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Drabicki, Arkadiusz; Cats, Oded; Kucharski, Rafał

DOI
10.1109/MT-ITS49943.2021.9529310

Publication date
2021

Document Version
Final published version

Published in
2021 7th International Conference on Models and Technologies for Intelligent Transportation Systems, MT-ITS 2021

Citation (APA)
Drabicki, A., Cats, O., & Kucharski, R. (2021). The potential of real-time crowding information in reducing bus bunching under different network saturation levels. In *2021 7th International Conference on Models and Technologies for Intelligent Transportation Systems, MT-ITS 2021* (2021 7th International Conference on Models and Technologies for Intelligent Transportation Systems, MT-ITS 2021). IEEE. https://doi.org/10.1109/MT-ITS49943.2021.9529310

2021 7th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS) | 978-1-7281-8995-6/21/$31.00 ©2021 IEEE | DOI: 10.1109/MT-ITS49943.2021.9529310

The potential of real-time crowding information in reducing bus bunching under different network saturation levels

Arkadiusz Drabicki
Department of Transportation Systems
Cracow University of Technology
Krakow, Poland
adrabicki@pk.edu.pl

Oded Cats
Department of Transport and Planning
Delft University of Technology
Delft, Netherlands
O.Cats@tudelft.nl

Rafał Kucharski
Department of Transport and Planning
Delft University of Technology
Delft, Netherlands
R.M.Kucharski@tudelft.nl

Abstract— **Bus bunching is a well-known problem in public transport networks. It is characterized by a self-amplifying relationship between uneven distribution of rising passenger loads and deteriorating service regularity. The focus of this study is to analyse whether this negative feedback loop can be addressed by providing real-time crowding information (RTCI) on next vehicle departures at stops. We integrate a departure choice model based on stated-preference analysis of passengers' willingness to wait with RTCI. A proof-of-concept application to a toy-network model shows that this prevents further progression of bunching effects in certain demand conditions. The RTCI usage reveals substantial benefits - in terms of relative reductions in on-board (over)crowding, headway deviations, as well as mitigated denial-of-boarding risk - in moderately saturated network. These gains may diminish though as high overcrowding eventually emerges in PT network. Nevertheless, our findings indicate that RTCI has the potential to improve travel experience and service utilisation efficiency, even without resorting to supply-side control strategies.**

Keywords—public transport; overcrowding; bus bunching; real-time crowding information; RTCI; willingness to wait

I. INTRODUCTION

Bus bunching is a notorious and recurrent phenomenon in busy urban public transport (PT) networks. Its working mechanism resembles a negative feedback loop between rising headway deviations and more uneven passenger load distribution between consecutive PT services (departures). This is principally driven by dwell times at stops, which are flow-dependent and increase with extra volumes of boarding (alighting) passengers, causing a delay in vehicle departure. In turn, the next arriving departure will have fewer passengers to pick up, leaving the stop ahead of schedule. In many cases, this effect becomes amplified along the PT line, eventually leading to buses 'bunching' together. This phenomenon has major negative consequences for PT passengers and operators, resulting in worse travel experience, disrupted service regularity, arising passenger overcrowding, uneven load and headway distribution in the PT network and thus lower operational efficiency etc.

To counteract this negative, self-amplifying bunching effect, various tactical and operational strategies have been proposed and implemented. Many of these strategies involve supply-side planning and interventions, such as: holding control strategies (which have been hitherto widely studied, e.g. [1], [2], [3], [4]), robust slack time planning [5], [6], bus overtaking [7], stop-skipping [8], [9], speed control [10], mixed optimisation strategies (e.g. [11], [12], [13]).

Another stream of research concerns the demand-side impacts on development of bus bunching effect. Firstly, [14] demonstrate how the common assumption of constant (uniform) passenger arrivals at stops underestimates the risk of bus bunching, which is likely to be induced (or amplified) with more non-uniform arrival patterns, concentrated around specific intervals. Secondly, a number of papers focus on the *top-down* application of boarding limits to directly counteract the on-going bunching effect. This strategy assumes that under specific conditions, the PT operator imposes a no-boarding policy, forcing a certain share of passengers to wait for a later departure. Studies have demonstrated its potential effectiveness especially in high-frequency PT services, and either as a sole measure [15] or in conjunction with holding controls [3], [16] and/or overtaking strategies [17].

In another work, [18] have studied this problem from an interesting game theory perspective. They show how the passengers' obedience of a no-boarding policy determines its overall effectiveness and benefits (or losses) for specific demand groups. Furthermore, findings reveal how the emergence of herding behaviour can nullify the effects of a no-boarding policy and amplify anew the bunching effect.

Another research notion concerns the effects of *bottom-up* shifts in boarding behaviour in the event of bus bunching, whereby a certain share of passengers waiting at the PT stop opt to skip the first incoming bus trip (which is possibly delayed and overcrowded) and wait for a second bus trip instead. [19] propose a dynamic queue swapping behaviour model. It assumes that passengers waiting at the stop do not aim to board the first arriving departure up to its capacity limits, but form equal boarding queues for both incoming bus departures. Findings reveal its effectiveness in terms of higher headway regularity, lower waiting and in-vehicle times, which can be further amplified by allowing for overtaking between buses. In another paper, [17] simulate how assumptions on different boarding rates can influence the on-going bunching effect. They conclude that a higher *back-bus preference* can be favourable for operators' service regularity and passengers' travel experience, especially if overtaking is not allowed. Both studies point out that such boarding behaviour could be beneficial in mitigating the bus bunching effect and should be encouraged by means of real-time passenger information systems.

Meanwhile, providing information regarding on-board passenger loads can induce a certain effect of **willingness to**

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wait (WTW) to reduce overcrowding – which has been revealed in a number of stated-preference studies [20], [21], [22], [23], [24]. Their findings already indicate influence of specific choice factors upon the stated WTW, which is driven, among others, by the propensity to avoid excessive overcrowding in the first departure, trip purpose (i.e. higher WTW in case of arrival time flexibility and non-obligatory trips), socio-demographics (e.g. higher WTW for elderly age groups). According to these stated-preference results, the WTW with **real-time crowding information (RTCI)** can potentially become a significant travel behaviour phenomenon: share of passengers willing to wait for a second, less-crowded PT departure can reach up to 50 – 80% of total waiting demand at the PT stop. Acceptable waiting times were found to oscillate between 3 – 25 [mins], with higher values attainable for regional rail trips [22, 24]. Finally, [25] developed a simulation model for instantaneous departure choice with current crowding information, indicating how the acceptance of deferred boarding among individual passengers can yield network-wide performance and travel experience improvements.

In a summary, state-of-the-art is yet characterised by certain research gap, related to potential RTCI efficacy in preventing the bus bunching disruptions. Simulation studies cited above mostly involve fixed assumptions on the passengers' boarding behaviour, i.e. with regards to the splitting (boarding) rate or the no-boarding policy criteria, yet (to the best of our knowledge) no evidence-based behaviour models.

In this study, we present simulation analysis of the instantaneous departure choice behaviour with access to RTCI at stops. The model is derived from our stated-preference passenger surveys [24], which reveal a potentially significant WTW behaviour with RTCI. A proof-of-concept application of this model to a toy network reveals that the RTCI-induced WTW behaviour might become useful against the unravelling bus bunching effect, depending on network demand conditions. Implications for further analytical works and the potential of RTCI as an 'anti-bunching' demand management tool are discussed in the final section of the paper.

II. METHOD

A. Simulation model - BusMezzo

The proposed departure choice algorithm is implemented within the mesoscopic BusMezzo PT assignment model [26]. The BusMezzo model assumes an explicit, disaggregate representation of the PT system. PT demand is represented by individual travellers (agents) progressing through the network, while PT supply is modelled in form of individual vehicle (bus) trips, described by explicit capacity constraints. It is an event-based model, which implies that simulation processed is triggered sequentially, at every single instance when an action takes place in the PT network – e.g. passenger's boarding decision, or bus trip entering (exiting) the stop. Passengers' actions are determined by the probabilistic choice model, described by means of a multinomial logit (MNL) formula.

Importantly, BusMezzo model is capable of representing the mutual, dynamic interactions between PT demand and supply, e.g. in form of flow-dependent dwell times, as well as the passenger overcrowding phenomena such as rising travel discomfort and/or denial-of-boarding and their impact on passengers' subsequent actions. Consequently, it is possible to capture the emergence of bus bunching phenomenon and how the underlying chain of events induces this negative feedback loop.

B. Departure choice model with RTCI

In this study, we consider the boarding decision problem, where passenger waiting at stop s chooses between boarding a bus trip r – which is due to depart now, versus staying and waiting for the next bus trip $r+1$ – which will arrive later. This resembles a typical binary choice problem, where probability of taking an action a is a function of its utility v_a, compared against the utility $v_{a'}$ of an alternative action. Choice probability is given by the multinomial logit (MNL) formula (1) which includes choice sensitivity parameter μ:

$$P_{a,s} = exp(\mu \cdot v_{a,s}) / \left(exp(\mu \cdot v_{d,s}) + exp(\mu \cdot v_{a',s})\right) \quad (1)$$

Furthermore, in our analysis we focus specifically on the case of a single bus corridor and assume no availability of alternative travel routes. In such particular instance, action utility is equal to the expected utility of path i, which is the sum of travel time components of each journey stage e, weighted by their relative (dis)utility coefficients. In our case, path utility simplifies to 2 trip components only: waiting time t^{wt} (dis)utility at the origin stop, and total in-vehicle time (dis)utility t^{ivt} towards the destination stop. Since our objective is to examine the impact of RTCI on the willingness to skip the first bus trip and wait for the next one, we set the expected utility $v_{r+1,s}$ of the second departure as the reference value, while the expected utility v_{r+s} of the first departure is multiplied by the WTW coefficient $\beta_{r,s}{}^{WTW}$, as given by the following formulas (2), (3):

$$v_{r,s} = \beta_{r,s}^{WTW}(\tau) \cdot \textstyle\sum_{e \in i} t_e^{ivt} \quad (2)$$

$$v_{r+1,s} = t_{r+1}^{wt} + \textstyle\sum_{e \in i} t_e^{ivt} \quad (3)$$

Without any prior crowding information, $\beta_{r,s}{}^{WTW} = 1$ and the default choice preference is to board the first incoming bus trip r - since the expected in-vehicle time disutility is equal for both departures, and the next bus trip $r+1$ always incurs additional waiting time disutility. However, availability of real-time crowding information (RTCI) for next bus departures may induce willingness to wait (WTW) for the second trip $r+1$ if it is shown to be less crowded at the time instance τ. In such moment, the perceived disutility of first trip r is relatively higher for passengers waiting at the stop s. This is reflected in the WTW coefficient $\beta_{r,s}{}^{WTW}$ which acts as a crowding multiplier of the first trip r. The additional travel time disutility imposed by $\beta_{r,s}{}^{WTW}$ depends on the ratio between mean acceptable waiting time at the origin $t_{r+1,s}{}^{WTW}$ vs. remaining in-vehicle time t^{ivt} to the destination:

$$\beta_{r,s}^{WTW}(\tau) = 1 + \frac{t_{r+1,s}^{WTW}(\tau)}{\sum_{e \in i} t_e^{ivt}} \quad (4)$$

In turn, the acceptable WTW threshold $t_{r+1,s}{}^{WTW}$ is a time-dependent function of the volume-capacity ratios of the next bus trips r and $r+1$, recorded most recently (at the time instance τ) at the last upstream stop m (or respectively stops m and n) visited by these trips along the line route L (5):

$$t_{r+1,s}^{WTW}(\tau) = f\left(\frac{q_{r,m}}{c_{r,m}}; \frac{q_{r+1,n}}{c_{r+1,n}}; \tau\right); \quad m, n \in L \wedge m, n < s \quad (5)$$

The mean acceptable WTW thresholds are based on empirical results from stated-preference passenger surveys [24] and specified in the Table (1). These findings show that willingness to wait is primarily dependent on the crowding level of the first trip *r*, implying up to a 10-minute waiting time acceptance if it is highly overcrowded (i.e., volume-capacity ratio exceeds 80%).

TABLE I. MEAN ACCEPTABLE WAITING TIME THRESHOLDS

t_{r+1}^{WTW} [mins]		**q/c - run r**		
		< 0; 0.6 >	(0.6; 0.8 >	(0.8; 1.0 >
q/c - run r+1	(0.8; 1.0 >	$0^{a.}$		
	(0.6; 0.8 >	$0^{a.}$		**10**
	< 0; 0.6 >	$0^{a.}$	**3**	

a. *zero values – no WTW applicable*

The above specification depicts the departure choice model in BusMezzo and how RTCI generated in real-time at the upstream stop(s) *m, n* influences the instantaneous boarding decisions at downstream stop(s) *s, s+1,…*

III. RESULTS

A. Simulation network setup

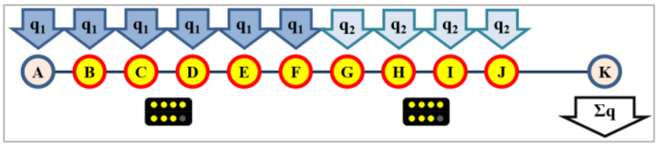

Fig. 1. Toy-network layout in simulation experiments. In the "RTCI" scenario, all boarding stops are equipped with information on current crowding levels on-board the next two incoming vehicle trips.

TABLE II. TOY-NETWORK - SUPPLY AND DEMAND DATA

input parameter		value
run time $t_{r,e}$	segments A – J	5 [mins]
	segments J – K	10 [mins]
origin demand q_s	stops A – F	300 [pass./hr]
	stops G - J	200 [pass./hr]

To illustrate the potential consequences of instantaneous RTCI availability for passengers in the event of bus bunching, the proposed model is applied to a toy-network shown in Figure (1). This network represents a simplified urban bus corridor with 10 origin stops (A – J) and a single destination stop (K), with an average nominal service headway of 5 [mins]. Additionally, in order to induce the bunching effect in our network, we assume that an initial dispatching disruption of an extra 1 [minute] applies to every second departure from the origin stop A. This implies that actual initial headway oscillates alternately between 4 [mins] and 6 [mins]. While line run times $t_{r,e}$ between stops are assumed constant, dwelling times at stops are guarded by a flow-dependent linear function, with dwell times increasing by 3 [secs] per each boarding passenger. Capacity of each bus vehicle is fixed to 200 [pass./veh.], and this limit is strictly observed. Passenger demand consists of 10 OD pairs between origin stops A - J and a single destination stop K. We assume uniform passenger generation rates of 200 [pass./hr] at upstream stops A – F and 300 [pass./hr] at downstream stops G - J. Network supply is generated for two additional 30-minute periods before and after the 60-minute demand generation period (thereby providing additional 'warm-up' and 'cool-down' service periods).

Passenger demand generation rates reflect a layout of a PT bus corridor which is increasingly loaded with passenger volumes along its route, until a final alighting point (i.e. stop K). Consequently, this enables us to inspect RTCI effects on boarding decisions for various network demand levels, ranging from little or no on-board crowding of buses approaching upstream stops B – D, moderately crowded at intermediate stops E – G, to overcrowded buses arriving at downstream stops H – J. Also, since no alighting is allowed at any origin stop A – J, it is possible to squarely analyse the evolution of bus bunching effect in relation to the RTCI-based boarding decisions.

In the following experiments, we analyse and compare results between the "no RTCI" scenario – where no prior crowding information is available and passengers always boarding the first incoming bus trip, versus the "RTCI" scenario – where passengers obtain and instantaneously utilise the crowding information from upstream stops to evaluate the WTW utility, depending on the (currently displayed) crowding levels of 2 next departures *r* and *r+1*.

B. Results – effects on service regularity

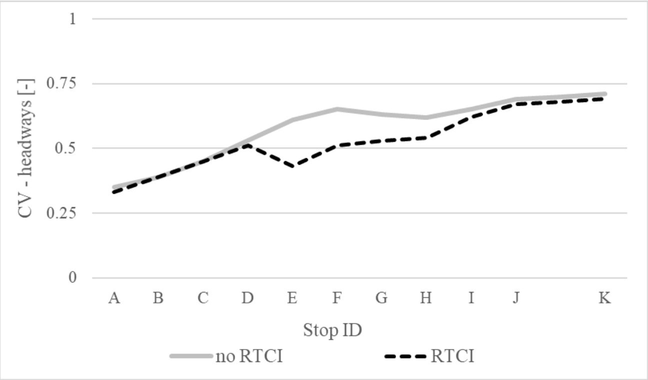

Fig. 2. Coefficient of headway variation plotted along consecutive stops, in the *no RTCI* (gray) and *RTCI* (black) scenarios.

Figure (2) summarises output service regularity, as measured by the coefficient of headway variation (headway CV - i.e., ratio between standard deviation vs. average of bus headways) at consecutive stops. Without RTCI access, headway CV increases linearly from ca. 0.3 at the departure from origin stop A up to 0.65 at the intermediate stop F, indicating a major destabilization of bus operations. It oscillates then (roughly) around this value along downstream line section, and the headway CV at the downstream stop J equals ca. 0.7. In the RTCI scenario, this negative trend is interrupted at stops D and E, where headway CV drops down to ca. 0.4. It hovers then around the value of 0.5 and rises again downstream of stop H, reaching analogous values (ca. 0.65) as in the former case.

Both these plots reveal different evolution of bunching disruption in our toy-network. In the no RTCI scenario, an initial delay upon dispatching from stop A eventually propagates and becomes a considerable disruption. The delayed bus trip is boarded by a larger number of waiting passenger at downstream stops than expected and thereby becomes even more delayed, while the next bus arrives on-time and picks up fewer passengers. This pattern is further amplified in downstream stops, with even greater discrepancy between actual headways and nominal schedules. Further growth in bunching disruption is inhibited along final segments, as passengers are denied from boarding the fully loaded lead bus, and excessive waiting flows are forced to board the successive bus.

Once passengers utilize RTCI in their boarding decisions, a different bus trajectory distribution can be observed. Although the initial delay persists at downstream stops, an improvement in service headways is especially noticeable around the middle line segment. This indicates a suppression of the bus bunching process, though the bunching effect is not fully avoidable (or mitigated) though. Nevertheless, simulation outputs demonstrate thus that RTCI utilization in boarding decisions contributes to lower headway variations in moderately crowded parts of the network, but is not as effective in highly overcrowded and disrupted service conditions.

C. *Results – effects on load distribution*

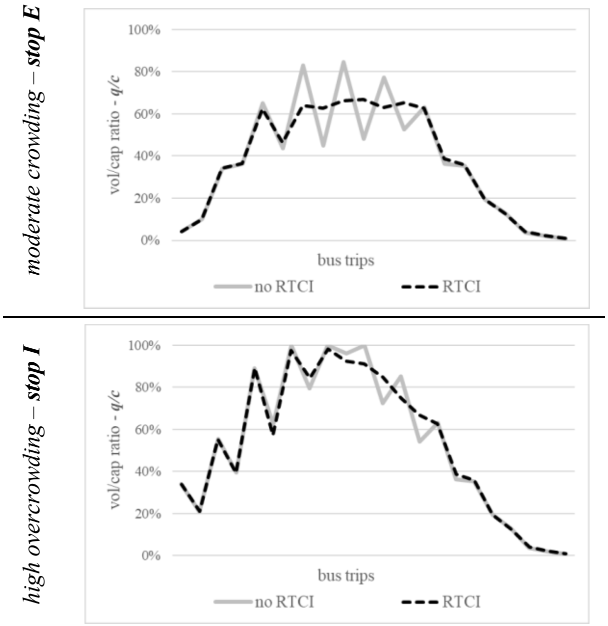

Fig. 3. Passenger load distribution patterns, emerging in moderate crowding (top) and high overcrowding (bottom) network conditions.

Figure (3) depicts passenger load distribution at selected stops, subject to different crowding conditions. In the no RTCI scenario, it is evident how bus bunching leads to increasingly uneven load distribution across consecutive vehicle trips. Consequently, individual vehicles are already approaching overcrowded conditions (over 80%) at middle-segment stops, while trailing bus trips have substantial residual capacity (ca. 50%). In contrast, the RTCI scenario produces a more equalised load distribution pattern, with majority of bus trips operating at 60 - 70% of their capacity.

Further on, results obtained at highly overcrowded downstream stops reveal a more nuanced picture of RTCI effects (Fig. (3), bottom). Initially, as rising network demand inflows amplify the bunching disruption (akin to the 'snowball' effect), the WTW decisions induced by RTCI access are not effective enough to mitigate wholly the trip loads' variability. However, as network inflows become relatively more stable afterwards, the RTCI access leads to a much more even distribution of bus trip loads. In contrast, in the no RTCI scenario, these still tend to bounce alternately between full and moderate utilization. Notably, crush capacity limits are only achieved in case of a single bus trip in the RTCI scenario, while being otherwise routinely exceeded without the RTCI access.

D. *Results – effects on travel experience*

TABLE III. RESULTANT TRAVEL EXPERIENCE CHANGES

network crowding	origin stop	**RTCI changes**		
		excess waiting time (EWT)	waiting time due to denied boarding	in-vehicle overcrowding *(q/c > 0.8)*
low	A	- 0.6%	n/a	n/a
	B	+ 0.2%		
	C	- 0.8%		
	D	+ 5.9%		
mid	E	+ 66.5%		- 81.6%
high	F	- 0.3%	- 100.0%	- 51.4%
	G	- 27.0%	- 100.0%	- 14.6%
	H	- 18.2%	- 86.1%	- 8.4%
	I	- 24.3%	- 52.1%	- 0.1%
	J	- 9.3%	- 18.0%	- 0.9%
total		**- 5.0%**	**- 41.7%**	**- 11.7%**

Table (3) presents the relative changes in travel (dis)utility components resultant from RTCI utilization in boarding decisions, compared against the baseline no RTCI scenario. We select here three measures reflecting the network overcrowding impact on passengers' travel experience. Firstly, an interesting outcome in the RTCI scenario pertains to global reduction in excess waiting time (EWT) of 5%. The EWT changes are not uniform along bus line segments, though. These are slightly worse at lower demand stops, which correlates with a sharp increase of WTW decisions particularly among passengers waiting at stop E, who are the first to acquire information on high (over)crowding of approaching buses. However, an opposite pattern is then visible at the remaining downstream stops, where EWT decreases by 10 – 30%, despite highly congested conditions. Consequently, although this might seem counterintuitive at first glance, since RTCI access encourages the WTW choice pattern - individual WTW decisions at different stops lead to an overall improvement of waiting utility in our case study network.

A second favourable effect associated with RTCI relates to a substantial reduction in waiting time due to denied boarding. The latter is overall 42% less prevalent. RTCI mitigates any denial-of-boarding risk at moderately crowded stops F and G, and also to a substantial degree at consecutive stops H and I (by ca. 85% and 50%, respectively). These benefits are attainable thanks to RTCI availability for passengers waiting at these stops, as well as WTW choices made at upstream stops. Passengers at the most congested stop J are not as likely to eliminate the denied-boarding probability, yet still RTCI decreases this risk by about 20%.

A similar pattern, though lower in magnitude, is traceable for the third performance measure - experience of high on-board overcrowding, corresponding to volume-capacity ratio greater than 0.8. Results for the RTCI scenario demonstrate that the share of passengers exposed to overcrowding is principally lower along the middle-line segment, by as much as 50 – 80% between stops E and G. This effect gradually diminishes then with rising network congestion downstream, indicating a 10 – 15% decrease between stops G and I, and merely negligible differences along final line segments I – K.

A more detailed inspection of RTCI impact on passengers' on-board comfort experience shows reductions in total in-vehicle travel time spent in the highest overcrowding conditions ($q/c > 0.8$) of 12%, as well as time spent in the lowest (uncrowded) conditions ($q/c \leq 0.6$) of 7%. Consequently, WTW decisions induced by RTCI amount to more favourable in-vehicle crowding conditions along the line. From the supply perspective, such findings imply a higher number of vehicle trips with moderate volume-capacity ratio (between 60 – 80%), coupled with lower shares of trip runs which are either massively overcrowded or underutilized.

IV. CONCLUSIONS

This study focuses on simulation analysis of the real-time crowding information (RTCI) provision impacts upon the bus bunching disruption in different network saturation levels. While state-of-the-art studies investigated demand-side anti-bunching strategies, these are mostly based on the *a priori* (fixed) assumptions regarding the max. boarding limits or queue swapping behaviour. In this work, we utilise an evidence-based model that describes the passengers' boarding choices with access to RTCI on the next vehicle departures at public transport (PT) stop. The model is derived from own stated-preference findings [24] on the willingness to wait (WTW) to reduce overcrowding and implemented in the mesoscopic BusMezzo PT assignment model.

A proof-of-concept model application revealed the potential effects of the WTW behaviour with RTCI in context of bus bunching as passenger demand rises in the PT network. Simulation findings on a toy-network showed that instantaneous RTCI on vehicle departures can facilitate boarding behaviour shifts which reduce the bunching disruption in moderately crowded conditions (as reflected by more even headway distribution). Although full service regularity could not be restored, this prevented further progression of bus bunching, unless more adverse passenger congestion conditions emerge in PT network. Furthermore, by encouraging passengers to wait for less-crowded PT departures, RTCI enhanced the bus capacity utilisation and resulted in more equalised distribution of passenger loads among consecutive bus departures.

In addition to greater operational efficiency, these effects translated into positive travel experience changes. A certain increase in waiting time due to WTW behaviour is clearly offset by lower on-board passenger overcrowding and a substantially decreased denial-of-boarding risk - particularly pronounced in moderate congestion conditions, by even as much as 50 – 80%. Interestingly, we observe that excess waiting time actually decreases when utilizing RTCI, though this effect is lower in magnitude (ca. 5% drop on global scale) and tends to vary locally. Total travel utility improvements are relatively modest (ca. 3%), albeit this can be attributed to the small-scale topology of our toy-network.

Our findings demonstrate the potential efficacy of WTW behaviour with RTCI in mitigating the bus bunching disruptions. Further analytical works are needed to provide more applicable and transferable conclusions. An interesting (and important) point will be especially to conduct simulations on a larger-scale bus network model. These will then confirm whether and how RTCI provision at various bus stops can bring a 'lasting' anti-bunching effect along the downstream network, or if the RTCI benefits are limited in scale and/or achievable only under specific conditions.

Our findings from a series of experiments on a simplified bus network model indicate that passengers' response to instantaneous RTCI on bus departure loads can influence the negative feedback loop between arising headway deviations vs. uneven passenger flow distribution. Potentially, this can lead to PT quality of service improvements even without resorting to additional supply control or demand management strategies. This points to the potential of future RTCI systems to act as a certain *soft* holding strategy, useful in counteracting the bunching disruptions. However, in contrast to conventional control strategies, it is not enforced *top-down* upon current PT operations, but arises as a *bottom-up* passenger decision pattern, yielding benefits for both passengers and operators. Finally, results demonstrated in this paper indicate how modern ATIS tools can be exploited to improve passengers' travel comfort and systematic capacity utilization, reducing the risk of excessive passenger loads (i.e. overcrowding) in PT services – an issue that is likely to become of paramount importance in context of the post-pandemic travel behaviour changes.

ACKNOWLEDGMENT

This study has been supported by research grant received within the Iwanowska Programme, organised by the Polish National Agency for Academic Exchange (NAWA) (agreement no. PPN/IWA/2018/1/00084).

REFERENCES

[1] Ceder, A. (2016). Public transit planning and operation: Modeling, practice and behavior. CRC press.

[2] Cats, O., Burghout, W., Toledo, T., & Koutsopoulos, H. N. (2010, September). Evaluation of real-time holding strategies for improved bus service reliability. In 13th International IEEE Conference on Intelligent Transportation Systems (pp. 718-723). IEEE.

[3] Delgado, F., Munoz, J. C., & Giesen, R. (2012). How much can holding and/or limiting boarding improve transit performance?. Transportation Research Part B: Methodological, 46(9), 1202-1217.

[4] Laskaris, G., Cats, O., Jenelius, E., Rinaldi, M., & Viti, F. (2019). Multiline holding based control for lines merging to a shared transit corridor. Transportmetrica B: Transport Dynamics, 7(1), 1062-1095.

[5] Adamski, A., & Turnau, A. (1998). Simulation support tool for real-time dispatching control in public transport. Transportation Research Part A: Policy and Practice, 32(2), 73-87.

[6] Daganzo, C. F. (2009). A headway-based approach to eliminate bus bunching: Systematic analysis and comparisons. Transportation Research Part B: Methodological, 43(10), 913-921.

[7] Schmöcker, J. D., Sun, W., Fonzone, A., & Liu, R. (2016). Bus bunching along a corridor served by two lines. Transportation Research Part B: Methodological, 93, 300-317.

[8] Sun, A., & Hickman, M. (2005). The real–time stop–skipping problem. Journal of Intelligent Transportation Systems, 9(2), 91-109.

[9] Liu, Z., Yan, Y., Qu, X., & Zhang, Y. (2013). Bus stop-skipping scheme with random travel time. Transportation Research Part C: Emerging Technologies, 35, 46-56.

[10] Daganzo, C. F., & Pilachowski, J. (2011). Reducing bunching with bus-to-bus cooperation. Transportation Research Part B: Methodological, 45(1), 267-277.

[11] Dessouky, M., Hall, R., Zhang, L., & Singh, A. (2003). Real-time control of buses for schedule coordination at a terminal. Transportation Research Part A: Policy and Practice, 37(2), 145-164.

[12] Gavriilidou, A., & Cats, O. (2019). Reconciling transfer synchronization and service regularity: real-time control strategies using passenger data. Transportmetrica A: Transport Science, 15(2), 215-243.

[13] Gkiotsalitis, K., & Cats, O. (2019). Multi-constrained bus holding control in time windows with branch and bound and alternating minimization. Transportmetrica B: Transport Dynamics, 7(1), 1258-1285.

[14] Fonzone, A., Schmöcker, J. D., & Liu, R. (2015). A model of bus bunching under reliability-based passenger arrival patterns. Transportation Research Part C: Emerging Technologies, 59, 164-182.

[15] Saw, V. L., & Chew, L. Y. (2020). No-boarding buses: Synchronisation for efficiency. Plos one, 15(3), e0230377.

[16] Zhao, S., Lu, C., Liang, S., & Liu, H. (2016). A self-adjusting method to resist bus bunching based on boarding limits. Mathematical Problems in Engineering, 2016.

[17] Sun, W., & Schmöcker, J. D. (2018). Considering passenger choices and overtaking in the bus bunching problem. Transportmetrica B: Transport Dynamics, 6(2), 151-168.

[18] Saw, V. L., & Chew, L. Y. (2020). No-boarding buses: agents allowed to cooperate or defect. Journal of Physics: Complexity, 1(1), 015005.

[19] Wu, W., Liu, R., & Jin, W. (2017). Modelling bus bunching and holding control with vehicle overtaking and distributed passenger boarding behaviour. Transportation Research Part B: Methodological, 104, 175-197.

[20] Kim, J. K., Lee, B., & Oh, S. (2009). Passenger choice models for analysis of impacts of real-time bus information on crowdedness. Transportation research record, 2112(1), 119-126.

[21] Kroes, E., Kouwenhoven, M., Debrincat, L., & Pauget, N. (2014). Value of crowding on public transport in île-de-France, France. Transportation Research Record, 2417(1), 37-45.

[22] Preston, J., Pritchard, J., & Waterson, B. (2017). Train overcrowding: investigation of the provision of better information to mitigate the issues. Transportation research record, 2649(1), 1-8.

[23] Kattan, L., & Bai, Y. (2018). LRT passengers' responses to advanced passenger information system (APIS) in case of information inconsistency and train crowding. Canadian Journal of Civil Engineering, 45(7), 583-593.

[24] Drabicki, A., Cats, O., Kucharski, R., Fonzone, A., & Szarata, A. (2020). Willingness to wait with real-time crowding information in urban public transport. (Working paper.)

[25] Noursalehi, P. (2017). Decision support platform for urban rail systems: real-time crowding prediction and information generation (Doctoral dissertation, Northeastern University).

[26] Cats, O. (2011). Dynamic modelling of transit operations and passenger decisions (Doctoral dissertation, KTH Royal Institute of Technology).

[27] Drabicki, A., Kucharski, R., Cats, O., & Szarata, A. (2020). Modelling the effects of real-time crowding information in urban public transport systems. Transportmetrica A: Transport Science, 1-39.

[28] Cats, O., West, J., & Eliasson, J. (2016). A dynamic stochastic model for evaluating congestion and crowding effects in transit systems. Transportation Research Part B: Methodological, 89, 43-57.