195   GENERALIZED TRAVEL TIME

196   Passenger travel experience in the assignment model is measured as perceived journey time

197   where waiting time is weighted twice as high as uncrowded in-vehicle time. Capacity constraints

198   are enforced so that passengers that are left behind have to wait for the next vehicle. Vehicle

199   specific on-board crowding affects boarding and alighting time as well as traveller journey time

200 perception. Crowded in-vehicle time is weighted higher than uncrowded in-vehicle time

201 according to the multipliers suggested in a meta-analysis performed by Wardman and Whelan

202 2011.

CASE STUDY: REAL-WORLD HIGH-DEMAND TRUNK LINE

204 Line 4 is the busiest and most frequent bus line in Stockholm, with more than 60,000 boarding

205 passengers per day and 4-5 minutes headways during large parts of the day. The line traverses

206 all major districts of Stockholm inner-city and connects major transfer stations to metro,

207 commuter train, local trains and bus terminals. It is the most important line out of the four high-

208 capacity trunk bus lines which operate in Stockholm inner-city and constitute the backbone of

209 its bus network. These lines are marked differently and are actively branded as the blue lines

210 which are designed to offer a high level of service. Boarding is allowed only through the front

211 door, where tickets are inspected but not sold. The line alternates between dedicated bus lanes

212 and regular city streets without grade separation. However, due to traffic conditions, the average

213 commercial speed (origin to destination, including stop dwell time) of buses on trunk line 4 was

214 merely 13 km/h during the rush hour in 2013. Additionally, delays and poor regularity

215 persistently causes passengers to experience unpredictable waiting and travel times.

216 In order to improve the level-of-service on this cardinal bus line, a field experiment was initiated

217 by Stockholm Municipality, Stockholm County and the bus operator, Keolis. The experiment

218 included the implementation of a range of physical and operational measures on line 4 and took

219 place in the spring of 2014, from March 17 to June 19. The most important of the improvement

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

221   (1) introduction of bus lanes on some line sections (see figure 1);

222   (2) continuous operation and control based on regularity (even-headway control and

223   control centre operations) and;

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

225   boarding).

226   Line 4 has previously been controlled through scheduled-based dispatching from six time point

227   stops. In the operation and control measure, drivers were instead instructed to keep even

228   headways to the preceding and successive buses by adjusting their speed or holding at stops

229   according to a real-time indicator projected through the bus PC display.

230   While the initial objective was to test free boarding through all three doors, the implementation

231   reflected a compromise among the stakeholders. The effect of this measure in the field

232   experiment was further diminished by the fact that it was implemented only on one bus line and

233   that it was not widely advertised. Many travellers were hence not aware of the possibility to

234   board through the third door.

235   In addition, four stops (out of 31) were cancelled in order to increase bus speeds and obtain

236   more balanced stop spacing (see figure 1). The direct dwell time effect of this measure can be

237   directly calculated, as the increase in number of travellers on the other stops was logged.

238   However, case study implementation does not allow detangling the traffic effects of this measure

239   from the introduction of bus lanes. The bus operator estimates that bus trip time saving was

240   approximately 30 seconds per cancelled stop, but a linear regression model of the stop-to-stop

241   travel time shows no significant effect at all related to stop cancellation.

242   On significant portions of its route, line 4 runs in parallel to ordinary city buses that offer local

243   accessibility. Previous research (West 2011) shows that regularity improvements (e.g., faster

244   boarding and headway control) on one bus line can positively affect other bus lines as well.

245   Other bus lines might in fact have either a positive effect on line 4 (relieving it) or a negative

246   effect (inducing more congestion and bunching). These effects are however not simulated and

247   quantified in this study.

OBSERVED RESULTS

249 An evaluation study compared AVL and APC records for the field experiment period with

250 records for the corresponding period one year earlier. For a detailed description of the data

251 available and its processing, the reader is referred to Fadaei and Cats (2016). Around 10% of the

252 buses are equipped with APC, which log all boarding and alighting activity, while all buses are

253 equipped with AVL, which records vehicle locations and run time between stops. Compared to

254 before the field experiment, bus speeds for both line directions improved noticeably. During

255 afternoon peak hour, the average inter-stop speed increased from 18.1 to 19.3 km/h for the

256 northbound direction and 16.2 to 17.6 km/h for the southbound direction.

257 In total, the average complete trip time from the first stop to the last one during the afternoon

258 peak period decreased by five minutes during the field experiment. Hence, the average complete

259 trip cycle time during this period became ten minutes shorter. Moreover, fewer trips were

260 exceedingly long and headway variability, measured in terms of the coefficient of variation,

261 decreased by 28%. These improvements could potentially help the operator to cut the fleet size

262 by two buses, from 27 to 25 buses. This calculation is based on maintaining the current planned

263 headway. Alternatively, the same fleet could be used for offering a higher frequency.

264 SIMULATION SETUP

265 The pilot study constituted a perfect opportunity to evaluate the joint impacts of these

266 measures. However, their simultaneous introduction does not allow drawing conclusions on

267 their isolated effects and marginal contributions to overall change in performance. We thus used

268 the bus simulation model to model the impact of isolated and combination of measures, whereas

269 we verified the scenario with all measures combined using the AVL and APC data collected

270 during the field experiment period. The analysis covers weekday afternoons 15:00 – 18:00. We

271 fitted observed run time data for each inter-stop from before (2013) and after (2014) to a

272 shifted lognormal distribution and estimated the demand for before and after cases based on

273 iterative proportional fitting of the empirically logged total boarding and alighting margins per

274   stop, which were obtained from APC. Overall, observed passenger demand levels remained the

275   same during the before and after periods, but travellers switched from the cancelled stops to

276   adjacent stops. In the direction towards Radiohuset, the number of boarding passengers per bus

277   trip were on average 165 before and 167 after (1% change). In the direction towards

278   Gullmarsplan, the number of boarding passengers were on average 201 before and 196 after (-

279   3% change). The largest change for an individual stop was a drop in alighting passengers from

280   13 to 9 at Odenplan. All other numbers stayed within +/-3 from before to after (including stops

281   with up to 26-27 boarding or alighting passengers). All the cancelled stops had three or less

282   boarding and four or less alighting passengers on average.

283   The model simulates traveller arrival at each stop assuming a Poisson generation process. The

284   simulated waiting time is then the time each passenger stays at the stop from his or her own

285   arrival until the next vehicle arrives in the simulation.

286   SCENARIO DESIGN

287   The simulation model was used for assessing the impact of each of the main measures on the

288   overall performance. The physical measures - additional bus lanes and stop cancellation - were

289   assessed as a whole through their impact on bus running time. In addition, the operational

290   measures included two distinct interventions - allowing boarding from the third door and even-

291   headway holding control. Both measures are expected to influence dwell times, passenger

292   volumes and service reliability. A simulation study of the even-headway control led to a series of

293   field experiments as described in Cats (2014). Following these developments, the field

294   experiment reported in this paper was devised and rolled out. Each time a bus is ready to depart

295   from a time point stop in the simulation model, it triggers the holding control. The simulated bus

296   line is controlled either through scheduled-based dispatching from the six time point stops

297   defined along line 4 or by maintaining even headways to the preceding and successive buses by

298   allowing buses to hold at each stop. The control strategy implementation accounts for the AVL

299   transmission and bus PC display (Cats et al. 2012).

12

300   Simulation scenarios were therefore designed for assessing the impact of each measure if

301   introduced independently. Table 1 summarizes the scenario design and indicates the different

302   measures that were considered in each scenario.

303   The simulation model enables the assessment of the potential benefits of truly allowing boarding

304   from all doors without ticket inspection. In order to reflect the field experiment adequately in

305   the 2014 scenario, the dwell time function was modified to reflect the actual implementation.

306   Ticket inspection is estimated to increase boarding time by one second per passenger compared

307   to boarding without ticket inspection and the number of door channels available for

308   boarding/alighting has a diminishing effect on total service time (doubling the number of door

309   channels decreases service time by 40%).

310   The impact of the construction works that occurred on the bridge, Lilla Västerbron, in one

311   direction 2013 and in the other direction 2014 was also analysed. By removing this effect from

312   the construction work in the simulation model, the effect of the improvement measures could be

313   identified. Furthermore, a number of combinations of the scenarios were analysed to enable

314   studying their interactions.

315   SIMULATION RESULTS

316   The total dwell time, total bus trip time, service regularity and total passenger travel time for

317   each scenario are presented in table 2. Dwell time is important in itself but is also a key

318   determinant of regularity and therefore of both passenger waiting time and in-vehicle travel

319   time. Total trip time and its variability are the most important determinants of fleet size and

320   hence the operational costs associated with provisioning a given service frequency.

321   By splitting the different measures into multiple simulation scenarios, we concluded that of the

322   saved vehicle travel time minutes, five were because of the street measures (bus lanes) and

323   removed stops, while free boarding through all doors would have decreased it by four minutes.

324   Together with the street measures and removed stops this would save eight minutes average

325   trip travel time.

326   While the headway control does not yield any visible improvement compared to the base case in

327   table 2, service regularity measured in terms of headway variation was improved (see figure 2).

328   Although this improved regularity shortened waiting time for passengers on average by 30

329   seconds, the headway holding caused an increased in-vehicle travel time that cancelled out the

330   time saving. However, the simulation scenario ("All") which combines headway control with

331   reduced run time and boarding all doors obtained small travel time improvements compared to

332   implementing these measures without headway control. So there are indications of synergy

333   effects between headway control and other measures improving regularity, which is the same

334   result as West (2011) obtained. When combining all measures, however, the effect is lower than

335   the sum of their marginal contributions.

336   For trunk line 4 the planned headway upon departure in the afternoon peak period is 4-5

337   minutes. However, the actual headway between consecutive trips varies considerably from one

338   bus to the other. In the extremes, this leads to the bunching phenomenon where buses run in

339   platoons which has negative implications on passengers waiting times, capacity utilization and

340   operational reliability. Improving service regularity was therefore one of the main objectives of

341   the pilot study. The after period shows a significant improvement in service regularity (see

342   figure 2) and fewer incidents of bus bunching.

343   The simulation model enables the analysis of individual passenger travel experience and the

344   respective travel time components and on-board crowding.   According to simulation results,

345   every traveller on line 4 saved seven minutes generalized travel cost (perceived journey time) in

346   the field experiment (compared to the before period), which is 20% of their total generalized

347   travel time (see figure 3). The average crowding multiplier decreased from 1.22 in the before

348   period to 1.17 in the after period. This means that on average the load was a bit above seat

349   capacity in both periods, but due to better regularity in the after period, fewer passengers were

14

350   forced to stand or sit in an overcrowded bus. The removed stops affected 4% of the passengers.

351   For an affected passenger, stop removal increased the walking distance by 100-150 metres,

352   which means that walk time for all passengers on average increased by less than 5 seconds.

353   Waiting time decreased the most in relative terms due to better regularity, by 35% (one and a

354   half minute or three minutes expressed as equivalent in-vehicle time) with all measures

355   combined. Total in-vehicle riding time decreased by two minutes, even though the time

356   passengers spent in vehicles that were holding increased by 20 seconds due to the headway

357   based holding strategy. Out of almost six minutes of observed travel time savings, one minute is

358   attributed to the changes in boarding regime, whereas physical street measures and removed

359   stops account for a reduction of almost five minutes. Headway based holding did not have a

360   significant effect on average travel time. Free boarding through all doors would decrease total

361   perceived journey time by 12% (three minutes per passenger) when compared to front door

362   boarding.

363   In summary, the pilot study improved the level-of-service while at the same time obtaining

364   greater operational certainty, leading to substantial passenger time savings and operational

365   benefits. The simulation results suggest that improved regularity and fewer bunching led to a

366   25 per cent reduction in passenger waiting times. In addition, improved regularity resulted with

367   a more even passenger loads. Approximately half of the regularity improvements are attributed

368   to the headway-based holding. However, the potential benefits from changing the boarding

369   regime have hardly materialized in the field experiment.

370   Based on a comprehensive analysis of empirical and simulation data we estimate that each

371   passenger saved four minutes perceived journey time (15 per cent of the total travel time) in the

372   pilot study.

MODEL VALIDITY

374   We compared the base scenario (2013) and the field experiment scenario (2014) to AVL data

375   from these periods and the simulation model proved to predict the trip travel time result of the

376   field experiment well, as shown in table 3. The model overestimates travel time by 1-2% in both

377   directions, both for 2013 and 2014, when looking at completed trips. Figure 4 shows that the

378   model predicts bus trajectories accurately. Since inter-stop travel time in the model is based

379   directly on the AVL data in question, the comparison of total trip travel time primarily confirms

380   the validity of the dwell time model (which is calibrated based on boarding and alighting data

381   from stops along the same bus route and similar stops). Hence the results from the analysis of

382   boarding regimes seem robust. The headway control module has been validated in several

383   earlier studies (Cats et al. 2012).

384   The headway variability depicted in figure 5 is clearly overestimated in the model for the before

385   period, while yielding more accurate outputs for the after period. A possible reason is that

386   drivers in reality adjust their speed between time point stops to achieve more even headways

387   even when this is not part of the strategy endorsed by the operator. Previous studies (Lin and

388   Bertini, Cats et al. 2012) found based on empirical and statistical analysis of vehicle positioning

389   data that drivers adjust their speed along the route to improve transit performance. There is a

390   noticeable difference between the simulated and observed headway variability in the first few

391   stops. In the simulation, buses follow the schedule when dispatching from the terminal, subject

392   to vehicle availability constraints. In reality, however, bus drivers may not perfectly adhere to

393   this dispatching regime, inducing imperfect headways from the start of the trip.

394   The model simulates traveller arrival at each stop assuming a Poisson generation process and

395   waiting time for each traveller is calculated as the time between his or her arrival and the next

396   simulated vehicle arrival. If waiting time gains instead are calculated from observed vehicle

397   arrivals (but maintaining the hypothesis that traveller arrival is a Poisson process), the sum is

398   roughly half as large. The results of this study suggest that the simulated gains in dwell time and

399   riding times are robust while the simulated waiting time gains are overestimated by a factor of

400   two due to the overestimation of the difference in headway variations. Hence, we estimate that

401   each passenger saved four minutes of travel time on average during the field experiment period.

402   ## CONCLUSION

403   Simulation models enable to test the impacts of transit improvement strategies prior to their

404   implementation and thus support their design. The individual as well as combined impact of

405   several measures was evaluated in this study using BusMezzo, a dynamic transit operations and

406   assignment model. Vehicle trip time and passenger travel time improvements from each

407   measure were estimated and the model accuracy was validated. The model slightly

408   overestimates travel times by 1-2% when looking at completed trips.

409   Our findings indicate that all three tested measures (boarding through all doors, headway-based

410   holding and bus lanes) had an overall positive impact on service performance. The impact of

411   boarding through all doors (6% reduction of bus trip time for the simulated full-scale scenario

412   and 2% from the less successful third-door boarding pilot) can be compared to previous studies

413   where the travel time reduction was calculated using linear regression. For instance, Diab and

414   El-Geneidy (2013) found that boarding from the third door in Montreal decreased bus trip time

415   by 2%.

416   The three tested measures exercised negative synergy effects with their combined effect being

417   smaller than the sum of their marginal contributions, except for headway-based holding which

418   exercised positive synergy effects with the two other measures. It is therefore advisable to

419   simulate alternative measures prior to their implementation to assess their impacts and refine

420   their design. These measures are relatively cheap compared to investments in new transit

421   infrastructure and large societal gains can therefore be achieved by their implementation. While

422   the simulation model has been implemented in the past to evaluate investments in large-scale

423   networks (e.g. Cats et al. 2016, Jenelius and Cats 2016), the scalability of the results reported in

424   this study can also be tested in the future using a large-scale case study.

425   Following its experience with the headway-based control during the field experiment, the bus

426   operator has decided to continue using it for service operations and control. Cats (2014)

427   outlined recommendations for alternative incentive schemes and business models that could be

428   deployed to promote regularity-driven operations.

429   Allowing free boarding through all doors can be beneficial for the operator, even when

430   accounting for the increased fare evasion, if ridership increases as an effect. Allowing free

431   boarding through all doors makes it possible to either use larger vehicles or to increase

432   frequency while maintaining regularity. The conclusion is that it could be economically

433   beneficial for the operator to allow free boarding through all doors on line 4 in Stockholm and on

434   comparable bus lines elsewhere.

435   The model validity examination performed in this study demonstrates that the simulation

436   model, BusMezzo, was able to reproduce key phenomena such as vehicle trajectories, bus

437   bunching and dwell time variations for different boarding regimes. Notwithstanding, the results

438   suggest that driver behaviour aspects such as dispatching from the first stop and speed

439   adjustments between stops play an important role that is unexplained by the model. Further

440   empirical investigation will be required to adequately capture these behavioural aspects.

441 ## ACKNOWLEDGEMENTS

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534 # FIGURES

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

539 **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**

540 *) The 2014 scenario was simulated both with the boarding regime that was used during the field experiment and
541 with free boarding through all doors
542 **) The 2014 scenario was simulated with the effects of the construction works on Lilla Västerbron for
543 validation purposes

544 **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%)

545

546   **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

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