Modeling Bus Bunching along a Common Line Corridor considering Passenger Transfer Behavior and Capacity Constraint

Abstract

Bus bunching is a longstanding problem in the real-life public transport system and degrades the efficiency and quality of the transit service. Various control schemes (e.g., holding, skipping, etc.) have been investigated to mitigate the adverse impacts of bus bunching problem. Nevertheless, existing researches inadequately capture the bus operation by simplifying some critical issues such as capacity constraint and transfer behavior in multi-line scenarios. The simplifications facilitate the formulations and analyses but may cause an unrealistic model and be impractical in reality. In this study, we formulate passenger behaviors including boarding, alighting, failing to board as well as transferring, and develop algorithms for bus trajectories and transfer passengers' routing results for a more realistic estimation of the bus operation. The results of numerical experiments examine the effects of passenger transfer behavior and bus capacity constraint on the propagation of bus bunching and demonstrate some useful insights: (a) Modeling routing of transfer passengers is considerable since the performances of bus operation with different passenger behaviors are distinct. This implies that motivated passenger behaviors (demand side) have the potential to cooperate with operation tactics (supply side) to alleviate the bus bunching problem. (b) The propagation of bus bunching problem from a disturbed bus line to an undisturbed bus line via the common corridor is enhanced because of the presence of transfer passengers. (c) Appropriate smaller bus capacity vehicles may lead more regular service as bus dwell times are constrained to avoid severe bus bunching. This verifies the applicability of boarding limit strategy or using different bus sizes to alleviate bus bunching problem in multi-line scenarios.

1 Introduction

In the last decade, more and more attention has been attracted on providing high-quality public transport services with the advocate of sustainable urban mobility. However, maintaining a reliable and efficiency bus operation is very challenging and the mismatching between the transit supply and passenger demand in bus operation is commonly observed. In fact, bus services in some metropolitan areas are criticized for being inefficient, irregular, and overcrowded. Low-quality bus services frustrate passengers and lead to a reduction in bus modal split rate. Among various existing issues in bus operation, bus bunching is a longstanding problem and has raised extensive researches.

1 Maybe find some data/research paper to justify the statement

Bus bunching states schedule disruption or headway irregularity in operation. From the perspective of passengers, a more intuitive description of bus bunching is an incidental phenomenon when two or more buses serve a stop with headways significantly shorter than designed. The bus bunching problem is prevalent in real life due to reasons of two aspects.

1. The bus system suffers inevitable endogenous uncertainties and exogenous random disturbances.
2. The natural characteristic of bus operation, a delayed bus picks more passengers while its following bus picks less, also enlarges the variability of bus headway.

Under a conventional operation without countermeasures, a bus tends to pair with its preceding or following bus and can hardly recover to designed schedule or expected headway especially when passenger demand and service frequency are both high.

Bus bunching degrades the reliability and effectiveness of transit service and concerns both passengers and transit agencies (Newell and Potts, 1964; Osuna and Newell, 1972; Hollander and Liu, 2008; Verbich et al. 2016). From the perspective of passengers, the average waiting time at stops are increased and more passengers are likely to encounter overcrowded experiences onboard. From the perspective of transit agencies, the underutilization of the pairing buses raises the operation cost to maintain the supply level, i.e. transit agencies have to provide more services or bear the risk of losing split rate.

The occurrence of bus bunching is mainly originated from the uncertainties of bus travel times on roads and bus dwell times at stops. On the one hand, bus travel times on roads are affected by some random issues such as urban traffic conditions, driver behaviors, etc. On the other hand, fluctuate passenger demands also induce the uncertainties of bus dwell times at stops (Liu and Sinha, 2007; Sorratini et al., 2008; Fonzone et al., 2015). Therefore, the resolve of bus bunching problem requires understanding and modeling both bus movements and passenger behaviors within bus operation. Although[2] several bus bunching models/bus dynamic formulations/bus trajectory algorithms were proposed in literature to capture the propagation of bus bunching, most of the existing studies focused on oversimplified scenarios in which some critical issues like passenger transfer behavior and capacity constraint were not well addressed.

In the light of the seminal work about bus bunching of Newell and Potts (1964), extensive researches have been conducted. In this section, we review the related literature in three directions. Fisrt, we review the methodologies of control schemes to mitigate bus bunching. Second, we present several studies that investigated bus bunching in multi-line scenarios. Third, we refer literature modeling passengers behavior.

Earlier literature focus on developing static control schemes in plan level such as adding slacks to schedules. Since the technique of intelligent transport and control system has been developing rapidly, various dynamic bus control schemes have been proposed. Among these, holding strategy is the most practical strategy in application as its efficiency have been testified in literature. Besides holding strategy, various strategies were proposed and investigated in specific conditions. For example, as the holding strategy deal the miny bus bunching well while fail to work in huge bunching, stop-skipping strategy and substitution strategy are investigated to cope with severe bunching. Coordinated speed adjustment are based on bus dedicated lane premise. The control strategies can be generally categorized into two groups:

1. Station strategies such as holding strategy, stop-skipping strategy and boarding limit strategy.

2. Inter-station control strategies such as coordinated speed adjustment and traffic signal priority.

Most of the existing studies investigated bus bunching in a single line scenario for facilitate of formulation and analyses, while urban corridors served by multiple bus lines is prevalent in real-life. The common line issue, as a special characteristic of urban public transportation networks, induces complex passenger routing behavior and capacity constraint limits bus dwell times at stops. A few researches noticed the effects of common line issue on bus operation and passenger behaviors. But either the passengers' transfer behavior or/and the bus capacity constraint was/were overlooked in their work. For example, Hernández et al. (2015) developed an optimization model for holding strategy on multiline system. They considered capacity constraint but ignored transfer behavior. Schmöcker et al. (2016) investigated the effects of common stops on bus bunching with and without overtaking issue. Their results show that the presence of common stops has positive effects when overtaking is possible. They focused on the equilibrium queuing behavior but ignored the passenger transfer behavior and the capacity constraint. Petit et al. (2019) developed an optimization model to implement substitution strategy in a multiline system, but assumed that different bus lines were independent of each other for the sake of simplicity.

To best of our knowledge, there is no existing analytical model or research considers transfer behavior and capacity constraint simultaneously. These two elements both have profound impacts on the formation and propagation of the bus bunching phenomenon.

What' more, most of the existing studies on bus bunching and control strategies ignored passenger equilibrium behavior under the control strategies, except these two papers, they formulated distributed passenger boarding behavior when bus overtaking are allowed. In fact, passenger behaviors are likely to have an impact on the propagation of bus bunching and the performance of control strategies.

Some methodologies and concepts such as fail-to-board probability (considering bus capacity constraint) and MSA algorithm are diverted from the technics of modeling passenger routing behavior in transit assignment studies. Schmöcker et al. (2008), Long et al. (2013), Szeto et al. (2014), Jiang et al. (2016) In our study, we focus on the transfer behavior and formulate a transfer-based equilibrium to simulate the routing result of transfer passengers.

It is necessary and crucial to consider multiple public transport lines with a more realistic model. Therefore, this study is motivated to fill the research gap by establishing a more realistic bus bunching model considering these two elements simultaneously.

In this study, we investigate bus bunching problem by modelling bus movements in a more realistic scenario considering common line issue, passenger transfer behavior and capacity constraint. The main contributions of this study are summarized in these aspects.

1. We propose a new bus bunching model considering passenger transfer behavior and capacity constraint simultaneously in a multi-line network. The impacts of transfer behavior and capacity constraint are illustrated by the proposed model.
2. We propose transfer-based equilibrium formulations to simulate the routing results of transfer passengers. The necessity of modeling transfer passenger's routing behavior is examined and inspires further discussions of control schemes considering passenger reaction.
3. We develop algorithms for bus trajectories and transfer routing results with a combination of event-based simulation and MSA iteration.
4. We propose a simulation-based evaluation indicator to evaluate the range of bus bunching. In multi-line scenarios, the indicator makes sense.

1We could add a short summary on the contribution of this summary on the contribution of this study before this paragraph

The[1] remaining of the paper is organized as follows: Section 2 describes the problem we focused on and illustrates basic assumptions and notations. Section 3 proposes the formulation of bus dwell time which takes in to account passenger behaviors and capacity constraint. Then, we develop the algorithm for bus trajectories in an event-based simulation framework. Section 4 proposes the formulations of transfer-based equilibrium and transfer cost function. Furthermore, MSA iteration algorithm and a special realization of the transfer-based equilibrium are illustrated. Section 5 illustrates the specifications by a small example and show the properties of this model by demonstrating the effects of transfer behavior and capacity constraint. Section 6 conducts experiments to analyse the sensitivity of the bus bunching problem to different transfer parameters and capacity settings. Finally, Section 7 gives the conclusions and points out future directions.

2 Problem description

We consider a transit network in which two types of passengers who have routing behaviors are embodied intuitively.

Type I) Passengers whose original and destination stops belong to different lines. For these passengers, they board before and alight after the common corridor and need to choose their interchange stops from the common stops.

Type II) Passengers whose origin and destination stops are all in the common corridor and could choose either one between two lines to their destinations.

2.1 Basic assumptions

The established formulations are developed on these basic assumptions.

A1) Passengers avoid transfers unless necessary.

A2) A stop has only one platform for passengers to board and alight. And buses follow the first-arrive-first-depart (FAFD) rule as a result.

A3) Travel times on the same section of the common corridor are equal for buses of two lines.

A4) Buses service frequency and passenger arrival rates are constant.

A5) The time required for boarding/alighting is estimated to be proportional of the number of boarding/alighting passengers.

A6) Passengers' origin and destination stops are given.

2.2 Notations

Indices and sets
Parameters
Variables

3 Modeling bus propagation in multi-line system

The main idea of our model is to give a more actual calculation of bus dwell times at common stops by considering passenger routing behaviors and bus capacity constraint.

3.1 Passenger boarding demand

First, we identify the boarding demands of passengers at common stops.

The arrival passengers at a common stop served by multi bus lines could be grouped according to their candidate lines.

The boarding demand of a specific bus contains all passengers whose candidate sets include this bus line.

Due to the capacity constraint, each type of passenger demand is composed of new arriving passengers and leftover passengers who already arrived before the preceding bus departing.

3.2 Numbers of boarding passengers under capacity constraint

The actual number of boarding passengers is constrained by the bus available capacity. Therefore, the formulations of numbers of alighting and onboard passengers are necessary.

Alighting passengers at a common stop includes passengers whose destination is the arriving stop and passengers who choose the arriving stop as an interchange stop.

The proportion of the latter among all transfer passengers could be identified by a so-called transfer-based equilibrium introduced bellows.

3.3 Numbers of leftover and onboard passengers

Formulations above indicate that onboard passengers on the arriving bus and leftover passengers at the stop are necessary to be identified.

There are two points need to acknowledge in the calculations:

1) All passengers involved in a boarding process have equal probabilities to board the bus successfully.

2) Leftover passengers at a common stop include passengers who don't want to board the last bus.

3.4 Bus dwell time constrained by bus capacity and passenger alighting time

Inspired by existing work about single-line bus bunching model considering bus capacity constraint, we derive bus dwell time by formulating the queue clearance time of passenger boarding demand and constrain it by available capacity on bus and passenger alighting time.

3.5 Algorithm for bus trajectories

Before conducting the calculations for bus dwell time and bus trajectories, some initialization is needed to start the algorithm.

1) Initialize the bus arrival times at the first stop of each line

2) Initialize dwell times of the first bus of each line at all stops served by it

4 Modeling transfer passenger routing

4.1 Transfer-based equilibrium

Like approach-based equilibrium formulations, we formulate a transfer-based equilibrium among transfer passengers on each bus to model their transfer behavior.

4.2 Transfer cost function

To implement the assignment of transfer passengers, explicit transfer cost function is necessary.

Due to the capacity constraint, part of transfer passengers may fail to board the following bus. Therefore, the expected transfer cost function at each stop involves probabilities that transfer passengers successfully board the arrival buses.

4.3 MSA

An MSA iteration is conducted based on the transfer cost function proposed in 4.1 to simulate the routing of transfer passengers.

5 A small network to illustrate the model

In this section, we use a small two-line transit network as an example to show the properties of the proposed model by demonstrating the effects of transfer behavior and capacity constraint on bus bunching.

5.1 System specifications

The example consists 10 stops divided into 5 stop sets. Input parameters include:

1) Constant bus departure intervals: $H^1 = H^2 = 6$ (min)
2) The departure time of the first bus of each line: $t^1 = 0$, $t^2 = 3$ (min)
3) Constant passenger arrival rates: $\Lambda_n = 5$ (pas/min) for $n \in \mathcal{S}^1 \cup \mathcal{S}^2 \setminus \{8, 10\}$
4) Evenly distribution of passenger demands: $\lambda_{n,j} = \frac{\Lambda_n}{|\mathcal{S}^D(n)|}$ for all $j \in \mathcal{S}^D(n); n \in \mathcal{S}^1 \cup \mathcal{S}^2 \setminus \left\{ n^1_{|\mathcal{S}^1|}, n^2_{|\mathcal{S}^2|} \right\}$
5) Constant travel times between successive stops: $T_{m,n} = 3$ (min) , $m \in \mathcal{M}^1 \cup \mathcal{M}^2, n \in \mathcal{S}^1 \cup \mathcal{S}^2 \setminus \{8, 10\}$

5.2 Effect of transfer behaviors

With the parameters above, we conduct algorithms introduced in 3.5 for bus trajectories.

It is observed from bus trajectories that buses run steadily and transfer passengers' routing result degenerates to equal assignment.

We compare the deviations of bus trajectories caused by the disturbance in two cases:

1) Transfer passengers routing based on their expected bus trajectories (undisturbed bus trajectories).
2) Transfer passengers routing based on real-time information about bus operation (disturbed bus trajectories).

The comparison demonstrates that transfer passengers' routing behavior based on real-time bus operation information makes more buses affected by the disturbance.

What's more, we conduct numerical experiments to reveal that the presence of transfer passenger flow enhances the propagation of bus bunching problem between bus lines.

5.3 Effect of capacity constraint

We devise a comparison between two capacity settings (i.e. 150 pas and 80 pas).

The bus capacity is the upper bound of the number of onboard passengers and limits the bus dwell time at stops when a bus encounters a large boarding demand caused by bus bunching.

6 Evaluation and sensitivity analysis

In this section, a set of evaluation indices are introduced to quantify the performance of bus operation affected by bus bunching.

6.1 Range of evaluation

As we trigger bus bunching by a small disturbance, we focus on evaluating the operation of affected buses instead of the overall system.

The numbers of affected buses at stops reveal the temporal and spatial distribution of the effect of bus bunching to some extent.

6.2 Evaluation measurements

We adopt two evaluation indexes: the average waiting time at stops and the standard deviation of bus time headway.

6.3 Sensitivity analysis

6.3.1 Sensitivity to transfer parameter

The sensitivity to transfer parameter considers the numerical experiments with the transfer parameter from 0, 0.2, up to 2 while other parameters follow the basic settings.

The results show that the propagation of bus bunching between two lines is more obvious as the proportion of transfer passengers increases.

6.3.2 Sensitivity to bus capacity

In this analysis, the bus capacity is set from 120, 140 up to 200 (pas) while other parameters follow the basic settings.

The results demonstrate that capacity constraint works when bus bunching occurs, and the impacts of bus bunching tend to be worse as the capacity setting increases.

7 Conclusions and further work

Conclusions:

1. The evolution of bus bunching is distinct when transfer passenger flow and capacity constraint are considered.
2. When bus bunching occurs, transfer passengers' routing behavior based on real-time bus operation information makes bus bunching maintain longer time.
3. The presence of transfer passenger flow enhances the propagation of bus bunching phenomenon.
4. An appropriate reduction in the bus capacity can alleviate the effect of bus bunching problems.

Further work:

1. Examine the effect of different combinations of bus service frequencies and offsets;
2. Generalize the modeling framework for a transit corridor served by more than two transit lines;
3. Relax the assumptions of the proposed model. For example, allowing more than one platform for different bus lines to board and alight passengers at some larger transfer stops;
4. Develop efficient real-time control strategies incorporating ATIS service based on the proposed model to mitigate the bus bunching problem.