Deployment Planning of Single-Line Modular-Vehicle Semi-Rapid Transit System

Tao Liu · Avishai (Avi) Ceder · Andreas Rau

Abstract With the advancements of autonomous and connected vehicle technologies, electric vehicle technologies, and information and communication technologies, new public transit (PT) systems are naturally emerged. This work proposes a practical framework for the deployment-planning of modular vehicles used in an innovative and upgraded semi-rapid transit system, named dynamic autonomous road transit (DART) system. This framework integrates timetable development and modular vehicle scheduling activities and it is three-fold. First, a timetable-generation component produces timetables with even headways. Second, the optimal number of DART vehicle modules is established to comply with the fluctuated passenger demand. Third, different deployment-planning schemes are investigated and evaluated using various performance measures from both PT operators’ and passengers’ perspectives. The suggested methodological framework is applied to a real-life case study in Singapore. The promising results demonstrate the effectiveness and flexibility of the developed DART modular-vehicle deployment-planning framework.

Keywords: Public transit · Dynamic autonomous road transit · Demand-based timetabling · Modular vehicles · Electromobility

Tao Liu
Department of Rapid Road Transport, TUMCREATE Ltd.,
Singapore
E-mail: tao.liu@tum-create.edu.sg

Avishai (Avi) Ceder
Faculty of Civil and Environmental Engineering, Technion–Israel Institute of Technology,
Haifa 32000, Israel
Added affiliation: Department of Civil and Environmental Engineering, The University of Auckland,
Auckland, New Zealand
E-mail: a.ceder@auckland.ac.nz

Andreas Rau
Department of Rapid Road Transport, TUMCREATE Ltd.,
Singapore
E-mail: andreas.rau@tum-create.edu.sg
1 Introduction

The world population has grown from 1 billion people in 1804 to 7.5 billion people in 2017. It is predicted that by 2050 the world population will rise to 9.8 billion, an increase of 2.3 billion people compared to that of 2017. Almost all population growth will take place in urban areas. The world’s urban population now stands at about 4 billion people, and is expected to reach almost 7 billion by 2050 (United Nations, 2015). In addition, the total number of motor vehicles on the planet exceeded 1 billion vehicles in 2010. It is estimated that the number of motor vehicles in use in the world will reach 2 billion motor vehicles by 2020, with cars representing at least 50% of all vehicles. By some estimates, the total number of vehicles worldwide could, reach 2.5 billion by 2050. The combination of rapid urbanization and motorization has resulted in many traffic-related problems, such as traffic congestion, traffic fatalities and injuries, traffic air and noise pollution, and energy consumption. Public transit (PT), as a cost-effective, sustainable and shared mobility system, is generally regarded as one of the best solutions to these traffic-related problems.

Existing conventional PT systems, especially buses, use an old concept of fixed routes, fixed stops, fixed timetables and fixed vehicle and driver scheduling. This traditional PT concept produces services that are not always appealing to potential and existing users, making them hesitant to use the service. To make the travel with a PT service a pleasant experience, innovative PT systems need to emerge with advanced, attractive service; this will help to successfully shift a significant amount of private car users to PT services in a sustainable manner (Ceder, 2016).

1.1 Semi-Rapid Transit System

The typical line capacities of different PT modes are shown in Table 1 (Vuchic, 2005). Following Vuchic (2002), system performances and investment costs of different PT modes are illustrated in Figure 1. These features of PT modes illustrate that there is a potential supply and efficiency gap between existing bus-type system and light rail transit (LRT)/mass rail transit (MRT) systems. Traditionally, tram and bus rapid transit (BRT) systems are introduced to bridge this gap.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Train Size</th>
<th>Minimum Headway (s)</th>
<th>Occupancy (pax)</th>
<th>Maximum Line Capacity (pax/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Bus</td>
<td>1</td>
<td>50-70</td>
<td>75</td>
<td>3,800-5,400</td>
</tr>
<tr>
<td>Articulated Bus</td>
<td>1</td>
<td>60-80</td>
<td>120</td>
<td>5,400-7,200</td>
</tr>
<tr>
<td>LRT</td>
<td>3</td>
<td>75-150</td>
<td>170</td>
<td>12,200-26,900</td>
</tr>
<tr>
<td>MRT</td>
<td>8</td>
<td>90-100</td>
<td>180</td>
<td>51,800-57,600</td>
</tr>
</tbody>
</table>

Data Source: Vuchic (2005).
Tram and bus rapid transit (BRT) systems are categorized as examples of a semi-rapid transit (SRT) system, which was technically defined by Vuchic (2002). The major difference of conventional bus systems, SRT and LRT/MRT systems is the right of way (ROW). Usually, conventional bus systems are mixed with road traffic and LRT/MRT systems are fully controlled and separated with other road traffic; while SRT systems are partially separated with other road traffic. Except the difference in ROW, these different PT modes also have different features, system performance, and investment cost. The main purpose of developing different PT modes, including SRT systems, is to achieve an intermodal balanced urban transportation system so as to improve the overall service efficiency of a well-coordinated transportation system.

1.2 Dynamic Autonomous Road Transit System

Nowadays, with the advancements of autonomous and connected vehicle technologies, electric vehicle technologies, and information and communication technologies, an innovative and upgraded semi-rapid transit (SRT) system, named dynamic autonomous road transit (DART) system, is currently being developed at TUMCREATE in Singapore. DART can be currently perceived as a highly efficient, integrated, flexible, road-bound autonomous electric PT system. The DART system is built on automation, modularity and seamless integration using intelligent transportation system (ITS) and intelligent roadside infrastructure.

The key elements of the DART system are: (i) autonomous vehicle modules (DART Modules), (ii) cooperative intelligent transportation system (DART Connect), (iii) intelligent stops and road infrastructure (DART Infrastructure), (iv) fully electric vehicle module (DART Power), and (v) central traffic management (DART Central).
These five elements, together with their relationship, are graphically illustrated in Figure 2.

Fig. 2 Key elements of the DART system

One of the main features of this new DART system is the use of autonomous electric zero-emission vehicle modules. Each module is capable of carrying up to 30 passengers and up to 10 modules can be closely connected and run together as a platoon. The DART vehicle modules can be coupled electronically to form platoons on shared line routes and decoupled when line routes diverge in order to serve demand. It is one of the most flexible ways for optimal capacity utilization and road space. The synchronized schedules of modules at transfer stations minimize the number of platoons and also reduce passenger transfer waiting time (Liu and Ceder, 2017). A simple illustration of the DART vehicle module platooning process is shown in Figure 3. It shows that individual vehicle modules form platoon with shared driving dynamics and merge and split, creating takes place at trunk and branches, respectively. The DART trunk lines are well-synchronized with the DART feeder lines and also well-coordinated with other public transport modes. By doing so, the service connectivity of the whole multi-modal public transport network will be significantly improved. In addition, some selected feasible operational control strategies are deployed in real time so as to improve the reliability and the actual occurrence of synchronized/coordinated multi-modal public transport service. The use of vehicle module concept and vehicle platooning strategy can greatly help improve the operational efficiency of vehicle fleet so as to reduce operational costs.
The purpose of this study is to develop a practical framework for the deployment planning of modular vehicles of a single-line DART system. The contribution of this research is threefold. First, we highlight the need of introducing a DART system into the existing commonly used PT systems including systematically define the elements and components of the DART system. Second, we develop a practical methodological framework that can be used for the deployment planning of modular vehicles of a single-line DART system. Third, the methodological framework is applied in a case study in Singapore using defined performance measures.

2 Methodology

The proposed methodological framework is schematically shown in Figure 4 in a flowchart format with input and output elements. It mainly integrates two PT operations-planning activities, namely timetable development and vehicle scheduling, together with a results evaluation component (Desaulniers and Hickman, 2007; Ceder, 2016). This framework, together with its formulations, can provide PT planners with a practical and flexible tool for the optimal deployment of the new proposed DART vehicle modules. The methodology is based on complying with the fluctuated passenger demand while minimizing the total number of vehicle modules required.

2.1 Timetable Generation

Single-line timetabling is aimed at developing a timetable for one PT line following some predetermined criteria, such as even headway, even load, and clock headway. The DART system timetables are generated by using a set of data sets, which include passenger demand data, network route data, inter-stop vehicle running time data, and stop dwell time data. In addition, some service criteria, such as desired vehicle occupancy, minimal service frequency and maximal passenger loads on the vehicles, are considered when creating timetables. Fixed-headway timetables are assumed for the DART system because of the advantage in reducing the total average passenger waiting time. Taking into consideration fluctuating passenger demand, different number of vehicle modules are used for better matching of supply

![Fig. 3 Illustration of DART vehicle module platooning](image)
and demand so as to generate timetables with even headways and approximate even loads on vehicles at the maximal load stops along a route.

2.2 Vehicle Modules Deployment

Three different vehicle module assignment strategies are considered when determining the number of vehicle modules required for each vehicle departure at the starting depot. These three strategies are described in below, and also explained by a small numerical example graphically illustrated in Figure 5.

- **Strategy C1**: Assigning the largest number of vehicle modules such that its capacity is less than or equal to the average observed passenger load, at the max-load point.
- **Strategy C2**: Assigning the smallest number of vehicle modules such that its capacity is greater than or equal to the average observed passenger load, at the max-load point.
- **Strategy C3**: Assigning the number of vehicle modules whose capacity is closest to the average observed passenger load, at the max-load point.
Fig. 5 Strategies for determining the number of vehicle modules required for each vehicle departure

The following corollary is used in calculating the total number of vehicle modules required, i.e., fleet size, of the single-line DART system. The formulation is based on the deficit function fleet size theorem proved by Ceder and Stern (1981).

**Corollary 1.** If, for a single-line with two terminals, a and b, and a fixed set of required vehicle module trips \( I \), all trips start and end with the schedule horizon \([T_1, T_2]\) and no deadheading (DH) trip insertions are allowed, then the minimum number of vehicle modules required to service all vehicle module trips in \( I \) is equal to the sum of the deficits. That is,

\[
\text{Min } N = D(a) + D(b) = \max_{t \in [T_1, T_2]} d(a, t) + \max_{t \in [T_1, T_2]} d(b, t)
\]

(1)

where \( N \) is the number of vehicle modules required; \( d(a, t) \) and \( d(b, t) \) are the deficit functions of terminal \( a \) and \( b \), respectively; \( D(a) \) and \( D(b) \) are the maximum values of deficit function \( d(a, t) \) and \( d(b, t) \), respectively.

2.3 Results Evaluation
The examination of the deployment-planning framework calls for criteria in evaluating the performance of the new SRT system. Three performance measures, from both operator perspective and user perspective, are selected: (i) total number of vehicle modules, (ii) total passenger wait time, and (iii) total passenger load discrepancy from a desired load.

3 Case Study

The suggested methodology is applied to a real-life case study in Singapore. Singapore is an island country with a population of 5.612 million in 2017 and with a population density of 7,796 pop./km² ranked third in the world, just behind Macau and Monaco (Singapore Department of Statistics, 2017). To meet the ever increasing and diversified mobility needs, the Singapore Land Transport Authority (LTA) has decided to develop a world-class transport system with the goal of achieving a PT share of 75% until 2030.

![Fig. 6 Case study in Singapore: (a) multi-layer public transit network of Singapore and (b) identified eighteen potential SRT lines in the study area](image)

The multi-layer PT network in Singapore is shown in Figure 6(a) including a road taxi network, a bus network and a MRT/LRT network. A study area was first identified by Tang (2017) using a multi-variable approach that incorporates a number of criteria to assess the suitability of road corridors for a DART system. Then, we further identified eighteen DART lines in the study area, as shown in Figure 6(b). This line/corridor identification process was based on a developed PT
model calibrated by using approximately 450 million smart card trip records collected in Singapore (Michalski, et al., 2016).

In our work, a single SRT line, Line 1 shown in Figure 6(b), is selected as a pilot study to understand the effectiveness and flexibility of the proposed DART vehicle module deployment-planning framework. The hourly maximum passenger load data for Line 1 of both directions is shown in Table 2. From it, we can see the maximum passenger load hour, i.e., the maximum number of total passengers for both directions, is from 8:00 to 9:00. Thus, this time period is selected as the case study period.

**Table 2 Hourly maximum passenger load information for Line 1**

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Eastbound</th>
<th>Westbound</th>
<th>Total Passengers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max-load Point</td>
<td>No. of Passengers</td>
<td>Max-load Point</td>
</tr>
<tr>
<td>5:00-6:00</td>
<td>55189</td>
<td>128</td>
<td>66499</td>
</tr>
<tr>
<td>6:00-7:00</td>
<td>67469</td>
<td>748</td>
<td>66459</td>
</tr>
<tr>
<td>7:00-8:00</td>
<td>54351</td>
<td>1594</td>
<td>66459</td>
</tr>
<tr>
<td>8:00-9:00</td>
<td>54351</td>
<td>2112</td>
<td>66459</td>
</tr>
<tr>
<td>9:00-10:00</td>
<td>54351</td>
<td>905</td>
<td>54509</td>
</tr>
<tr>
<td>10:00-11:00</td>
<td>54351</td>
<td>465</td>
<td>54509</td>
</tr>
<tr>
<td>11:00-12:00</td>
<td>54351</td>
<td>423</td>
<td>54509</td>
</tr>
<tr>
<td>12:00-13:00</td>
<td>54501</td>
<td>547</td>
<td>54509</td>
</tr>
<tr>
<td>13:00-14:00</td>
<td>54481</td>
<td>654</td>
<td>Transfer Station 5</td>
</tr>
<tr>
<td>14:00-15:00</td>
<td>54501</td>
<td>675</td>
<td>Transfer Station 5</td>
</tr>
<tr>
<td>15:00-16:00</td>
<td>54481</td>
<td>790</td>
<td>54489</td>
</tr>
<tr>
<td>16:00-17:00</td>
<td>54501</td>
<td>884</td>
<td>54489</td>
</tr>
<tr>
<td>17:00-18:00</td>
<td>54501</td>
<td>1211</td>
<td>54489</td>
</tr>
<tr>
<td>18:00-19:00</td>
<td>54501</td>
<td>1427</td>
<td>54489</td>
</tr>
<tr>
<td>19:00-20:00</td>
<td>54501</td>
<td>910</td>
<td>Transfer Station 5</td>
</tr>
<tr>
<td>20:00-21:00</td>
<td>54501</td>
<td>687</td>
<td>Transfer Station 5</td>
</tr>
<tr>
<td>21:00-22:00</td>
<td>54481</td>
<td>654</td>
<td>Transfer Station 5</td>
</tr>
<tr>
<td>22:00-23:00</td>
<td>54501</td>
<td>591</td>
<td>Transfer Station 5</td>
</tr>
<tr>
<td>23:00-24:00</td>
<td>54501</td>
<td>258</td>
<td>Transfer Station 5</td>
</tr>
<tr>
<td>24:00-1:00</td>
<td>54501</td>
<td>41</td>
<td>Transfer Station 5</td>
</tr>
</tbody>
</table>

For the considered case study problem, we investigated four different headways of Line 1; that is, headway of 5 minutes, 4 minutes, 3 minutes and 2 minutes. Combined with the three different vehicle module assignment strategies, totally twelve different scenarios are created. After implementing the proposed methodology, the results of the three different performance measures for these twelve scenarios are summarised in Table 3.
The results of the methodology are graphically displayed in Figure 7 to facilitate the decision making of PT schedulers. In this case study, we defined the total passenger-hour cost as the sum of the total average passenger waiting time (WT) and the total average passenger load discrepancy hour (LD), with a weighting factor of 0.5 for each of them. Figure 7 shows that four Pareto-efficient solutions are found from the total twelve solutions. Solution 2 results in the least number of vehicle modules required, which is 16 vehicle modules. Solution 11 results in the least total passenger-hour cost of 58.025 pass·h.

With this graphical information in hand, the PT schedulers are able to choose a desired solution or a desired set of solutions based on their preferences and practical considerations, by taking account of both PT user and operator interests.
4 Conclusions

This work proposes a practical framework for the deployment-planning of single-line modular vehicles used in an innovative and upgraded semi-rapid transit system, named dynamic autonomous road transit (DART) system. This framework integrates timetable development and modular vehicle scheduling activities and it is three-fold. First, a timetable-generation component produces timetables with even headways. Second, the optimal number of DART vehicle modules is established to comply with the fluctuated passenger demand. Third, different deployment-planning schemes are investigated and evaluated using various performance measures from both operators’ and passengers’ perspectives. The suggested methodological framework is applied to a real-life case study in Singapore. The promising results demonstrate the effectiveness and flexibility of the developed DART modular-vehicle deployment-planning framework. The framework will be further extended to address the deployment-planning of modular vehicles for a DART network.

Acknowledgements: This work was financially supported by the Singapore National Research Foundation under its Campus for Research Excellence And Technological Enterprise (CREATE) programme. Any opinions, findings, conclusions or recommendations expressed in this paper are solely those of the authors, and do not necessarily reflect the views of the Foundation.

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