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CBVC-B: A System for Synchronizing Public-Transport Transfers Using Vehicle-to-Vehicle Communication

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Abstract

This work proposes a communication-based vehicle control system for buses (CBVC-B) to synchronize passenger transfers in public-transport (PT) networks. The CBCV-B, using vehicle-to-vehicle communication, enables PT drivers to share their vehicle location, speed, direction, and passenger information with their peers within the same communication group. The main purpose of the CBVC-B is to increase the actual occurrence of planned direct-passenger transfers by the use of certain dynamic control tactics in real-time operation. A detail description of the CBVC-B is illustrated in this work including its main components and main features. The sequential decision-making process of the real-time deployment of operational control tactics in the CBVC-B is formulated as a finite-horizon Markov decision process model. The potential benefits of the proposed CBVC-B are also discussed from the perspectives of both the PT users and the PT operator. It is formulated as a bi-objective optimization problem. The Pareto optimal solutions can be displayed for the PT operators so as to serve as a basis for their decision-making process when selecting operational control tactics.

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Keywords: Public transport; transfer optimization; communication-based vehicle control; operational tactics; V2V communication

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1. Introduction

Synchronized public-transport (PT) timetables are created to enable PT passengers to enjoy seamlessly direct transfers, and thus improve the level-of-service of PT systems. However, due to the dynamic, stochastic and uncertain nature of traffic, planned synchronized PT transfers are not always materialized. Missed direct transfers will not only frustrate the existing PT passengers, but also result in a loss of new PT users.

A recent study by Chowdhury and Ceder (2013) identified the attributes that can define a connection as being planned transfer. According to their study, five attributs: network integration, integrated timed-transfer, integrated physical connection of transfers, information integration, and fare and ticketing integration, are recognized to be the essential elements of the definition of a planned transfer. On the contrary, an unplanned transfer is defined as a connection that has been created without any guidance on how to make the connection (Chowdhury and Ceder, 2013).

Generally speaking, measures usually employed to achieve a planned synchronized transfer can be classified as the manner shown in Fig. 1. First, transfers can be classified into two categories: planned transfers and unplanned transfers. To planned transfers, at network design stage, the network integration and integrated physical connection of transfers need to be achieved first to reduce transfer walking time (Ceder and Wilson, 1986; Ceder, 2007; Chowdhury and Ceder, 2013). At operational planning stage, maximal synchronized timetables (MSTs) are then created for transit routes to maximize the number of simultaneous bus arrivals at transfer nodes (Ceder, 2001; Shafahi and Khani, 2010). The MSTs problem is usually formulated as mixed integer mathematical programming models and heuristic algorithms are developed to solve them due to their NP-hard characteristics. The outputs of the models are the departure times of transit routes. However, because of the variability of traffic conditions, the need to comply with passenger demand and the stochastic running time of vehicles, this MSTs approach is not realistic in practice, and scheduled transfers are not always materialized.

Another approach to alleviate the uncertainty of simultaneous arrival of vehicles is to use some selected operational tactics, such as holding, skip-stop, short-turn. Generally, it can be classified into two categories: static operational tactics (SOTs) and dynamic operational tactics (DOTs). DOTs mean that there are communications between drivers and operational tactics are used in real time, while SOTs are not. Studies (Hadas and Ceder, 2008a; Hadas and Ceder, 2008b; Hadas and Ceder, 2010; Ceder et al., 2013; Nesheli, et al., 2013) using SOTs showed that the frequency of simultaneous transfers can be significantly improved and also the total passenger travel time can be reduced.

The potential benefits of using SOTs to synchronize PT transfers have been demonstrated with numerical simulations and case studies. However, the disadvantage is that operational tactics are used statistically, not dynamically. It is still difficult to use them in real-life operational control of PT vehicles. The main challenge is how to use the selected operational control tactics on line and in real time.

The rapid development of information and communication technology modernizes the image of PT systems and opens the door to dispatch vehicles dynamically and in real time. Xu et al. (2001) studied the transit holding problem with real-time information available and showed that with the availability of real-time vehicle location information, the total passenger waiting time could be reduced. Liu et al. (2013) proposed a inter-vehicle communication based sheme to synchronize PT transfers in Beijing, China. Their results showed that using this sheme the total number of direct transfers was considerably increased, and the total passenger travel time was significantly reduced.

Vehicle-to-vehicle (V2V) communication is a new emerging technology. It enables drivers to share their vehicle location, speed, direction, and passenger information with their peers within the same communication group. It is recognized as an important component of intelligent transportation systems (ITS) and has been widely used in transportation field. For example, communication-based train control (CBTC) system is employed to increase the train line capacity by safely reducing the headway between trains traveling along the line (Zeng, et al., 2007; Pascoe and Eichorn, 2009). Liu (2011) investigated the bus bunching problem, and the theoretic analysis and case study results showed that using a vehicle-to-vehicle communication scheme, bus drivers can drive in a cooperative manner and bus bunching can be significantly reduced.

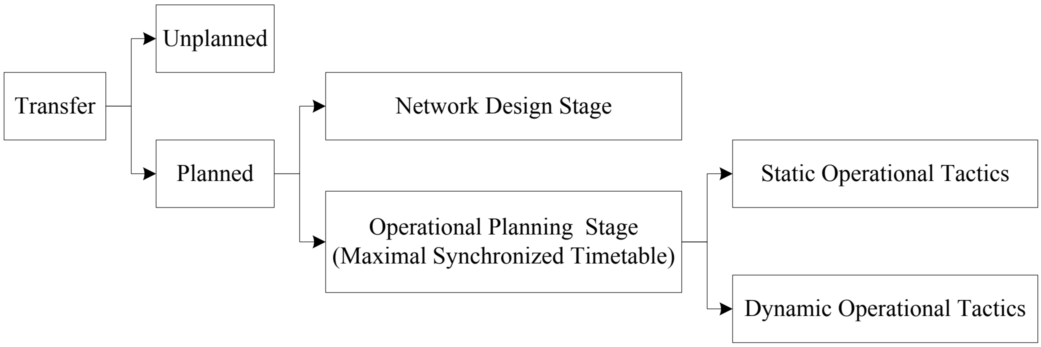

Fig. 1. Classification of public-transport transfers and related measures to achieve synchronized transfers

The main purpose of this work is to use certain selected DOTs to increase the total number of direct transfers in PT networks. It is realized through a communication-based vehicle control system for buses (CBVC-B) using V2V communication. The aim of the proposed CBVC-B is to increase the actual occurrence of planned direct-transfers by the use of some selected dynamic control tactics in real-time operation.

The remaining parts of this work are organized as follows. In section 2, a detail description of the CBVC-B, from main components to main features, is presented. In section 3, a finite-horizon Markov decision process model is used to describe the decision making activity of the real-time deployment of operational control tactics in CBVC-B. In section 4, the potential benefits of the CBVC-B are analyzed from the perspectives of both the PT user and the PT operator. Finally, conclusions and possible future research are given in section 5.

2. Overview of the CBVC-B

In this section, we provide a detail description of the CBVC-B. The main components of the system are introduced first, and then followed the main features.

2.1. Main components

The CBVC-B described here is similar to the system introduced by Liu et al. (2013). In this system, a transit network is divided into several small parts by trasfer stops or shared route segments. Each part is assigned a communication center to be responsible for the communication coordination of vehicles within that part. Vehicles belong to a communication center are in a same communication group and can share information with their peers. The CBVC-B can mainly perform the collection, transmission, storage, processing, and dissemination of vehicles and passengers information.

In fact, buses in Beijing began to be equipped with GPS device in 1999. After the Beijing 2008 Summer Olympics, now almost all buses in the central business district are equipped with GPS device. A systematic description of the system architecture of the CBVC-B is shown in Fig. 2. An on-board device (OBD) is installed on the bus to receive signals from GPS satellites. The OBD can record information about bus vehicle ID, vehicle location, vehicle speed, time, route direction, route ID and driver ID. A Sim card is embedded in the OBD. By using so, the recorded data can be transmitted to the database in the communication control center through GSM/GPRS networks.

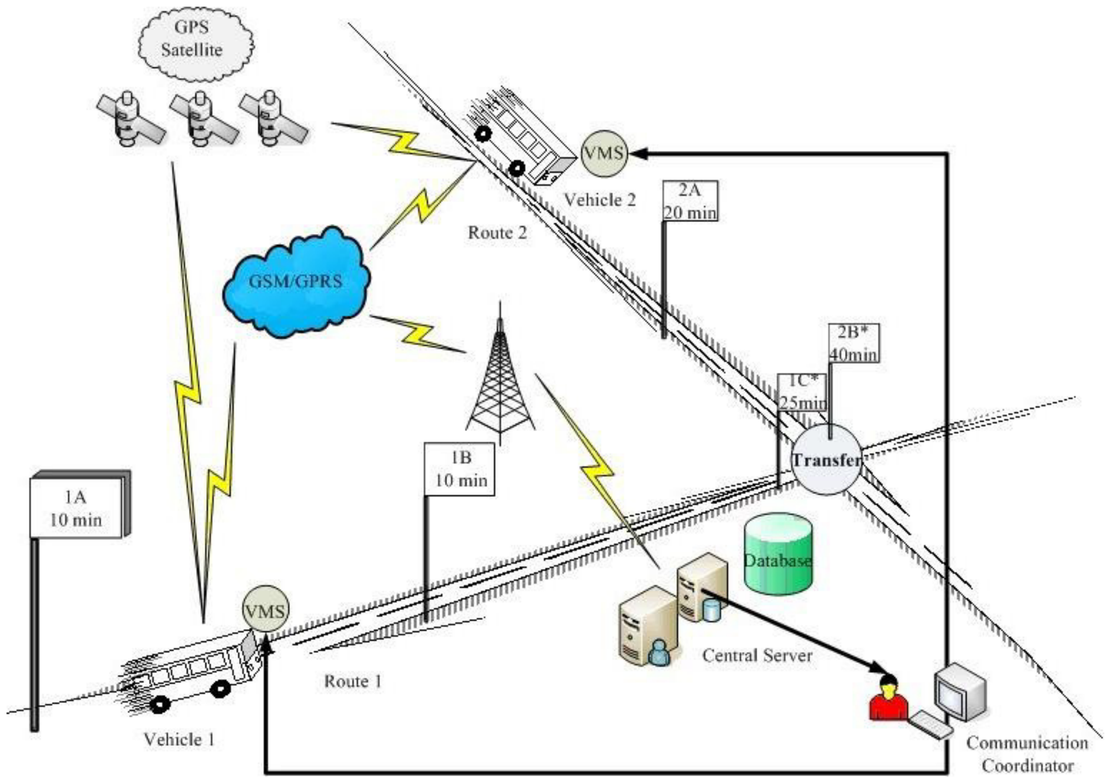

Fig. 2. The system architecture of CBVC-B

GPS data is transmitted to the communication center in a time interval of 30 seconds. The data is visualized in GIS maps. The real-time location of vehicles can be seen in a user-friendly vehicle monitoring system developed for the bus agencies as shown in Fig. 3. By doing so, the communication coordinator has knowledge about the relatively accurate location, direction and speed information of the vehicles of a same group. Based on the knowledge, advisory speed information, holding time information, skip-stop information, etc., are disseminated to the drivers in the same group. Drivers will follow the advisory information so as to guarantee that they can meet simultaneously or within a given time window at the planned transfer point.

The advisory information can be displayed online to drivers on the on-board variable message sign (VMS) installed in the vehicle where can be easily noticed by drivers. This will allow for a peer-to-peer (P2P) cooperative communication between drivers in a communication group. Through this V2V communication system, drivers can drive in a cooperative manner.

It is to note that the basic assumption of CBVC-B system is that drivers will comply with the recommended vehicle control tactics so as to materialize the direct transfers of passengers without waiting time. The control center will have a record of this compliance to help minimizing issues associated with driver behavior.

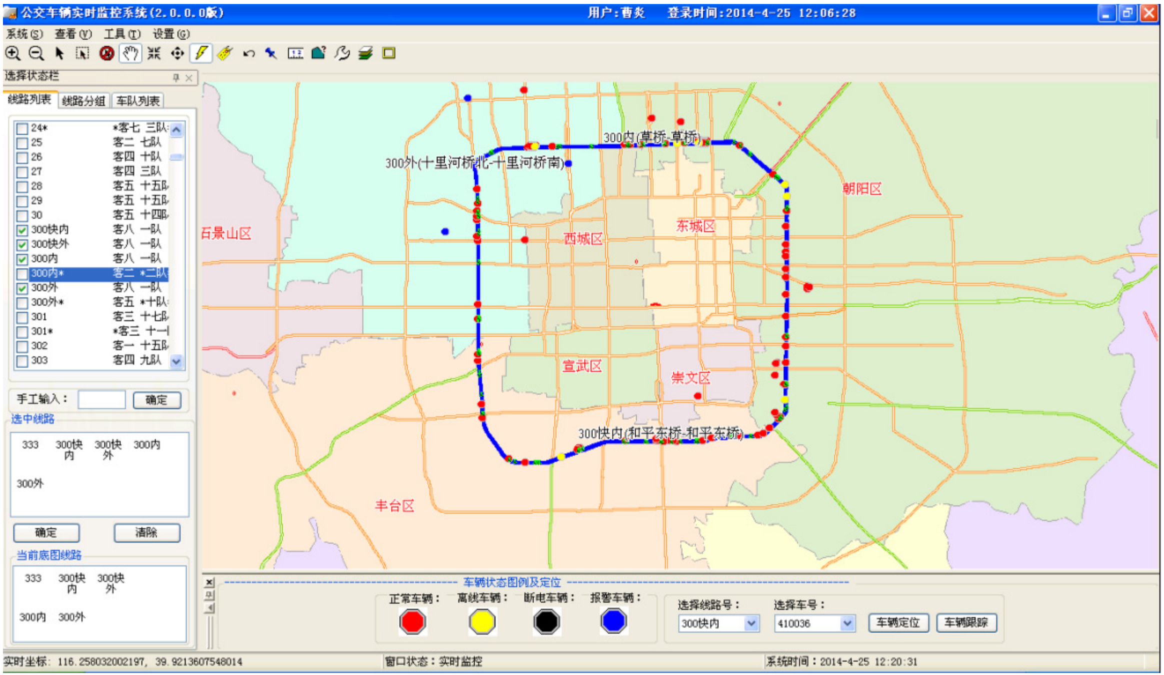

Fig. 3. The user-friendly public-transport vehicle monitoring interface for communication coordinators
(Note: Blue line represents bus route; Red nodes represent buses)

2.2. Main features

The main features of the CBVC-B are related to the whole transit network communications comprised of different decentralized and parallel groups. The communication-based control process can be performed at the same time between different communication groups. However, technically bus drivers of a same communication group are not exactly communicated in a direct P2P manner. It is more like a client-server (CS) manner. So, the whole control process is termed semi-decentralized group communication.

In a communication group, bus drivers leading to a same transfer point serve as clients and the communication control center serves as the central server. Bus drivers through the central server share vehicle and passenger information with their peers. The central communication center is responsible for the communication coordination of vehicles on the route segments leading to it and delivers advice on the real-time vehicle control tactics to bus drivers. Drivers follow the advisory information and then can adjust their running in a cooperative manner in order to achieve a simultaneous arrival. Once a bus passes the communication control center it automatically joins another group of vehicles. The communication group is self-organized.

In Fig. 4, a small transit network Fig. 4 (a) is used to illustrate these concepts. The transit network is divided into four communication groups by four transfer points as shown in Fig. 4 (b). Each group has two routes leading to the transfer point, and a central server is assigned to be responsible for the communication between bus drivers.

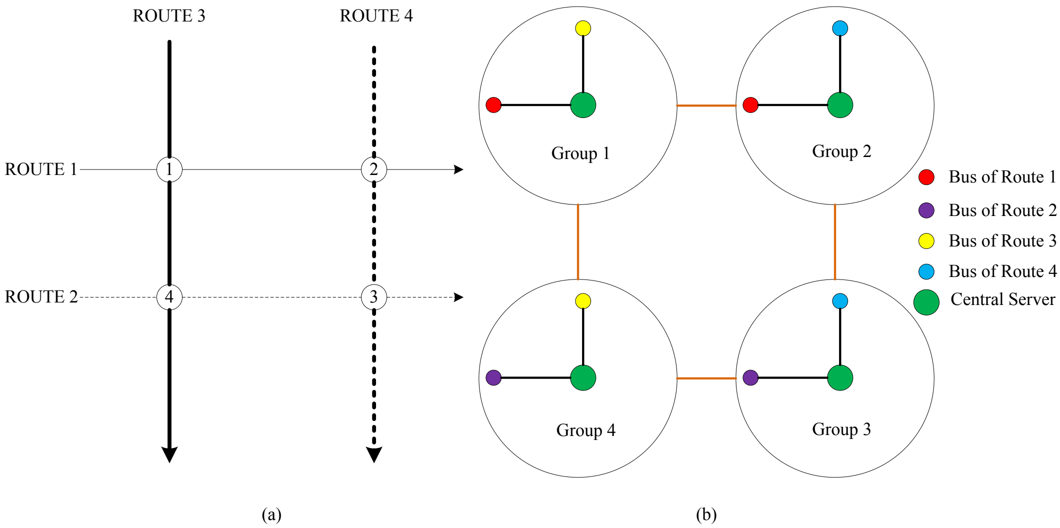

Fig. 4. Cooperative group communication between bus drivers in a transit network: (a) an example bus transit network [From Ceder, 2001]; (b) semi-decentralized group communication between bus drivers of the example

3. Real-Time Operational Control Tactics Deployment

This section provides a finite-horizon Markov decision process model for the decision making process of the real-time operational control tactics deployment of a bus driver in a communication group in the CBVC-B. Notations are given firstly.

3.1. Notations

T	set of decision epochs
S	set of states
A_s	set of actions in state s
$R_t(s,a)$	set of rewards received when choosing action $a \in A_s$ in state s at decision epoch t
$p_t(\cdot \mid s,a)$	transition probability when choosing action $a \in A_s$ in state s at decision epoch t
$d_t(s)$	decision rule
π	decision policy
AT_n	arrival time of bus n at transfer point

3.2. The MDP Model

The Markov decision process (MDP) model is useful for sequential decision making under uncertainty. It can take into account both the current outcomes of the system and future decision making opportunities (Puterman, 2005). Generally, a MDP model can be describe as the follows.

$$\{T, S, A_s, p_t(\cdot \mid s,a), r_t(s,a)\} \tag{1}$$

The real-time operational tactics deployment activity of a bus driver in a communication group can be divided into some decision epochs as shown in Fig. 5. In this decision making activity, the decision time horizon of a bus driver is divided into N decision epochs $T=\{1,2,\cdots,N\}, N \prec \infty$, and together with $N-1$ periods. At the beginning of a decision period, the communication coordinator will disseminate advisory information to bus drivers. Because the number of decision epochs for a bus driver is finite, it is a finite-horizon MDP model, and it is memoryless and randomized. At decision epoch $t, t \in T$, a bus occupies a state $s, s \in S$ and will choose an action from the action set A_s. Here the action set corresponds to operational control tactics $a_{t,i}$ that disseminated by the communication coordinator. The main possible real-time operational control tactics for a bus driver are list as follows (Ceder, 2007).

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

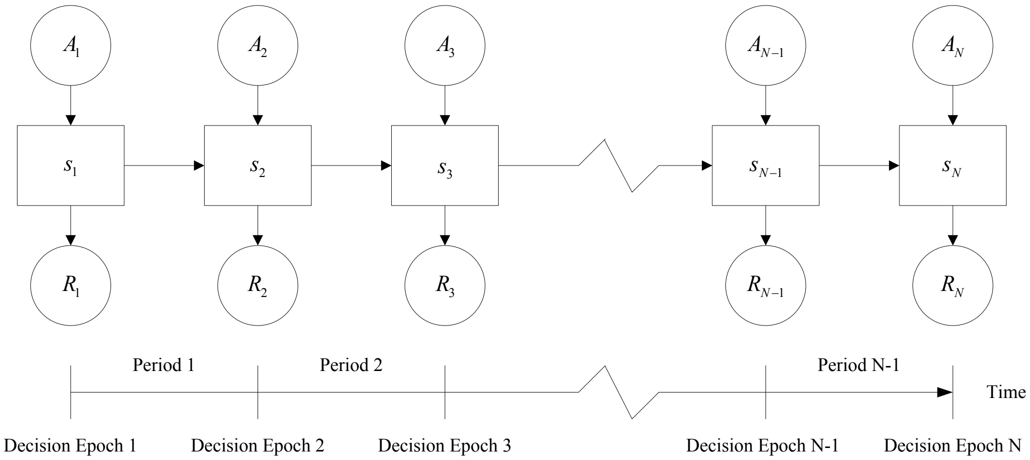

Fig. 5. Symbolic representation of the dynamic operational tactics deployment process in CBVC-B

At each decision epoch, the communication coordinator will deliver a set of possible operational control tactics to the bus driver. Then the bus driver will select an operational control tactic $a_{t,i}$ with a probability $p(a_{t,i})$ from it. Generally, the following equation holds.

$$\sum_{a_{t,i} \in A_s} p(a_{t,i}) = 1 \tag{2}$$

After taking an action, the bus driver will receive a reward $r_t(s,a)$ defined by $s \in S$ and $a \in A_s$. Here a reward corresponds to an average running time between stops or holding and dwell time at stops. The total "reward" received contributes to the final arrival time AT_n of a bus at the transfer point. The transition probability of each state is defined as follows.

$$p_t(s_{t'} \mid s_t, a_{t,i}) = \begin{cases} 1 & t' = t+1 \\ 0 & t' \neq t+1 \end{cases} \tag{3}$$

The decision variable set is a collection of the actions taken at each decision epoch. The objective is to minimize the total arrival time gaps of buses leading to the same transfer point, and thus increase the number of simultaneous arrivals of the whole transit network. That is:

$$Min \sum_{n,n' \in N^+, n \neq n'} \left| AT_n - AT_{n'} \right| \tag{4}$$

A decision rule $d_t(s)$ specifies the action taken at stage $s \in S$; a policy π is a sequence of decision rules, i.e., $\pi = (d_1, d_2, \cdots, d_N)$. The goal is to find a set of optimal policies that can minimize Eq. (4). Because this problem is a finite-horizon discrete-time MDP model, it can be done using the Backward Induction Algorithm. See Puterman (2005) for a detail description.

4. Benefits Assessment and Distribution

The number of direct transfers can be increased by using some selected operational tactics. However, it also has impacts on the total passenger travel time. What is more, from the perspective of bus agencies, it is also related to their operational costs. Therefore, how to evaluate the potential benefits of the CBCV-B and the distribution of benefits among PT users and PT operator should be carefully investigated.

Consider a transit network that is divided into a set of communication groups $G, g \in G$ and a communication group g with a set of routes $R_g, r_g \in R_g, g \in G$.The benefits of using operational control tactics can be evaluated with the following two objectives:

$$Min\ Z_1 = a_1 \sum_{g \in G} \sum_{r_g \in R_g} IPH_{r_g} + a_2 \sum_{g \in G} \sum_{r_g \in R_g} PWH_{r_g} + a_3 \sum_{g \in G} \sum_{r_g \in R_g} ESH_{r_g} \tag{5}$$

$$Max\ Z_2 = \sum_{g \in G} N_g \tag{6}$$

where:

IPH_{r_g} = In-vehicle passenger hours on route r_g in communication group g;

PWH_{r_g} = Passenger waiting hours on route r_g in communication group g;

ESH_{r_g} = Empty-space hours on route r_g in communication group g;

N_g = Number of direct transfers of communication group g;

a_i = Weighting factor

The first objective including three components and all are measured in passenger-hours. The first and second components in the right of equation (5) are the perspective of the PT users and the third component is the perspective of the PT operator. The first and third components can be calculated with the time-based passenger-hour load profile as shown in Fig. 6. And the second component can be calculated as the following equation for passengers arriving randomly at transit stops (Ceder, 2007).

$$\sum_{g \in G} \sum_{r_g \in R_g} PWH_{r_g} = \sum_{g \in G} \sum_{r_g \in R_g} \frac{E(H_{r_g})}{2} \left(1 + \frac{Var(H_{r_g})}{E^2(H_{r_g})} \right) D_{r_g} \tag{7}$$

where $E(H_{r_g})$ is the average headway; $Var(H_{r_g})$ is the variance of headway; D_{r_g} is the passenger demand boarding the route.

To the second objective, a direct transfer can be defined as a transfer with zero transfer waiting time or with an interval of t seconds.

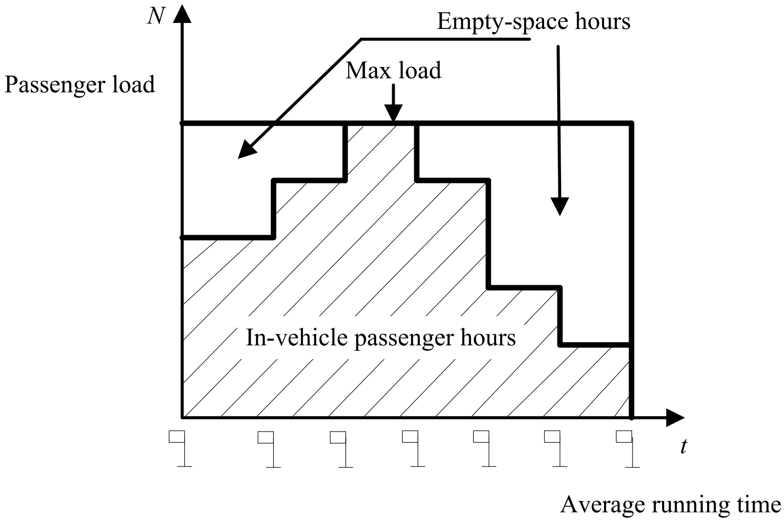

Fig. 6. Passenger-hour load profile used to calculate IPH_{r_g} and ESH_{r_g}

The Pareto optimal solutions of the bi-objective mathematical programming problem can be displayed in a Cartesian coordinate system in two dimensions where Z_1 and Z_2 are the x-axis and y-axis, respectively (Zeleny, 1982). It can assist the communication coordinator in disseminating operational tactics to bus drivers.

5. Summary

This work introduces a communication-based vehicle control system for buses (CBVC-B). The CBVC-B is a decision support system for synchronizing public-transport (PT) transfers using vehicle-to-vehicle communication. The purpose of the CBVC-B is to ensure the actual occurrence of planned PT passenger transfers by the use of certain selected control tactics in real-time operation. The system architecture of CBVC-B and its semi-decentralized group communication feature are described in details. The decision making process of the real-time operational control tactics deployment of the CBVC-B is formulated as a finite-horizon Markov decision process (MDP) model. In the MDP model, the action set corresponds to operational control tactics which are disseminated by the communication coordinator. The potential benefits of the CBVC-B are investigated, in this work, from the perspectives of both the PT user and the PT operator. The problem is formulated as a bi-objective mathematical model.

Future work will focus on numerical simulation, experimental validation, and demo software development of the CBVC-B. Finally, it is worth mentioning that the CBVC-B can help not only to synchronize PT transfers, but also to reduce bus bunching, integrating inter-modal PT networks, and providing PT user with real-time travel information.

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