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Scheduled Platoons of Public Transport Autonomous Modular Vehicles

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1 Introduction

Emerging technologies, such as connected and autonomous vehicles, electric vehicles and modular vehicles, are surrounding us at an ever-increasing pace. Together with the concept of shared mobility, these technologies have a great potential of transforming our existing transportation systems into far more user-oriented, system-optimal, smart and sustainable urban mobility systems with increased service connectivity, synchronization, coordination, and with satisfied user experiences. To cope with this revolution, public transport (PT) agencies and governments need to harness these innovative emerging technologies for transforming the existing PT systems into more advanced and attractive ones (SUMC, 2016; Buehler, 2018).

This study addresses the operations planning needs of the development of an innovative dynamic autonomous road transport (DART) system for Singapore (Rau, 2018). The current PT system in Singapore mainly includes two modes, namely mass rapid transit (MRT) system and bus transit system. The DART system is developed to bridge the capacity gap between the MRT and bus systems by proving a fully autonomous, high capacity, high flexibility service that would operate at relatively high speeds utilizing the existing road infrastructure and the most advanced emerging technologies. One of the main features of this new DART system is the use of autonomous electric zero-emission vehicle modules.

Among the emerging technologies, vehicle platooning is a promising direction that may bring benefits such as reducing energy consumption, reducing road-space usage, enhancing traffic safety and reducing the inconvenience or transfer waiting times of passengers (Bhoopalam, et al., 2018; Boysen, et al., 2018). In recent years, several vehicle platooning projects, e.g., SARTRE, PATH, GCDC, Energy-ITS and SCANIA, were introduced conceptually around the world (Kavathekar and Chen, 2011; Bergenhem, et al., 2012). However, these vehicle platooning projects are mostly focused on the platooning of cars, heavy vehicles or a mix of the two. The platooning of PT vehicles is missing. The development of autonomous modular vehicles opens the door of conducting PT vehicle platooning.

Following Bhoopalam et al. (2018), vehicle platooning planning activities can be classified by three categories: (1) scheduled platoon planning, (2) real-time platooning, and (3) opportunistic platooning. This work addresses the scheduled platoon planning of the DART system developed for Singapore. It is expected that the new mathematical models and solution methods developed in this work will serve as an effective and efficient tool for conducting scheduled autonomous modular vehicle platoon planning of the DART system.

2 Methodology

The scheduled platoon planning problem is formulated as a bi-objective integer programming problem. The first objective is to minimize the total number of vehicle modules required, i.e., the fleet size. The second objective is to minimize the total number of vehicle platoons (each is comprised of a few modules) in the network; that is, coupling as many vehicle modules as possible under the platoon size constraint. This bi-objective integer programming problem is a special case of the PT timetable synchronization design problem (Ceder, et al., 2001), which was proven to be a NP-hard problem (Liu and Ceder, 2016).

A two-stage interactive optimization approach is developed to find good feasible solutions of the problem in a reasonable computation time. At the first stage, the bi-objective integer programming problem is simplified as a corresponding single-objective timetable synchronization design problem; this problem can be solved by using the algorithms and procedures developed by Ceder et al. (2001) and Ceder (2016). The result of this single-objective timetable synchronization design problem provides an initial timetable of vehicle modules of the DART system. This initial timetable may be infeasible and not optimal. Thus, at the second stage, three operators, namely (1) splitting vehicle platoons (SPLIT), (2) shifting the departure times of vehicle modules (SHIFT) and (3) inserting deadheading (DH) vehicle modules trips, are employed to revise, refine and optimize the initial timetable so as to generate a set of Pareto-efficient solutions of the problem. These three operators are performed in a human-computer interactive manner by using a graphical scheduling technique based on the deficit function theory (Ceder, 2016; Liu and Ceder, 2017).

3 Numerical Example

The following example problem, illustrated in Figure 1, is used to provide a better understanding of the solution procedures and demonstrate the performance of the solution method described in Section 2. This example network is comprised of four terminals, i.e., terminals *a*, *b*, *c*, and *d*, and two merging nodes, i.e., node 1 and 2, and includes four routes, namely Route 1: *a*→ 1 → 2 → *c*; Route 2: *b* → 1 → 2 → *d*; Route 3: *c* → 2 → 1 → *a*; Route 4: *d* → 2 → 1 → *b*. The numbers beside the arcs are vehicle's average travel times (min). For the designed DART system, the headway is assumed to be fixed as 5 minutes, i.e., H = 5 min. The schedule horizon T is set as [8:00, 8:25). The maximum size of a vehicle platoon is set as 10 vehicle modules, and the maximum capacity of each stop is also set as 10 vehicle modules.

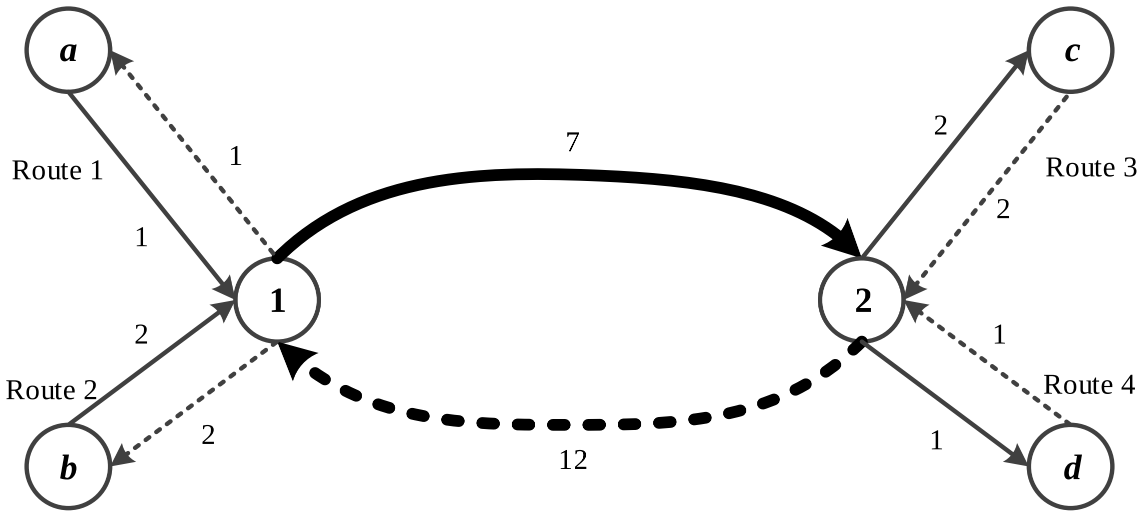

Figure 1. A four-route example network with four terminals and two merging nodes

After implementing the two-stage interactive optimization procedures, six feasible solutions are generated. These solutions are graphically displayed in Figure 2 with respect to the two optimization objectives so as to facilitate the decision making of the DART planners. Figure 2 shows that solution S_1 and solution S_5 are the Pareto-efficient solutions of the problem. Solution S_1 results in the minimum number of vehicle platoons created in the network, and solution S_5 has the minimum number of vehicle modules required.

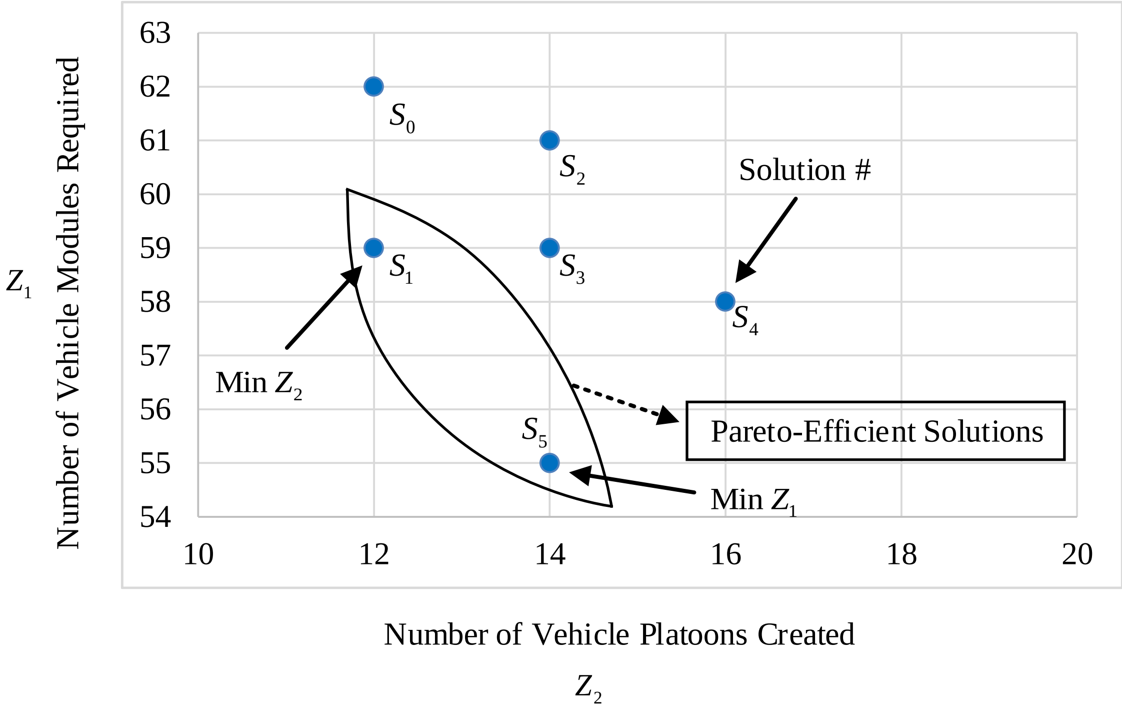

Figure 2. Trade-off between the number of vehicle modules required Z_1 and the number of vehicle platoons created Z_2 of the example problem in a 2D space

The corresponding two timetables of solution S_1 and solution S_5 are presented in below Table 1(a) and Table 1(b), respectively.

Table 1. Final Pareto-optimal timetables of the example network:

(a) Timetable 1: Solution S_1

Route 1: $a \rightarrow 1 \rightarrow 2 \rightarrow c$				Route 3: $c \rightarrow 2 \rightarrow 1 \rightarrow a$			
Trip ID	Dep. at *a*	Arr. at *c*	# of modules	Trip ID	Dep. at *c*	Arr. at *a*	# of modules
1	8:01	8:11	5	11	8:00	8:15	5
2	8:06	8:16	5	12	8:05	8:20	6
3	8:11	8:21	5	13	8:10	8:25	5
4	8:16	8:26	2	14	8:15	8:30	2
5	8:21	8:31	4	15	8:20	8:35	5
Route 2: $b \rightarrow 1 \rightarrow 2 \rightarrow d$				Route 4: $d \rightarrow 2 \rightarrow 1 \rightarrow b$			
Trip ID	Dep. at *b*	Arr. at *d*	# of modules	Trip ID	Dep. at *d*	Arr. at *b*	# of modules
6	8:00	8:10	5	16	8:01	8:16	5
7	8:7.5	8:17.5	3	17	8:8.5	8:23.5	3
8	8:10	8:20	5	18	8:11	8:26	5
9	8:15	8:25	5	19	8:16	8:31	5
10	8:20	8:30	4	20	8:21	8:36	4
DH trip	Dep. from	Arr. at	Dep. time	Arr. time	# of modules		
21: DH_1	*c*	*d*	8:11	8:14	3		

(b) Timetable 2: Solution S_5

Route 1: $a \rightarrow 1 \rightarrow 2 \rightarrow c$				Route 3: $c \rightarrow 2 \rightarrow 1 \rightarrow a$			
Trip ID	Dep. at *a*	Arr. at *c*	# of modules	Trip ID	Dep. at *c*	Arr. at *a*	# of modules
1	8:01	8:11	5	11	8:00	8:15	5
2	8:06	8:16	5	12	8:05	8:20	6
3	8:11	8:21	5	13	8:10	8:25	5
4	8:16	8:26	2	14	8:15	8:30	2
5	8:21	8:31	4	15	8:20	8:35	5
Route 2: $b \rightarrow 1 \rightarrow 2 \rightarrow d$				Route 4: $d \rightarrow 2 \rightarrow 1 \rightarrow b$			
Trip ID	Dep. at *b*	Arr. at *d*	# of modules	Trip ID	Dep. at *d*	Arr. at *b*	# of modules
6	8:00	8:10	5	16	8:00	8:15	5
7	8:7.5	8:17.5	3	17	8:8.5	8:23.5	3
8	8:10	8:20	5	18	8:11	8:26	5
9	8:15	8:25	5	19	8:16	8:31	5
10	8:20	8:30	4	20	8:21	8:36	4
DH trip	Dep. from	Arr. at	Dep. time	Arr. time	# of modules		
21: DH_1	*c*	*d*	8:11	8:14	3		
22: DH_2	*a*	*b*	8:15	8:18	3		

4 Case Study in Singapore

Singapore is an island country with an area of 719.9 km^2. By the end of 2017, the total population is 5.6123 million (SDoS, 2018). The current population density is 7,796 pop./km^2, which ranked the third in the world. Because of the limited land resource, high population density and rapid increasing travel demand, Singapore has decided to adopt a package of integrated transport policies to manage its transportation systems.

Singapore intends to develop a world-class PT system with increased service attractiveness, convenience, reliability, affordability, synchronization, and coordination. Figure 3 (a) shows the current multi-layer PT networks in Singapore, which mainly includes MRT/LRT, bus and road taxi networks. The peak hour PT mode share in 2016 is 67%, which is very high compared to other cities around the world. In a recent document, named Land Transport Master Plan 2013, released by the Land Transport Authority (LTA), the goal of achieving a PT mode share of 75% during peak hours was set for the year of 2030. The DART system is introduced to bridge the capacity gap between the existing bus transit systems and LRT/MRT systems in Singapore for an integrated multi-modal hierarchical PT system for Singaporeans. The identified backbone lines of the DART system are shown in Figure 3 (b). The developed mathematical models and solution methods are applied to address the scheduled autonomous modular vehicle platoon planning problem in this DART system developed for Singapore.

(b)

(a)

Figure 3. Case study in Singapore: (a) multi-layer public transport network of Singapore and (b) identified backbone lines of the DART system

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