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Communication-based Cooperative Control Strategy for Public-Transport Transfer Synchronization

Tao Liu · Avishai (Avi) Ceder

Abstract Improving public-transport (PT) service reliability is one of the most important tasks in PT-operations planning. Synchronized transfers in PT networks are utilized to reduce the inter-route or inter-modal passenger transfer waiting time, provide a well-connected service, and improve the attractiveness of the PT service. However, in practice, it is a well-known phenomenon that synchronized transfers are not always materialized because of some stochastic and uncertain factors, such as traffic disturbances and disruptions, fluctuations of passenger demand and erroneous behaviour of PT drivers. As a result, missed direct-transfers will not only frustrate existing users, but also discourage potential passengers from using the PT service. This missed-meeting problem can be mostly avoided by a real-time control system using selected online operational tactics, such as skip-stop/station, holding, changes in speed. This work proposes a communication-based cooperative control (CCC) strategy established upon a library of selected operational tactics, using automatic vehicle location system, to increase the actual occurrence of synchronized transfers; thus to reduce the average passenger transfer waiting time. The performance of the CCC strategy is compared with other three control strategies, namely without-control (WC), conventional schedule-based control (CNC) and communication-based non-cooperative control (CNC) strategies, using system performance indicators. A Monte Carlo method-based simulation procedure is developed to address the endogenous randomness within vehicle travel time,

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passenger demand and driver behaviour. The proposed methodology has been applied to a detailed numerical example and a case study in Auckland, New Zealand. The simulation and optimization results show that the CCC strategy has the best performance, across all strategies examined, in improving the actual occurrences of planned synchronized transfers, reducing average passenger transfer waiting time and in reducing vehicle bunching percentage. The CCC strategy thus has a large potential for increasing the efficiency, thus transfer-based, of PT networks and improving the attractiveness of the PT service.

Keywords: Public Transport · Transfer Synchronization · Control strategies· Service reliability

1 Introduction

Improving public-transport (PT) service reliability is one of the most important tasks in PT-operations planning. Unreliable PT service found as one of the main reasons to reduce considerabley the attractiveness of PT service (Ceder, 2007). As a result, continued unreliable PT service will not only frustrate the existing passengers, but will also cause a loss of potential new users. Transfer synchronization is an instrument commonly used by PT planners and operators to increase the connectivity of PT service. In New Zealand for example, the Public Health Advisory Council lists good service connectivity as a major point in improving accessibility to PT (Public Health Advisory Committee, 2010). The goal of developing an integrated and better-connected PT network which can allow seamless and smooth transfers between hierarchical high and low frequency lines was recently proposed for Auckland (Auckland Transport, 2013). Synchronized PT transfers are utilized to reduce the inter-route or inter-modal passenger transfer waiting time and provide a well-connected service. This paper focuses on the PT transfer synchronization problem by using a communication-based cooperative control strategy.

The PT transfer synchronization problem can be analysed at the planning level and at the operation level. At the planning level, planning tools of maximal synchronized timetable (MST) and timed transfer system (TTS) were introduced to planners in order to maximize the number of simultaneous arrivals of PT vehicles at transfer nodes (Domschke, 1989; Ceder et al., 2001; Vuchic, 2005). However, in practice, it is a well-known phenomenon that synchronized transfers are not always materialized as planned because of some stochastic and uncertain factors, such as traffic disturbances and disruptions, fluctuations of passenger demand and erroneous behaviour of PT drivers. This missed-connection problem can be mostly avoided, if the movement of vehicles on PT routes is well-controlled in real time, at the operation level, by using some selected online operational tactics, such as skip-stop/station, holding, and changes in speed (Ceder, 2007).

To date there are three main decision-making problems that were not well addressed yet about using operational tactics. First, in the previous studies, researchers examined the effect of only one or two operational tactics while, in fact, there is a group of operational tactics that can be used. The combinatorial effect of these operational tactics is not well investigated yet. Second, the PT network structure of previous studies includes only one route or a small unidirectional network with link travel time and passenger demand assumed to be deterministic; certainly not fully a realistic assumption. Third, operational tactics of previous studies are used in a static, not dynamic, manner; that is, without real-time communication among PT drivers and dispatchers. The rapid development of information and communication technology, especially the current vehicle-to-vehicle communication technology, opens the door to use operational tactics in real time. This study, in comparison with others, uses the availability of real-time information to quickly correct schedule deviations and allows for increasing the chances of simultaneous (without wait) transfers.

To solve these challenging decision-making problems efficiently, a comprehensive optimization framework is required to analyse, in real time, the combinatorial effect of various operational tactics on the whole PT network under dynamic and stochastic conditions. In order to do so, this study develops a communication-based decentralized cooperative optimization framework to support the dynamic decision-making process of PT operators in choosing operational tactics and determining the optimal values of the selected operational tactics. Based on this decision-making framework, various control strategies for increasing PT transfer synchronization are investigated and compared in this study.

1.1 Literature review

The PT transfer synchronization problem has been extensively studied in the literature. The problem attempts to maximize the number of simultaneous arrivals of PT vehicles at transfer nodes so that passengers will have minimum waiting time when transferring from one route to another (Ceder, 2007). In general terms, measures usually utilized by PT planners and operators to achieve maximum synchronized transfers can be classified into two stages: planning stage and operation stage (Hadas and Ceder, 2010).

The planning stage aims at developing synchronized (coordinated or timed) PT timetables (schedules) for given networks and passenger demand so as to minimize transfer waiting time of all passengers. In the literature, the PT timetable synchronization problem is usually formulated as integer-programming problems (e.g., Klemt and Stemme, 1988; Domschke, 1989; Bookbinder and Desilets, 1992; Voß, 1992; Ceder et al., 2001; Eranki, 2004; Wong et al., 2008; Shafahi and Khani, 2010; Ibarra-Rojas and Rios-Solis, 2012; Wu et al., 2015). Knoppers and Muller (1995) investigated the impact of fluctuations in passenger arrival times on the possibilities and limitations of synchronized PT transfers. They concluded that transfer synchronization is gainful when the arrival time of the feeder line is within a time window with a length relatives to the headway of the connecting line. In most of previous studies, route departure times are usually chosen as decision variables. In addition, Wong et al. (2008) and Wu et al. (2015) also treated running times and headway as decision variables. Some studies extended the concept of simultaneous arrival of vehicles into arrival within a time window (Eranki, 2004), and also including consideration of avoiding bus bunching and oriented synchronization (e.g., Ibarra-Rojas and Rios-Solis, 2012). Ginkel and Schöbel (2007) studied the transfer synchronization between a train and its feeder bus service on the condition that the scheduled train service is behind of schedule due to some unexpected disturbances. They termed this train-bus transfer synchronization problem as delay management problem (DMP). A bi-criteria integer programming model was proposed for the DMP, aiming to minimize both the total delays of all vehicles across all stations and the weighted number of missed connections.

Most of these previous studies assumed that all the input variables, e.g., vehicle travel time, dwell time, passenger demand and route structure, are static and deterministic, i.e., not subject to uncertainty. Another approach for modelling this problem by taking into consideration of uncertainty is the use of stochastic programming. Lee and Schonfeld (1991) considered the stochastic arrivals of PT vehicles at transfer nodes and proposed to add slack times into schedule to reduce the missed connection. Wu, et al. (2015) recently developed a stochastic integer programming model to capture the stochastic property of vehicle travel times. Slack times are inserted in the timetable to mitigate the randomness caused by random traveling times. However, it is known that adding slack time will reduce the average vehicle running time, and thus increase the total passenger travel time. In some worst cases, it may cause service deteriorations further along the route. As pointed by Daganzo and Pilachowski (2011), this medicine (slack) is sometimes worse than the illness (irregular headways).

Because of the NP-hard complexity of the optimization models, it is impossible for large PT networks to obtain exact solutions efficiently by using exsisting commercial optimization software. Therefore, various kinds of heuristic solution algorithms were proposed, such as regret methods and improvement algorithms (Domschke, 1989), iterative improvement algorithm (Bookbinder and Desilets, 1992), FIRST-MIDDLE-CHOOSE procedure (Ceder et al., 2001), optimization-based heuristic method (Wong et al., 2008) and other meta-heuristic algorithms, e.g., tabu search (Voß, 1992), genetic algorithm (Shafahiand and Khani, 2010; Wu et al., 2015) and multi-start iterated local search algorithm (Ibarra-Rojas and Rios-Solis, 2012). All in all, the main objective is to develop a maximum synchronized timetable so as to minimize transfer waiting time and improve transfer service reliability.

Nonetheless, it has been known for more than 50 years (Newell and Potts, 1964) that if no control strategies are used, even a very small disturbance can cause serious off-schedule running; this schedule deviation may be amplified and propagated along the route, causing serious service disruptions and deteriorations. In order to control the inherent randomness in PT operation, control actions such as holding, skip-stop/segment and changes in speed are utilized (Ceder, 2007). Osuna and Newell (1972), Barnett (1974) and Newell (1974) showed how holding vehicle at a chosen stop can be used to reduce both the average passenger waiting time and average in-vehicle passenger delay. However, control actions, in these studies, are used in a static, not dynamic, fashion; that is without considering real-time vehicle location and passenger demand information.

The rapid development of information and communication technology (ICT), such as automatic vehicle location (AVL), geographic information systems (GIS) and automated passenger counters (APC), opens the door to use operational tactics to improve the performance of PT systems in real time. In the context of transfer synchronization, the importance of using ICT has been addressed by Dessouky et al. (1999, 2003) and Chowdhury and Chien (2001), who investigated how holding vehicles at timed transfer terminals can improve service connectivity and reduce transfer delay when using bus tracking and passenger counting technologies. In addition, some researchers investigated how real-time holding (Eberlein, et al., 2001; Fu and Yang, 2002; Daganzo, 2009; Daganzo and Pilachowski, 2011; Xuan, et al., 2011; Cats, et al., 2012), skip-stopping (Sun and Hickman, 2005) and boarding limits (Delgado, 2012) can be used to reduce vehicle bunching and improve service reliability.

Recent studies focused on examining the combinatorial effects of selected operational tactics (control actions) on alleviating the uncertainty of simultaneous arrival of PT vehicles at transfer nodes and correcting schedule deviations. Hadas and Ceder (2010) developed a dynamic programming-based optimization model to improve transfer synchronization and minimize the total passenger travel time through deploying a set of preferred operational tactics. Ceder et al. (2013) developed an optimization and simulation-based model to investigate the impact of holding and skip-stop tactics on total passenger travel time and the number of simultaneous transfers. Nesheli and Ceder (2014) extended and refined the work of Ceder et al. (2013) by introducing the possibility of skip-segment tactics compared with only skip an individual stop. Later, Nesheli et al. (2015) further added another tactic, short-turn, in the previous study to investigate the combinatorial effect of three tactics. Liu et al. (2014a; 2014b) proposed a communication-based vehicle control system (CBVC) for bus transit system to coordinate the movement of buses along their routes in a vehicle-to-vehicle (V2V) communication environment. A case study of a PT network in Beijing showed that by applying the proposed methodology, the number of direct transfers can be considerably increased and the total passenger travel time can be significantly reduced. Taking into consideration of the stochastic and time-varying characteristics of vehicle travel times and passenger demand, Liu et al. (2015) further developed a predictive control methodology to dynamically optimize, in a receding horizon control manner, the PT vehicle movement process in schedule-based networks.

1.2 Objectives and contributions

The above literature review clearly indicates that the communication-based cooperative control strategy for public-transport transfer synchronization is a new research issue with both theoretical and practical importance. The purpose of this study is to develop a communication-based cooperative control strategy, used in the current CBVC system, for increasing the actual occurrences of planned synchronized transfers and reducing passenger transfer waiting time through the use of a library online operational tactics. The contribution of this research is threefold. First, we systematically defined the elements and components used in the communication-based decentralised cooperative optimization framework. Second, the control logics of four different control strategies are clearly explained. Third, the performance of these control strategies are compared and illustrated through a detailed numerical example and a case study in Auckland, New Zealand.

The rest of this paper is organized as follows. Section 2 provides the background information on operational tactics and clearly explains the communication-based decentralized cooperative optimization framework. Section 3 presents the formulation of the control logics in the four control strategies. Various performance indicators are also developed for comparing and evaluating the performance of control strategies. A Monte Carlo method-based simulation procedure for PT network simulation is provided in Section 4. Section 5 provides a detailed numerical example. Section 6 is a case study of a small PT network in Auckland, New Zealand. Finally, section 7 concludes this paper, and provides concluding remarks.

2 Library of tactics and optimization framework

This section first breifly summaries the possible operational tactics, also referred to as control actions, that can be used to improve service reliability in PT operations. Then, a communication-based decentralised cooperative optimization framework for supporting the real-time deployment of operational tactics is presented.

2.1 Background on operational tactics

Once the movement of PT vehicles deviates from the planned state, e.g., deviating from schedule, remedial operational tactics are employed to correct damages occurred in the system, and drag the movement of vehicles back to the desired state. In the context of transfer synchronization, operational tactics are used to correct schedule deviations in order to maximize the simultaneous arrivals of vehicles at transfer stops/stations. Generally speaking, there is a package, or ‘library’ of operational tactics that can be used by PT operators. The main possible operational tactics are listed as follows:

- Holding the vehicle (at terminal or at mid-route point)
- Skip-stop operation
- Changes in speed (not above the lawful speed limit)
- Deadheading operation
- Short-turn operation
- Short-cut operation
- Adding a reserve vehicle
- Leapfrogging operation with the vehicle ahead

The working principles of each operational tactics are described in detail by Ceder (2007). The library of operational tactics serves as a basis of the sequential decision-making process in maintaining the synchronized schedule and achieving maximal transfer synchronization.

2.2 Optimization framework

In this study, a communication-based decentralized cooperative optimization framework is introduced to support the sequential decision-making process of PT operators in selecting and deploying operational tactics. This optimization framework was first described by Liu et al. (2014a; 2014b), for synchronizing transfers in dynamic PT operations. For the sake of simplicity and presentation, the following notations are used.

N	set of transfer nodes in the network
R	set of routes in the network
S^r	set of route segments of route $r, r \in R$ in the network
$U\left(S^r\right)$	set of transit stops in route segment S^r
G	set of communication groups including vehicles moving towards the same transfer node
T	set of tactics deployment decision epochs of a vehicle belonging to a communication group
I	set of required vehicle trips, $i = 1, 2, \cdots n,\ i \in I$
S	set of possible states of a vehicle at a transit stop
A	set of available tactics
A_s	set of available tactics in state s
t	a decision epoch at a stop
s	a state at a stop $s \in S$
a	a tactic $a \in A$
P	a state propagation process
$v_t\left(a\right)$	value of tactic $a \in A_s$ at decision epoch t
$d_t\left(s\right)$	decision rule of state s at decision epoch t
π	control strategy
MST	maximal synchronized timetable of a network
$SAT_{i,u}$	scheduled arrival time of vehicle trip i at stop u
$AAT_{i,u}$	actual arrival time of vehicle trip i at stop u
$SDT_{i,u}$	scheduled departure time of vehicle trip i at stop u
$ADT_{i,u}$	actual departure time of vehicle trip i at stop u
$NB_{i,u}$	number of boarding passengers of vehicle trip i at stop u
$NA_{i,u}$	number of alighting passengers of vehicle trip i at stop u

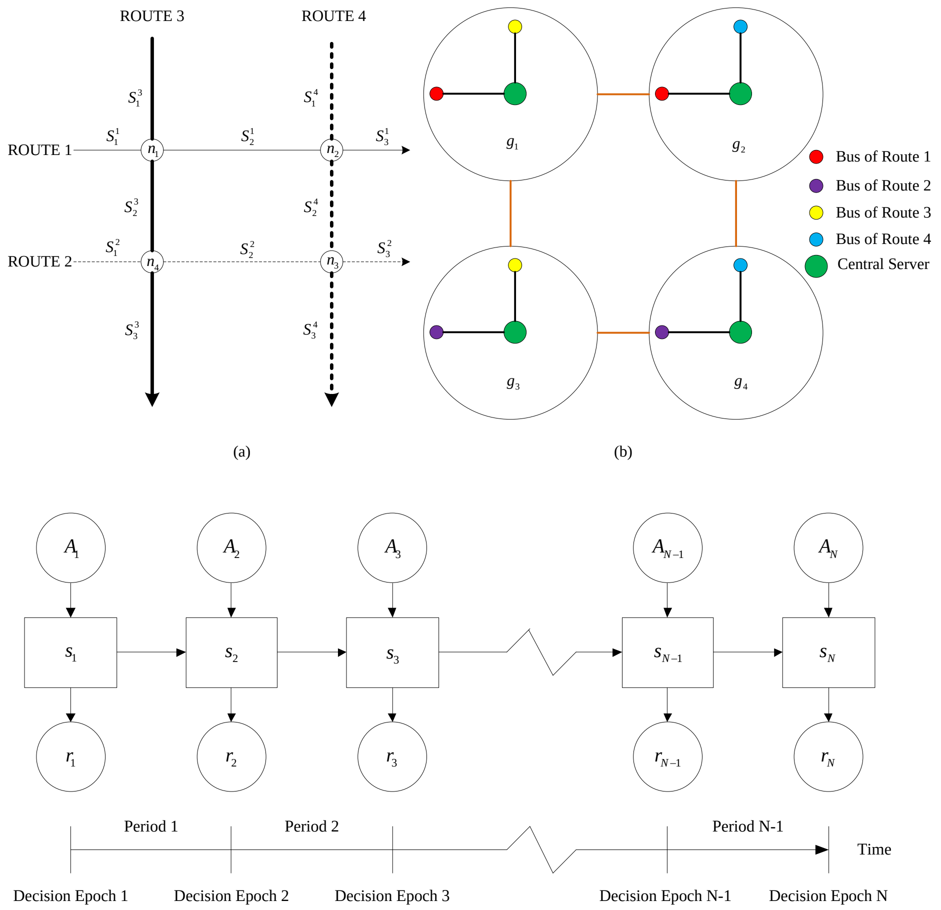
An example of the optimization framework is illustrated in Figure 1 (a) using a simple four-route PT network with four transfer nodes and twelve route segments. Under the optimization framework, the whole network is divided into a set of route segments S^r by the transfer nodes n_i distributed in the network. Vehicles moving on route segments that lead to the same transfer nodes belong to the same communication group. As it is shown in Figure 1 (b), the simple PT network is divided into four communication groups. Each communication group is assigned a central server with a communication coordinator.

Using this optimization framework, a central server with a communication coordinator is responsible for the communication coordination of vehicles on the route segments leading to a same communication group. It is assumed that the global positioning system (GPS)-based AVL devices embedded in the PT vehicles can provide the control centre with real-time vehicle location information. Thus, the control centre can continuously monitor the vehicles on the route segments leading to the group. The recorded vehicle data, including location, speed, time, etc., information, can be transmitted to the database in the communication control centre in real time through GSM/GPRS networks. These data are visualized in geographic information system (GIS) maps. In addition, the transfer control centre can communicate with PT drivers in real time via the wireless communication system. The control centre has information on each route leading to it, including planned departure time, passenger demands, transferring passengers, running time, and dwell time. Based on that knowledge, advisory optimal control actions are disseminated to the drivers in the group so they can arrive simultaneously or within a given time window at the same transfer point. The advisory information can be displayed online to the driver on the on-board variable message sign (VMS) installed in the vehicle, allowing for peer-cooperative communication. The basic assumption of the communication-based cooperative control framework is that drivers will comply with the recommended (feasible) control actions so as to materialize the direct transfers of passengers without long waiting time. The control centre will have a record of this compliance to help minimize issues associated with driver behaviour. The main advantages of dosing so are that operational tactics can be used in real time and drivers can drive in a cooperative manner. This decentralized control approach also reduces the complexity of the control problem, and enables control strategies can be applied in practice.

As shown in Figure 1 (c), a route segment is further divided into several small route sections by the stops u distributed in the route segment. The last stop s_N is the transfer stop that the route segment leads to. The route section is further divided into a few smaller intervals. An interval is a basic unit controlled by the communication control centre, which delivers advisory control action a, $a \in A$ to a PT driver when the vehicle arrives at each interval. New information is sent to the driver when the vehicle moves to the next interval.

Definition 1 (Control Action). A control action a is defined as an operational tactic that is used by the PT driver at a decision epoch t.

Definition 2 (Decision Rule). A decision rule $d_t\left(s\right)$ prescribes how to select an operational tactic from the available library of tactics for a vehicle trip in a specific state s at a specific decision epoch t.



(a) (b)

(c)

Fig.1 Decentralized communication-based cooperative optimization framework: (a) an example PT network, (b) communication groups of the example network, and (c) symbolic representation of the dynamic decision-making process

The time of the vehicle moving on the route segment is comprised of a set of decision epochs. At each decision epoch, the state of the vehicle is monitored through the communication center. There are three possible states at each decision epoch: ahead of schedule, $AAT_u < SAT_u$; on schedule, $AAT_u = SAT_u$; and behind schedule, $AAT_u > SAT_u$. Based on the state of the vehicle at the stop, suggested control action a with optimal value $v_t(a)$ is disseminated to drivers. Once the driver chooses a suggested control action and deploys it appropriately with the optimal value, the current schedule deviation can be mostly corrected. Figure 2 describes how control actions are used to maintain a planned vehicle trajectory. It illustrates the case in which traffic conditions cause the vehicle to slow down before Stop 2, together with a passenger overflow at Stop 2. This makes the current vehicle running behind schedule. Thus, a real-time responsive control action, e.g., speed up, is needed to keep the vehicle running on schedule or correcting the schedule deviation to the utmost at the next stop. This real-time response can help to return service to schedule and avoid the further propagation of schedule deviation along the route and keep service reliable.

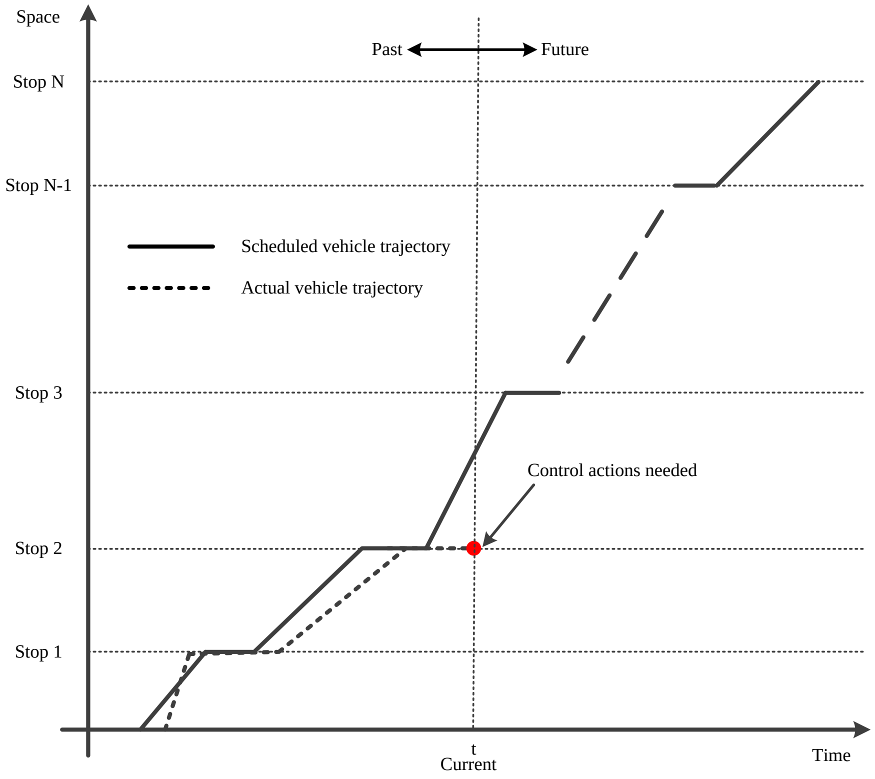


Fig. 2 Time-space diagram for dynamic PT operations

Definition 3 (Control Strategy). A control strategy π is defined as a sequence of decision rules, i.e., $\pi_i = \{d_1(s), d_2(s), \cdots d_n(s)\}$ for the whole decision epoch. Each decision rule $d_t(s)$ is associated with a decision epoch t and a decision state s. The control strategy π specifies the decision rule used at each decision epoch.

Definition 4 (State Propagation Process). A state propagation process P is defined as a set of states of all decision epochs, i.e., $P = \{s_1, s_2 \cdots s_n\}$ for the whole decision horizon T. Each state s_t is associated with a decision epoch t.

Vehicles in a PT network are treated as dynamic random elements. Their movements on the route segment are controlled by some selected dynamic control actions/operational tactics in real time. The main purpose of controlling these selected moving elements in a PT network with random variables is to maximize their encounter probability at predefined transfer nodes.

The dotted line in Figure 3 illustrates a possible state propagation process of a vehicle from stop 1 to stop N on a PT route segment. A stable state propagation process $P^* = \{s_1, s_2 \cdots s_n\}$ is defined as a state propagation process that the states of its each decision epochs are on schedule, i.e., $s_1 = s_2 = \cdots = s_n =$ on schedule. This means that all the green nodes in Figure 3 are connected.

An optimization procedure is thus needed to support both PT operators and drivers to efficiently search and deploy an optimal decision policy $\pi_i^* = \left(d_1^*(s), d_2^*(s), \cdots d_n^*(s)\right)$, defined from a library of feasible operational tactics, with respect to some predetermined system-performance criteria, e.g., a stable or quasi-stable state propagation process. The optimal decision policy is the collection of all the optimal decision rules $d_t^*(s)$ at each decision epoch. The optimal solution of the whole network $\Gamma^* = \left(\pi_1^*, \pi_2^*, \cdots \pi_{s^r}^*\right)$ is the collection of all the optimal decision policies.

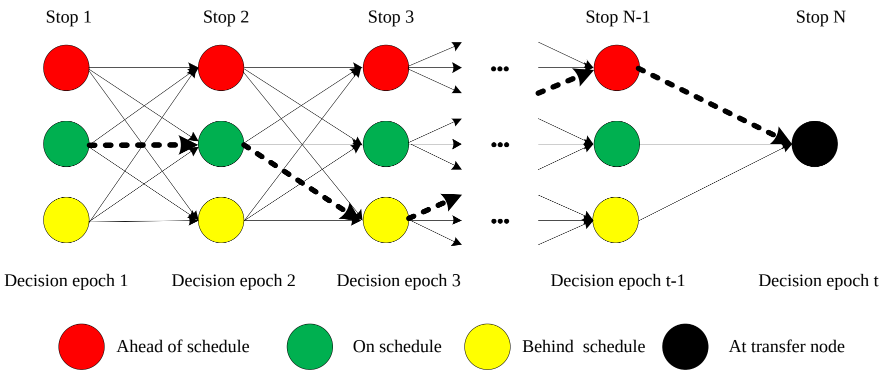


Fig. 3 Graphical representation of the dynamic vehicle state propagation process; this is of the movement of a vehicle on a route segment

It can be seen that the proposed optimization framework for the PT transfer synchronization problem is decentralized, dynamic and cooperative. This communication-based cooperative control strategy is based on a predetermined maximum synchronized timetable MST. It intends to keep each vehicle individually on schedule, increase the number of direct transfers and reduce the total deviation of total passenger travel time from the planned maximal synchronized timetable MST.

3 Formulation of control strategies

The first part of this section presents the proposed communication-based cooperative control (CCC) strategy. In addition, other three control strategies, i.e., without control (WC) strategy, conventional schedule-based control (CSC) strategy and communication-based non-cooperative control (CNC) strategy, are also presented here mainly as comparisons purposes. The second part then introduces some evaluation criteria that are used to evaluate the performance of these four control strategies.

3.1 Control strategies

The underlying principles of the four control strategies are explained in detail as follows. These strategies are presented in an order that the latter strategy is based on and integrated some control rules of the former strategy.

3.1.1 Without control (WC) strategy

The without control strategy means that no control actions are applied at each decision epoch. PT operators and drivers do not adopt any corrective measures for the current PT systems. Vehicles are just left to their own devices, and move freely and randomly along their route segments. This is the most common situations in current practice. Intuitively, it will have the worst performances. This control strategy is mainly used for comparison purpose.

3.1.2 Conventional schedule-based control (CSC) strategy

In the conventional schedule-based control strategy, a planned timetable is usually released to PT drivers privately or publically in advance. Then, at some predetermined control points, the driver needs to apply a holding control action in order to keep the vehicle on schedule. Denote $CDT_{i,u}$ as the current time which would be the actual departure time of vehicle trip i at stop u if no control actions are used. Then, the actual departure time of the vehicle $ADT_{i,u}$ is defined as follows:

if

$$CDT_{i,u} < SDT_{i,u}$$

then

$$ADT_{i,u} = SDT_{i,u}$$

else

$$ADT_{i,u} = CDT_{i,u}$$

The conventional schedule-based control strategy only uses holding tactic, and based on the current departure time and scheduled departure time information. It can be seen that this control strategy does not make use of any real-time communication between drivers and control centre. It mostly depends on the pre-planned timetable and drivers' control efforts at stops/stations. Usually, this control strategy is used for a single route to regularize its headway, i.e., reducing vehicle bunching.

3.1.3 Communication-based non-cooperative control (CNC) strategy

The CSC strategy only considers station control with holding tactic, and do not consider other inter-station control tactics, e.g., possible changes in speed or traffic signal priority. Under the communication-based control framework, the real-time vehicle location information and the schedule deviation between the actual vehicle trajectory and the scheduled vehicle trajectory can be continuously monitored and disseminated to drivers through the control centre. This information can be displayed online on the VMS installed on the vehicle. Thus, PT drivers can dynamically adjust their running speed so as to reduce the schedule deviations from the planned maximum synchronized timetable MST. Under this communication-based non-cooperative control (CNC) strategy, the actual arrival time $AAT_{i,u}$ of vehicle trip i at stop u is defined as follows:

$$AAT_{i,u} = SAT_{i,u} + \theta \cdot \left| CAT_{i,u} - SAT_{i,u} \right| \tag{1}$$

where $CAT_{i,u}$ is the current arrival time of vehicle trip i at stop u if no inter-station control actions are applied; θ is a randomization parameter describing the drivers' random schedule recovery behaviour. This parameter is defined as control strength with a random value ranging from 0 to 1. It is used to capture the inter-station control strength of drivers' schedule recovery behaviour on reducing the schedule deviation. If $\theta = 0$, it means a very strong control effort of the driver that completely eliminates the schedule deviation and keep the vehicle arriving on time. On the contrary, if $\theta = 1$, the vehicle will arrive at time $CAT_{i,u}$. It means that there is no drivers' schedule recovery effort or the effort is futile.

This drivers' schedule recovery effort can be realized through automatically and continually deploying the speed change control action by drivers themselves while driving between stations. The underlying principle of the station control in the CNC strategy is the same as that in the CSC strategy. That is the control logic used to determine the actual departure time is the same. Also only holding tactic is used in the station control. The CNC strategy further considers the inter-station control by taking advantage of the real-time vehicle trajectory and schedule deviation information provided by the control centre. However, one potential limitation of this strategy is that the vehicle trajectory and schedule deviation information are just shared between the control centre and the driver himself, not shared with other drivers who are in the same communication group. It means that a driver has only his/her own vehicle travel information, and does not know any other vehicle travel information of his/her peers. To remedy this undesirable “illness”, the “medicine” of a communication-based cooperative control (CCC) strategy is developed.

3.1.4 Communication-based cooperative control (CCC) strategy

In the CCC strategy, vehicle trajectory information is not only disseminated to the vehicle itself, but also to its peers in the same communication group. Thus, drivers have full information on both his/her own vehicle trajectory and his/her peers' vehicle trajectories. By doing so, drivers can drive in a cooperative, coordinated and adaptive manner. Thus, the collective motion of vehicles in a PT network will be self-organized. Intuitively, this strategy, with more real-time information available, may have better performance than the CNC strategy.

The proposed control logic for the CCC strategy is formulated as follows:

if

station u is not a transfer station; $NB_{i,u} = 0$ and $NA_{i,u} = 0$

then

$$v_t\left(skip-station\right)=1$$

else

if

station u is not a transfer station and $\max\left\{NB_{i,u}, NA_{i,u}\right\} \neq 0$

then

compute the actual arrival time $AAT_{i,u}$ and the actual departure time $ADT_{i,u}$ as follow

$$AAT_{i,u} = SAT_{i,u} + \theta \cdot \left|CAT_{i,u} - SAT_{i,u}\right|$$

$$ADT_{i,u} = \max\left\{CDT_{i,u}, SDT_{i,u}\right\}$$

else (station u is a transfer station)

compute the actual arrival time $AAT_{i,u}$ and the actual departure time $ADT_{i,u}$ as follow

$$AAT_{i,u} = SAT_{i,u} + \theta \cdot \left|CAT_{i,u} - SAT_{i,u}\right|$$

$$ADT_{i,u} = \max\left\{CDT_{i,u}, SDT_{i,u}, AAT_{j,u} + \max_{j\in R_i}\left(\Delta_{j,i}\right)\right\}$$

where $v_t\left(skip-station\right)=1$ means skip-station; R_i is the set of vehicle trips that are planned to be synchronized with vehicle trip i; $\Delta_{j,i}$ is the required walking time from vehicle trip j to vehicle trip i.

The CCC strategy comprises of three control actions, namely skip-station/stop, holding and changes in speed. Under this CCC strategy, whether to hold a vehicle at the transfer station or not depends not only on its own current departure time if without using tactics and the scheduled departure time, but also on the actual arrival times of its peer vehicles and the associated transfer walking time needed. It should be pointed out that if there are large disruptions happened, which will cause a very long delay to some of the peer vehicles, then the total travel time of the vehicle may increase. However, taking into consideration of the schedule recovery behaviour of drivers, it is assumed that this long delay situation can be mostly avoided.

3.2 Evaluation of control strategies

The examination of the four control strategies calls for criteria in evaluating their performance and also in selection of the best control actions for implementation. The four control strategies are compared with indicators concerned with the transfer waiting time, the transfer connection, vehicle travel time and the schedule adherence of vehicles.

3.2 .1 Transfer waiting time indicator

The transfer waiting time refers to the difference between the actual departure time and the time that passengers are ready for departure at the boarding platforms. It has an important factor on passengers' perception of transfer service reliability. Let $RDT_{i,u}$ denote the time that passengers are ready for departure for vehicle trip i at transfer station u . The average transfer waiting time $\overline{wt}$ for a PT network with $|I|$ vehicle trips and $|N|$ transfer stations is:

$$\overline{wt} = \frac{\sum_{i=1}^{|I|}\sum_{u=1}^{|U|}\left(ADT_{i,u} - RDT_{i,u}\right)}{|I|\cdot|U|} \tag{2}$$

3.2.2 Transfers connection indicator

The transfer connection measures the connectivity of the PT service. Using this performance indicator, it can clearly see how good or bad the planned transfers are materialized. Two criteria are used in the analysis: the number of connected transfers and the number of missed transfers. A transfer from vehicle trip j to vehicle trip i is defined as a connected transfer if $RDT_{i,u} \leq ADT_{i,u}$; otherwise, it is defined as a missed transfer.

3.2.3 Vehicle travelling indicator

Two measures, the average vehicle travel time and the average vehicle travel speed, are used in the analysis of vehicle travelling. The average vehicle travel time $\overline{tt}$ for a PT network with $|I|$ vehicle trips is defined as:

$$\overline{tt} = \frac{\sum_{i=1}^{|I|} tt_i}{|I|} \tag{3}$$

where tt_i is the travel time of vehicle trip i from the beginning of the route to the end of the route. Let L_r denote the length of route r and I_r denote the set of vehicle trips of route r, then the average vehicle travel speed $\overline{ts}$ is defined as:

$$\overline{ts} = \frac{1}{\sum_{r=1}^{|R|} |I_r|} \sum_{r=1}^{|R|} \sum_{i=1}^{|I_r|} \frac{L_r}{tt_i} \tag{4}$$

Both the operators and passengers are concerned with these two measures since they are directly related to the operation costs and service efficiency.

3.2.4 Schedule adherence indicator

Schedule adherence measures are associated with the headways and the deviations from the planned maximum synchronized timetable. Three measures are used in the analysis: the average schedule deviation, the average standard deviation of headways and vehicle bunching percentage. Although the transfer waiting time and transfer connection indicators are the most important two indicators of the transfer reliability, the schedule adherence indicator is also very important since it evaluates the effectiveness of control strategies from a system-wide point of view, i.e., not just focues on trasnfer stations.

The average schedule deviation refers to the average difference between the actual departure time and the scheduled departure time. It is defined as:

$$\overline{sd} = \frac{\sum_{i=1}^{|I|} \sum_{u=1}^{|U|} \left(ADT_{i,u} - SDT_{i,u} \right)}{|I| \cdot |U|} \tag{5}$$

A large variation of headways will lead to long waiting time for randomly arriving passengers. Let $H_{i,u}$ denote the headway of vehicle trip i between its former vehicle, and $|U_r|$ denote the number of stations in a route r. For a given route r with $|I_r|$ vehicle trips, its average standard deviation of headways $\overline{\sigma(H)}$ is deined as:

$$\overline{\sigma(H)} = \frac{1}{|I_r|} \sum_{i=1}^{|I_r|} \sqrt{\frac{1}{|U_r - 1|} \sum_{r=1}^{|U_r|} \left(H_{i,u} - \frac{1}{|U_r|} \sum_{u=1}^{|U_r|} H_{i,u} \right)^2} \tag{6}$$

The vehicle bunching percentage is defined as the percentage of vehicle headways that are less than a threshold headway $\Delta(h)$.

$$\Pr\left(H_{i,u} < \Delta(h)\right),\ i \in I_r, u \in U_r, r \in R \tag{7}$$

4 Monte Carlo method for network simulation

For a given PT network, the travel times between each two stops are treated as random variables, and also the numbers of boarding/alighting passengers at each stop are not deterministic. Computation of the system-performance measures requires a proper simulation model. To understand and investigate the potential effects of the four control strategies, a Monte Carlo method-based simulation procedure is used. The Monte Carlo method is a useful method used to simulate the random behaviour of a system. It has been widely used in traffic and transportation systems simulation (e.g., Papacostas, 1987; Yin, et al., 2004; Yan, et al., 2012; Liu, et al., 2013). The Monte Carlo method-based simulation procedure used in this study is outlined as follows:

Step 1 (Initialization): Set the sample number $k = 1$.

Step 2 (Sampling): For a given PT route, the inter-station travel time r_m is assumed to be a random variable with a given mean and variance. For each vehicle trip, generate a vector of travel times based on the associated inter-station travel time distribution functions. For each station, sample the control strength θ within a given range.

Step 3 (Calculating parameters): Based on the passenger boarding/alighting rate and the sampled interstation travel times for each vehicle trip, calculating parameters used for constructing vehicle trajectory, which include vehicle arrival/departure time at each stop, headways, the number of boarding/alighting passengers, dwell time at each stop.

Step 4 (Deploying control strategies): The four proposed control strategies are applied to optimize the motion processes of vehicles. After the optimization, a set of new vehicle trajectories is obtained for each route.

Step 5 (Collecting performance indicators): Based on the modified new vehicle trajectories, the values of the performance indicators are collected.

Step 6 (Termination): If sample number $k < k_{\max}$, where $k_{\max}$ is the predetermined sample size, then increase sample number $k := k + 1$ and go to step 2; otherwise, stop.

After the termination of the simulation, the values of performance measures can be collected. Then, the mean value of these parameters can be calculated and thus comparisons of the performances of the control strategies can be conducted.

5 Numerical example

In this section, a detailed numerical example is used to investigate the performances of the four control strategies. The example PT network, shown in Figure 4, is adapted from the example 1 in Ceder, et al., (2001).

5.1 Data settings

The simple example PT network has two routes with two transfer stops, namely, stop 8 and 14. Route Ⅰ has 10 stops and route Ⅱ has 11 stops. The lengths of route Ⅰ and route Ⅱ are set as 11.5km and 15.75 km, respectively. The numbers on the arcs represent the travel times r_m (min). Both the average travel speeds of the two routes are set as 15km/h. After implementation of the heuristic algorithm proposed by Ceder, et al., (2001), the maximum synchronized timetable can be obtained. Table 1 summaries the resulted departure times for the two routes, and the corresponding meeting times at the two transfer stops. This maximum synchronized timetable totally results in 4 simultaneous arrivals of vehicles from the two routes. It should be noted that by considering both directions, both the direct transfers from route Ⅰ to route Ⅱ and from route Ⅱ to route Ⅰ can be achieved. Thus there are 8 connected transfers.

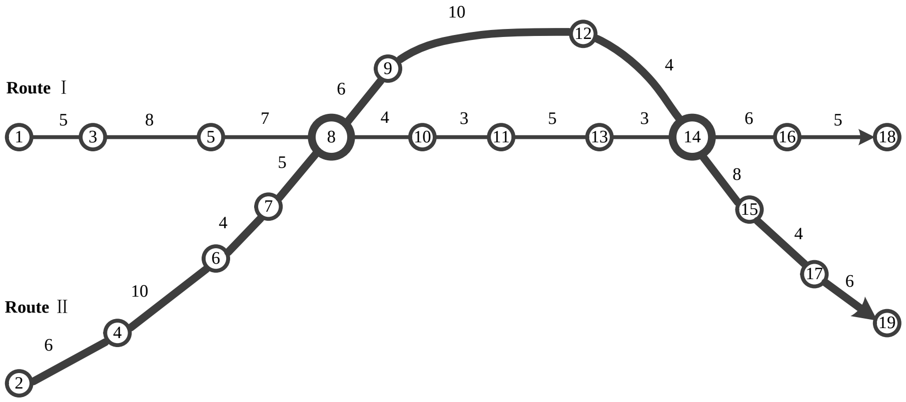


Fig. 4. The example PT network (adapted from Ceder, et al., 2001)

The travel times between stops r_m are assumed to follow the normal distributions $N\left(r_m, 0.01r_m^2\right)$. The average passenger boarding rate and alighting rate at each stop (pass/min) is shown in Table 2. The marginal dwell times per boarding and alighting passenger are taken as 4s and 2s, respectively. It is assumed that the vehicle capacity is enough to meet the passenger demand, i.e., no passengers will be left on the platform and wait for the next bus. The control strength θ is set within the range of 0 to 0.2. For simplicity, the required walking times for all the transfers from route Ⅰ to route Ⅱ and from route Ⅱ to route Ⅰ are all set as 30s. The threshold headway $\Delta(h)$ is taken as 60s.

Table 1. Maximal synchronized timetable for the example PT network

Departure time (min)		Meeting time at stop 8 (min)	Meeting time at stop 14 (min)	Total no. of meetings
Route Ⅰ	Route Ⅱ			
5	0	25		4
13	8	33		
21	16	41		
26			61	

Table 2. Average boarding and alighting rate at each stop (pass/min).

Route	Stop	1	3	5	8	10	11	13	14	16	18	
Route Ⅰ	Boarding	1.250	0.625	0.375	1.250	0.250	0.625	1.000	0.750	0.125	0.000	
	Alighting	0.000	0.000	0.000	1.000	0.125	0.750	1.250	0.500	1.000	1.625	
	Stop	2	4	6	7	8	9	12	14	15	17	19
Route Ⅱ	Boarding	0.500	2.125	1.250	0.750	1.500	0.125	1.000	1.625	0.375	0.125	0.000
	Alighting	0.000	0.000	1.000	0.875	1.500	0.625	0.500	1.750	1.250	0.875	1.000

5.2 Simulation results

The Monte Carlo method-based simulation procedure is applied to simulate the example PT network under four different control strategies. The procedure is coded in Matlab R2012b and implemented on a personal computer with 64 bit operating system, Inter Core i5-3570 CPU @3.40GHZ, and 8.00 GB RAM. The sample size $k_{\max}$ is set as 2000. After the simulation and optimization, the final statistical results on the performance measures of route Ⅰ and route Ⅱ under the four different control strategies are accumulated and summarized in Table 3 and Table 4, respectively. The total number of connected and missed transfers for the whole network of each control strategy are graphically shown in Figure 5. The average passenger transfer waiting time per control strategies is shown in Figure 6.

From Figure 5 and Figure 6, we can draw an immediate conclusion that applying the CCC strategy can: (1) significantly improve the number of connected transfers and thus reduce missed transfer connections, and (2) dramatically reduce the average passenger transfer waiting time. Without using any operational tactics, there are four successful connected transfers and four missed transfer connections. Both the CSC and CNC strategies cannot considerably improve the number of connected transfers. However, using the CCC strategy, all the eight planned transfers are materialized. What’s more, under the CCC strategy the average passenger transfer waiting time can be reduced to 68 seconds that is a reduction of 86.18%, compared to the WC scenario with 492 seconds. The CSC strategy increases the average passenger transfer waiting time, and the CNC strategy only leads to a slight reduction of 8.54%.

It is clear from the above results that the use of the CCC strategy can remarkably improve the occurrence of planned transfers and significantly reduce the average passenger transfer waiting time. It can be seen from Table 3 and Table 4 that the CCC strategy performs better than the WC and CSC strategies on almost all the performance measures. However, compared to the CNC strategy, the CCC strategy increases the average vehicle travel time, and thus reduce the average vehicle travel speed. It also slightly increases the average schedule deviations. These drawbacks are mainly come from holding vehicles at transfer stops in order to increase the probability of successful connected transfers. However, since these increase and reduction are very slight, these drawbacks are not so significant, especially compared to the considerable improvement in connected transfers and reduction in transfer waiting time. Another interesting finding from this numerical example study is that the CSC strategy cannot considerably reduce the vehicle bunching percentage when there are vehicles that are heavily delayed and behind of schedule.

Table 3. Simulation results of different control strategies for route Ⅰ

Performace measures	Control strategies			
	WC	CSC	CNC	CCC
Average transfer waiting time (s)	231	273	192	39
Number of connected transfers	2	2	2	4
Number of missed transfers	2	2	2	0
Average vehicle travel time (s)	2939	2939	2835	2855
Average vehicle travel speeed (km/h)	14.09	14.09	14.60	14.50
Average schedule deviation (s)	100	72	25	34
Average standard deviation of headways	112.02	94.99	41.14	40.49
Vehicle bunching percentage	12.28%	12.28%	0.00%	0.00%

Table 4. Simulation results of different control strategies for route Ⅱ

Performace measures	Control strategies			
	WC	CSC	CNC	CCC
Average transfer waiting time (s)	261	328	258	29
Number of connected transfers	2	1	2	4
Number of missed transfers	2	3	2	0
Average vehicle travel time (s)	3779	3922	3832	3841
Average vehicle travel speeed (km/h)	15.01	14.46	14.80	14.76
Average schedule deviation (s)	123	82	28	34
Average standard deviation of headways	133.34	88.66	46.83	41.73
Vehicle bunching percentage	9.52%	0.00%	0.00%	0.00%

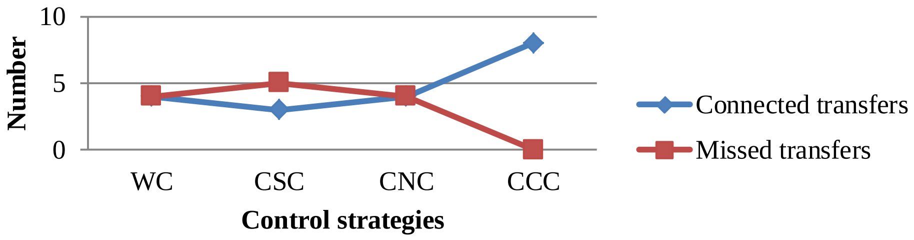


Fig. 5. Number of connected and missed transfers for the four control strategies

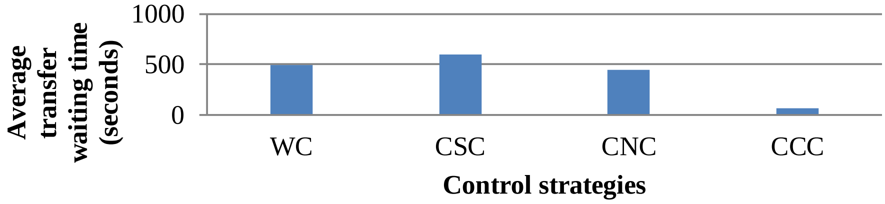
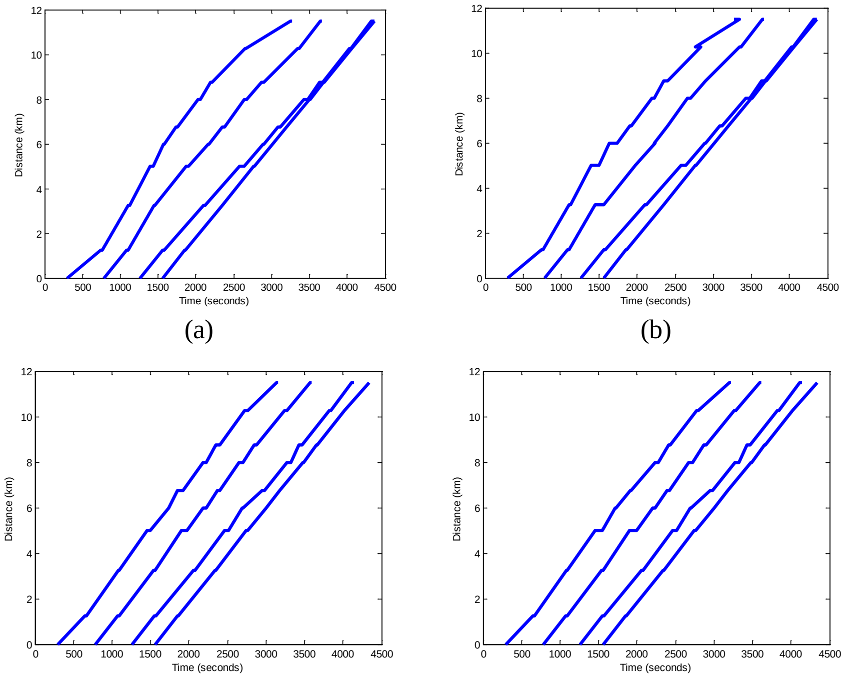
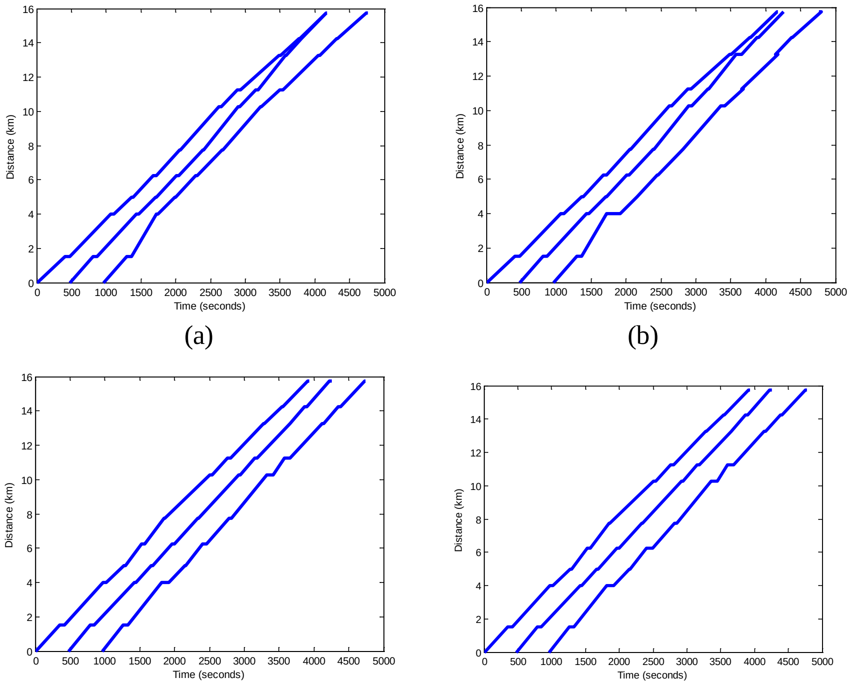


Fig. 6. Average transfer waiting time for the four control strategies



(a) (b) (c) (d)

Fig. 7. Vehicle trajectories of route Ⅰ under different control strategies: (a) WC; (b) CSC; (c) CNC; (d) CCC



(a) (b)

(c) (d)

Fig. 8. Vehicle trajectories of route Ⅱ under different control strategies: (a) WC; (b) CSC; (c) CNC; (d) CCC.

The simulated vehicle trajectoris of route Ⅰ and route Ⅱ are graphically shown in Figure 7 and Figure 8, respectively. It can be seen from these figures that without using any control actions, no surprisingly, vehicles intend to be hunching and have larger headway variations and schedule deviations than the other three strategies. Although the CSC strategy can somewhat reduce the schedule deviations, it cannot help to improve the number of transfer connections and even leads to an increase of transfer waiting times. The CNC and CCC strategies, however, can perfectly eliminate vehicle bunching, and also have almost the same headway and schedule deviations. Therefore, we can conclude that the CCC strategy is the most promising one among the four control strategies on improving the system-wide performance.

6 Case study

To assess and compare the effectiveness of the proposed control strategies and their potential for future implementation, the four control strategies and the proposed Monte Carlo method-based simulation procedure have been applied to a real-life example of a small bus network in Auckland, New Zealand. The Auckland Regional Public Transport Plan was recently released with the aim of developing an integrated and well-connected PT network which can allow Aucklanders to have seamless and smooth transfers between hierarchical high and low frequency PT routes (Auckland Transport, 2013). Planning and operation tools are thus needed to help develop an integrated multi-modal PT system, including bus, ferry, and train, for the future sustainable development of the country's largest and busiest city. Transfers in the current PT systems are usually criticized for not being convenient and efficient for users. Thus, synchronization of transfers, through better operations control will definitely reduce the inter-route or inter-modal passenger transfer waiting time and make the PT service more reliable and attractive for car users, as part of the target to reduce traffic congestion, pollution and improve its sustainability.

Study routes are based on a small existing bus network in one section within the North Shore and Auckland central business district (CBD) area, as depicted in Figure 9. The PT network selected as the case study is mainly comprised of three bus routes with two transfer points, namely the Northern Express (NEX), Route 858 and Route 880. The NEX has a segregated bus lane with two-way and dedicated park and ride facilities along the Northern Motorway corridor. It provides efficient and reliable service from Albany in North Shore city to the Britomart Transportation Centre in Auckland CBD. The NEX has a very large volume of users during peak hours. Route 858 runs north–south (parallel and to the east of the NEX for much of its route) from Long Bay to Auckland CBD. Route 880 is feeder loop that transfers with the NEX and Route 858 at transfer point 1 and point 2, respectively.

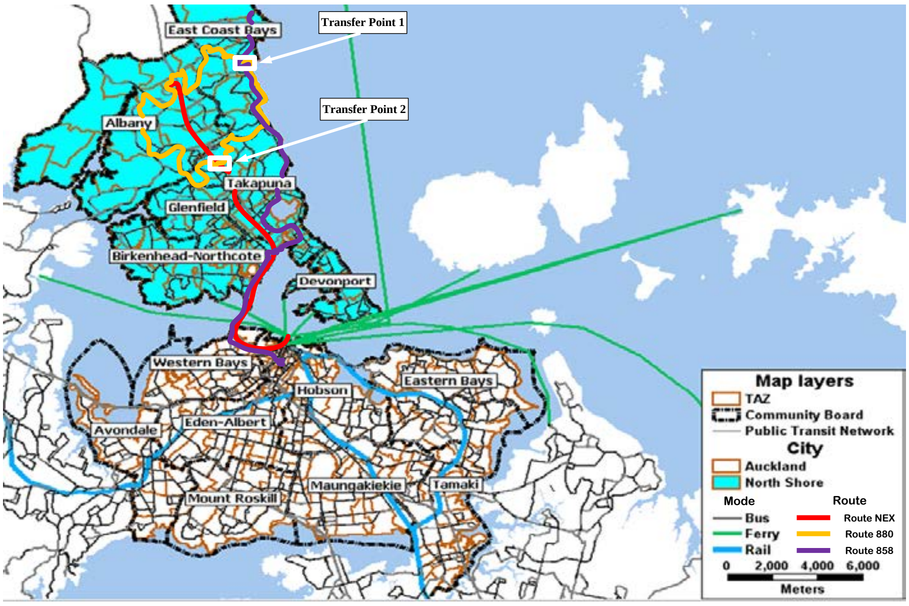


Fig. 9. Study routes in public transport systems of Auckland city and North Shore

The data used in the case study is collected from the Auckland Transport (AT) in May 2014. The buses in the current AT are equipped with AVL system, which can detect the arrival time and departure time at a bus stop. Thus, it provides a very good way to collect data on bus location, vehicle ID, arrival/departure times at stops and calculated travel times between stops. These recorded data are transmitted, through a communication system, to transit dispatchers. Thus, the control centre can monitor the schedule adherence of vehicles.

Timetables of the current three bus routes are not synchronized at the initial timetable development stage. Thus, a shifting departure time procedure, using the algorithm developed in Ceder, (2007), is first adopted to modify the current timetables so as to make these timetables of the three routes synchronized. The data for each route, as the inputs of the simulation model, contain the vehicle ID, stop ID, the arrival and departure times, the dwell times, the number of boarding and alighting passengers, and the number of passengers on-board the bus upon departure. In addition, the scheduled departure times are known from the timetable. The scheduled inter-stop travel times are taken from the current timetables. For simplicity, the standard variance of the inter-stop travel time is set as 0.15*(travel time) by statistical analysis of historical AVL data. The numbers of boarding and alighting passengers at each stop are collected by road-side checkers, and are proportionated into average boarding rate and alighting rate of each stop. In the simulation model, the average passenger boarding and alighting times are set as 4s and 2s, respectively. The headways of the three routes are taken as 5 minutes. The control strength θ is set as a random number within the range of 0 to 0.35. The required transfer walking times for both transfer point 1 and point 2 are set as 30s. The threshold headway $\Delta(h)$ is taken as 60s. The time horizon of the simulation is set as 12 hours in order to generate enough data for statistical analysis. The Monte Carlo simulation-based optimization procedure is implemented in Matlab to generate statistical analysis results of the four control strategies.

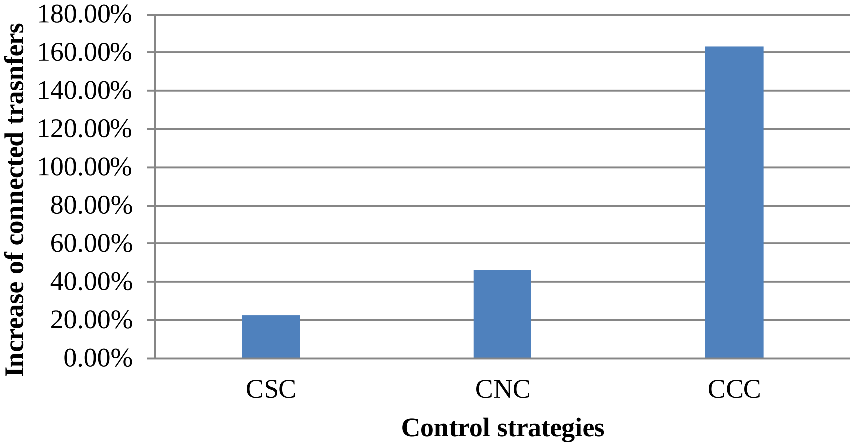


Fig. 10. Optimization results on connected transfers compared with the without-control (WC) strategy

Figure 10 plots the increase of the observed number of direct transfers under the CSC, CNC and CCC strategies, compared to the WC strategy. It can be seen that applying the CCC strategy the number of connected transfers can be increased by more than 160%. However, the increase of using the CSC and CNC strategies is less than 50%. It clearlly demostrates that utilizing the CCC strategy can significantly improve the number of connected transfers and thus increase the reliability of planned transfers.

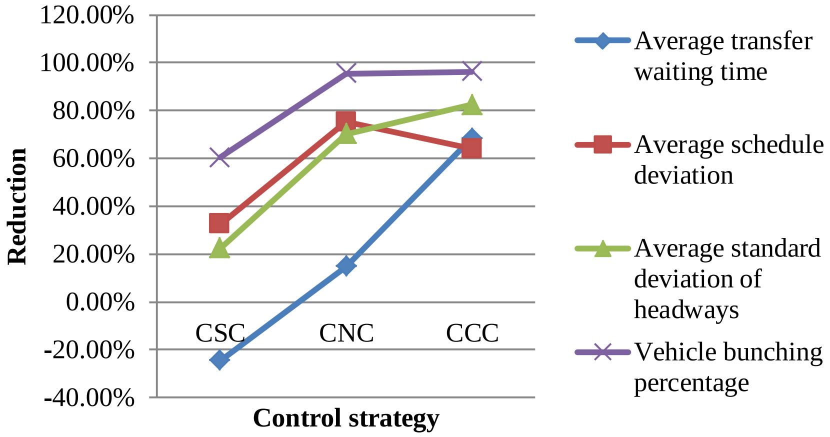


Fig. 11. More results of the simulation-based optimization modeling in terms of % reduction corresponding to the without-control (WC) strategy

More simulation results are shown in Figure 11 in terms of % reduction corresponding to the without-control (WC) strategy. From this figure it is apparent that the CCC strategy can achieve the best improvement record of average transfer waiting times. At the same time, the CSC strategy results in an increase of the transfer waiting time compared with the WC strategy. With respect to average schedule deviations all are resulted in improvement (reduction of) between 30% and 80%. The CNC strategy has the best performance in reducing average schedule deviation. As for the ability of regularizing vehicle headways, the CNC and CCC strategies attain almost the same improvement. The % of vehicle bunching can be reduced nearly to 0, except for some cases, such as an extended bus delay caused by serious traffic jam or a heavy flow of boarding passenger at intermediate stops. The scheduled headways cannot be well maintained even with the help of bus driver’s schedule recovery efforts. These results clearly demonstrate that the CCC strategy is enabling the improvement of the actual occurrence of planned coordinated transfers, reducing transfer waiting times and increasing the reliability and regularity of the PT service.

7 Summary and Conclusions

Synchronized transfers in public transport (PT) networks are utilized to reduce the inter-route and/or inter-modal passenger transfer waiting time, provide a well-connected service, and improve the attractiveness and image of the PT service. However, in practice, it is a well-known phenomenon that synchronized transfers are not always materialized because of some stochastic and uncertain factors, such as traffic disturbances and disruptions, fluctuations of passenger demand and erroneous behaviour of the PT drivers. As a result, missed direct-transfers will not only frustrate existing users, but also discourage potential passengers from using the PT service. This missed-meeting problem can be mostly avoided if the movement of vehicles on PT routes is well-controlled by real-time-based selected online operational tactics, such as skip-stop/station, holding, and changes of speed.

The rapid development of information and communication technology (ICT) opens the door for providing more advanced and attractive PT service through better real-time operations control by using some new technologies, such as automatic vehicle location, automated passenger counters and geographic information systems. This research proposes a communication-based decentralized cooperative optimization framework to reduce the uncertainty of meetings between PT vehicles at planned transfer points by using selected online operational tactics. This work systematically defines the elements and components used in the optimization framework. Most of the previous studies of this theme examine only the effect of one or two operational tactics on improving the reliability of the PT service; in this work the optimization framework used can investigate the performance of a library (large number) of tactics. In addition, under the communication-based cooperative control strategy, real-time vehicle location information and optimal control actions can be relayed to drivers using the same communication group. Thus, drivers have full information on both their own vehicle location and on their peers' vehicle location. Thus, drivers can drive in a cooperative, coordinated and adaptive manner so as to attain a better connectivity between routes at planned transfer points.

Because of the endogenous randomness in vehicle travel time, passenger demand and driver behaviour, a Monte Carlo method-based simulation procedure is developed to examine the communication-based control strategy, as compared to other three control strategies. A detailed numerical example and a case study in Auckland, New Zealand, are exhibited using simulation and optimization; following are the conclusions derived from these tests.

First, the utilization of a combination of selected online operational tactics improves the actual occurrence of planned coordinated transfers, reduces transfer waiting times and increases the reliability and regularity of the PT service. That is, because of both positive and negative effects of each tactic on the performance of the PT system, a mixture use of more than a few tactics enables complementary executions in real-time operations, thus maximizing the overall system-wide performance.

Second, the proposed communication-based cooperative control strategy attains the best performance-based results in comparison with other three control strategies, namely without-control, conventional schedule-based control and communication-based non-cooperative control strategies. That is, improving the actual occurrence of planned coordinated transfers, reducing average passenger transfer waiting time and reducing vehicle bunching percentage. It is to note, however, that the proposed strategy will slightly increase the average schedule deviation, compared with the communication-based non-cooperative strategy, because of holding vehicles at transfer points for increasing the number of connected transfers. Thus, a trade-off situation exists between improving transfer connectivity and reducing schedule deviation. The decision related to this trade-off depends on the number of passengers aiming at making transfers.

Third, the behaviour of drivers related to schedule recovery plays an important role in increasing schedule adherence and improving the actual occurrence of planned coordinated transfers. However, this behaviour is largely depends on the compliance of drivers of the control actions relayed by the control center.

The main limitation of this study is the lack of accurate information on the number of transferring passengers. One possible way to get this information is by the use of smartphone PT Apps integrated with the communication-based vehicle control system. This will create real-time interactions between the control center, the drivers, and the passengers.

Future research tends to focus on: (i) incorporating more feasible tactics in the optimization framework; (ii) optimizing the control logic of the communication-based control strategy; (iii) integrating vehicle and crew scheduling; and (iv) case studies of actual implementation.

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