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Imran, Aishah Mahyarni; Van Oort, Niels; Cats, Oded; Hoogendoorn, Serge; Van Der Pot, Pieter

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Combining Speed Adjustment and Holding Control for Regularity-based Transit Operations

Aishah Mahyarni Imran, Niels van Oort, Oded Cats, Serge Hoogendoorn
Transport and Planning
Delft University of Technology
Delft, the Netherlands
aishahmahyarni@gmail.com,
{n.vanoort, o.cats, s.p.hoogendoorn}@tudelft.nl

Pieter van der Pot
Tender team, Research Department
Keolis Nederland
Deventer, the Netherlands
pieter.vanderpot@keolis.nl

Abstract— **Vehicle bunching often occurs in high-frequency transit systems leading to deterioration of service reliability. It is thus necessary to control vehicles during operations. Holding control is a common solution for this situation, but it may result in longer vehicle running times. Speed adjustments can contribute to more regular operations while preventing prolonged trip times. This paper proposes a control strategy, which combines these two strategies to maintain the regularity of transit operations. The findings based on simulation study for trunk bus services in the Netherlands suggest that combining the two strategies implies both the positive and negative attributes of each control.**

Keywords—control strategy, speed adjustment, holding control, bunching

I. INTRODUCTION

Vehicle bunching is a common problem in a high-frequency transit system. This phenomenon deteriorates the service reliability of transit system operations and affects both the passengers and the operators [1]. Findings demonstrated that during the operations of transit system, there is a 10% of inevitable bunching occurrence caused by random variation, hence, the need to deploy control strategy to prevent this problem is undeniable [2].

The vast majority of research devoted to resolving the bunching problem is concerned with holding control [3]. However, it might prolong the total vehicle trip time and holds passengers onboard [4]. Consequently, some argue that implementing a speed adjustment obtains better effects [5, 6, 7]. Not only does speed adjustment provide regularity, it also prevents prolonging trip times by allowing speeding up. Speed adjustment by slowing down can also be considered as holding en-route, which arguably induces fewer inconveniences compared to holding at the stop [5, 6, 7]. Still, it has a drawback, as it is less stable under conditions with more variability [8].

While each control strategy has its pros and cons, past research shows that the combination of different control strategies has potential benefits. By considering the reduction in the commercial speed value due to holding, [9, 10, 11] developed strategies based on control theory, which force a maximum possible commercial speed and successfully improve the headway variance. Different approach shown in [12] using a simulation-based optimization method, adding speed adjustment as a complementary control for holding. It is capable to minimize the headway variance as well as the total passenger travel time. Teng and Jin [13], on the other hand, set speed adjustment as a main and continuous measure to ensure regularity. By considering that this strategy lacks of stability, thus, signal and holding control are implemented at the intersections and stops when necessary. Wu et al. [14] took the same approach of combining speed adjustment, holding control and signal priority control, however, with different objectives to improve bus punctuality as well as traffic condition at the intersection. In addition to the type of the strategies, this study emphasized the benefits of real-time information exchange to the overall performance of the control strategy. Communication has been proven effective in determining better performance of the control strategies [15, 16, 17].

Based on the findings from previous studies, this paper proposes integrating speed adjustment and holding control by aiming at reducing the waiting time induced onboard. We consider thus speed adjustment to be the main control strategy and holding as the supporting strategy, with communication between buses. Little is known about the impacts of this combination. The objective of this paper is to assess the impacts of the combined control strategy for regularity-based operations.

II. CONTROL STRATEGY METHODOLOGY

This paper presents the proposed control strategy as a rule-based strategy, departing from the following assumptions:

1) Real-time communication between the vehicles is available at all times
2) The service runs on a dedicated lane
3) The effects of acceleration and deceleration can be neglected
4) Arrival time predictions are based on the scheduled trip time between stops [18]

In the proposed concept of the integrated speed adjustment-holding strategy, there are two control decision triggers: upon entering a road segment (link) and upon entering a stop (node). The stop associated with the controlled vehicle is the nearest stop to approach, while the link associated is the upstream link of the approached stop.

In the case where slowing down an early vehicle is required, and speed adjustment has reached its minimum speed boundary, holding control acts as an additional control strategy at the control point stop. Conversely, a late vehicle may speed up as long as the maximum speed

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boundary is not exceeded. Figure 1 below depicts the general framework of the proposed control logic.

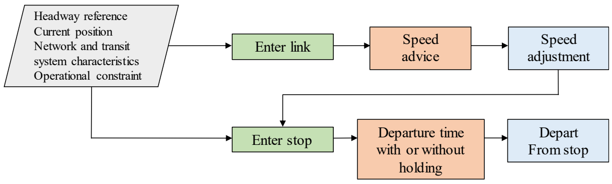

Fig. 1. General concept of the control strategy.

Both strategies in this combination aim at evening out headways, considering the headway between the observed vehicle and its preceding and following vehicle. Therefore, the strategy requires communication between three consecutive vehicles at each vehicle observation. In this framework, vehicle communication works in an event-based manner, which allows information exchange every time the vehicle finishes an event (e.g. dwelling, holding, departing and arriving).

A. Notations

In the formulation, there are sets of input defined for the system, as follows.

- J : a set of lines
- K : a set of vehicles controlled
- L : a set of upstream links
- S : a set of stops
- ε : additional time (delay in headway calculation, the reaction time of driver, acceleration and deceleration effect)
- v^{max} : maximum speed allowed in the system
- v^{min} : minimum speed allowed in the system
- $x_{j,s}$: location of line j stop s, measured from the first stop j ($x_{j,1} = 0$)
- $d_{j,k,s}$: departure time of line j vehicle k from stop s
- $w_{j,k,s}$: dwelling time of line j vehicle k at stop s
- $a_{j,k,s}$: estimated arrival time of line j vehicle k at stop s
- $a^p_{j,k,s}$: predicted arrival time of line j vehicle k at stop s
- $a^a_{j,k,s}$: actual arrival time of line j vehicle k at stop s
- $t^p_{j,l}$: scheduled trip time at line j link l
- $t^s_{j,k,l}$: suggested trip time of line j vehicle k on the upstream link l
- $t_{j,k,l}$: allowable trip time of line j vehicle k on the upstream link l
- $h^e_{j,k}$: even headway between vehicle k and its preceding and following
- $h^f_{j,k,k-1}$: even headway between vehicle k and its preceding vehicle k -1
- TPS : time point stop/control points for holding control, ($TPS \subseteq S$)
- h : suggested holding time
- h^{max} : maximum holding time
- h^{min} : minimum holding time to consider at TPS

B. System description: Control at link

Enter link. Prior to the control procedure, the system receives input, which can be distinguished into two: (i) the static input, such as the headway reference, transit system characteristics and the operational constraints; (ii) the dynamic input such as vehicle position, which keeps changing during the operations. Vehicle position lets the system know which control to apply for the corresponding vehicle. When a vehicle is about to enter a link, the system triggers a speed advice.

Speed advice. There are several processes to derive a speed advice for the vehicle during the operations, as explained below.

1) Arrival time prediction: In this step, the positions of the vehicle *k–1, k,* and *k+1*; the preceding, controlled and following vehicle respectively, in line j are translated into the arrival time at stop s. For the controlled vehicle k, it is notated by $a_{j,k,s}$. For the controlled vehicle k and its following $k+1$, this value is predicted as $a^p_{j,k,s}$ and $a^p_{j,k+1,s}$. Meanwhile for the preceding vehicle $k–1$, it is taken from the actual value noted as $a^a_{j,k–1,s}$. When it is predicted, the prediction is derived from the scheduled trip time between stops given in the timetable, $t^p_{j,l}$ and the actual arrival times of the vehicle at the previous stop, $a^a_{j,k,s–1}$. The formulation of the arrival time prediction itself is given in Equation (1) for vehicle k as follows:

$$a_{j,k,s} = a^p_{j,k,s} = a^a_{j,k,s-1} + t^p_{j,l} \tag{1}$$

2) Headway checking: The arrival time prediction is further used to find out the desirable even headway, $h^e_{j,k}$. This value becomes the reference of the desired arrival time of the controlled vehicle, as well as the advised trajectory. To attain the even headway, $h^e_{j,k}$, one should consider the headway of the vehicle k to its preceding and following vehicles, as shown in Equation (2):

$$h^e_{j,k} = (a_{j,k-1,s} + a_{j,k+1,s})/2 \tag{2}$$

3) Speed advice: After calculating the even headway, the system will suggest a value of trip time to the controlled vehicle, $t^s_{j,k,l}$, so that it can satisfy the advised trajectory on link l. There is a parameter ε to capture the additional time that may occur. Operational traffic constraints are also introduced here, as the minimum speed, v^{min}, and maximum speed, v^{max}, which define $t_{j,k,l}$, the allowable trip time to ride on link l. Equation (3) describes the formulation for $t_{j,k,l}$:

$$t_{j,k,l} = \frac{x_{j,s} - x_{j,s-1}}{max\left[min\left(\frac{x_{j,s} - x_{j,s-1}}{t^s_{j,k,l}}\right), v^{max}, v^{min}\right]} \tag{3}$$

$$t^s_{j,k,l} = a_{j,k-1,s} + h^e_{j,k} - d_{j,k,s-1} + \varepsilon$$

In this formulation, the difference between $x_{j,s}$ and $x_{j,s–1}$ is equal to the length of link l at line j.

Speed adjustment. The execution of speed adjustment refers to the calculated speed advice. In this paper, the simulation tool BusMezzo performs the speed adjustment in terms of trip time to ride between the stops. BusMezzo is an event-based simulator, which is built within a mesoscopic traffic-simulation model, Mezzo. It allows modelling the dynamics of transit operations for large-scale networks and considers the movement of each vehicle involved [19].

C. *System description: Control at stop*

Enter stop. Different control is applied when the vehicle is at the stop.

Departure time. Similar to speed advice, there are several steps to determine the departure time, as follows.

1) Arrival time prediction: After the arrival of the controlled vehicle at the observed stop, the arrival time data of the vehicles will be updated based on the actual condition and derived into headway value, once the controlled vehicle is ready to depart from the stop.

2) Headway and early departure check: Headway informs about whether the vehicle is ahead of schedule. When the forward headway of vehicle k is greater than the even headway ($h^{f}_{j,k,k-1} > h^{e}_{j,k}$), the vehicle is late and hence there is no need to apply holding. Conversely, holding control can be applied for the vehicle k if stop s belongs to the set of control points, TPS. The system gives the advice in the form of departure time $d_{j,k,s}$ as formulated in Equation (4):

$$d_{j,k,s} = min(a_{j,k-1,s} + h^{e}_{j,k},\ a_{j,k,s} - w_{j,k,s} + h^{max}), \quad \forall TPS \subseteq S \text{ and } h > h^{min} \tag{4}$$

$$h = min(a_{j,k-1,s} + h^{e}_{j,k},\ a_{j,k,s} - w_{j,k,s} + h^{max}) - (a_{j,k,s} + w_{j,k,s})$$

Where,

$a_{j,k,s}$: estimated arrival time of line j vehicle k at TPS

$w_{j,k,s}$: dwelling time of line j vehicle k at stop s

Depart from stop. The advice given from this process is the departure time. After vehicle k departs from the observed stop s, it enters the next link l and is treated again with the control process at the link, with different reference of stop s and link l.

D. *Performance indicators*

The performance of the proposed control strategy is assessed based on the coefficient of variation (CoV) of the headway and passengers' generalized travel time. CoV headway represents the regularity by indicating the headway variability during operations [20]. Meanwhile, generalized travel time captures how the passengers perceive the resulted travel time. Hence, each time component including waiting time at stop, waiting time onboard, holding time, and riding, has a different weight.

III. Application

A. *Case study description*

A case study of Keolis AllGo bus operations in Almere, the Netherlands, is considered, using AVL and smartcard data during morning peak hours, in the period of April-May 2018. AllGo is a bus rapid transit system with a scheduled headway of 5 minutes, which runs on dedicated lanes. Figure 2 below pictures the average demand condition of two analyzed lines, Line M5 and M7. An obvious difference between the occupancy pattern of the two direction can be observed, as in Direction 1, the passenger demand is high at the beginning of the route, while in Direction 2, it is the other way around.

The AllGo operations are currently controlled to achieve high punctuality, using a scheduled-based holding control. The two case study lines, M5 and M7, consist of 16 and 17 stops respectively, and have the longest routes among the AllGo network, with 9.1 and 10.8 kilometers length.

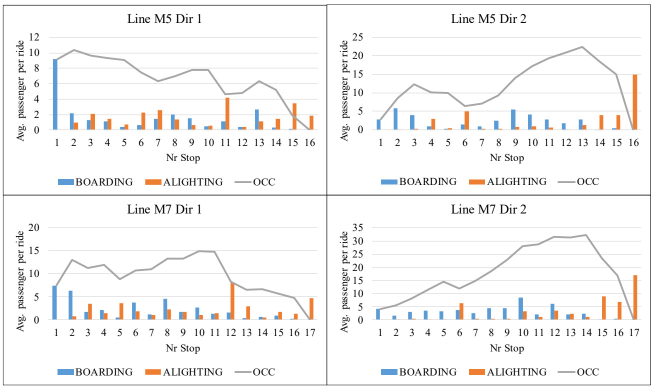

Fig. 2. Average passenger demand per ride

In order to assess the performance of the proposed control strategy, two scenarios are introduced in this paper as follows.

Scenario 1: Normal Condition, captures the normal operations of the network. Simulation settings in this scenario are derived from the situation in the morning peak hour of the AllGo network. This is the main scenario to analyze.

Scenario 2: Tight Schedule, is set to further evaluate the strategies when the timetable design becomes tighter. In normal conditions (i.e. Scenario 1), more than 50% of the scheduled trip time is designed based on the value at the 100th percentile of the actual trip time distribution. Since the design of scheduled trip time affect the efficiency of measures [21], we modified the timetable in Scenario 2, by reducing the trip time designed from using the value at 100th to 85th percentile of the trip time distribution, which is a common industry practice. This modification affects the arrival time prediction as well.

In each scenario, we tested different strategies to allow performance comparison between the proposed control strategy and the other strategies, as follows.

- SB : schedule-based holding control. The control points are selected based on the actual control points applied in AllGo network. There are one control point in Line M5 (Stop 11 for Direction 1 and Stop 6 for Direction 2) and two control points in Line M7 (Stop 6 and 12 for both directions).
- EH : even headway-based holding control, applied at the same control point as SB does, with a maximum holding time of 60 seconds.
- EHALL : even headway-based holding control, with control point at all stops and a maximum holding time of 60 seconds.
- SA : speed adjustment-only strategy.

- SH : the proposed control strategy combining holding control and speed adjustment.

In SA and SH, different speed limits are defined based on speed distribution from empirical data as described in table I below.

TABLE I. SPEED RANGE DEFINITION

Strategies	Descriptions
SA/SH1	SA/SH with a speed limit ranging between 5th-95th percentile of speed distribution
SA/SH2	SA/SH with a speed limit ranging between 25th-95th percentile of speed distribution
SA/SH3	SA/SH with a speed limit ranging between 15th-75th percentile of speed distribution

B. Simulation setting

The regularity performance obtained by the proposed strategy is compared with the results from implementing each control strategy in isolation, using a dynamic public transport operations and assignment simulation model, BusMezzo. There are several inputs defined for the simulation, including trip time distribution between stops, dwelling time function (both derived from the Dutch AVL system, see [22]), passenger demand (based on Dutch smartcard transactions, see [23]), and transit system characteristics. In addition, there are additional parameters to weight the travel time components. These parameters are defined as 2, 1.5 and 1 for waiting at stop, waiting onboard/holding, and riding respectively [6].

The BusMezzo simulation is stochastic, thus it is able to model uncertainty in operations and to simulate it in a real-time manner [19]. Consequently, the simulation requires multiple runs to achieve statistically significant results. The number of runs required is determined by Equation (5) below.

$$N \geq \left(\frac{t_{\alpha/2} * S_n}{E}\right)^2 \qquad (5)$$

In Equation (5), N is the number of minimum runs, $t_{\alpha/2}$ is the student t-value for confidence level α, S_n is the standard deviation of the measured variable based on the initial runs, and E is margin of error. 100 simulation runs were found necessary to attain a 95% level of accuracy and were thus carried out for each strategy.

IV. RESULT AND ANALYSIS

Table II summarizes the results obtained for the given strategies in Scenario 1. The proposed strategy, SH, demonstrates 11–63% regularity improvement in comparison to holding control in most cases. Meanwhile, when comparing SH with SA, the regularity improvement obtained is less significant, ranging between 0–39%.

With respect to the travel time obtained, table II suggests that SH produces 0–4 minutes longer total generalized travel time, compared to holding control.

These results show that there are tradeoffs in using the proposed strategy. To understand this issue, the more detailed results are provided in the given subsections.

TABLE II. RESULT SUMMARY (SCENARIO 1)

Indicator	Line, Dir	SB	EH	EH ALL
Avg. CoV headway per line (%)	Line M5, Dir 1	11%	13%	10%
	Line M5, Dir 2	11%	9%	7%
	Line M7, Dir 1	9%	10%	10%
	Line M7, Dir 2	9%	9%	9%
Avg. generalized total travel time per passenger (min)		**39**	40	41
Indicator	**Line, Dir**	**SA1**	**SA2**	**SA3**
Avg. CoV headway per line (%)	Line M5, Dir 1	6%	**5%**	**5%**
	Line M5, Dir 2	28%	**5%**	6%
	Line M7, Dir 1	7%	6%	**5%**
	Line M7, Dir 2	30%	5%	**4%**
Avg. generalized total travel time per passenger (min)		43	40	41
Indicator	**Line, Dir**	**SH1**	**SH2**	**SH3**
Avg. CoV headway per line (%)	Line M5, Dir 1	6%	6%	**5%**
	Line M5, Dir 2	17%	**5%**	8%
	Line M7, Dir 1	6%	7%	**5%**
	Line M7, Dir 2	28%	5%	**4%**
Average generalized total travel time per passenger (min)		43	41	41

A. Coefficient of variation (CoV) of the headway

Table II presents the average of the CoV of the headways for each line, depicting the headway variability. This section shows the headway variability for every stop.

Figures 3 and 4 show the regularity results for Line M5. In direction 1, as can also be observed from Table II, the CoV of the headway resulted from the SH strategy is lower than the one obtained by holding control strategies. Speed adjustment continuously controls the variability of trip time, and since the system runs in dedicated lane, the control advice is implemented well.

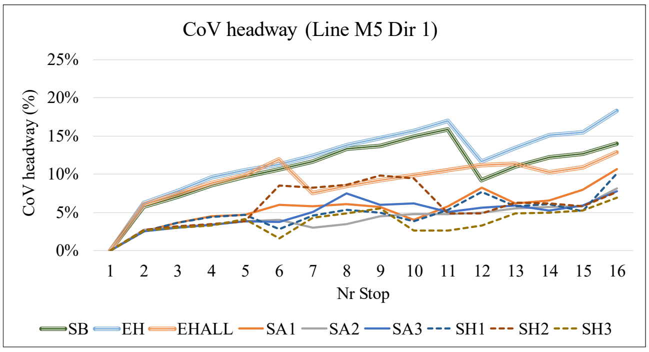

Fig. 3. CoV headway of Line M5 Direction 1

Slight difference, however, is seen between the results of SH and SA. SH2 yields a noticeable increase in irregularity, compared to SA2, which has the same speed range. These two strategies allow higher speed limit ranging between 25th-95th percentile of speed distribution. Compared to the actual trip time, the schedule for the first five stops is longer. The first trip between stop 1 and 2 is early and drags the following vehicles to speed up as well. However, the earliness leads the vehicles to slow down. With the applied speed range, SA2 and SH2 cannot be as slow as the other strategies. Since the schedule is loose, the slowest speed taken by SA2 and SH2 are still considered early. Thus, SH2 applies holding as an addition to recover the earliness. When the following vehicle enters the route and speeds up due to the same reason as its preceding, the controlled vehicle is still slowing down. This condition leads to variability of headways, as seen at Stop 6 in figure 3 for SH2.

Differently in Direction 2, a noticeable irregularity is observed for SH1, which explains the other cases where SH is outperformed by holding control.

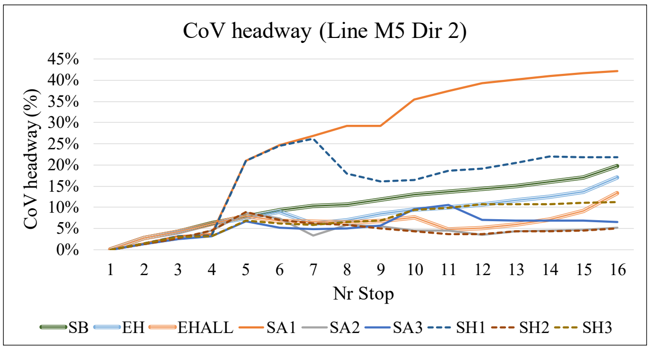

Fig. 4. CoV headway of Line M5 Direction 2

As opposed to the case in Direction 1, here, the first vehicle tends to be late compared to the schedule, which influences the following vehicle to also ride slower. In SH1, the minimum speed limit allows the vehicle to be much slower. Since the communication is done in an event-based manner, the longer the vehicle rides, the longer its communication will disconnect with its adjacent vehicles. It then triggers sudden change in speed advice given when a new vehicle enters the route and hence leads to headway variability. Thus, for this case, wider speed range worsens the variability obtained and the longer it takes to stabilize.

Besides speed range, demand pattern also affects the effectiveness of SH. As in holding control, the effectiveness of this strategy depends on the demand pattern and the control point location(s) [24]. In this case, the demand pattern of Direction 1 becomes an advantage for SA. The demand is high at the early stops and does not vary along the route, thus SA is able to perform well. The results from Line M5 Direction 2 capture better the impact of having holding ability in SH. In figure 4 between SH1 and SA1, the high demand condition in combination with high demand variation magnifies the irregularity for SA, while for SH it becomes an advantage to improve the regularity.

The results from Line M7 show no significant differences and therefore are not discussed in this section. The interested reader is referred to [3].

B. *Generalized travel time*

In this subsection, table III, IV and V further indicate the results shown in table II for every travel time component.

The maximum difference between the average waiting time of each strategy is only <5% of the average value, as seen in table III. Meanwhile, when comparing SH and EHALL, both allow holding at all stop, SH yields 23–97% average total holding time reduction compared to EHALL.

Different pattern is found in trip time component. Table IV shows that the lower the minimum speed limit, the shorter the holding time required. Notwithstanding, the average trip time becomes much longer. SH causes 1–31% of prolonged trip time between stops, which cancels out the holding time reduction it attains. For the same reason, even without holding at all, SA1 also results in longer generalized total travel time. SB, conversely, gives the lowest generalized travel time, since it generates the least holding time in comparison to the other strategies.

TABLE III. AVERAGE WAITING TIME

Indicator	Line, Direction	SB	EH	EHALL
Avg. Waiting Time (s)	Line M5, Dir 1	149	149	**147**
	Line M5, Dir 2	151	**150**	**150**
	Line M7, Dir 1	150	149	**147**
	Line M7, Dir 2	150	149	148
Indicator	**Line, Direction**	**SA1**	**SA2**	**SA3**
Avg. Waiting Time (s)	Line M5, Dir 1	148	149	148
	Line M5, Dir 2	157	151	151
	Line M7, Dir 1	148	149	149
	Line M7, Dir 2	**145**	149	150
Indicator	**Line, Direction**	**SH1**	**SH2**	**SH3**
Avg. Waiting Time (s)	Line M5, Dir 1	148	148	148
	Line M5, Dir 2	157	152	152
	Line M7, Dir 1	148	149	149
	Line M7, Dir 2	**145**	149	150

TABLE IV. AVERAGE TOTAL HOLDING TIME

Indicator	Line, Direction	SB	EH	EHALL
Avg. Total Holding Time (s)	Line M5, Dir 1	12	10	78
	Line M5, Dir 2	0	11	48
	Line M7, Dir 1	120	52	127
	Line M7, Dir 2	45	46	64
Indicator	**Line, Direction**	**SA1**	**SA2**	**SA3**
Avg. Total Holding Time (s)	Line M5, Dir 1	0	0	0
	Line M5, Dir 2	0	0	0
	Line M7, Dir 1	0	0	0
	Line M7, Dir 2	0	0	0
Indicator	**Line, Direction**	**SH1**	**SH2**	**SH3**
Avg. Total Holding Time (s)	Line M5, Dir 1	12	42	33
	Line M5, Dir 2	29	29	20
	Line M7, Dir 1	47	98	34
	Line M7, Dir 2	27	14	2

TABLE V. AVERAGE TRIP TIME BETWEEN STOPS

Indicator	Line, Direction	SB	EH	EHALL
Avg.Trip Time between Stops (s)	Line M5, Dir 1	66	66	66
	Line M5, Dir 2	66	66	66
	Line M7, Dir 1	73	73	73
	Line M7, Dir 2	75	75	75
Indicator	**Line, Direction**	**SA1**	**SA2**	**SA3**
Avg.Trip Time between Stops (s)	Line M5, Dir 1	72	69	72
	Line M5, Dir 2	89	72	76
	Line M7, Dir 1	85	79	84
	Line M7, Dir 2	99	79	77
Indicator	**Line, Direction**	**SH1**	**SH2**	**SH3**
Avg.Trip Time between Stops (s)	Line M5, Dir 1	72	67	71
	Line M5, Dir 2	84	72	76
	Line M7, Dir 1	83	76	84
	Line M7, Dir 2	98	79	76

By observing the average trip time between stops, the results indicate that the system instructs vehicles to slow down more often than speeding up. One potential reason behind this is the timetable, as shown also in the previous section. When the timetable is loose as in Line M5 Direction 1, the system will consider the vehicle to be early and hence advises it to slow down. However, when it is too tight as in Line M5 Direction 2, the vehicle will be late and force the following vehicles to slow down as well. Therefore, SH1 obtains much longer travel time due to its low minimum speed limit, while SH2 and SH3 only show 0–2 minute difference compared to holding control, in addition to high regularity.

C. Scenario 2: Tight schedule

To have a better understanding of control strategies, we also analyzed the second scenario, with tighter schedule. The resulted changes are presented and discussed in the two following subsections with respect to the CoV of the headway and passengers' generalized travel time.

1) Changes in CoV headway

Table VI presents the resulted changes in the CoV of the headways. In vast majority of the cases shown in the table, the headway regularity deteriorates in Scenario 2, marked with a negative value.

Hypothetically, SB would be most affected by this change because its dependency on the quality of the scheduling. The results demonstrate that SB deteriorates more in comparison to other holding controls. However, the effect is more significant for SA and SH. These strategies are based on headways, but in this study, timetable determines the arrival time prediction for the speed adjustment. The worst performing strategy is SH1 for Line M5, Direction 1 with a performance reduction of 305%. At the same time, this strategy also generates the greatest improvement in Line M7, Direction 2.

TABLE VI. CoV CHANGES BETWEEN SCENARIO 1 AND SCENARIO 2

Indicator	**Line, Dir**	**SB**	**EH**	**EH ALL**
Changes in avg. CoV headway per line (%)	**Line M5, Dir 1**	**7%**	**23%**	–9%
	Line M5, Dir 2	–2%	–3%	–32%
	Line M7, Dir 1	–53%	–14%	–33%
	Line M7, Dir 2	–67%	–18%	–33%
Indicator	**Line, Dir**	**SA1**	**SA2**	**SA3**
Changes in avg. CoV headway per line (%)	**Line M5, Dir 1**	–295%	–5%	–29%
	Line M5, Dir 2	–29%	–159%	–177%
	Line M7, Dir 1	–200%	0%	–49%
	Line M7, Dir 2	**40%**	–57%	–70%
Indicator	**Line, Dir**	**SH1**	**SH2**	**SH3**
Changes in avg. CoV headway per line (%)	**Line M5, Dir 1**	–305%	–12%	–44%
	Line M5, Dir 2	–106%	–60%	–92%
	Line M7, Dir 1	–300%	–29%	–60%
	Line M7, Dir 2	**61%**	–40%	–48%

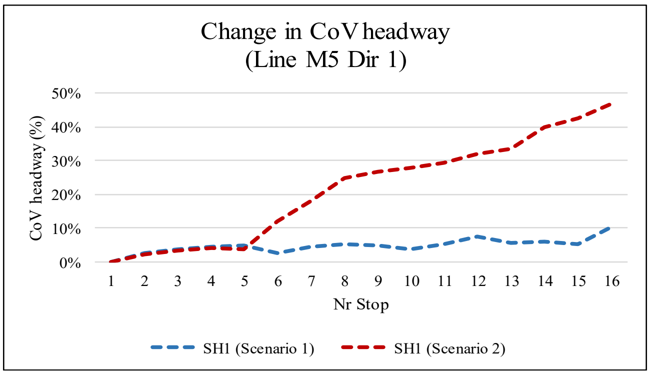

Fig. 5. CoV headway changes in Line M5 Direction 1

Figure 5 depicts the worsening in irregularity for SH1 in Line M5, Direction 1. Here, the average CoV of the headways increases from 6% to 24%. Since the schedule is tighter, the first trip tends to be late. In general, this situation is similar to the one shown in Scenario 1, Line M5, Direction 2. In SH1, however, it is difficult to apply holding, because the trips are late rather than early.

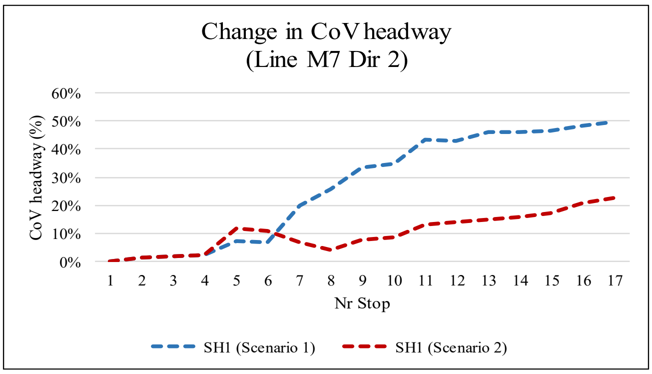

Fig. 6. CoV of headways changes in Line M7 Direction 2

Figure 6 demonstrates that in Line M7, Direction 2, however, the irregularity has improved by 61%. Modification in the schedule improves the accuracy of the arrival time prediction. In Scenario 1, the scheduled trip time from Stop 5 to Stop 6 is 45% longer than the average of the actual trip time. Thus, the vehicle excessively reduces its speed in this link to match the prediction. It causes the similar situation as the previous one, in Line M5 Direction 1 for strategy SH1. In Scenario 2, the arrival time prediction for this line is more accurate with 11% difference. The vehicles do not have to reduce its speed significantly, and it improves the overall regularity (see more detail in [3]).

By running the Scenario 1 and 2, several insights into the proposed control strategy can be concluded. There are three factors found important in determining the regularity performance of the control strategy, including speed range, demand pattern and arrival time prediction. Among the three factors, arrival time prediction is always the root cause of the irregularity. In the case study, it can be seen from how timetable design affects the control suggestion given by the system. When the timetable design cannot give an accurate prediction, the effect from the other factors become more important.

2) Change in generalized travel time

Tables VII-X show the changes in travel time components, due to the modification in the timetable. Table VII depicts the difference in generalized total travel time. All strategies produce longer travel times, ranging between 7–9% or 3–4 minutes.

From table VIII, it is shown that the difference is even smaller in the average waiting time value, but its variability is higher due to worse performance in regularity. Meanwhile, table IX indicates a large reduction in holding time value, noted by the positive value.

Reduction in holding time does not necessarily indicate an improvement in the operations. For example in SB, modification in Scenario 2 reduces the possibility of SB to perform holding because the trips are late. It, however, results in increase in the irregularity as shown in table VI.

TABLE VII. CHANGE IN GENERALIZED TOTAL TRAVEL TIME

Indicator	SB	EH	EHALL
Generalized Total Travel Time (%)	–9%	–8%	**–7%**
Indicator	**SA1**	**SA2**	**SA3**
Generalized Total Travel Time (%)	–8%	–8%	–9%
Indicator	**SH1**	**SH2**	**SH3**
Generalized Total Travel Time (%)	–8%	**–7%**	**–7%**

TABLE VIII. CHANGE IN AVERAGE WAITING TIME

Indicator	Line, Direction	SB	EH	EHALL
Avg. Waiting Time (%)	**Line M5, Dir 1**	0%	0%	0%
	Line M5, Dir 2	1%	0%	0%
	Line M7, Dir 1	0%	0%	0%
	Line M7, Dir 2	0%	0%	0%
Indicator	**Line, Direction**	**SA1**	**SA2**	**SA3**
Avg. Waiting Time (%)	**Line M5, Dir 1**	–3%	0%	0%
	Line M5, Dir 2	0%	0%	–1%
	Line M7, Dir 1	–2%	0%	0%
	Line M7, Dir 2	–3%	0%	1%
Indicator	**Line, Direction**	**SH1**	**SH2**	**SH3**
Avg. Waiting Time (%)	**Line M5, Dir 1**	–3%	0%	0%
	Line M5, Dir 2	0%	1%	0%
	Line M7, Dir 1	–4%	0%	1%
	Line M7, Dir 2	–2%	0%	1%

TABLE IX. CHANGE IN AVERAGE TOTAL HOLDING TIME

Indicator	Line, Direction	SB	EH	EHALL
Avg. Total Holding Time (%)	**Line M5, Dir 1**	**100%**	–20%	63%
	Line M5, Dir 2	–5%	60%	75%
	Line M7, Dir 1	**100%**	**100%**	**100%**
	Line M7, Dir 2	**100%**	63%	53%
Indicator	**Line, Direction**	**SA1**	**SA2**	**SA3**
Avg. Total Holding Time (%)	**Line M5, Dir 1**	-	-	-
	Line M5, Dir 2	-	-	-
	Line M7, Dir 1	-	-	-
	Line M7, Dir 2	-	-	-
Indicator	**Line, Direction**	**SH1**	**SH2**	**SH3**
Avg. Total Holding Time (%)	**Line M5, Dir 1**	32%	88%	92%
	Line M5, Dir 2	67%	61%	**90%**
	Line M7, Dir 1	**100%**	**100%**	**100%**
	Line M7, Dir 2	–28%	–135%	–877%

TABLE X. CHANGE IN AVERAGE TRIP TIME BETWEEN STOPS

Indicator	Line, Direction	SB	EH	EHALL
Avg.Trip Time between Stops (%)	**Line M5, Dir 1**	0%	0%	0%
	Line M5, Dir 2	0%	0%	0%
	Line M7, Dir 1	0%	0%	0%
	Line M7, Dir 2	0%	0%	0%
Indicator	**Line, Direction**	**SA1**	**SA2**	**SA3**
Avg.Trip Time between Stops (%)	**Line M5, Dir 1**	–9%	**6%**	5%
	Line M5, Dir 2	**–1%**	5%	2%
	Line M7, Dir 1	–1%	**8%**	8%
	Line M7, Dir 2	14%	6%	–5%
Indicator	**Line, Direction**	**SH1**	**SH2**	**SH3**
Avg.Trip Time between Stops (%)	**Line M5, Dir 1**	–8%	4%	4%
	Line M5, Dir 2	–5%	7%	3%
	Line M7, Dir 1	–3%	4%	9%
	Line M7, Dir 2	**18%**	6%	–4%

For EH, EHALL, SH, the total holding time is also reduced in most of the cases. As aforementioned, tight schedule indirectly affects the way that the system determines the earliness of the trips. Thus, these strategies also show reductions in holding time. SH, however, gives different results in Line M7 Direction 2, where the holding time increases. In Scenario 1, the inaccuracy of arrival time prediction to Stop 6, makes it difficult for the vehicle to apply holding time.

In the average trip time between stops, there are no differences in the value for holding control. In SH and SA, on average, the trip time between stops decreases. The vehicle does not slow down as often as in Scenario 1, because the "early trips" occur less frequently.

The greatest difference is obtained by SH1 in Line M7, Direction 1, which reinforces the importance of accuracy in the arrival time prediction. Not only does inaccuracy affect the regularity, it also influences the travel time.

The results given above only capture the average value. As addition, tables XI and XII present the summary of changes in the variability of the travel time components.

TABLE XI. CHANGE IN WAITING TIME VARIABILITY

% change in waiting time variability	**SB**	**EH**	**EHALL**
	(–1) – (–53)	9 – (–25)	(–13) – (–34)
	SA1	**SA2**	**SA3**
	31 – (–343)	32 – (–171)	(–11) – (–206)
	SH1	**SH2**	**SH3**
	54 – (–333)	46 – (–76)	(–10) – (–103)

TABLE XII. CHANGE IN TRIP TIME VARIABILITY

% change in trip time variability	**SB**	**EH**	**EHALL**
	37 – (–61)	37 – (–60)	38 – (–60)
	SA1	**SA2**	**SA3**
	30 – (–12)	24 – (–24)	14 – (–20)
	SH1	**SH2**	**SH3**
	34 – (–16)	25 – (–19)	17 – (–20)

Tables XI and XII present the range of changes in the waiting times and trip time variability, with negative and positive values indicating increases and decreases in variability, respectively. The waiting time variability increase in most cases as can be expected based on the results of increase in irregularity, which are reported in table VI. For trip times a more mixed pattern can be observed. From these results, it is concluded that the increase in the total generalized travel time is caused by the higher uncertainty occurred in Scenario 2.

V. DISCUSSION AND CONCLUSION

This study presents a control strategy combining speed adjustment and holding control. Employing a combined control has proven to yield a better regularity performance. However, it is found that under some conditions, the proposed strategy obtains a longer trip time by resorting to both holding and slowing down. The findings suggest that combining the two strategies implies combining both the positive and negative attributes of each control.

The performance obtained by each strategy is highly influenced by line characteristics. Schedule-based holding control is affected by scheduling, while the headway-based holding control is affected by the control point locations and the demand pattern. These results validate the findings from the past literature. For speed adjustment-holding and speed adjustment, three aspects affect their performance: speed range, demand pattern and arrival time prediction. From the three factors listed above, the proposed strategy and speed adjustment are most sensitive to the arrival time prediction.

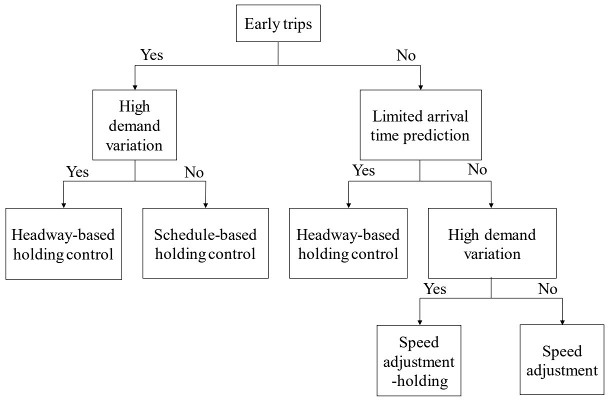

Fig. 7. Indication of selecting different control strategies based on the line characteristics

For implementation, these characteristics can be used to identify the preferable control strategy as proposed in figure 7. 'Early trips' refers to cases where the vehicle is ahead of schedule. 'High demand variation' implies that the dwelling time is highly varied along the route (i.e. not concentrated only at the begin of the route). 'Limited arrival time prediction' corresponds to the condition where the arrival time prediction method is not robust in producing an accurate prediction.

Several limitations are associated with this study. First, the simulation does not capture the driver behavior. Consequently, it cannot capture other disturbances due to driver behavior (e.g. lateness, reaction towards control strategy). Furthermore, as the strategy follows an event-based manner, the methods of arrival time prediction and the control decision are limited, as they cannot be executed continuously. Lastly, the assumption that the system is running in a segregated lane ignores two disturbances: the external disturbance from the traffic and the effect of speed adjustment on other road users, which might affect the overall result.

In general, the proposed control strategy, as well as speed adjustment, need to be studied further to investigate its performance under a large range of conditions prior to field implementation. In contrast, holding control strategy performs well under different conditions without many requirements as reported based on a full-scale implementation in [20].

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