A Combined Bus Splitting And Holding Strategy to Prevent Bus Bunching Using Autonomous Modular Buses

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SHORT SUMMARY

Autonomous modular buses (AMBs) with en-route coupling and decoupling capability can be more effective in preventing bus bunching than strategies available with traditional buses, such as bus-holding and stop-skipping, which suffer from shortcomings. Our previous work introduced *bus-splitting*, a novel alternative to stop-skipping that directs a modular bus to decouple into individual units when it experiences a longer than normal headway. Despite outperforming stop-skipping, bus-splitting alone cannot eliminate bunching completely since it cannot increase short headways. In this work, we propose combining bus-splitting with bus-holding so that headways that are either shorter or longer than required can both be corrected. We use a macroscopic simulation to compare our combined strategy with the original bus-splitting strategy as well as stop-skipping (both standalone and combined with bus-holding). We find that the combined strategy outperforms all the others by reducing passengers' average travel cost and its variation, especially for busy bus lines.

Keywords: Autonomous modular buses; Bus bunching; Bus holding; Bus splitting; Stop skipping

1. INTRODUCTION

The stochastic nature of public transport systems leads to headway variability and bus bunching, causing both the average and the variability of passengers' travel cost to increase significantly. Most scientific literature on bus bunching focuses on strategies that temporarily hold buses at a subset of bus stops along a bus line to increase headways that have become too short (Daganzo & Pilachowski, 2011; Delgado et al., 2012; Berrebi et al., 2018). However, these *bus-holding* strategies when implemented alone cannot speed up late buses. Another category of strategies is *stop-skipping*, in which buses skip some stops to decrease headways that are too long (Liu et al., 2013; Niu, 2011; Sun & Hickman, 2005). These strategies are effective to some extent, but they impose additional waiting and walking time on passengers whose stop is skipped, making them unpopular in practice (Menendez, 2021).

In our recent work (Khan et al., 2022), we propose *bus-splitting*, an alternative to stop-skipping that is the first to use *Autonomous modular buses* (AMBs) to mitigate bus bunching. An AMB consists of modular units that can combine and split as required, with each unit or combination of units capable of operating independently (Figure 1). In particular, our bus-splitting strategy uses AMBs that can perform *in-motion transfer*, which allows the modular units to couple and decouple while moving on roads, so that passengers can transfer from one unit to another while traveling (NextFutureTransportationInc., 2018). Like stop-skipping, our bus-splitting strategy can speed up late buses, but unlike the former, it does so without skipping any stops completely. Therefore, it avoids the additional cost that stop-skipping imposes on passengers whose stop is skipped, reducing the passenger travel cost by a far greater amount.

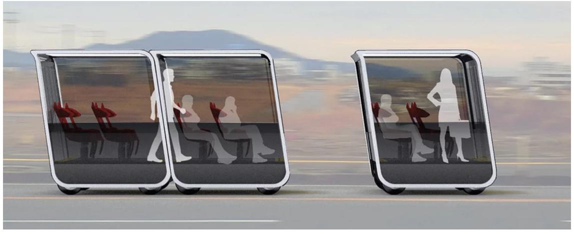


Figure 1: AMB concept as presented by (NextFutureTransportationInc., 2018).

However, bus-splitting cannot eliminate bus bunching completely because, like stop-skipping, it cannot increase short headways. Strategies that combine stop-skipping with bus-holding (which increases short headways) have proven more effective than adopting either strategy alone (Eberlein, 1996; Sáez et al., 2012). However, these hybrid strategies still impose additional cost on passengers whose stop is skipped. Based on this insight, we propose replacing stop-skipping with bus-splitting in this combination. This could correct both short and long headways while avoiding the additional cost imposed by stop-skipping. Here, we develop the dynamics of this combined strategy and compare it with three other strategies: standalone bus-splitting, standalone stop-skipping, and stop-skipping combined with bus-holding.

2. METHODOLOGY

Conceptual Illustration of Bus-Splitting

Since bus-splitting is a novel concept, we provide an example in Figure 2. When the headway grows larger than a given *control threshold* times the target headway, the bus decouples (i.e. splits) into two modular units en-route to the subsequent stop (called the *control stop*). The first modular unit (i.e. *leading unit*) skips the control stop, while the other (i.e. *trailing unit*) stops to serve passengers. The leading unit then serves passengers at the next stop immediately downstream (called the *recoupling stop*), and waits for the trailing unit to arrive so that the units can recouple before proceeding. This requires some re-distribution of passengers among the units before decoupling, which occurs en-route to the control stop.

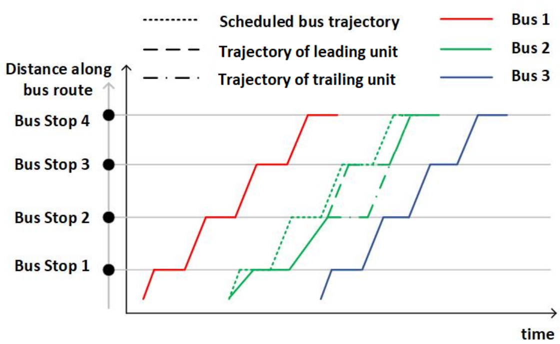


Figure 2: Illustrative time-space trajectory diagram of bus-splitting.

Model Summary

We describe the dynamics of stop-skipping and bus-splitting in (Khan et al., 2022) using a discrete macroscopic model which deals with passenger arrivals, boardings, alightings, and departures in a non-continuous aggregate manner. A summary is presented below, along with the modifications required to integrate bus-holding.

We consider a bus line serving a cyclical route with S stops. Passengers arrive at each stop $s \in \{1, S\}$ following a Poisson process with fixed rate λ_s. The total demand is thus $M = S\bar{\lambda}$ where $\bar{\lambda}$ is the average arrival rate. When a bus arrives at stop s, each passenger on board alights with probability p_s. The fleet comprises N buses with capacity K each, and the target headway is H. The distance between s and the next stop is D_s. The cruising speed of buses is V_{bus}, so that the expected cruising time between stop s and the next stop is $C_s = {}^{D_s}\!/\!_{V_{bus}}$. The actual cruising time is stochastic and includes an independent error term. We assume boarding and alighting are sequential, and take β and α time per passenger respectively. The fixed extra time lost at each stop (due to acceleration, deceleration, door operation, etc.) is E. The buses make multiple cycles around the route in fixed order without overtaking.

Both the stop-skipping and bus-splitting policies are non-predictive, distributed, and myopic. The stop-skipping policy simply dictates that whenever a bus departing a stop experiences a headway greater than a certain control threshold γ times the target headway, it skips the next (i.e. control stop). There are two restrictions: (i) a bus cannot skip two consecutive stops (to prevent passengers from facing excessive walking time[1]), and (ii) a stop cannot be skipped by two consecutive buses (to prevent excessive waiting time for passengers at that stop).

For the bus-splitting policy, each modular bus consists of two identical modular units coupled together. Our bus-splitting policy dictates that whenever a bus experiences a departing headway greater than γH, its modular units decouple en-route to the next (control) stop. The leading unit skips the control stop and serves the subsequent (recoupling) stop. The trailing unit serves the control stop and recouples with the leading unit at the recoupling stop. This ensures that no passengers are forced to miss their desired alighting stop, so no extra walking time is incurred. When the decision to split is made, passengers are re-distributed among the two units based on their desired alighting stop. This exchange, as well as the decoupling, happens while the bus is traversing the segment upstream of the control stop. The load is split equally among the two units before decoupling. Since no stop is skipped completely, a stop may become a control stop for consecutive buses. However, the other restriction that two consecutive stops cannot both be control stops applies here as well because a decoupled modular unit cannot be split further. Once the units have recoupled, they may decouple again immediately afterward.

For the standalone stop-skipping and bus-splitting policies described above, the buses cycle continuously, immediately restarting at stop 1 after serving stop S, and all stops are operationally identical (i.e. each stop can be a control stop). Furthermore, we assume that each bus stop has only one docking bay, so a bus does not dock at a stop before the previous bus has departed.

For the policies combined with bus-holding, we assume that stop 1 is the *depot* where any number of buses can be held simultaneously and all buses must stop (i.e. the depot cannot be a control stop for either stop-skipping or bus-splitting). The bus-holding policy simply dictates that departing headways at the depot cannot be shorter than H, i.e. buses with shorter headways are held until time H after the previous bus's departure. The order between the buses is maintained, so buses are dispatched from the depot in a first-in-first-out manner. Passengers who do not intend to alight at the depot remain on board during the holding period.

Experimental Setting

Our methodology places no assumptions on the variability of the segment lengths D_s, arrival rates λ_s, and alighting probabilities p_s across stops. For our experiments, however, we focus our attention on a quasi-homogeneous bus route in which all stops have approximately equal importance

[1] We assume that passengers whose stop is skipped alight at the next stop and walk back to their desired stop with speed V_{walk} before exiting.

with respect to these three quantities. For each stop s, D_s, λ_s and p_s are drawn from normal distributions with means $\overline{D}$, $\overline{\lambda}$, and $\overline{p}$ respectively, and standard deviations equal to 10% of the respective mean. This allows us to model a relatively symmetric system with some degree of heterogeneity between stops.

We select our initial conditions to start the experiments with the system in (unstable) equilibrium. The load on each bus when starting its first cycle is equal to the expected average load L. The buses are initially dispatched with headways equal to the target headway H. The expected cycle time of a bus is τ. The minimum fleet size required to satisfy the average demand is N_{min}. To account for the non-uniformity of the demand, we set the fleet size to be $N = \lceil \eta N_{min} \rceil$, where $\eta > 1$ is the fleet size multiplier. The parameter values used in our experiments are shown in Table 1. The sources of the independent parameter values and the expressions of the above-mentioned dependent variables are available in (Khan et al., 2022).

Table 1: Independent Parameter Values

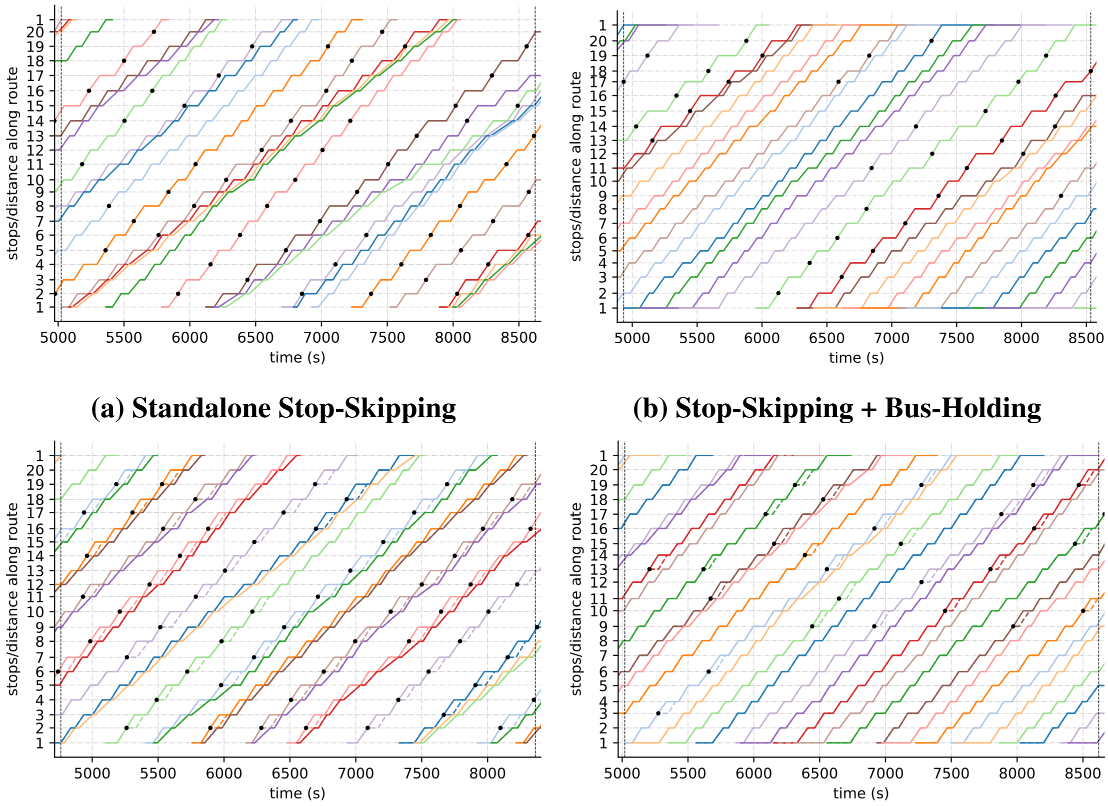
Input Parameter	Notation	Units	Value
Number of stops	S	-	20
Average stop spacing	$\overline{D}$	m	400
Bus capacity	K	pax	80
Unit capacity	$K/2$	pax	40
Bus cruising speed	V_{bus}	km/h	20
Walking speed	V_{walk}	km/h	4.5
Fixed time lost per stop	E	s	20
Boarding time per passenger	β	s/pax	4
Alighting time per passenger	α	s/pax	3
Waiting time weight factor	w_{wait}	-	2.1
Walking time weight factor	w_{walk}	-	2.2
Fleet size factor	η	-	1.5
Control threshold	γ	-	1.5

We evaluate the policies with respect to the average travel cost Q per passenger, which is a weighted sum of the waiting time T_{wait}, in-vehicle time T_{veh}, and walking time T_{walk}. The weight of each component is the value of a unit of that component as a multiple of the value of a unit of in-vehicle time. We simulate our system in Python using a discrete event simulation in which updates are processed each time a bus arrives at a stop. We use the first two cycles of the fleet as a warm-up period, and the *evaluation period* lasts for the next hour. All our results are based on the evaluation period only.

3. RESULTS AND DISCUSSION

Sample Comparison

Figure 3 presents time-space plots showing the bus trajectories during the evaluation period for a representative instance under each of the four policies. Under standalone stop-skipping (Figure 3(a)), the system deteriorates significantly, with large bunches and significant headway variability. Under skipping-plus-holding (Figure 3(b)), long headways are limited, and there are also fewer large gaps. Standalone bus-splitting (Figure 3(c)) results in smaller bunches than standalone stop-skipping; these bunches maintain relatively even headways from each other, giving the system some stability. Splitting-plus-holding (Figure 3(d)) is the most successful at limiting long headways and minimizing headway variability. The standalone policies are forced to trigger their respective control actions much more frequently than their counterparts which incorporate bus-holding, indicating that bus-holding reduces the number of headways that grow long.



(a) Standalone Stop-Skipping **(b) Stop-Skipping + Bus-Holding**

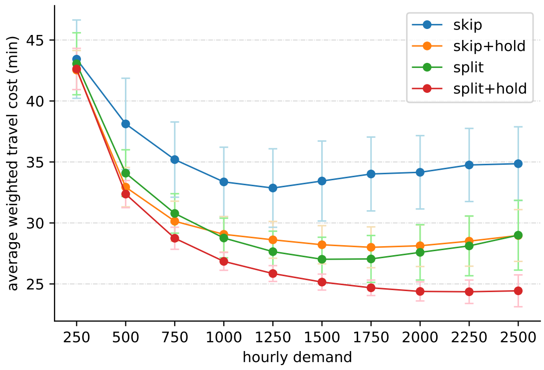
(c) Standalone Bus-Splitting **(d) Bus-Splitting + Bus-Holding**

Figure 3: Bus trajectories during the evaluation period from a representative instance under each policy. Each color represents a particular bus making multiple cycles. The black dots represent stops where the control action is triggered. The dashed lines in (c) and (d) represent the trailing units. Stop 1 is the depot in (b) and (d). Parameter values are taken from Table 1. The hourly demand is $M = 1500$, the fleet size is $N = 12$ and the target headway is $H = 203$s.

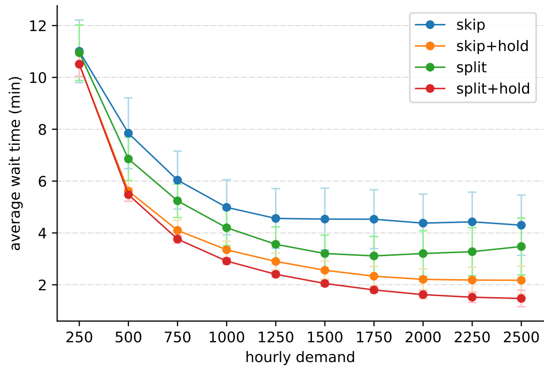
Policy Robustness

We now evaluate the effectiveness of the policies under a wide range of demand settings. The fleet size N and target headway H are adjusted as the demand M increases, to maintain a constant expected cycle time τ and expected average load L. We perform 500 iterations with each set of parameter values and present the average results and standard deviations. The key takeaways of the results shown below are not affected by changes in other parameter values, including the number of stops S, the control threshold γ, the fleet size factor η, and the starting time and duration of the evaluation period.

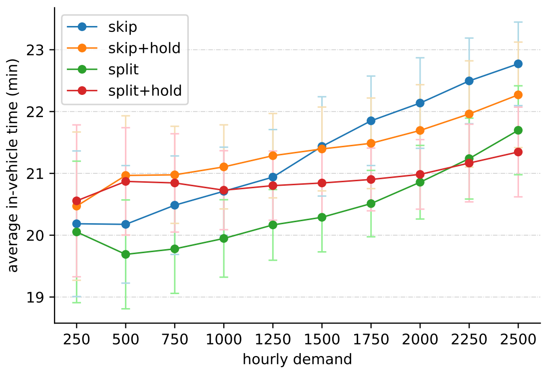
Figure 4 shows how the average weighted travel cost Q and each of its travel time components vary with the demand M. Figure 4(a) shows that standalone stop-skipping results in the highest cost, skipping-plus-holding and standalone bus-splitting have similar costs, and splitting-plus-holding consistently has the lowest cost. Splitting-plus-holding maintains a non-increasing trend in Q as the demand increases, whereas Q starts increasing for higher demand levels with all the other policies. This indicates that splitting-plus-holding is the most successful at averting bus bunching for busier bus lines. Furthermore, splitting-plus-holding also results in a significantly lower variation in Q, indicating a more reliable travel experience, which holds great importance for passengers' mode choice decisions and utility.



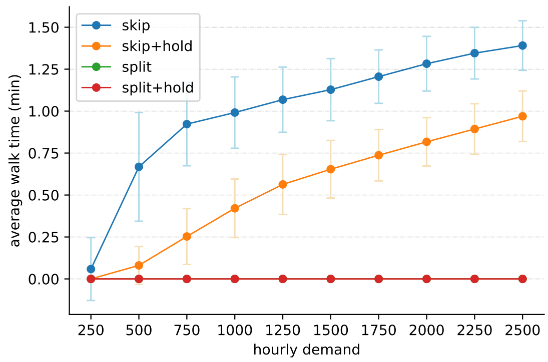
(a) Average Weighted Travel Cost Q



(b) Average Waiting Time T_{wait}



(c) Average In-vehicle Time T_{veh}



(d) Average Walking Time T_{walk}

Figure 4: Average weighted travel cost (a) and each of its components (b)-(d) under a range of values of the demand M.

Figure 4(b) shows that in terms of the average waiting time T_{wait}, the policies with bus-holding and bus-splitting outperform their standalone and stop-skipping counterparts respectively, so that splitting-plus-holding performs best. As the fleet size increases with the demand, resulting in more frequent buses (i.e. smaller target headway H), T_{wait} decreases, particularly in the low demand range. Once the demand is in the higher range, T_{wait} becomes stable since further reductions in H are smaller, and are offset by the effect of increasing bus bunching.

In contrast, Figure 4(c) shows that the average in-vehicle time T_{veh} increases with the demand. This is purely due to the effects of bus bunching, since the demand has no effect on the average distance traveled. This increase is steeper for the standalone policies, which indicates that bus-holding is a major factor in limiting bus bunching. The bus-splitting policies maintain a lower T_{veh} than their stop-skipping counterparts, partially because the latter impose additional in-vehicle time on those passengers whose intended alighting stop is skipped.

Figure 4(d) confirms that the bus-splitting policies do not impose any walking time T_{walk}, whereas T_{walk} increases with the demand under the stop-skipping policies.

4. CONCLUSIONS

This paper proposes a new method to mitigate bus bunching by using AMBs. We develop a hybrid control strategy that combines the recently developed AMB-dependent "bus-splitting" strategy with the conventional bus-holding strategy. Bus-splitting directs a modular bus facing an undesirably long headway to decouple into two individual autonomous units, each of which serves one stop while skipping the other. This allocates resources in parallel, decreasing the service time required and thus shortening the headway. Conversely, bus-holding elongates undesirably short headways by temporarily holding the bus back when it reaches the depot. The combined strategy is therefore able to correct both types of headway deviations, unlike either of its constituent strategies. We compare our proposed strategy with three benchmarks: the original (standalone) bus-splitting strategy, its non-AMB counterpart stop-skipping, and a combination of stop-skipping and bus-holding. We find that our proposed strategy achieves a significantly lower average passenger travel cost than any of the benchmarks across the entire range of demand settings tested, and more-so for busy bus lines with high demand. Furthermore, it also significantly decreases the variation in the average travel cost, thus providing the most reliable travel experience for passengers.

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