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Impacts of Bus Overtaking Policies on the Capacity of Bus Stops

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Abstract

Long bus queues at busy stops plague bus systems in many cities. Since berths are laid-out in tandem, buses' overtaking maneuvers are often prohibited or restricted, which can significantly reduce a bus stop's discharge capacity. When overtaking is allowed, aggressive drivers may perform disruptive oblique insertion maneuvers that would undermine stop capacity and compromise safety. This paper develops parsimonious yet realistic simulation models to examine the impacts of different overtaking policies on bus-stop capacity. Key realistic features are considered, including the oblique insertions resulting from overtaking, impacts of a nearby traffic signal, and bus traffic characteristics (reaction and move-up times). Extensive numerical experiments unveil many new findings. Some are at odds with those reported by previous studies. In addition, we examine two strategies that can improve the stop capacity without incurring disruptive oblique insertions. Practical implications of our findings are discussed, especially on choosing the most productive overtaking policy and means to minimize the capacity lost to buses' mutual blockage at stops. These implications have broad applications to various types of bus stops.

Keywords: bus stop capacity; bus queues; overtaking maneuvers; near-side and far-side stops; oblique insertion; simulation

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1. Introduction

1.1 Background and literature review

Bus stops are major bottlenecks for busy bus systems (Fernandez and Planzer, 2002). Long bus queues are often observed at the most congested stops during peak periods (Tan et al., 2014; Luo et al., 2018; Li et al., 2020). These bus queues increase passenger delays and bus agencies' operating costs, thus degrading the reliability and attractiveness of bus service and increasing car dependency (Phillips et al., 2015; Berrebi and Watkins, 2020; Yao et al., 2021). They also often incur roadway congestion for the general traffic (Nguyen-Phuoc et al., 2018).

An important reason for bus queueing is the mutual blockage between the buses dwelling at multiple berths laid out in tandem (Gu et al., 2011). Thus, a stop's bus-carrying capacity is largely affected by whether buses are allowed to overtake other buses at the stop. Allowing overtaking maneuvers may enable buses to discharge faster, thus potentially increasing a stop's capacity. However, previous studies on bus-stop capacity (e.g., Gu et al., 2011, 2015; Shen et al., 2019) often focused on the *no-overtaking* (NO) policy under which buses must strictly follow the first-in, first-out rule at a stop.

Only a few works have modeled and compared the effects of different overtaking policies. Gibson and his coauthors (Gibson et al., 1989) are probably the first that studied the so-called "*limited-overtaking*" (LO) stops. (The term "limited-overtaking" has been used in several later studies, including Gu and Cassidy, 2013; Bian et al., 2019; and Luo et al., 2022.) In a stop of this kind, a bus completing service is allowed to overtake a downstream dwelling bus to exit the stop (termed "*overtaking-out*" maneuvers in Bian et al., 2019; see Fig. 1a), but a queued bus cannot overtake dwelling buses to enter a vacant downstream berth (termed "*overtaking-in*" maneuvers; see Fig. 1b). Gu and Cassidy (2013) formulated analytical queueing models for estimating the capacity of LO stops that are isolated from nearby traffic signals. Bian et al. (2019) examined the effects of both types of overtaking maneuvers, but they only studied 2-berth stops with exponentially-distributed bus dwell times. Liu et al. (2022) extended that work to stops with normally-distributed dwell times. Most of the above studies proposed analytical formulas for estimating stop capacities under various overtaking policies and showed capacity improvements by allowing overtaking. However, they exhibit several common limitations. First, they overlooked the impacts of bus traffic dynamics, e.g., the time for a bus to react to the speed change of a downstream bus (the reaction time) and the time for moving across the berths (the move-up time). Although these times seem insignificant compared to bus dwell times, we will show in this paper that their effects on the bus-stop capacity are noticeable. Second, these works usually ignored the impacts of neighboring traffic signals.[1] Lastly, but very importantly, buses' overtaking-in maneuvers often result in *oblique insertions* due to the length of an ordinary bus; see Fig. 1b[2]. The oblique insertions will block the passing lane and thus prevent upstream buses from discharging. Unfortunately, the damages created by oblique insertions have never been explored in the literature.

We next review the methodologies used in the bus-stop queueing literature.

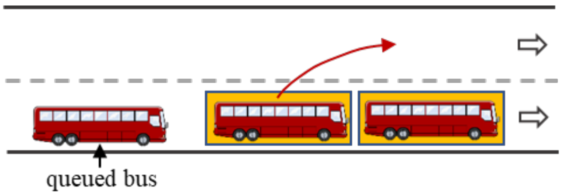
[1] Of note, the model proposed in the Transit Capacity and Quality of Service Manual (TCQSM, Kittelson & Associates, Inc., 2013) captures the effects of bus traffic dynamics and nearby signals. However, this model has several problems; see the details in the first paragraph of Section 1.2.

[2] Real world examples of oblique insertions can be found in Fig. 1 of Luo et al. (2018) and http://www.hinews.cn/news/system/2009/06/19/010504378.shtml (in Chinese).

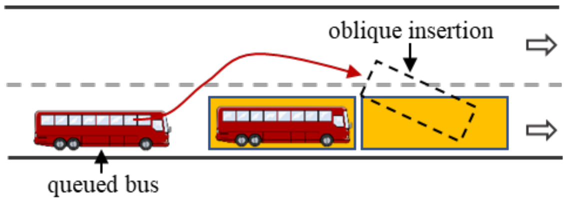
1.2 Research methodologies

Three methodologies have been used to study bus-stop queueing. The TCQSM (Kittelson & Associates, Inc., 2013) proposed a simple model for estimating bus-stop capacities based on the so-called “failure rate”. The model can be applied to multi-berth stops located near traffic signals. The bus reaction and move-up times are incorporated via a well-defined “clearance time” term. However, this model has several flaws. For example, it calculates a multi-berth stop’s capacity as the product of a single-berth stop’s capacity and a *fixed* “number of effective loading areas”. The latter aims to capture the effect of mutual blockage between buses dwelling in different berths (i.e., loading areas) on the capacity. Nevertheless, the “number of effective loading areas” was shown to vary with the coefficient of variation in bus dwell time and the neighboring signal settings (e.g., Gu et al., 2015; Shen et al., 2019). For more detailed reviews of the TCQSM model, please refer to Gibson (1996), Fernández (2010) (which criticized earlier versions of the TCQSM model), Gu et al. (2015), and Shen et al. (2019).

The second method is through simulation, e.g., IRENE, PASSION, BusSIGSIM (Gibson et al., 1989; Gibson, 1996; Fernandez, 2001a, b, Fernandez and Planzer, 2002; Fernandez and Tyler, 2005; Cortés et al., 2010; Fernández, 2010). The outcomes of these simulation models were also used to calibrate simple bus delay formulas (Tirachini and Hensher, 2011; Tirachini, 2014). These simulation models have accounted for a high level of detail regarding traffic dynamics and bus-passenger interactions. Regrettably, not many general insights were found in those works regarding how overtaking policies affect stop capacities under various operating conditions.



(a) Overtaking-out



(b) Overtaking-in

Fig. 1. Two types of overtaking maneuvers.

The last methodology is formulating analytical queueing models built upon the queueing-theory approaches. Some works relied on the classic multi-server queueing models (Huo et al., 2018; Wang et al., 2018), where the servers were assumed to operate independently of each other. But those classic models failed to capture the mutual blockage between buses at stops. Other studies formulated exact queueing models (Gu and Cassidy, 2013; Gu et al., 2015; Bian et al., 2019) and approximations (Shen et al., 2019; Wang et al., 2021). However, these analytical works exhibit various limitations regarding the overtaking policies, number of berths, and dwell time distributions examined.

Although many researchers favor analytical queueing models out of the three methodologies, simulation models developed in-house will be used in this paper due to the following reasons:

(i) Exact analytical queueing models are difficult to develop, especially when more realistic features, e.g., the bus traffic dynamics and the impacts of nearby signals, are incorporated (see a discussion in the Introduction section of Shen et al., 2019). Hence, some researchers had to resort to approximation techniques. But approximations bring errors that can be larger than simulation errors. Theoretically, the latter can be reduced to near zero if sufficient simulation runs are performed. Moreover, it is often difficult to extend an analytical queueing model to solve even a moderately different queueing problem. A brand new model is often needed if a different operating feature is incorporated. For example, the method built upon the renewal theory, Markov process, and complex analysis can be used to solve the stop queueing problem under the NO policy, but cannot tackle the problem under the LO policy. The queueing method used in Bian et al. (2019) cannot be extended to stops with bus dwell times that are not exponentially distributed.

(ii) Due to the complexity of developing analytical queueing models, existing models have all made idealized assumptions (e.g., exponentially distributed dwell times, two-berth stops, no traffic dynamics, no oblique insertion). Thus, most analytical results are inaccurate and cannot be directly applied in real practice. Even key findings from those results could be flawed, as we shall see momentarily.

(iii) The complexity of analytical queueing models also renders it difficult to derive insights directly from the models themselves. It turns out that most findings reported by the previous analytical studies came from the analysis of numerical results instead of examining the models themselves. Hence, the advantage of analytical queueing models over simulation is very limited.

(iv) On the other hand, simulation models can be relatively easily developed to capture a sufficient level of realism. They can be easily extended to model additional realistic features or different types of bus stops.[3] Due to the level of detail and realism incorporated, findings unveiled from the simulation results have better practical implications. Finally, the simulation runtime becomes reasonable, thanks to the more powerful computers and technologies developed (e.g., distributed computing) in recent decades.

1.3 Overview of our paper and main contributions

We will simulate a wide range of bus stops with various stop layouts, overtaking policies, and berth numbers, considering realistic features such as bus traffic dynamics, oblique insertions, and nearby signals. These features distinguish our paper from the previous studies and define our unique contributions. For example, although Shen et al. (2019) also modeled bus traffic dynamics and signal effects, that work focused on the NO policy only. Gibson (1996) examined the effects of key signal parameters (cycle time, effective green, and the distance from the stop to the signal) on a near-side stop's capacity, but that work did not study far-side stops or the impacts of traffic dynamics and oblique insertions. And while Bian et al. (2019) compared four overtaking policies (NO, LO, overtaking-in only, and free overtaking), they didn't explore stops with more than two berths, more general dwell-time distributions, traffic dynamics, signal effects, and oblique insertions. Nevertheless, factors with second-order effects, e.g., the bus acceleration and deceleration processes and the passenger boarding and alighting processes, are simplified in our paper to ensure computational efficiency.

For brevity, we focus on the bus-stop capacity only, which is a key measure when determining a stop's location, layout, and operating policies. Here a stop's capacity is defined as the *expected* maximum flow of buses discharging from the stop. This definition is consistent with the literature (see

[3] For example, in their later versions, PASSION was extended from single-berth stops to multi-berth ones, and IRENE was extended to cope with neighboring signalized intersections (e.g., Gibson et al., 1989; Gibson, 1996; Cortés et al., 2010; Fernández, 2007).

Gibson et al., 1989; Gu et al., 2011; Shen et al., 2019). Note that the bus discharge flow is maximized when the inflow is sufficiently large, so that a persistent bus queue is present upstream of the stop. Given the existence of a persistent bus queue, each arriving bus will first join the queue before entering a berth. Thus, the bus arrival process will not affect the stop capacity.

By examining a large variety of operating conditions, we intend to deliver a broader image of how distinct overtaking policies affect the capacities of isolated, near-side, and far-side stops. Our analysis unveils new findings on the cause-and-effect relationship between the stop capacity and key input factors. Some findings answer questions that were never properly addressed in the literature (e.g., the effects of oblique insertions and bus traffic dynamics). Others correct the biased results of previous studies (e.g., on whether the LO or NO policy yields a greater capacity). These findings offer another major contribution of our paper.

Moreover, we examine two strategies that can produce greater capacities than LO without creating disruptive oblique insertions. They can be implemented in real practice with the assistance of proper regulation or stop management systems. The investigation of these strategies is yet another contribution.

Finally, we show that our findings have wider implications for managing bus stops and choosing the optimal overtaking policy, even if some assumptions made for our simulation models are relaxed.

The rest of the paper is organized as follows. Section 2 describes the overtaking policies and the simulation model framework. Results for the isolated, near-side, and far-side stops under various policies are presented and discussed in Section 3. Section 4 describes two overtaking management strategies and examines their performance compared to conventional policies. Section 5 summarizes the findings and discusses their practical implications for a broader scope of stops. Section 6 concludes the paper.

2. Bus-stop types, overtaking policies, and simulation setup

We state the assumptions in Section 2.1. Sections 2.2 and 2.3 describe the policies governing bus overtaking maneuvers at a multi-berth stop and the stop's proximity to a signalized intersection, respectively. Section 2.4 presents the simulation framework.

2.1 Assumptions

Bus stops are differentiated in various operating aspects, e.g., whether they are segregated from the general traffic or not, whether a passing lane is present, and whether the stop is close to nearby signals. For the simplicity of analysis, we make the following assumptions:

(i) Only curbside bus stops are considered.

(ii) A dedicated bus lane is deployed in the proximity of the stop, so that bus operations in and out of the stop are segregated from the general traffic. For a near- or far-side stop, this bus lane is extended downstream or upstream to the neighboring intersection, respectively. A passing lane is provided at the stop (only) if overtaking maneuvers are allowed.

(iii) All the buses and berths are identical in size.

(iv) The berths in the stop are shared by all bus lines, i.e., a bus can enter any available berth to serve its passengers.

(v) We characterize the bus movements in and out of the berths by two parameters (Shen et al., 2019): the reaction time of a queued bus when its downstream bus changes speed (Daganzo, 2006), τ; and the move-up time for a bus to traverse a berth, t_m. These parameters represent the first-order approximation of the real bus traffic dynamics (see Daganzo, 2006, 2007, for similar treatments of vehicle traffic). In other words, the time loss incurred by bus acceleration and deceleration is factored into bus dwell times and queueing times, while the detailed acceleration and deceleration processes are simplified. This is because considering the bounded acceleration of bus traffic would only create minor differences (Daganzo, 2007). Fig. 2 illustrates the simplified (solid) and actual (dashed) bus trajectories in a time-space diagram.[4]

(vi) Bus dwell times are independent and identically distributed, following a gamma distribution with mean μ_S and coefficient of variation C_S. Gamma distributions are more flexible than the exponential distribution used in Bian et al. (2019) and were often used to model bus dwell times (e.g., Gu et al., 2011, 2015; Shen et al., 2019).

(vii) Buses form a queue upstream of the stop before they can enter available berths.

(viii) When a conflict occurs in the passing lane between an entering bus and an exiting bus, the exiting bus always has the priority.

Relaxation of some of the above assumptions will be discussed in Section 5.3.

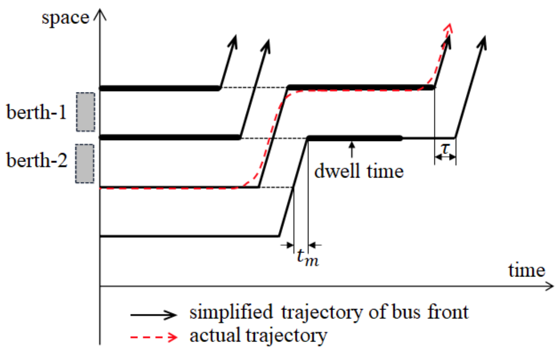


Fig. 2. Bus reaction and move-up times (the bold lines are bus dwell times).

2.2 Bus overtaking policies

Consider a c-berth stop as shown in Fig. 3. Five overtaking policies are defined as follows.

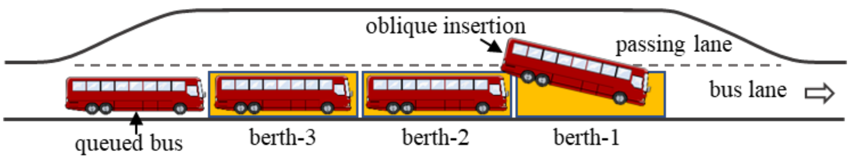


Fig. 3. A curbside stop with c = 3 berths.

The first policy is NO, where bus overtaking maneuvers are prohibited. This policy has been commonly observed in the real world[5] and extensively studied in the literature (Gu et al., 2011, 2015; Bian et al., 2019; Shen et al., 2019). Under this policy, a bus can discharge from the stop only when all the downstream buses have departed the stop. Queued buses will enter the stop in platoons when all the c berths are vacated.

[4] The sum of reaction and move-up times is equivalent to the "clearance time" defined in the TCQSM (Kittelson & Associates, Inc., 2013) for "on-line" stops (i.e., curbside stops).
[5] https://news.sina.com.cn/c/2009-07-11/040615934472s.shtml (in Chinese).

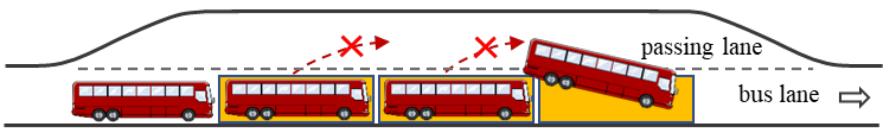
The second policy is LO, which entails that overtaking-out maneuvers are allowed, but overtaking-in maneuvers are prohibited (Gibson et al., 1989; Gu and Cassidy, 2013; Bian et al., 2019). The policy is formulated this way because the overtaking-out maneuvers are less disruptive to the bus traffic. The LO policy is also commonly seen in real bus stops[6].

In addition, some bus stops impose no restrictions on bus overtaking maneuvers. This may be due to a lack of management or an attempt to increase the stops' bus-carrying capacities. However, when a typical-sized (e.g., 12-meter-long) bus enters a berth by overtaking other buses, it may not be able to fully maneuver its rear end into the berth. The resulting oblique insertion may block the passing lane partially or completely; see Fig. 3. Buses dwelling in upstream berths are thus unable to exit through the passing lane. This phenomenon was often observed at stops where bus driver behavior is not effectively regulated[7]. Oblique insertions only occur where the target berth's immediate upstream berth is occupied (Zhao et al., 2019). For example, in Fig. 3, if berth-1 and 2 are both vacant while berth-3 is occupied, a queued bus can fully enter berth-1 since there is enough space for that bus to maneuver its tail into berth-1 after bypassing the bus dwelling in berth-3.

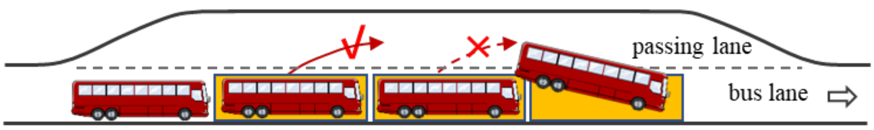
We consider the following three free-overtaking (FO) policies that are characterized by their distinct disruptive effects of bus overtaking-in maneuvers. (The term "free-overtaking" was also commonly used; see Bian et al., 2019, and Liu et al., 2022.)

(i) The *FO-PB* (Free-Overtaking-with-Passing-lane-Blocked) policy specifies that an oblique insertion will block the entire passing lane; see Fig. 4a.

(ii) The *FO-UB* (Free-Overtaking-with-Upstream-berth-Blocked) policy states that an oblique insertion will only block part of the passing lane so that the bus in the immediately upstream berth cannot exit while further upstream ones can; see Fig. 4b. This may occur where the berth is longer, or the lane is much wider than a bus. A bus dwelling immediately upstream of the oblique insertion cannot safely maneuver its head into the passing lane, but further upstream buses can use the passing lane to bypass the obliquely inserted bus. We define FO-PB and FO-UB to represent two distinct levels of blockage of the passing lane. In reality, they may co-exist at a stop, depending on the driver's behavior.



(a) FO-PB.



(b) FO-UB.

Fig. 4. Free-overtaking policies with different passing lane blockages due to an oblique insertion.

(iii) The *FO-NB* (Free-Overtaking-with-No-Blockage) policy stipulates that the overtaking-in maneuvers will never block the upstream bus traffic. We include this idealized policy in the analysis because it furnishes a capacity upper bound for all the other policies. Moreover,

[6] https://www.keyunzhan.com/bus/news_26125/ (in Chinese).
[7] See Yu (2000) and http://news.sohu.com/20110413/n305735754.shtml (in Chinese).

there are indeed real stops following this policy. One example is the sawtooth stops illustrated in the TCQSM (Kittelson & Associates, Inc., 2013); see Fig. 5[8].

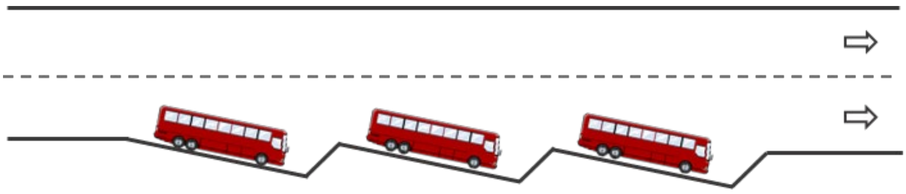


Fig. 5. The layout of a sawtooth bus stop.

Note that we do not include the policy where overtaking-in is allowed, but overtaking-out is prohibited. This policy has been shown by previous studies (Bian et al., 2019; Liu et al., 2020) and our simulation experiments to be inferior to LO.

The five overtaking policies are summarized in Table 1.

Table 1. Five overtaking policies.

Policy	Overtaking-in	Overtaking-out	Damage created by an oblique insertion
NO	No	No	-
LO	No	Yes	-
FO-PB	Yes	Yes	The passing lane is completely blocked
FO-UB	Yes	Yes	Only the bus in the immediately upstream berth is blocked
FO-NB	Yes	Yes	No blockage

2.3 Proximity to signalized intersections

We consider three types of stops distinguished by proximity to the nearest signalized intersection: stops isolated from signals, near-side stops located close to a downstream signal (Fig. 6a), and far-side stops located close to an upstream signal (Fig. 6b).

We define "buffer" as the lane area between the stop and the signalized intersection and denote d the buffer length; see Fig. 6a and b. This parameter is normalized as the multiple of a berth's length and rounded down to the nearest integer. In other words, d represents the number of buses that can reside in the buffer. Further denote D the intersection length in the bus travel direction, again normalized and rounded down as an integer multiple of the berth length. We assume that all the buses are through-moving at the intersection, and they will stay in the same lane after exiting the stop or the intersection. The signal is assumed to follow a fixed-time plan described by the cycle length, C, and the effective green duration, G. Similar setups on near- and far-side bus stops can be found in Gu et al. (2013, 2014) and Shen et al. (2019).

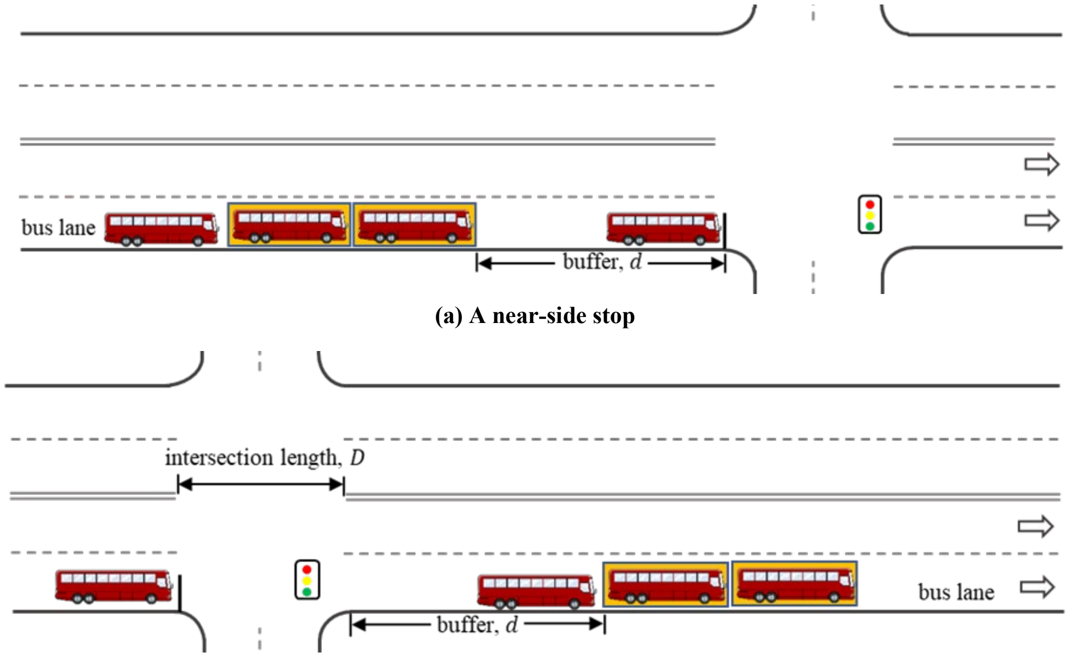
Exiting buses from a near-side stop will form a queue in the buffer during red periods. If that queue spills back to the stop, dwelling buses will be blocked, reducing the stop's capacity. On the other hand, for a far-side stop, buses queued upstream of the intersection cannot discharge if the stop and the buffer are both full. Hence, a long red period may starve the far-side stop after the stop serves all the buses queued in the buffer.

2.4 Simulation framework

We develop a parsimonious discrete-time simulation model to emulate the three types of stops under the five overtaking policies. The model only uses key operating parameters as inputs, including the number of berths, dwell time distribution, move-up and reaction times, buffer size, and signal timing

[8] This stop design is uncommon, partly because it occupies a much wider area than a regular curbside stop.

parameters. The bus arrival rate is set high enough to ensure a persistent queue is present. (Recall that in this case the bus arrival process will not affect the stop's capacity. Thus, parameters like the bus arrival rates are not needed.)



(a) A near-side stop

(b) A far-side stop

Fig. 6. Bus stops near signalized intersections.

Flowcharts of the simulation framework are presented in Appendix A. The program is developed using Matlab R2016b. Code can be downloaded from: https://github.com/Sangen-Hu/Bus-stop-Simulation.

To obtain the expected bus discharge rate, 200 simulation runs are first conducted for each numerical instance, and each run emulates bus operations for 10 hours with distinct random seeds. If the average discharge flow of the 200 runs does not converge, more runs will be performed until convergence is attained. We define the convergence criterion as the standard error in capacity being less than 0.5 bus/hour. The simulation was executed on a PC with Core i7-8700 CPU @ 3.20 GHz and 16 G RAM. The average runtime for simulating an NO isolated stop with three berths is around 7 minutes.

3. Numerical results and findings

The parameter values used in the simulation are furnished in Section 3.1. Section 3.2 compares the capacities of isolated stops under the five overtaking policies. Capacities of isolated, near-side, and far-side stops are presented and compared in Section 3.3.

3.1 Parameter values

The parameter values listed in Table 2 will be used in our simulation experiments unless otherwise specified. These values are selected by referring to previous studies (e.g., Jiang and Yang, 2014; Shen et al., 2019; Tian et al., 2021). The discrete time step is set to 0.54 s. This value is selected to ensure that key time-based parameter values (t_m and τ) are integer multiples of the time step. Longer durations used in the simulation (e.g., the bus dwell times and the signal periods) are rounded to the nearest integer multiples of the time step.

Table 2. Simulation parameter values.

Class	Parameter	Definition	Value
Bus traffic characteristics	t_m	Move-up time	2.16 s
	τ	Reaction time	1.62 s
Dwell time distribution	μ_S	Mean dwell time	25~50 s
	C_S	Coefficient of variation in dwell time	0~1
Stop layout	c	Number of berths	2~4
	d	Normalized buffer size	0~3
Signalized intersection	C	Cycle length	80~180s
	D	Normalized intersection length	2
	G/C	Green ratio	0.5

3.2 Isolated stop capacities under five overtaking policies

The isolated stop's capacity is plotted against C_S under the five overtaking policies for $c = 2, 3, 4$ and $\mu_S = 25$ s in Fig. 7a-c, respectively, and for $c = 3$ and $\mu_S = 50$ s in Fig. 7d. We start by examining the NO policy (Section 3.2.1), and then conduct head-to-head comparisons where one or two policies are added in each of the following Sections 3.2.2 to 3.2.4.

3.2.1 NO stops

Capacities under the NO policy are plotted against C_S as the solid curves in Fig. 7a-d. At first glance, the curves are similar to those reported in analytical studies (Gu et al., 2011, 2015). For example, the capacity decreases as C_S grows, and it decreases faster for stops with more berths.

However, scrutinization reveals that the simulated capacities are significantly lower than the analytical predictions in Gu et al. (2011, 2015). Table 3 shows the percentage differences between the simulated and analytical capacities for certain parameter values. The reduction is surprisingly large, given that the only difference between the analytical and simulation models is the incorporation of reaction and move-up times, which are very small (1-3 s). The table also shows that the capacity reduction increases with c. This is because buses enter a c-berth NO stop in c-bus platoons and a lost time of $c(\tau + t_m)$ is incurred to each bus when a platoon enters and exits the stop. In addition, the capacity reduction decreases with C_S and μ_S. This is because when C_S or μ_S grows, a c-bus platoon's mean dwell time increases under the NO policy for $c \geq 2$ (Gu et al., 2011), while the lost time $c(\tau + t_m)$ remains the same. The increased platoon dwell time dilutes the capacity reduction caused by the lost time.

Table 3. Percentage capacity reduction after considering the bus reaction and move-up times.

	$c = 2, \mu_S = 25$ s	$c = 3, \mu_S = 25$ s	$c = 4, \mu_S = 25$ s	$c = 3, \mu_S = 50$ s
$C_S = 0$ (deterministic dwell times)	24%	32%	38%	19%
$C_S = 0.6$ (as recommended by St. Jacques and Levinson, 1997)	20%	22%	28%	12%
$C_S = 1$ (exponential dwell times)	17%	20%	22%	11%

3.2.2 Comparing NO and LO stops

Capacities under the LO policy are plotted as the black dashed curves in Fig. 7a-d. Despite the similar trends to previous analytical studies (Gu and Cassidy, 2013), we also observed significantly lower capacities than theoretical values due to the incorporation of τ and t_m. For example, the percentage reductions for $c = 2, 3$, and 4 when $C_S = 0.6$ (a value recommended by St. Jacques and Levinson, 1997) are 16%, 20%, and 22%, respectively. More importantly, a key prediction in Gu and Cassidy (2013), i.e., that the LO capacity falls below NO for small C_S (< 0.4), is not found in Fig. 7a-

c. There are two potential reasons behind this new finding. We take a 2-berth stop as an example to explain them. First, after considering traffic dynamics, a bus dwelling in the upstream berth may enter the berth later than the one dwelling downstream. Thus, the upstream bus is more likely to complete its service later than the downstream one, especially when C_S is small. Second, even if the upstream bus finishes its service slightly earlier than the downstream one and departs by overtaking, it will take the next queued bus $\tau + t_m$ to move into the upstream berth. If the downstream berth is vacated during the queued bus's move-up process, that bus will still proceed to the downstream berth. In both cases, the LO stop tends to behave like an NO stop. As a result, the solid and dashed curves in Fig. 7a-c nearly overlap for $C_S < 0.2$. This finding further manifests the necessity of considering bus reaction and move-up times and the limitations of analytical queueing models in the literature.

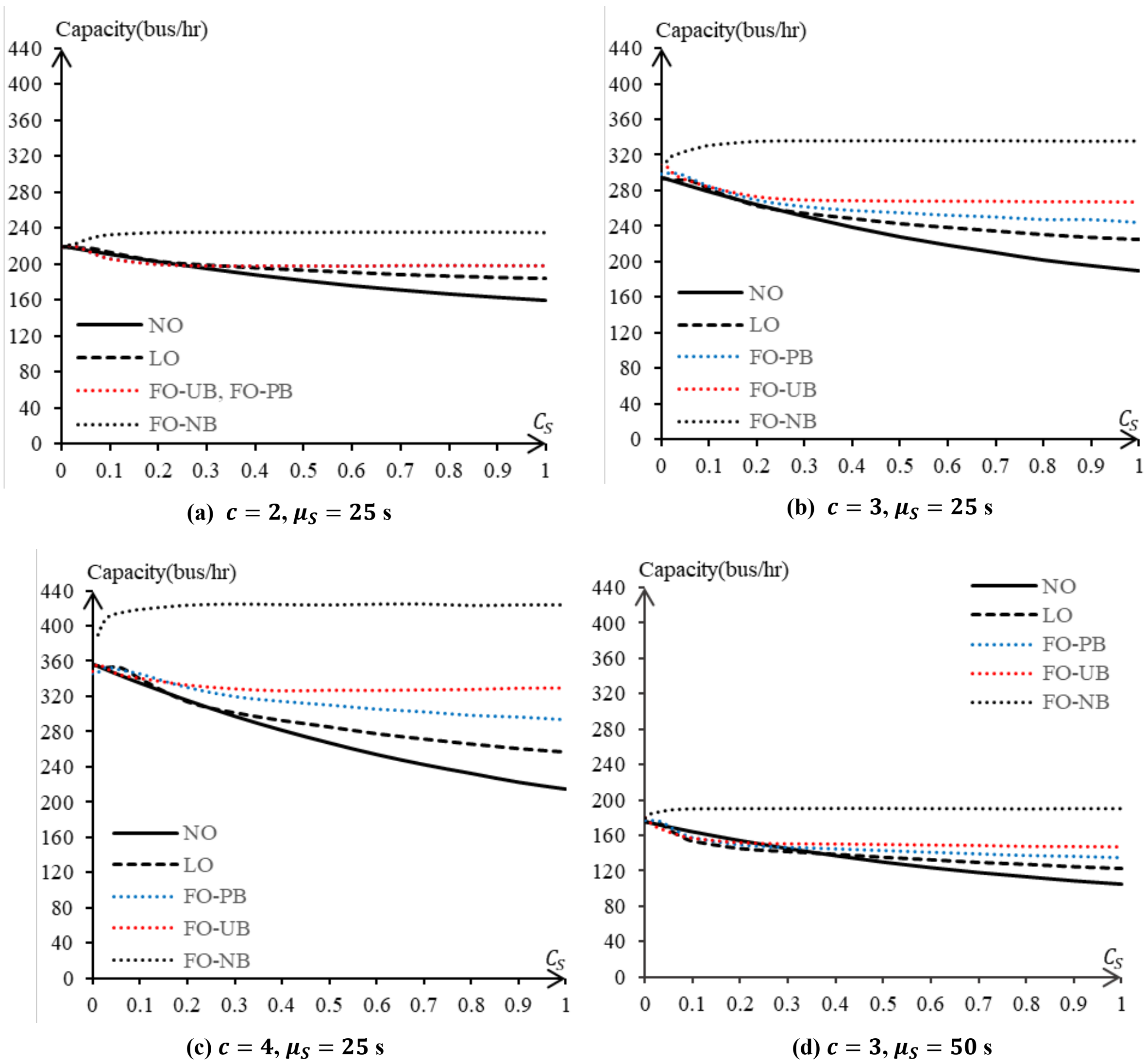


Fig. 7. Isolated stop capacities under five overtaking policies.

The above effect of bus traffic dynamics diminishes as μ_S grows; see in Fig. 7d that the LO capacity falls below NO for $\mu_S = 50$ s and $C_S \leq 0.35$, which partially agrees with the prediction of Gu and Cassidy (2013). Nevertheless, the advantage of LO over NO is shown to be greater than predicted in the previous work.

3.2.3 Comparing regulated (NO and LO) and unregulated (FO-PB and FO-UB) stops

Moreover, completely removing overtaking restrictions yields even greater capacities, despite the negative impacts of oblique insertions. Fig. 7a shows that FO-PB and FO-UB (they are identical for 2-berth stops), the red dotted curve, consistently outperforms NO and LO for $C_S \geq 0.25$. The same is observed in Fig. 7b and c for $C_S \in [0, 1]$ and in Fig. 7d for $C_S \geq 0.3$. In the latter figures, FO-PB and FO-UB are represented by the blue and red dotted curves, respectively. In addition, the gaps between these curves grow with C_S and c. This is expected since the mutual blockage between buses created by overtaking restrictions worsens as C_S or c increases. Table 4 summarizes the percentage differences between the FO-PB and FO-UB capacities and that of NO when $C_S = 0.6$ for the four cases shown in Fig. 7a-d. The percentage differences in capacity between LO and NO are also included for comparison.

Table 4. Percentage capacity differences between four policies, using NO as the basis ($\boldsymbol{C_S = 0.6}$).

	$c = 2, \mu_S = 25$ s	$c = 3, \mu_S = 25$ s	$c = 4, \mu_S = 25$ s	$c = 3, \mu_S = 50$ s
FO-UB	13%	23%	29%	21%
FO-PB	13%	16%	21%	15%
LO	8%	9%	10%	7%

The above findings can explain why seemingly beneficial policies for regulating bus behavior at busy stops have failed. Years ago, several Chinese cities (e.g., Beijing and Changsha) enforced the NO policy at all bus stops in response to the endless passenger complaints about chaotic bus overtaking maneuvers (e.g., Ma, 2004). Unfortunately (and unexpectedly), this policy backfired by creating excessively long bus queues during rush hours (Ma, 2004; Lou and Luan, 2004). Overwhelmed by the even stronger public complaints, the traffic management agencies revoked this policy precipitously, leaving the chaos at stops to resume thereafter. A possible reason for the policy failure is: NO is generally the least productive among the four policies, while the FO policies are the most productive regardless of the disruptive oblique insertions; see Fig. 7a-d. The capacity loss by regulating overtaking maneuvers is around 8-23% (for $C_S = 0.6$).

A traffic management agency can learn strategies to solve the above dilemma through proper modeling and analysis of stop capacities under various overtaking policies. For example, the LO policy does not incur oblique insertions and is significantly more productive than NO. This policy may be suitable for some stops in the above cities. Even more productive but nondisruptive strategies will be introduced in Section 4. Further discussions on the practical issues can be found in Section 5.

Besides, the marginal capacity brought by each additional berth is diminishing, as is evident by comparing Fig. 7a-c. This is qualitatively consistent with the numbers of effective loading areas in the TCQSM (Kittelson & Associates, Inc., 2013) and the predictions in Gu et al. (2011).

3.2.4 Comparing against the capacity upper bound

The capacity upper bound under FO-NB is plotted as the black dotted curves in Fig. 7a-d. Unsuprisingly, this upper bound is almost insensitive to C_S because a saturated c-berth stop operating under the FO-NB policy can be viewed as a combination of c single-berth stops. The gap between the LO, NO capacities and the upper bound represents the large damages created by overtaking restrictions, which increase with C_S. And the gap between the FO-PB, FO-UB curves and the upper bound shows the damages caused by oblique insertions are also sizeable. Comparison across Fig. 7a-c reveals that the above damages increase with c. This is again due to the fact that the mutual blockage between buses created by overtaking restrictions aggravates as C_S and c grows.

3.3 Near- and far-side stop capacities

Including a nearby signal in the model introduces four more parameters: the buffer size d, the cycle length C, the green duration G, and the intersection length D. Hence, a full-scale parametric analysis would be too lengthy. For simplicity, we specify $C_S = 0.6$, $\mu_S = 50$ s, $D = 2$, and $\frac{G}{C} = 0.5$. This allows us to focus on the effects of the stop layout and location (described by c and d), the cycle length C, and the overtaking policies. Specifically, Fig. 8a-d plot the near-side stop capacities against $C \in [80, 180]$ s under the five overtaking policies for $(c, d) \in \{2, 3\} \times \{0, 3\}$ (operator $\times$ represents the Cartesian product). Fig. 9a-d plot the far-side stop capacities against C for the same ranges of parameters.

Major findings are summarized as follows:

(i) The capacity diminishes as C (and hence the red period) grows, regardless of c, d, and the overtaking policy. This is because, for near-side stops, queued buses are more likely to spill from the buffer to the stop in a long red period. On the other hand, far-side stops are more likely to be starved during long red periods.

(ii) Increasing the buffer size can significantly improve the capacity since a near- or far-side stop's capacity approaches that of an isolated stop as d increases. As a result, the capacities under NO, LO, FO-PB, and FO-UB are less insensitive to C when d is large.

(iii) NO is again the least productive policy, while FO policies are still the most productive in general.

(iv) For near-side stops, LO produces a capacity comparable to the FO policies when C is large and d is small; see Fig. 8a and c. This is good news since LO does not incur oblique insertions, which are usually unwelcome due to their disruptive nature and safety concerns. In general, the capacity gap between FO and LO policies diminishes as C (and the red period) increases or d decreases. This is because an oblique insertion occurring before the start of a red period will block upstream bus(es) from discharging into the intersection. Those blocked buses are stranded in the following red period, which reduces the number of buses that can be served during the red period. The above effect is greater when the red period is longer or d is smaller.

Findings (i) and (ii) are consistent with predictions of a previous theoretical study (Shen et al., 2019). But that study only examined the NO policy.

Table 5 shows the significant percentage capacity losses due to the nearby signal when $C = 120$ s. The tabulated numbers unveil that a far-side stop produces less capacity than its near-side counterpart when $d = 0$. The reason is that buses need to travel across the intersection in a green period before entering a far-side stop. This is consistent with the previous finding for the NO policy (Shen et al., 2019). With a large buffer, the two types of stops have similar capacities.

In sum, this section demonstrates that overtaking-regulated policies (LO and NO) are significantly less productive than FO policies for most stops. However, oblique insertions associated with FO policies are not embraced by passengers, drivers, and traffic managers. Those disruptive maneuvers create delays to upstream buses, evoking complaints and even dangerous driving behavior. Worse still, oblique insertions often raise safety issues. For example, passengers boarding or alighting through the rear door of an obliquely-inserted bus must walk to the street, exposing themselves in front of the upstream bus and other traffic (e.g., bikes), and vehicles attempting to overtake an obliquely-inserted bus may cause scratches. Oblique insertions are also prohibited in modern bus rapid transit (BRT) systems due to the requirement of platform-level boarding. Therefore, overtaking-in maneuvers are often prohibited in real bus stops to prevent oblique insertions[9], leaving NO and LO the only available options. In light of this, the next section proposes two alternative strategies that can potentially produce greater capacities than NO and LO without incurring oblique insertions.

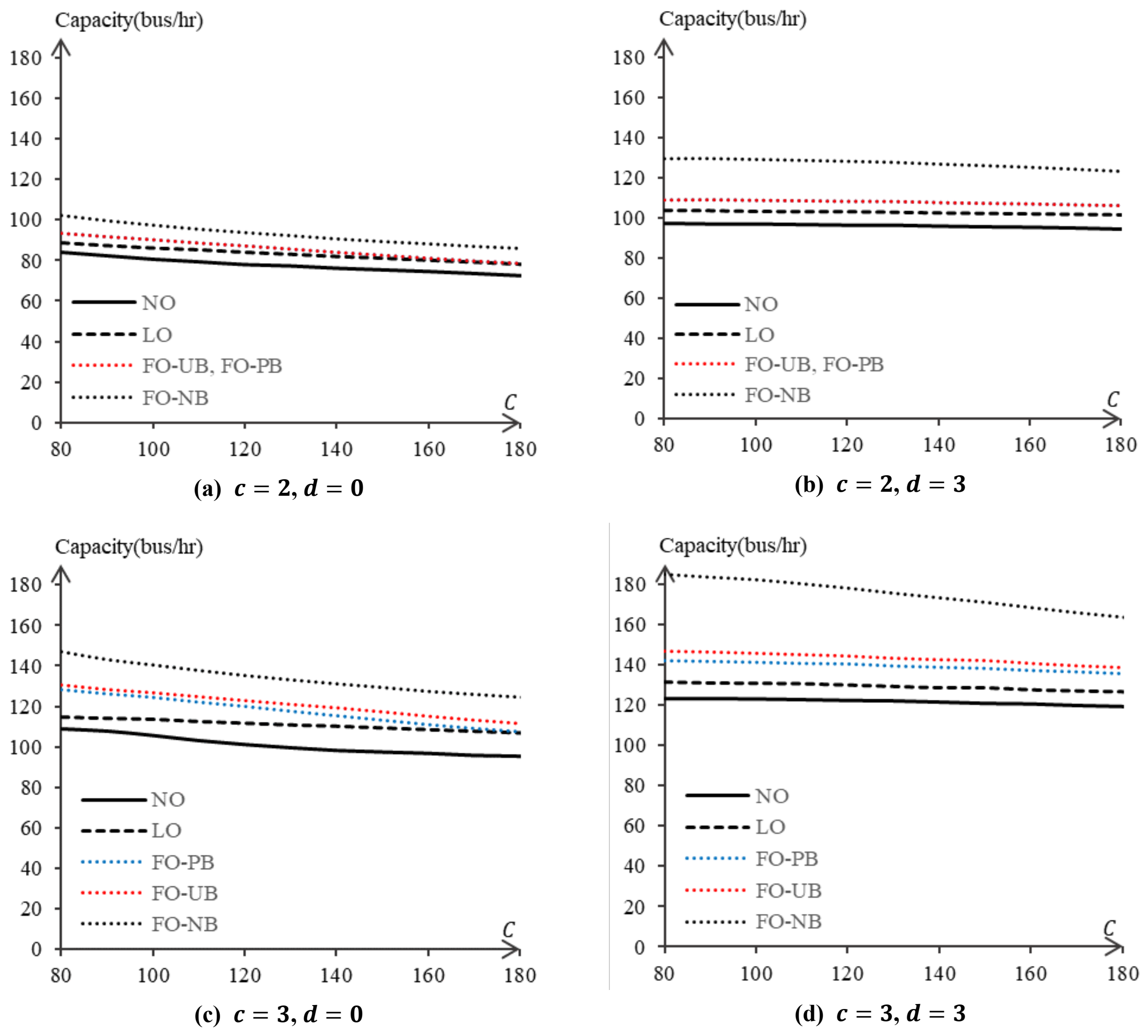


Fig. 8. Near-side stop capacities under five overtaking policies.

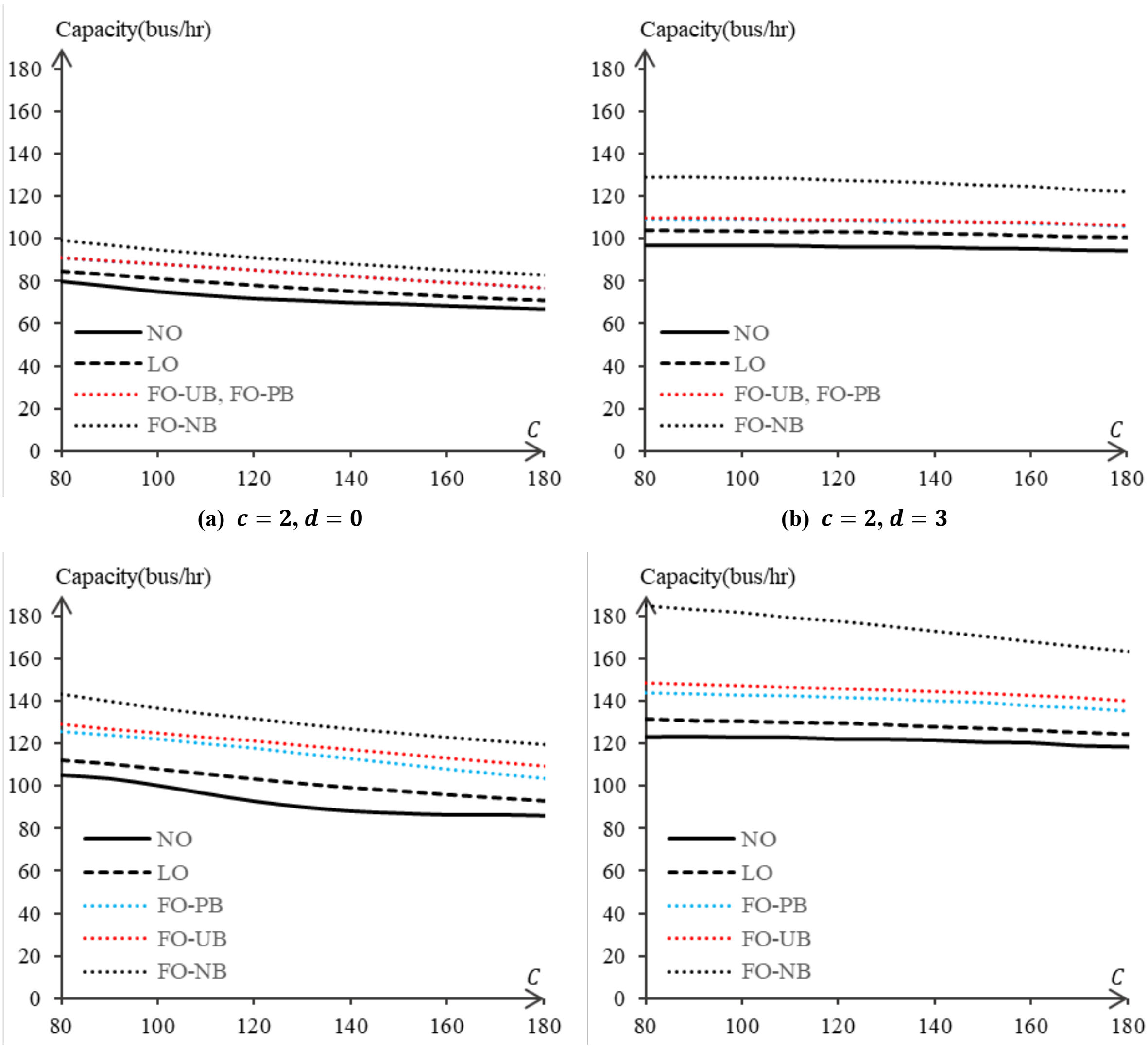
4. Alternative strategies for regulating overtaking maneuvers

Section 4.1 examines a dynamic strategy where overtaking-in maneuvers are allowed only if no oblique insertion is incurred. Section 4.2 investigates a design in which every two berths are grouped to form a sub-stop, and sub-stops are separated to allow overtaking-in maneuvers.

4.1 Free overtaking with oblique insertion prohibited

A straightforward strategy is to simply prohibit oblique insertions while allowing overtaking-in if that does not create an oblique insertion (i.e., if there are two consecutive vacant berths in the stop). We term this strategy FOOIP (Free-Overtaking-with-Oblique-Insertion-Prohibited), which applies to stops with three or more berths.

[9] https://news.sina.com.cn/o/2011-11-30/150723551255.shtml (in Chinese).



(a) $c = 2, d = 0$ (b) $c = 2, d = 3$

(c) $c = 3, d = 0$ (d) $c = 3, d = 3$

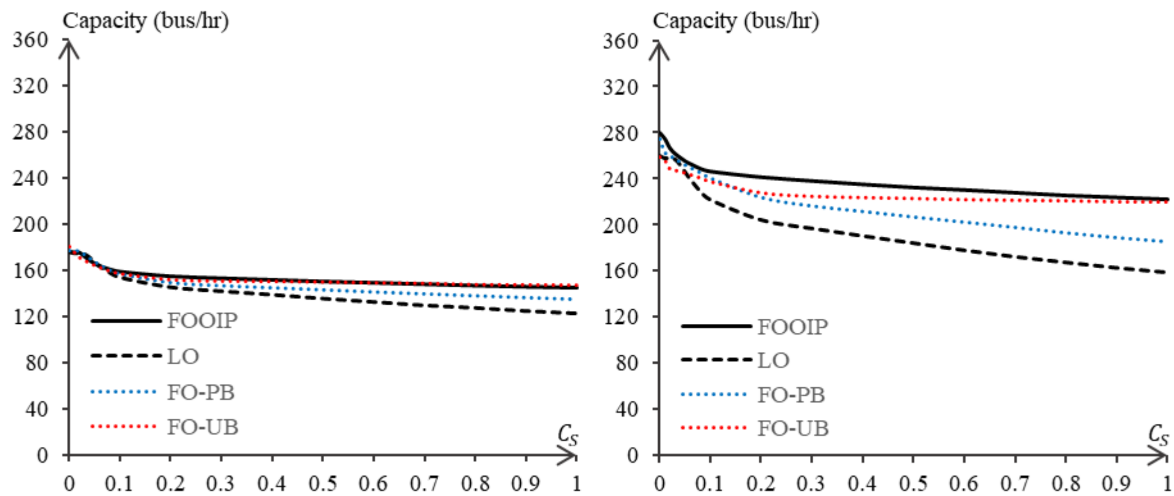
Fig. 9. Far-side stop capacities under five overtaking policies.

Table 5. Percentage capacity losses compared to isolated stops ($C = 120$ s).

c	d	Near-side stop					Far-side stop				
		NO	LO	FO-PB	FO-UB	FO-NB	NO	LO	FO-PB	FO-UB	FO-NB
2	0	19.8%	19.2%	20.6%	20.5%	27.9%	26.2%	24.9%	22.0%	22.0%	29.8%
2	3	1.0%	1.1%	1.2%	1.0%	1.5%	1.0%	0.7%	0.6%	0.7%	1.7%
3	0	17.8%	15.6%	15.1%	17.5%	28.9%	24.6%	22.0%	16.6%	18.6%	30.8%
3	3	0.9%	2.0%	0.5%	3.3%	6.4%	1.2%	2.0%	-0.4%	2.1%	6.6%

Simulated capacities of this new policy are compared against LO, FO-PB, and FO-UB for 3- and 5-berth isolated stops with $\mu_S = 50$ s in Fig. 10a and b, respectively. The figures show that the FOOIP's capacity also decreases with C_S. More importantly, this policy largely outperforms LO and FO-PB and even outmatches FO-UB for $c = 5$. Take $C_S = 0.6$ as an example, FOOIP's capacity is 12% and 30% greater than LO for 3- and 5-berth stops, respectively. These results manifest the policy's great effectiveness.

Since FOOIP is a dynamic strategy, under what conditions a bus can perform overtaking-in may seem confusing to drivers and passengers. This may lead to passenger complaints and drivers' incompliance. A berth navigation system can be installed to assist the bus drivers in resolving the confusion. The system will display real-time berth availability (monitored via detectors installed on each berth) and inform drivers on whether to overtake or not and which berth to enter (e.g., via a signal or changeable message sign). In addition, regulations on bus driver behavior (e.g., penalties for oblique insertions) can be enacted to ensure drivers' compliance.



(a) c = 3 **(b) c = 5**

Fig. 10. Capacities under the FOOIP strategy.

4.2 Stops consisting of two-berth LO sub-stops

Another idea to eliminate oblique insertions features a buffer space (of a berth's size) inserted between two consecutive berths so that overtaking-in maneuvers will never lead to an oblique insertion. However, this design renders a significant waste of space. For example, in a 5-berth-long stop, only three berths can be used while the other two must be converted to buffers. In comparison, an alternative design, where a stop consists of 2-berth sub-stops separated by one-berth-long buffers, can better utilize the space. The LO policy can be applied between the two berths in each sub-stop, as illustrated in Fig. 11. Buses queued upstream of the stop can freely enter any downstream sub-stop using the passing lane.[10] This strategy, termed TBLOS (Two-Berth-LO-Substops) in this paper, eliminates oblique insertions and is easier for drivers to comply with than the FOOIP strategy. The design was first discussed by Gibson et al. (1989) with a simple example of four berths separated into two sub-stops. It has also been implemented in real stops, e.g., the Jinan University & Normal University Station in the Guangzhou BRT corridor (Guo, 2016).

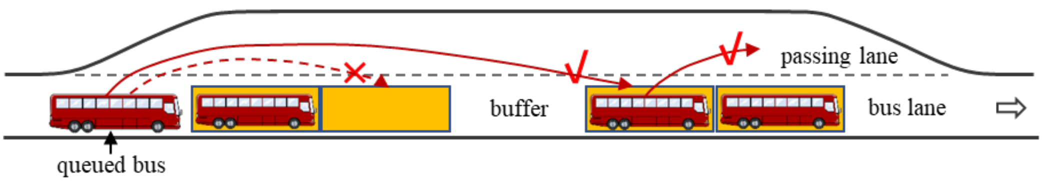


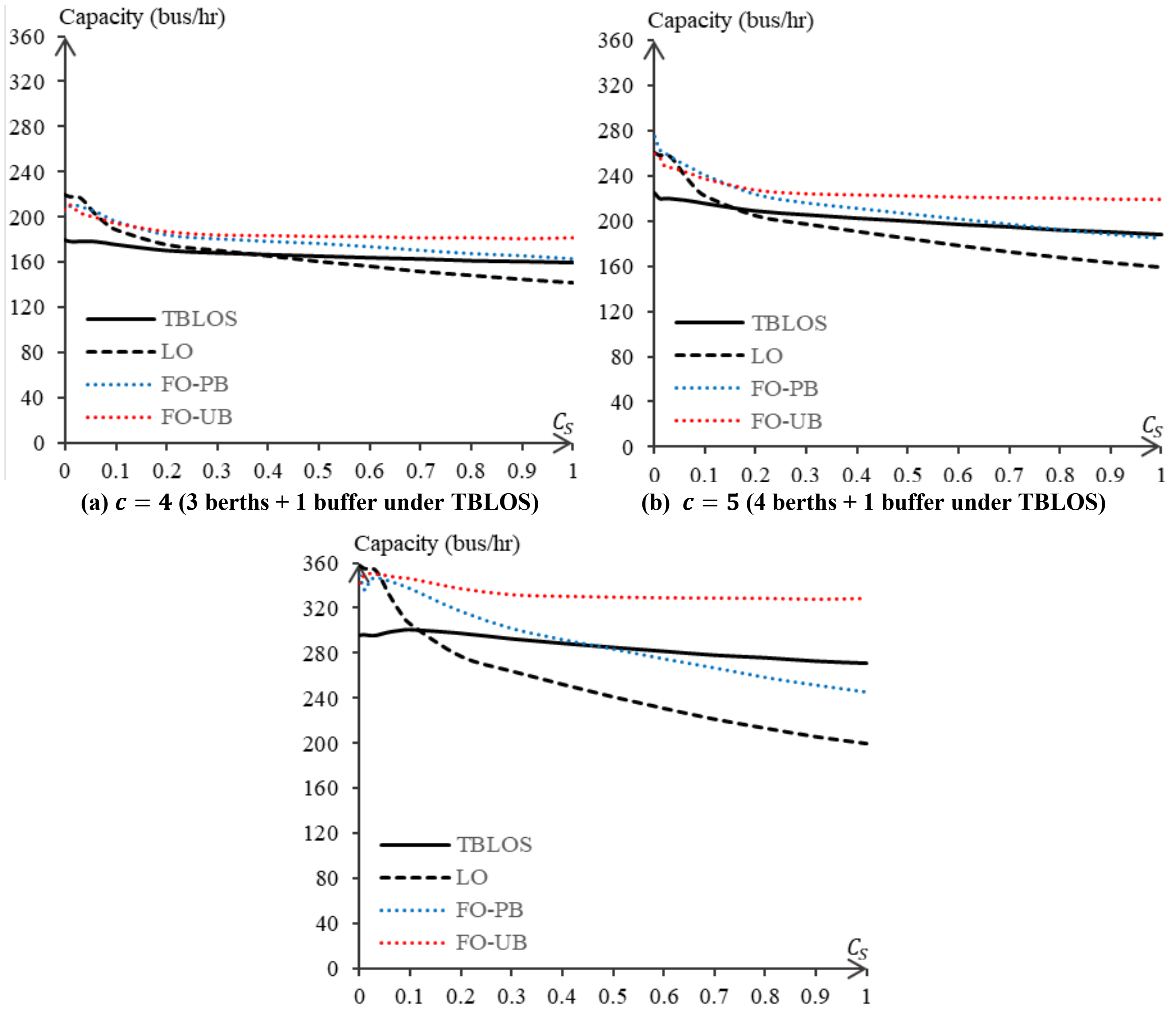
Fig. 11. A 5-berth-long TBLOS stop with four berths and a buffer.

Simulations are performed for: (i) a 4-berth-long TBLOS stop with three available berths and a buffer located before two downstream berths; (ii) a 5-berth-long TBLOS stop with four available berths and a buffer as shown in Fig. 11; and (iii) an 8-berth-long TBLOS stop with six available berths and

[10] The use of one-berth-long buffers is conservative. Zhao et al. (2019) showed that a buffer that is 0.7 times the berth size is sufficient to ensure successful overtaking-in maneuvers without oblique insertion; see Figure 7 of the cited paper.

two buffers. To ensure fairness, we compare their capacities against LO, FO-PB, and FO-UB stops with $c = 4$, 5, and 8 berths, respectively, so that the stops in each head-to-head comparison are equally long. We set $\mu_S = 50$ s. Results are plotted in Fig. 12a-c.

Unsurprisingly, the figures show that the TBLOS capacity still exhibits a decreasing trend in general as C_S grows. Specifically, Fig. 12a shows that the TBLOS design outperforms LO when $C_S \geq 0.4$ (the coefficients of variation in bus dwell times at real stops commonly fall in this range; see St. Jacques and Levinson, 1997), even after losing one of the four berths. Fig. 12b and c further show that TBLOS is more competitive for longer stops. For 5-berth-long stops, TBLOS tops LO when $C_S \geq 0.15$; and for 8-berth-long stops, TBLOS even outmatches FO-PB when $C_S \geq 0.45$. Take $C_S = 0.6$ as an example, TBLOS produces 5%, 11%, and 22% more capacity than LO for $c = 4$, 5, and 8, respectively.



(a) $c = 4$ (3 berths + 1 buffer under TBLOS) **(b) $c = 5$ (4 berths + 1 buffer under TBLOS)**

(c) $c = 8$ (6 berths + 2 buffers under TBLOS)

Fig. 12. Capacities of TBLOS stops.

The TBLOS design is especially beneficial for long stops serving dozens of bus lines, e.g., the busiest stops in the Guangzhou BRT corridor. A shortcoming of this design is that it takes time for passengers to walk from one sub-stop to another. A passenger navigation system can be deployed to resolve this problem. The system will predict the sub-stop and berth each bus will dwell in based on its current position (in cruise or in the upstream bus queue) and relay this message to the passengers in advance. Before real-world implementation of this system, the lead time for prediction, prediction error, and the resulting platform crowding problem need to be studied. In addition, variants of this design may be considered, e.g., one that consists of three-berth-sub-stops separated by buffers. The design may also be applied to stops where each berth is assigned to a fixed set of bus lines. The above issues will be explored in our future work.

It is worth noting that similar capacity advantages (compared to LO) have been found for near- and far-side stops operating under the FOOIP and TBLOS strategies. The detailed results are omitted for brevity.

5. Discussions

We start the discussion by summarizing the key findings of this paper in Section 5.1. The practical implications of these findings are elaborated in Section 5.2. Section 5.3 discusses the cases where our assumptions are relaxed.

5.1 Summary of key findings

The key findings from Sections 3 and 4 are summarized as follows:

(i) The effects of bus traffic dynamics (reaction and move-up times) on the stop capacity are sizeable. Results indicate that previous analytical queueing models ignoring this factor (Gu et al., 2011, 2015; Gu and Cassidy, 2013; Bian et al., 2019) are inaccurate. The stop capacity was overestimated by 10-40% by those analytical queueing models. As a result, the competitiveness of the NO policy was significantly exaggerated.

(ii) Under all the policies investigated, the stop capacity always declines with the variation in dwell times, and the marginal capacity gained by each additional berth diminishes. A near- or far-side stop's capacity declines with the signal cycle length but grows with the buffer size between the stop and the signal. A near-side stop is more productive than its far-side counterpart since, at a far-side stop, buses queued upstream of the intersection need to travel across the intersection to enter the stop.

(iii) Despite the disruptive effects of oblique insertions, FO policies yield significantly higher capacities than overtaking-restricted policies (NO and LO), especially when C_S or c is large. On the other hand, NO is almost always the least productive. This explains why overtaking regulations with good intentions backfired by creating intolerably long bus queues.

(iv) LO is appealing for near-side stops with long cycle length and short buffer, for it yields nearly the same capacity as FO-PB.

(v) Two strategies that can improve stop capacity without inducing the disruptive oblique insertions are examined. The first rests on dynamically controlling buses' overtaking-in maneuvers (i.e., the overtaking maneuvers that would not incur an oblique insertion will be allowed). It even outperforms FO policies for stops with three or more berths. The second strategy adds a space between any two consecutive pairs of berths. And it outweighs LO by a large margin, especially for long stops.

5.2 The choice of overtaking policies and means to improve bus-stop capacities

Our findings have implications on how best to regulate overtaking maneuvers and improve capacities for real stops. For example, in cities where bus stops are highly congested and the drivers and passengers can tolerate the negative impacts of oblique insertions, FO policies should be applied. The NO policy should never be used at busy stops unless no passing lane is available.

When oblique insertions are not allowed, FOOIP can be applied if the bus drivers are compliant, or a berth navigation system is deployed to ensure compliance. For stops with four or more berths, the TBLOS design can be used. LO will be the best choice if neither of the two strategies is applicable.

A transit planner who seeks a higher stop capacity may consider placing the stop at the near side rather than the far side of a signalized intersection, increasing the distance between the stop and the intersection, reducing the signal's cycle length, or reducing dwell time variations. The latter can potentially be done via strategies that equalize bus headways (e.g., Sun and Hickman, 2005; Daganzo and Pilachowski, 2011; Delgado et al., 2012; Estrada et al., 2016; Wu et al., 2017) since dwell time and headway variations are positively correlated. However, these strategies may also alter bus dwell time distributions. Thus, their overall effect on bus-stop capacity requires further analysis.

5.3 Relaxing some assumptions in Section 2.1

A strong assumption in Section 2.1 (assumption (ii)) is the presence of a dedicated bus lane. This assumption may not be satisfied at many real-world stops. However, we believe our main findings still hold for stops without bus lanes. This is because buses enjoy the "de facto priority" around the stop area as cars intend to avoid close interactions with the slow-moving buses near a stop (Gibson et al., 1989). If the passing lane is shared between buses and the general traffic, bus overtaking maneuvers will be hampered. As a result, LO would still produce more capacity than NO for a wide range of operating conditions, but the advantage diminishes with the general traffic intensity in the shared lane[11]. Moreover, FO-PB and FO-UB policies cannot be applied when the passing lane is shared with the general traffic since oblique insertions would block the traffic. Hence, LO, FOOIP, and TBLOS are the best choices for these stops.

In addition to curbside stops (assumption (i)), bay stops are also common in the real world. If a bay stop is accompanied by a dedicated bus lane, that lane will serve as a passing lane, and all our analyses and results of curbside stops can be directly applied. However, things are different if no bus lane is present because the general traffic can block buses exiting from the stop's downstream end. In this case, a bay stop's capacity can be much lower than predicted by our simulation models, depending on the traffic intensity in the adjacent lane. Further analysis is needed for this case, which will be performed in future work.

Assumption (iii) stipulates that all the buses are identical. In reality, if articulated and ordinary buses share a multi-berth stop, oblique insertions and even overtaking-in maneuvers will be prohibited due to articulated buses' length and poor maneuverability. Thus, LO may be the only policy outmatching NO.

Lastly, in many cities, each berth in a stop is assigned to serve an exclusive set of bus lines, which violates assumption (iv). This design is convenient for the waiting passengers but significantly compromises a stop's capacity, especially under the NO and LO policies (Shen et al., 2023). FO policies might be the only choice for busy stops of this kind. In addition, a modified TBLOS design might also prove beneficial, where each sub-stop is assigned to a specific bus line set, but the lines of the same set can share the two berths in the associated sub-stop. However, detailed capacity analysis of this design needs further modeling work.

[11] This was verified by our simulation outcomes considering the impacts of general traffic. Details are omitted for brevity. A similar finding was also reported by Bian et al. (2019).

6. Conclusions and future research

This paper develops parsimonious simulation models for estimating bus-stop capacities under a large range of overtaking regulation policies and operating conditions. The models can help practitioners obtain more accurate capacity estimates for the design purpose. Results reveal important findings that were never reported before (e.g., the performance of FO policies with oblique insertions and the sizeable effects of bus traffic characteristics); see Section 5.1. Some are at odds with previous studies (e.g., the advantage of LO over NO even when C_S is small). Moreover, two alternative overtaking regulation strategies are proposed, which can produce significantly higher stop capacities without creating oblique insertions; see Section 4.

Our findings can explain the previous policy failures (see Section 3.2.3) and inform practitioners of effective management policies and measures to maximize the stop capacity (see Section 5.2).

Our simulation work can be extended to study: (i) capacities of buses and the general traffic at a bay stop without a bus lane; and (ii) stops where each berth is assigned to a prespecified set of bus lines. Another interesting topic is the integrated design of signalized intersections with near- and far-side stops that can promote both the bus and general traffic (e.g., Ma et al., 2017; Gu et al., 2021). We also plan to conduct field experiments on various overtaking management strategies and designs simulated in this paper. Results can be used to verify our simulation model and findings.

Acknowledgments

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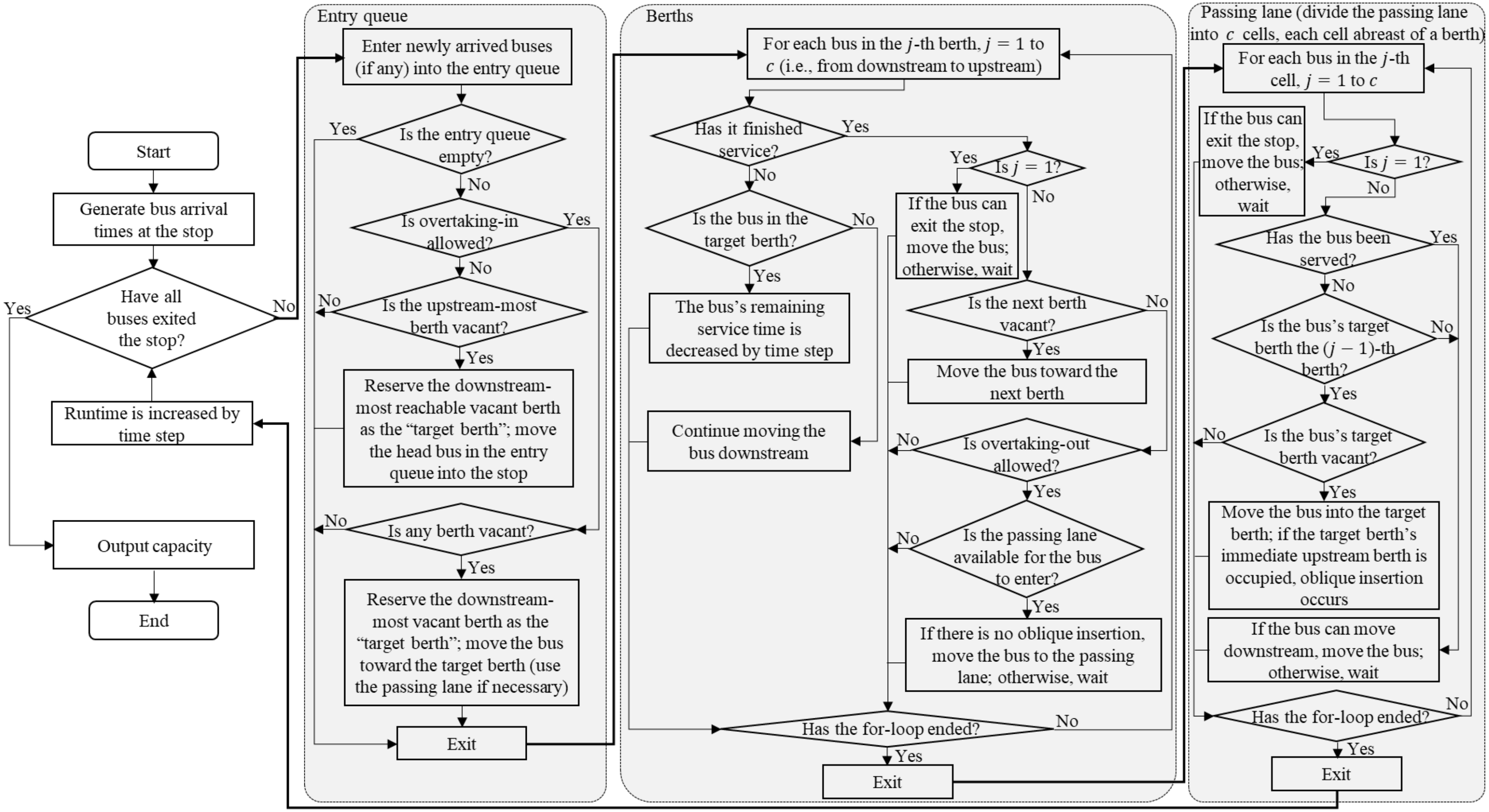
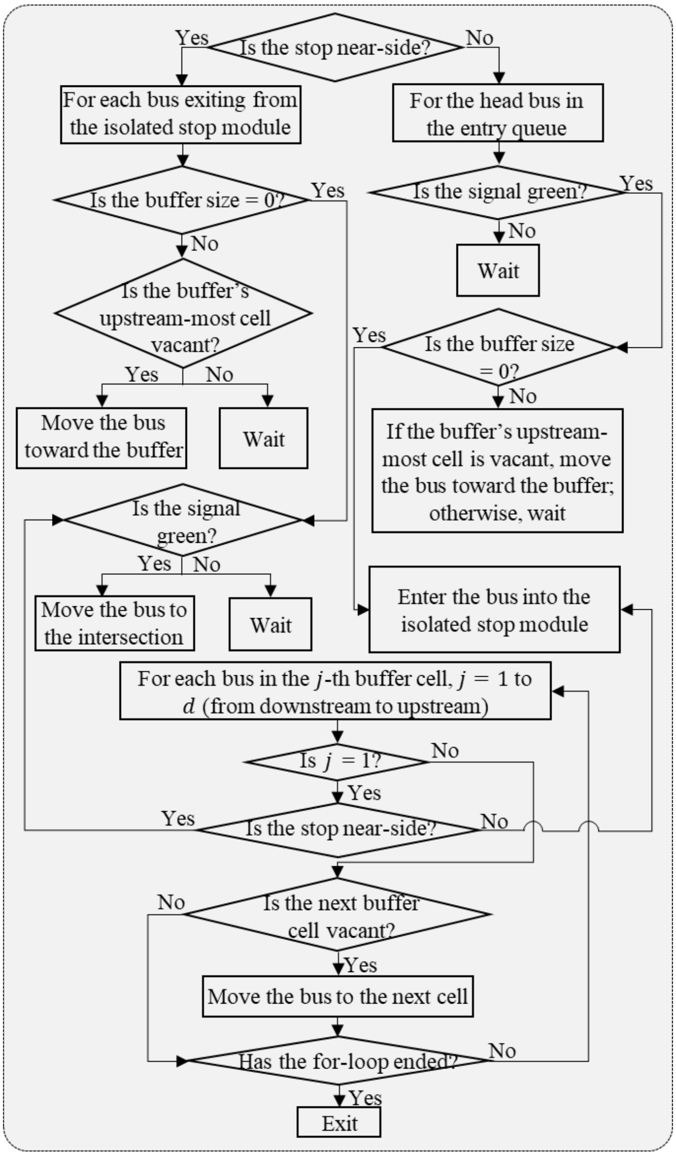
Appendix A. Simulation flowcharts

Fig. A1a and A1b show the flowcharts for the isolated stop module and the near/far-side stop module, respectively. The isolated stop module is called in the near/far-side stop module. Some straightforward details (e.g., the bus reaction and move-up processes) are omitted to keep the flowcharts brief.



(a) The isolated stop module



(b) The signal and buffer module

Fig. A1. Flowcharts of the simulation model.

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