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A Bus Rapid Transit Timetable Design Method Integrating All-Stop, Short-Turn and Limited-Stop Strategies

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ABSTRACT

Bus rapid transit (BRT) operates with an exclusive road environment, specialised platforms and technology-enhanced devices, which allows it to provide a higher quality of service compared with conventional bus transit. However, the temporally and spatially imbalanced distribution of passenger demand leads to a waste of BRT system investment. To improve operation efficiency, this paper presents a timetable-based optimisation method which integrates multiple operational strategies, including all-stop, short-turn and limited-stop services. A rule-based heuristic algorithm is developed to generate operational solutions for the stopping pattern and departure timetable for the analysis time period. The proposed model and algorithm enable detailed considerations of interactions among successive BRT vehicle journeys along with passengers' boardings and alightings at stations, and the interdependencies between multiple service hours are involved. The method is validated through a real-world case study of the Fengpu Express BRT route in Shanghai, China. Sensitivity analyses are made in response to changes in OD profiles, average boarding and alighting time and maximum total mileage. Results show that the timetable-based multi-operational strategy reduces the total travel time of passengers under the same operational cost, which could facilitate future timetable design and stopping patterns of urban BRT corridors in a cost-efficient manner.

KEYWORDS

bus rapid transit; multiple operational strategies; heuristic algorithm; short-turn service; limited-stop service; all-stop service.

1. INTRODUCTION

Bus rapid transit (BRT) is a ground-based public transportation system with dedicated platforms and reserved right-of-way. Typically operated along medium-capacity corridors, BRT undertakes a significant portion of travel demand with lower operational costs than urban rail systems. High-quality service is delivered due to its exclusive operating environment, technology-enhanced devices and larger vehicle capacity.

Similar to other public transit modes, BRT does not always experience high passenger volumes at all stops across time periods. In fact, variations in passengers' origins and destinations often lead to spatially and temporally imbalanced demand distribution. To maintain service quality, transit agencies provide conventional all-stop and frequent services, which leads to high operational costs and waste of resources. Nowadays, with fare collection at both boarding and alighting stops [1], video surveillance systems equipped onboard and at stations [2], automatically collected vehicle trajectory data [3], and connected and automated BRT system [4], it becomes feasible to obtain passengers origin and destination stations along with their interactions with BRT vehicle journeys. Therefore, it is theoretically important and practically applicable to better balance BRT demand and supply.

Flexible operational stopping strategies are major solutions to improve service efficiency and maintain a high level of service, including short-turn (serving the route segment with high demand) [5], limited-stop (visiting a subset of the stops along the bus route) [5], deadheading (empty vehicles only operating one-way segment and returning to the depot) [6], etc. Although previous researchers developed optimisation methods of providing short-turn services, limited-stop services and mixed strategies, most were frequency-based. That said, decision variables were service frequency only or frequency combined with the stops served, which failed to capture the interplays between transit operations and passengers across continuous time periods. Consequently, the modelling of vehicle holding time, passenger waiting time and in-vehicle time was not accurate enough. For example, holding time would be saved for a BRT vehicle journey if the passengers arriving at the stations were mostly taken by a previous vehicle that just left, which would also reduce the in-vehicle travel time of passengers in the current vehicle. Additionally, the operation of a BRT vehicle journey between terminals could span across hours. Since passenger arrival rate and their destinations at each stop varies on an hourly basis, the optimal service design might change. To address these problems, we propose a timetable-based optimisation model to integrate multiple parallel operational strategies of all-stop, short-turn and limited-stop service with detailed descriptions of BRT vehicle operation as well as passenger boarding and alighting process. A rule-based heuristic algorithm is developed to generate solutions for the integrated operational strategy, including stops served and departure timetable. The model and algorithm are validated through a real-world case study of a BRT route in Shanghai, China. Results show that the multi-operational strategy improves BRT service quality and efficiency, which could facilitate future timetable design and stopping patterns of urban BRT corridors in a cost-efficient manner.

The remainder of the paper is organised as follows: Section 2 presents the review of previous studies. Section 3 describes the formulation of the optimisation model. Section 4 develops a rule-based heuristic algorithm that could efficiently solve the proposed model. Section 5 presents a real-world case study in Shanghai, China. Sensitivity analyses are provided to give further recommendations for applying the method. Conclusions are summarised in Section 6.

2. LITERATURE REVIEW

In relation to this study, four parts of the literature are summarised and reviewed in the following: all-stop strategy, short-turn strategy, limited-stop strategy and the integration of multiple operational strategies.

All-stop service is a common strategy for conventional transit routes. Under given demand patterns, single-line timetable optimisation aims to minimise departure delays compared with passengers' expected departure times [7] and improve the robustness of delay recovery [8]. At the network level, service connectivity across modes and routes is of high importance [9]. Therefore, timetable design for conventional services plays a crucial role in coordinating transfers with other lines within a single transit network [10], optimising feeder bus routes [11], and enabling seamless transfers to other transit modes [12]. Some researchers also embedded vehicle scheduling in the timetable coordination optimisation [13].

Short-turn service aims at enhancing transit efficiency on the basis of full-length services. Dating back to the late 1980s, researchers developed models and algorithms to optimise various variables, including relative offset, full-length service frequency, short-turn service frequency, turnback points, fleet size and vehicle size. Reducing fleet size and passenger waiting time were the primary objectives for early studies. Furth (1987) proposed algorithms to balance loads and minimise overall costs, including fleet size and passenger waiting time, by optimising the relative offset and full-length service frequency. In this model, the scheduling mode, turnback points for the short-turn pattern and vehicle sizes were predetermined. The relative offset refers to the ratio of the time interval between a full-stop bus vehicle journey and the preceding short-turning bus vehicle journey to the headway of the full-stop pattern [14]. Ceder (1989) developed a framework to design transit timetables and vehicle schedules with short turns. Given initial candidate short-turn points, i.e. route timepoints at which the vehicle turns back, a minimax H algorithm was developed to determine optimal timepoints to minimise fleet size and passenger waiting time [15]. Delle Site and Filippi (1998) implied that the interdependencies between operational periods made it impractical to simply divide them into sub-periods. They introduced a multi-period model with variable demand and vehicle sizes to optimise turnback point locations, vehicle sizes, full-length service frequencies, relative offsets and fare [16]. Tirachini et al. (2011) added passenger in-vehicle time on the basis of previous optimisation objectives and established a short-turn model as a single-period approach [17]. With similar objectives, Ji et al. (2016) described the seat-searching process of passengers as a Markov model to incorporate seat availability. Turnback points, the frequency of the full-stop pattern and the multiple between the frequencies of short-turning and full-stop patterns were the decision variables [18]. Leffler et al. (2017) proposed a real-time short-turning strategy for high-frequency bus services to minimise total generalised traveller costs [19]. Chen et al. (2018) proposed a continuum approximation modelling framework to optimise headways of regular service and short-turning services [20]. Yuan et al. (2022) developed an integrated optimisation model for the train timetable, rolling stock assignment and short-turning strategy. Their objective was to reduce passengers' total waiting time on platforms [21]. Other short-turn studies aimed at improving service reliability. Liu et al. (2020) proposed a short-turn strategy to enhance the reliability of bus operations by analysing passenger demand and optimising the operation area and departure times of short-turn vehicles [22]. Tian et al. (2022) alleviated bus bunching by converting some regular trips to short-turning trips, which significantly reduced schedule deviation and total passenger waiting time [23]. Ghaemi et al. (2018) established a mixed integer linear program (MILP) model to optimise train short-turning strategies during complete railway blockages [24]. Strathman et al. (2001) studied an automated bus dispatching system developed with holding, short turning and reassignment strategies in Portland, Oregon, to improve service regularity and balance passenger loads [25]. Cats (2014) conducted field experiments in Stockholm to test a regularity-driven bus operation scheme, which aimed at reducing bus bunching and improving service reliability through real-time control strategies [26].

Studies on limited-stop design include a single limited-stop route and parallel bus routes [27]. At the operational level, Tetreault´ and El-Geneidy (2010) used AVL (automatic vehicle location) and APC (automatic passenger counting) data to select stops for implementing limited-stop bus service, taking into account both running time savings and passenger walking distances [28]. Other researchers developed optimisation models and algorithms for limited-stop service. With objectives of minimising waiting time, in-vehicle travel time and operator cost, Leiva et al. (2010) established a set of models to optimise the frequencies, vehicle sizes and optimal set of normal and limited-stop services based on predefined candidate lines [29]. Chiraphadhanakul and Barnhart (2013) designed served stops and frequency of a limited-stop service parallel with the local service (i.e. buses serving all the intermediate stops) [30]. Chen et al. (2015) combined the artificial bee colony (ABC) and Monte Carlo method considering vehicle capacity and stochastic travel time for a single limited-stop route [27]. Larrain and Muñoz (2016) proposed a design algorithm for limited-stop services in a corridor to optimise the frequencies of limited-stop services and then calibrated a regression model to estimate the benefits [31]. Yi et al. (2016) proposed a guideline of selecting optimal limited-stop bus routes, to save total travel time under different scenarios [32]. Considerations on passenger assignment were embedded in the limited-stop service design in later studies. Soto et al. (2017) developed a bilevel framework including limited-stop service generation and capacitated frequency optimisation and assignment [33]. Limited-stop service was used as a general concept which encompassed short-turn, deadheading, express and zonal services with predefined stop design. Zhang et al. (2018) used the degree assessment of unbalanced passenger demand, which was based on the different passenger demand between stations and the imbalance of passengers within the station, to judge the necessity of implementing the limited-stop service for a bus route [34]. Wang et al. (2018) developed a mathematical model to address the optimal frequency and served stops of limited-stop bus services while considering passengers' service choices [35]. Liang et al. (2021) designed a cooperatively coevolutionary algorithm and solved the limited-stop service design and frequency setting problem at the transit network level [36]. Additionally, researchers improved existing models from other aspects, such as fare payment modes and trip purposes [37] and passenger onboard crowding [38], to better illustrate passenger cost and operator costs.

Integration of multiple strategies (including all-stop, short-turn, limited-stop and deadheading) is an effective way to deal with imbalanced passenger flow distribution [39]. Ulusoy et al. (2010) developed an integrated model for all-stop, short-turn and express transit services [40]. In their study, short-turn and all-stop routes were predetermined candidate routes, and frequencies and limited stops were optimised through a designed algorithm. Cortés et al. (2011) developed a model that combined short turning and deadheading in an integrated strategy for a single transit line. Frequencies, vehicle capacities and stop design were integrated [41]. Tang et al. (2018) proposed a methodology based on deficit function to adjust some trips to use multiple operational strategies and minimise the number of buses needed [42]. In their following studies, a network-based methodology was developed to generate vehicle departures of limited-stop, short-turn and limited-stop mixed with short-turn based on a given timetable of full-route service [43]. Passengers' preferences were incorporated to integrate full-route, short-turn, limited-stop, deadheading, limited-stop mixed with deadheading and limited-stop mixed with short-turn strategies in multiline optimisation [44].

Previous researchers developed optimisation methods on a single short-turn strategy, a single limited-stop strategy and the integration of multiple strategies. Most research on short-turn strategy determines the optimal stop design and frequency setting of both all-stop and short-turn services, applying relative offset or integer multiples to avoid bunching. As for limited-stop services, researchers optimise the frequency of limited-stop service and the skipped or served stops for a single limited-stop route or parallel with all-stop routes. Although short-turn or limited-stop service brings flexibility to transit operations, the performance of a single operational strategy on imbalanced demand distribution is limited. Combinations of multiple strategies enable saving passenger time and operation costs. However, most existing studies are frequency-based approaches, which have room for improvement to fine optimisation from the following aspects: i). capturing interactions between successive transit vehicle journeys; ii). matching passengers boarding, riding and alighting process to specific transit vehicle journeys; iii). considering interdependencies between multiple time periods. Therefore, it is necessary to develop timetable-based optimisation of mixed stopping strategies. Although timetable optimisation has been studied for all-stop services [45, 46], to the authors' best knowledge, only in Tang et al. [43] timetable-based departures of flexible operational strategies were optimised. However, the full-route service timetable was given in their study, with the objective of minimising the total changes in passenger travel time with respect to the existing schedule.

Therefore, the presented study contributes to the existing literature by: (1) modelling the detailed interactions between passengers' arrival, boarding, riding and alighting processes, and BRT vehicle's departure, running along segments and holding at stops across time periods; (2) developing a timetable and stopping pattern design model which integrates all-stop, short-turn and limited-stop services on a BRT corridor; (3) designing a rule-based heuristic algorithm to solve the problem, with the optimisation results analysed in a real-world case.

3. MODEL FORMULATION

The proposed model aims to minimise the total travel time of passengers transported by BRT vehicle journeys during the analysis period. The travel time for each passenger is calculated from the time arriving at the boarding station to the time alighting from the BRT vehicle. Integration of short-turn and all-stop or limited-stop and all-stop is considered for the given OD (origin and destination) profile. During the analysis period, one specific stopping pattern of limited-stop or short-turn service is used besides all-stop vehicle journeys. Two sets of decision variables are optimised: the stops served by short-turn or limited-stop services, and the BRT vehicle departure timetable. Key parameters and variables are shown in *Table 1*.

Table 1 – Model parameters and variables

Parameters	Meanings
N	The number of BRT stations
T_s	Starting time of the analysis time period, measured as the last BRT vehicle departure in the previous hour; accurate to minutes
T_e	Ending time of the analysis time period; accurate to minutes
R_{max}	The maximum number of all-stop vehicle journeys that could be dispatched during the study period $[T_s, T_e]$
r	Index of BRT vehicle journey
i	Index of BRT station, $1 \leq i \leq N$
i, j	Index of the passenger boarding and alighting BRT stations; $1 \leq i, j \leq N$
d_{i-1}^{i}	The running time between BRT vehicle departure at station $i-1$ and arrival at station i (s)
l_{i-1}^{i}	The distance between stations $i-1$ and i (m)
φ	Summation of the deceleration and acceleration time for BRT vehicles at stations (s)

Parameters	Meanings
q_{ij}	The arrival rate of passengers travelling from station i to j at station i (p/s); $1 \leq i, j \leq N$
β	The average boarding time per passenger (s/p)
α	The average alighting time per passenger (s/p)
ω	The minimum ratio of all-stop vehicle journeys in total dispatched vehicle journeys; $0 \leq \omega \leq 1$
h_{max}	The maximum deviation between the starting time and the first vehicle departure of the analysis period; measured in minutes
t	Time of the current moment, accurate to seconds
Z	Total travel time of passengers taken by BRT vehicle departures during the analysis period (s)
t_i^r, t_j^r	Arrival times of the rth BRT vehicle journey at station i, j, respectively, accurate to seconds
h_i^r	Dwell time of the rth BRT vehicle journey at station i (s)
b_i^r, a_i^r	The number of passengers boarding and alighting from the rth vehicle journey at station i, respectively (p)
τ_{ij}^r	The latest arrival time of all passengers from station i to j who are able to catch the rth vehicle journey at station i
R_0	The number of all-stop vehicle journeys dispatched during the analysis period
R_1	The number of limited-stop vehicle journeys dispatched during the analysis period
R_2	The number of short-turn vehicle journeys dispatched during the analysis period
R	Total number of vehicle journeys dispatched during the analysis period; $R = R_0 + R_1 + R_2$
ρ_r	Departure time of the rth vehicle journey, accurate to minutes; $1 \leq r \leq R$
p_i^1	A binary variable indicating whether station i is stopped for limited-stop service; 1-stop, 0-nonstop; $1 \leq i \leq N$
p_i^2	A binary variable indicating whether station i is stopped for short-turn service; 1-stop, 0-nonstop; $1 \leq i \leq N$
s_r^0	A binary variable indicating whether the rth vehicle journey is an all-stop service departure; 1-all-stop vehicle journey, 0-not all-stop vehicle journey; $1 \leq r \leq R$
s_r^1	A binary variable indicating whether the rth vehicle journey is a limited-stop service departure; 1-limited stop vehicle journey, 0-not limited stop vehicle journey; $1 \leq r \leq R$
s_r^2	A binary variable indicating whether the rth vehicle journey is a short-turn service departure; 1-short turn vehicle journey, 0-not short turn vehicle journey; $1 \leq r \leq R$

Passengers are assumed to board the first BRT vehicle journey arriving at their origin stations which also serve their destination stations. Terminals of the short-turn service are assumed to be at the first and last station served, whereas terminals of limited-stop and all-stop services are the first and last stations of the entire BRT route. The holding time of BRT vehicles at stations is measured as the acceleration and deceleration time entering and exiting stations plus passenger boarding and alighting time. For each BRT vehicle journey, the accumulation of passengers at stations starts from the arrival time of the last vehicle and ends at the arrival time of the current vehicle. Those who arrive during vehicle holding at stations are assumed to take the next vehicle journey to prevent indefinite boarding and holding.

The model optimisation enables detailed considerations of BRT vehicle journeys and passengers: (1) vehicle departures at the end of the previous hour are likely to influence the passengers left to be transported during the analysis period, which results in changes in objective values; (2) in-vehicle time of passengers varies with stopping strategies and holding time at served stops; (3) changes in passenger arrival rate in later time period would make a difference to the objective, as departures during the analysis time period would be in operation till the early next hour. With the interdependencies of passengers and BRT vehicles across continuous time periods depicted, the optimised timetables are more aligned with real-world scenarios.

3.1 Objective function

The optimisation objective is to minimise the total travel time of passengers taken by BRT vehicle journeys during the analysis period. The travel time for a passenger is measured from the arrival time at the origin BRT station to the alighting time. Total travel time is derived by summing the individual travel time of all boarding passengers across BRT vehicle journeys. The objective is calculated from *Equation 1*;

$$\min Z = \sum_{r=1}^{R}\sum_{i=1}^{N-1}\sum_{j=i}^{N}\int_{\tau_{ij}^{r-1}}^{\tau_{ij}^{r}} q_{ij}\left(t_j^r - t\right)dt \tag{1}$$

where t_j^r could be obtained from *Equations 2-3*, and τ_{ij}^r could be derived from *Equation 7*.

3.2 Constraints

1) BRT vehicle arriving time at stations

For the rth BRT vehicle journey, arriving time at station i could be obtained through the arriving time at the upstream station $i-1$, dwell time at station $i-1$ and vehicle running time in between, as shown in *Equations 2 and 3*;

$$t_i^r = t_{i-1}^r + h_{i-1}^r + d_{i-1}^i, \quad 1 < i \le N \tag{2}$$

$$t_i^r = \rho_r, \quad i = 1 \tag{3}$$

where t_{i-1}^r is the arriving time of vehicle journey r at station $i-1$. The arriving time at the initial station, t_1^r, is set equal to its departure time, ρ_r. d_{i-1}^i is the BRT vehicle running time between stations $i-1$ and i, which is influenced by signal control schemes and road conditions. It is recommended to estimate the parameter d_{i-1}^i from cumulative probability distributions based on historical BRT operation trajectories, to guarantee that most BRT vehicles could pass through the segment within the calibrated running time.

2) BRT vehicle dwell time at stations

The dwell time of BRT vehicles is related to passenger boardings, alightings and the deceleration and acceleration time of BRT vehicles entering and exiting stations, which could be calculated using *Equation 4*;

$$h_i^r = \begin{cases} \max(b_i^r\beta, a_i^r\alpha) + \varphi; & if \quad s_r^0 = 1 \\ \max(b_i^r\beta, a_i^r\alpha) + \varphi; & if\ s_r^1 = 1\ and\ p_i^1 = 1 \\ \max(b_i^r\beta, a_i^r\alpha) + \varphi; & if\ s_r^2 = 1\ and\ p_i^2 = 1 \\ 0; & otherwise \end{cases} \tag{4}$$

where b_i^r and a_i^r are the number of passengers boarding and alighting from the rth BRT vehicle journey at station i, respectively. b_i^r and a_i^r are derived from *Equations 6 and 7*.

3) Passengers latest boarding time for BRT vehicle journeys

For passengers whose origin and destination stations, i, j, are in service by all strategies, the latest boarding time on the rth vehicle journey is equal to the vehicle arrival time at station i, as shown in *Equation 5*. For passengers whose origin or destination stations are skipped by short-turn or limited-stop routes, the latest boarding time on the rth BRT vehicle journey is the same as that of the previous journey, i.e. the $r-1$th BRT vehicle journey.

$$\tau_{ij}^{r}=\begin{cases} t_i^r; & if\ s_r^1=1\ and\ p_i^1p_j^1=1 \\ t_i^r; & if\ s_r^2=1\ and\ p_i^2p_j^2=1 \\ t_i^r; & if\ s_r^0=1 \\ \tau_{ij}^{r-1}; & if\ s_r^1=1\ and\ p_i^1p_j^1=0 \\ \tau_{ij}^{r-1}; & if\ s_r^2=1\ and\ p_i^2p_j^2=0 \end{cases} \tag{5}$$

4) The number of passengers boarding and alighting at stations

The number of passengers boarding and alighting from the rth vehicle journey at station i, are calculated through *Equations 6 and 7*. To obtain these two variables, passengers from i to j who are able to catch the rth BRT vehicle journey are required. A timely service principle is used, i.e. passengers arriving at the station will be served by the upcoming BRT vehicle stopping at their origins and destinations. As a result, by comparing the passenger arrival time with the latest boarding time at station i, it is possible to deduct whether the passenger takes the rth BRT vehicle journey.

$$b_i^r=\sum_{j=i+1}^{N}\int_{\tau_{ij}^{r-1}}^{\tau_{ij}^{r}} q_{ij}\,dt\,, 1\le i<N \tag{6}$$

$$a_i^r=\sum_{j=1}^{i-1}\int_{\tau_{ji}^{r-1}}^{\tau_{ji}^{r}} q_{ji}\,dt\,, 1< i\le N \tag{7}$$

5) Stopping patterns of short-turn and limited-stop services

Served stops are determined within each strategy of all-stop, short-turn and limited-stop services, as indicated in *Equations 8-9*. In limited-stop service, BRT vehicles stop at the initial and terminal stations and skip intermediate ones, constrained by *Equation 8*. Short-turn journeys serve continuously along segments and skip the rest, i.e. an interval within the entire route, constrained by *Equation 9*.

$$\begin{cases} s_1^1 s_N^1=1 \\ \sum_{i=1}^{N} s_i^1<N \end{cases} \tag{8}$$

$$\begin{cases} \prod_{i=j}^{k} p_i^2=1 \\ \sum_{i=1}^{N} p_i^2=k-j+1 \\ 1\le j<k\le N \\ k-j<N-1 \end{cases} \tag{9}$$

6) Operational strategies of BRT vehicle journeys

Each BRT vehicle journey operates with a single strategy, as illustrated in *Equation 10*. The total number of BRT vehicle journeys for limited-stop, short-turn and all-stop strategies, respectively, are derived from *Equations 11-13*. The total number of BRT vehicle journeys is shown in *Equation 14*.

$$s_r^0+s_r^1+s_r^2=1,\quad 1\le r\le R \tag{10}$$

$$\sum_{r=1}^{R} s_r^0 = R_0 \tag{11}$$

$$\sum_{r=1}^{R} s_r^1 = R_1 \tag{12}$$

$$\sum_{r=1}^{R} s_r^2 = R_2 \tag{13}$$

$$R_0 + R_1 + R_2 = R \tag{14}$$

7) Combinations of operation strategies

The optimisation model generates timetables on an hourly basis. For each analysis time period, one stopping pattern among limited-stop and short-turn strategies is used along with the all-stop strategy. This is constrained by *Equation 15*. Besides, the minimum number of all-stop vehicle journeys in total vehicle journeys is controlled, as indicated in *Equation 16*.

$$R_1 R_2 = 0 \tag{15}$$

$$\frac{R_0}{R} \geq \omega \tag{16}$$

8) Vehicle departure time constraint

The departure time of the first vehicle journey is set to be within a limited difference from the starting time of the analysis period, in order to alleviate large gaps between continuous service hours, as indicated in *Equation 17*. *Equation 18* regulates the departure time of each vehicle journey within the analysis time period;

$$0 \leq \rho_1 - T_s \leq h_{max} \tag{17}$$

$$T_s \leq \rho_r \leq T_e, 1 \leq r \leq R \tag{18}$$

where h_{max} denotes the maximum deviation of the first departure from the starting time of the analysis period.

9) Total operating mileage constraint

To constrain the operating cost of vehicles, the total mileage of all vehicle journeys is set to be no more than that of the maximum all-stop departures, as shown in *Equation 19*.

$$R_0 \sum_{1<i\leq N} l_{i-1,i} + R_1 \sum_{1<i\leq N} l_{i-1,i} + R_2 \sum_{1<i\leq N} \delta_{i-1}^2 \delta_i^2 l_{i-1,i} \leq R_{max} \sum_{1<i\leq N} l_{i-1,i} \tag{19}$$

4. SOLUTION ALGORITHM

The solutions include two parts: stopping patterns of limited-stop (p_i^1; $i = 1, \dots N$) or short-turn strategies (p_i^2; $i = 1, \dots N$), and the timetable of vehicle journeys ($\rho_r, s_r^0, s_r^1, s_r^2$; $r = 1, \dots, R$). These two sets of decision variables are nested. The optimal timetables vary with stopping patterns, due to total operating mileage constraints. Therefore, a rule-based heuristic algorithm is proposed in this section to solve the problem. The solution procedure is illustrated in *Figure 1*.

The solution space is first narrowed to an acceptable range by selecting candidate-stopping patterns. Here, two criteria regarding efficiency and effectiveness are used to select candidate-stopping patterns. For the given OD distribution, the effectiveness of a stopping pattern is evaluated by the ratio of the number of trips that could be finished in total OD demand. This criterion guarantees a high proportion of demand carried by short-turn/limited-stop services, which reduces the additional waiting time for passengers with unserved origins and destinations, i.e. they have to wait for the next all-stop vehicle journey. Efficiency is calculated as the number of trips that could be finished divided by the total number of served stops. This criterion decreases the in-vehicle travel time of passengers taking short-turn/limited-stop vehicle journeys. A stopping pattern shows efficiency and effectiveness when both measures are relatively high, guiding the problem-solving towards minimising the objective. Two thresholds are used for selection: the minimum ratio of trips that could be fulfilled in total OD demand e_{min} and the top δ candidate stopping patterns to be kept.

Second, given each candidate stopping pattern, the number of limited-stop/short-turn vehicle journeys that could be dispatched are identified, with the ratio of all-stop in total vehicle journeys varying from ω to 100%. Therefore, we obtain the number of vehicle journeys per strategy corresponding to candidate stopping patterns.

Third, the departure timetables are optimised. In this step, we first determine the departure time for all-stop vehicle journeys as evenly distributed. This is based on the characteristic of the problem, that optimising total passenger travel time requires relatively balanced all-stop departures. Next, an iterative insertion step is performed by placing limited-stop/short-turn vehicle journeys in available time slots between successive all-stop vehicle journeys. The analysis period is split into multiple sub-sections by all-stop vehicle departures. Therefore, the departure time of short-turn/limited-stop vehicle journeys is converted to 0-1 decisions on the 1-minute slots within these subsections. As the model captures the interactions between vehicle journeys and passengers, the objective value requires calculations by matching passengers with vehicle journeys each time when a new solution is generated. This step reduces the computational load of the objective value by limiting the influential ranges of adding a short-turn/limited-stop vehicle journey within one subsection, i.e. the matching process is only performed in the subsection where the insertion occurs. Additionally, the changes of objective values for inserting at all locations are saved in the memory, which reduces the time for the same calculations in later insertions.

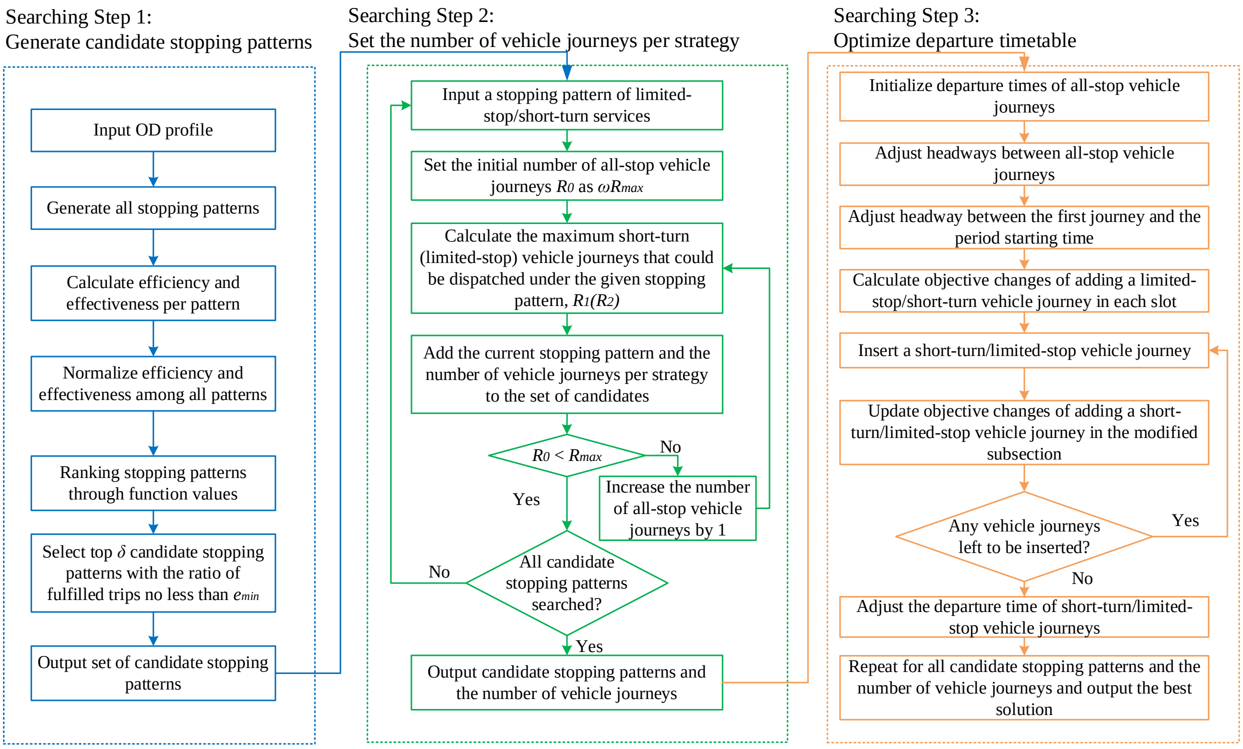


Figure 1 – The proposed heuristic algorithm

Searching Step 1: Generate candidate stopping patterns for short-turn and limited-stop services.

Establish stopping pattern alternatives for short-turn and limited-stop services, and select candidate stopping patterns. The selection is performed based on two measurement criteria: effectiveness and efficiency of station utilisation. The overall evaluation of a stopping pattern is the sum of the normalised values of both indicators among all stopping patterns. Filter all stop patterns with the minimum threshold of the ratio of trips that could be fulfilled in total OD demand e_{min}, and output the top δ candidate stopping patterns to the next step.

Searching Step 2: Generate combinations of the number of vehicle journeys per service strategy.

This step calculates possible combinations of all-stop services and short-turn/limited-stop services. Under the constraint of maximum total mileage, the maximum short-turn or limited-stop vehicle departures could be determined given the stopping pattern and the number of all-stop vehicle journeys. Therefore, all combinations of the number of all-stop and short-turn/limited-stop vehicle journeys are calculated with varying numbers of all-stop vehicle journeys from $\omega R_{\max}$ to $R_{\max}$.

Searching Step 3: Optimise departure timetable.

1) Set the initial departure time for all-stop vehicle journeys. The analysis period starts from T_s and ends at T_e. Divide the time period by the number of all-stop vehicle journeys R_0. The initial headway is then obtained as $\left\lfloor \frac{T_e-T_s}{R_0} \right\rfloor$ (rounding down to the nearest integer). Set the headway for the first R_0-1 all-stop vehicle journeys as $\left\lfloor \frac{T_e-T_s}{R_0} \right\rfloor$. The headway between the (R_0-1)th and R_0th vehicle journey is $T_e-T_s-(R_0-1)\left\lfloor \frac{T_e-T_s}{R_0} \right\rfloor$.
2) If the headway between the (R_0-1)th vehicle journey and the R_0th vehicle journey is larger than $\left\lfloor \frac{T_e-T_s}{R_0} \right\rfloor$ (Δh is the difference), adjustments are made to further guarantee balanced all-stop vehicle departures. Increase the length of Δh subsections among all subsections between the first (R_0-1) vehicle journeys to $\left\lfloor \frac{T_e-T_s}{R_0} \right\rfloor+1$. This step finds the optimal departure plan for all-stop vehicle journeys by iteratively looking into $\binom{\mathrm{R}-1}{\Delta\mathrm{h}}$ alternatives.
3) If the departure deviation of the first vehicle journey is larger than h_{max}, update the departure time of the first vehicle journey to T_s+h_{max}, recalculate headway using $\left\lfloor \frac{T_e-T_s-h_{max}}{R_0-1} \right\rfloor$, and repeat (1) and (2) to adjust all-stop vehicle departure times.
4) Calculate objective changes of inserting an additional limited-stop/short-turn vehicle journey in each time slot. Calculate the changes of objective after adding a short-turn/limited-stop vehicle journey into an available time slot between all-stop vehicle journeys. Every time the objective is calculated, a matching process is required between passengers and BRT vehicle journeys. This calculation is confined to a limited influential range, i.e. the subsection between all-stop vehicle journeys where the short-turn/limited-stop vehicle journey is to be inserted.
5) Insert a short-turn/limited-stop vehicle journey. Find the best slot within each subsection which brings the maximum reduction to the objective. Insert a short-turn/limited-stop vehicle journey.
6) Update the objective changes of adding an additional limited-stop/short-turn vehicle journey in the modified subsection. When a new vehicle journey is to be added, the positions of all existing short-turn/limited-stop vehicle journeys within the subsection are cleared. The additional vehicle journey along with existing ones are re-inserted into available time slots in the modified subsection, and the changes in the objective function are calculated for all possible insertions. These solutions and corresponding objective changes are then updated for the modified subsection.
7) Repeat 5) and 6) until no short-turn/limited-stop vehicle journeys are left to be inserted.
8) Adjust the departure time of short-turn/limited-stop vehicle journeys. If the number of short-turn/limited-stop vehicle journeys in the previous subsection is greater than the current, dispatch all short-turn/limited-stop vehicle journeys in the current subsection 1 minute earlier and compare the changes of the objective function. If the objective value decreases, adjust the departure time of these short-turn/limited-stop vehicle journeys to the current plan. If no, proceed to the next two subsections.
9) Repeat 1) – 8) for other candidate stopping patterns and the number of vehicle journeys per strategy. Output the best solution of stopping pattern and departure timetable with the minimum objective.

5. CASE STUDY

5.1 The studied route

The proposed model and algorithm are validated through a case study in Shanghai, China. A BRT route with 13 stations upward and downward across different municipal districts of Shanghai, Fengpu Express BRT line, is studied. As shown in *Figure 2*, the upward direction is from Nanqiao Bus Station to Shendu Highway Station, numbered in ascending order. The total length of the BRT line is 21 km.

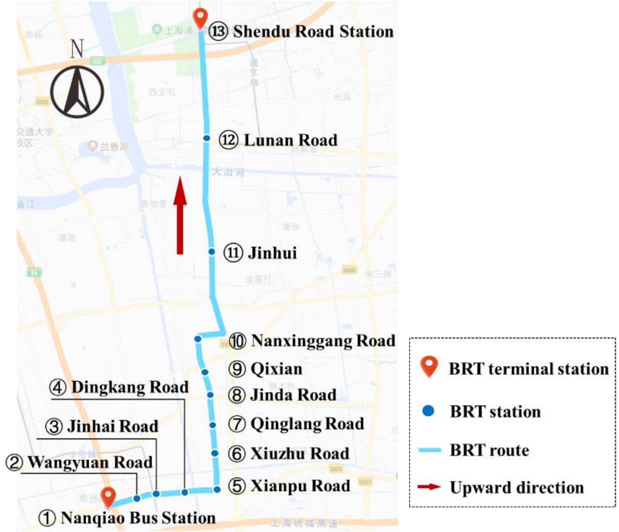


Figure 2 – BRT station location

BRT passenger demand in the upward direction is collected from 11 October to 15 October 2021, based on smart card data. The analysis period is the morning peak from 7:00 to 8:00 am, whereas the interactions of various departures are within a wider range of time periods. Based on the measurement of one-way trip time, vehicle departures between 7:00-8:00 are likely to reach terminals between 7:00-9:00. Similarly, vehicle departures between 6:00-7:00 are likely to be in service between terminals in 7:00-8:00. Therefore, the analysis is expanded to 6:00-9:00. Current departure timetable and OD distribution of the upward line from 6:00-9:00 are exhibited in *Table 2* and *Figure 3*, respectively. The cumulative probability distribution of BRT running time between stations at 7:00-9:00 is drawn based on GPS (Global Positioning System) data collected from 11 October to 15 October 2021. As indicated in *Figure 4*, the turning point at 95% is observed for most segments. Therefore, we use the 95th percentile to estimate segment running time. Other model parameter settings are shown in *Table 3*.

Table 2 – Current departure timetable of Fengpu Express line from 6:00 to 9:00 am

Strategy	Timetable				
All-stop	06:05	06:13	06:22	06:30	06:38
	06:46	06:54	07:00	07:06	07:12
	07:18	07:24	07:30	07:37	07:45
	07:53	08:00	08:08	08:15	08:23
	08:30	08:38	08:46	08:55	

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	0	9	0	48	21	3	13	9	15	6	25	9	380	538
2	0	0	0	5	11	0	6	1	2	1	1	1	51	79
3	0	0	0	1	4	2	1	0	1	1	4	0	24	38
4	0	0	0	0	4	1	8	8	6	12	1	2	56	98
5	0	0	0	0	0	1	6	15	8	2	6	2	182	222
6	0	0	0	0	0	0	0	1	1	0	0	1	60	63
7	0	0	0	0	0	0	0	3	9	4	8	3	163	190
8	0	0	0	0	0	0	0	0	1	1	1	0	33	36
9	0	0	0	0	0	0	0	0	0	3	12	10	456	481
10	0	0	0	0	0	0	0	0	0	0	18	7	911	936
11	0	0	0	0	0	0	0	0	0	0	0	5	82	87
12	0	0	0	0	0	0	0	0	0	0	0	0	172	172
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum	0	9	0	54	40	7	34	37	43	30	76	40	2570	2940

Figure 3 – OD distribution of Fengpu Express line (upward) from 6:00 to 9:00 am

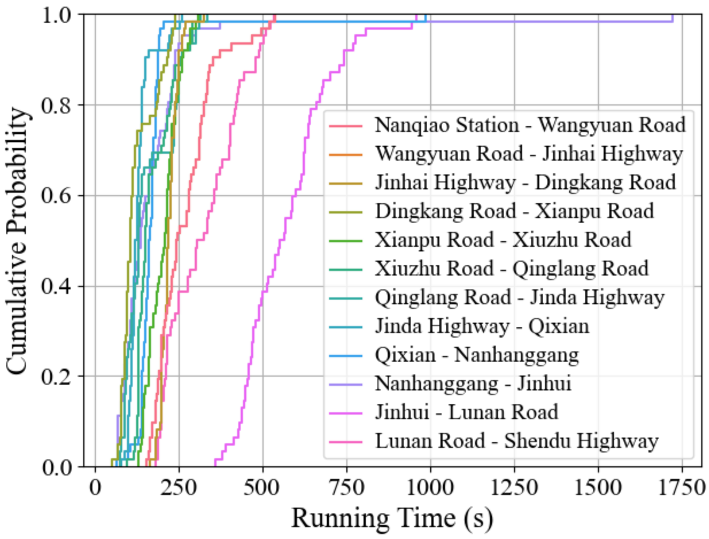


Figure 4 – Distribution of BRT vehicle running time between stations

Table 3 – Parameter setting

Symbol	**Value**
R_{max}	9
N	13
φ	40s
β	3s/p
α	3s/p
e_{min}	60%
h_{max}	480s
δ	3
ω	0.5

5.2 Results

Integrated operational strategies of all-stop and short-turn services are adopted to fit the OD profile. The optimised departure timetable in the upward direction is shown in *Table 4*. All-stop vehicle journeys are operated along the entire route. The stops served by short-turn vehicle journeys cover a segment in between, including Nanqiao Bus Station, Wangyuan Road Station, Jinhai Road Station, Dingkang Road Station and Xianpu Road Station, as indicated in *Figure 5*.

Table 4 – Departure timetable of the upward direction from 7:00 to 8:00 am

Strategy	**Timetable**				
All-stop	07:02	07:10	07:18	07:27	07:36
	07:45	07:53			
Short-turn	07:03	07:09	07:16	07:22	07:29
	07:35	07:42	07:50		

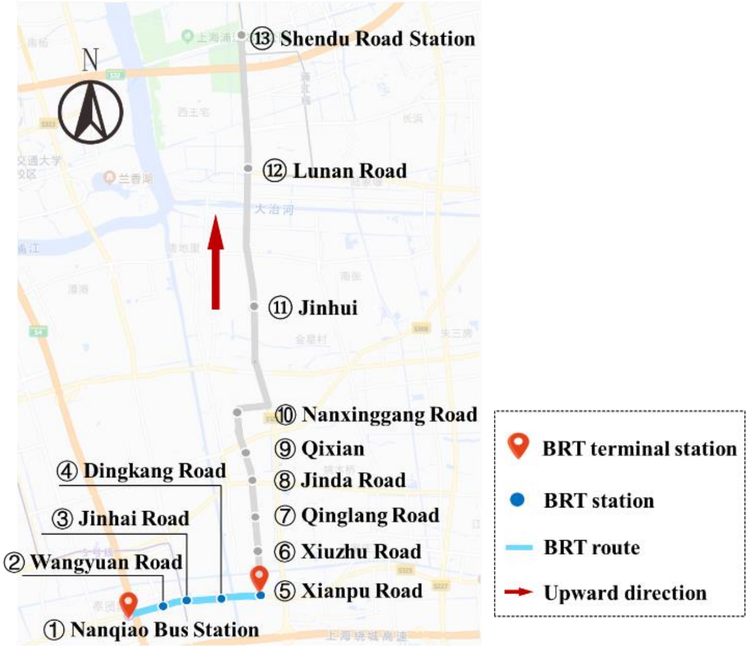


Figure 5 – Stopping patterns of short-turn vehicle journeys

The OD distribution for the whole day is used to validate the proposed multi-operational strategy. Results are analysed for three cases including the current timetable, the all-stop strategy only and the multi-operational strategy. *Figure 6* presents representative OD distributions during morning peak, off-peak, evening peak and night hours.

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	0	3.5	0	21.5	7	1	4.5	4.5	5.5	2.5	10.5	4	118.5	183
2	0	0	0	2.5	3.5	0	3	0.5	0.5	0	0.5	0.5	13	24
3	0	0	0	0.5	2	0.5	0.5	0	0.5	0.5	1.5	0	6.5	12.5
4	0	0	0	0	2	0.5	4	2.5	3	6	0.5	0	20.5	39
5	0	0	0	0	0	0.5	3	4.5	1	0.5	3	1	61.5	75
6	0	0	0	0	0	0	0	0.5	0	0	0	0.5	18	19
7	0	0	0	0	0	0	0	1.5	4.5	2	3	1.5	49.5	62
8	0	0	0	0	0	0	0	0	0.5	0.5	0	0	11.5	12.5
9	0	0	0	0	0	0	0	0	0	1.5	5	2.5	157	166
10	0	0	0	0	0	0	0	0	0	0	8.5	3	326	337.5
11	0	0	0	0	0	0	0	0	0	0	0	2.5	32.5	35
12	0	0	0	0	0	0	0	0	0	0	0	0	79	79
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum	0	3.5	0	24.5	14.5	2.5	15	14	15.5	13.5	32.5	15.5	893.5	1044.5

(a)

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	0	1	1	1	6	1	4	1	4	2	1	5	29	56
2	0	0	0	1	2	1	3	0	4	6	0	1	8	26
3	0	0	0	1	2	0	2	0	0	0	0	0	4	9
4	0	0	0	0	1	1	6	3	4	9	2	1	10	37
5	0	0	0	0	0	0	3	1	3	1	0	1	23	32
6	0	0	0	0	0	0	0	0	0	0	0	0	3	3
7	0	0	0	0	0	0	0	0	1	1	1	1	15	19
8	0	0	0	0	0	0	0	0	0	0	0	1	6	7
9	0	0	0	0	0	0	0	0	0	1	0	4	46	51
10	0	0	0	0	0	0	0	0	0	0	2	8	60	70
11	0	0	0	0	0	0	0	0	0	0	0	1	8	9
12	0	0	0	0	0	0	0	0	0	0	0	0	16	16
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum	0	1	1	3	11	3	18	5	16	20	6	23	228	335

(b)

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	0	2	1	5	15	6	12	2	6	4	2	8	21	84
2	0	0	0	1	9	5	14	4	10	12	1	5	15	76
3	0	0	0	0	3	2	4	0	2	1	0	2	4	18
4	0	0	0	0	1	2	5	1	3	4	0	0	5	21
5	0	0	0	0	0	3	7	1	10	6	0	2	15	44
6	0	0	0	0	0	0	0	0	1	1	0	1	3	6
7	0	0	0	0	0	0	0	0	0	1	0	1	4	6
8	0	0	0	0	0	0	0	0	1	1	0	2	4	8
9	0	0	0	0	0	0	0	0	0	1	1	3	26	31
10	0	0	0	0	0	0	0	0	0	0	1	4	38	43
11	0	0	0	0	0	0	0	0	0	0	0	5	22	27
12	0	0	0	0	0	0	0	0	0	0	0	0	21	21
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum	0	2	1	6	28	18	42	8	33	31	5	33	178	385

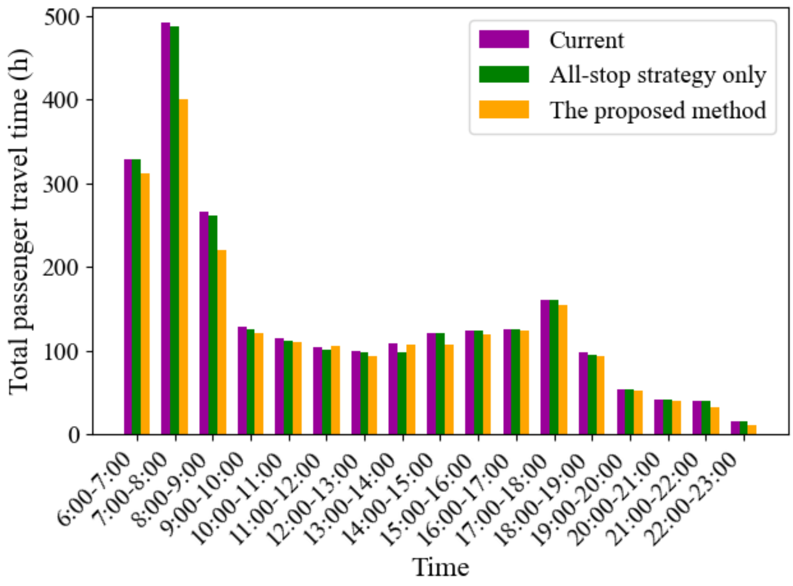
(c)

O \ D	1	2	3	4	5	6	7	8	9	10	11	12	13	Sum
1	0	1	0	2	2	2	4	1	2	7	1	7	1	30
2	0	0	0	0	3	2	15	1	5	12	1	3	11	53
3	0	0	0	0	3	0	5	0	2	1	0	1	0	12
4	0	0	0	0	0	1	1	0	1	0	1	0	0	4
5	0	0	0	0	0	1	2	0	0	0	0	0	2	5
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	2	0	0	1	3
8	0	0	0	0	0	0	0	0	0	0	0	0	1	1
9	0	0	0	0	0	0	0	0	0	0	0	0	4	4
10	0	0	0	0	0	0	0	0	0	0	0	2	5	7
11	0	0	0	0	0	0	0	0	0	0	0	2	1	3
12	0	0	0	0	0	0	0	0	0	0	0	0	11	11
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum	0	1	0	2	8	6	27	2	10	22	3	15	37	133

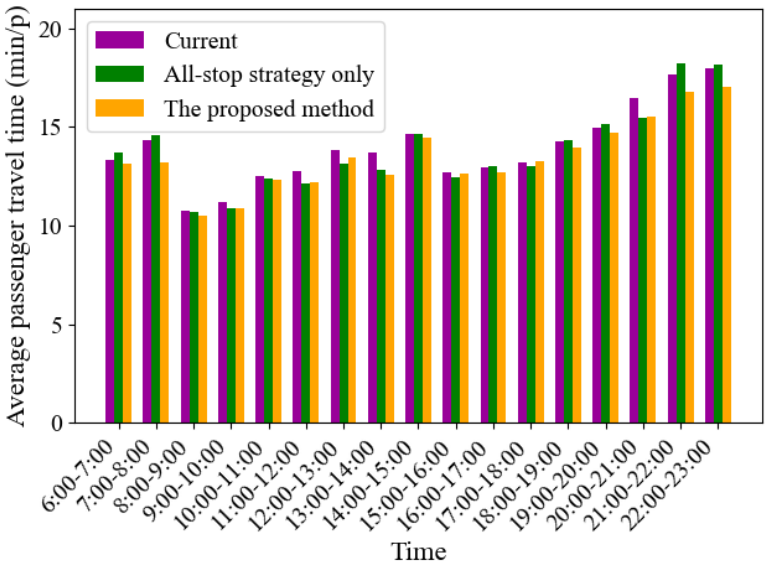
(d)

Figure 6 – OD distribution of Fengpu Express BRT line (upward, per hour): a) 7:00-9:00; b) 10:00-14:00; c) 17:00-19:00; d) 21:00-23:00

Total passenger travel time and average travel time are calculated for the three cases. Results are exhibited in *Figure 7*. Overall, the total passenger travel time decreased by 18.72% (492.1 vs 399.99 hours) and 17.83% (486.78 vs 399.99 hours) compared to the current timetable and all-stop strategy, respectively. The proposed algorithm outperforms in most studied hours, except that a small portion saw higher total travel time, e.g. 11:00-12:00. This is because BRT vehicle journeys within these service hours carry more passengers.



(a)



(b)

Figure 7 – Comparison of total travel time and average travel time under current, all-stop only and the integration of multiple strategies: a) Total travel time during the analysis time period; b) Average passenger travel time during the analysis time period

5.3 Optimisation effectiveness analysis

To evaluate the effectiveness of the proposed algorithm, two comparative analyses were performed. All algorithms were implemented in Python 3.9 and executed on an AMD Ryzen 7 7840HS w 3.80 GHz computer.

1) Evaluating the effectiveness of Steps 1 and 2

Optimisation results were performed using the first genetic algorithm (GA) for comparing the effectiveness of Steps 1 and 2. Stopping patterns were encoded as 0-1 variables for each stop, and the number of all-stop vehicle journeys was encoded as a real number. The number of short-turn/limited-stop vehicle journeys was determined through the maximum total mileage constraint. In the GA algorithm, Step 3 from our proposed algorithm was embedded during the initialisation and evolution process, i.e. generating optimised timetables given stopping patterns and combinations of the number of vehicle journeys per strategy. As shown in *Table 5*, the optimisation results of GA and the developed algorithm are close. However, the computational time could be greatly reduced (96.36%) using Steps 1 and 2 in the proposed algorithm.

Table 5 – Comparison between Steps 1 and 2 in the proposed algorithm and the first genetic algorithm

Method	Objective value (h)	Average travel time (min/p)	CPU time (h)
The proposed algorithm	891.09	19.34	0.14
The first GA	890.94	19.33	3.85

2) Evaluating the effectiveness of Step 3

Optimisation results were generated using the second genetic algorithm (GA) for comparing the effectiveness of Step 3. With predefined stopping patterns and the number of vehicle journeys per strategy (from Searching Steps 1 and 2), the departure times of each vehicle journey were encoded as real numbers. As shown in *Table 6*, the optimisation results of our algorithm outperform GA. In addition, the computational time is reduced (92.92%) through the heuristic searching step 3.

Table 6 – Comparison between Step 3 in the proposed algorithm and the second genetic algorithm

Method	Objective value (h)	Average travel time (min/p)	CPU time (h)
The proposed algorithm	891.09	19.34	0.08
The second GA	927.09	20.12	1.13

5.4 Sensitivity analysis

In this section, sensitivity analyses of passengers' average boarding and alighting time, O-D profiles and maximum total mileage are conducted to further understand the impacts of key parameters.

1) Average boarding and alighting time

The optimisation results under different average boarding and alighting times per passenger are analysed. The average boarding time per person is raised from 3 seconds to 4 seconds, with a unit increment of 0.5 seconds. Similarly, the average alighting time per person varies from 1 second to 4 seconds.

Results of the generated timetables between 7:00-8:00 am are exhibited in *Tables 7-9*. The optimised timetables vary with changes in the unit boarding time per passenger. Passengers' average alighting time has little impact on the optimised timetable.

Table 7 – Departure timetable between 7:00-8:00 am (average boarding time = 3s/p)

Strategy	Timetable				
All-stop	07:05	07:14	07:24	07:34	07:44
	07:54				
Short-turn	07:04	07:12	07:18	07:24	07:32
	07:38	07:45	07:48	07:54	

Table 8 – Departure timetable between 7:00-8:00 am (average boarding time = 3.5s/p)

Strategy	Timetable				
All-stop	7:03	7:11	7:19	7:27	7:36
	7:45	7:54			
Short-turn	7:04	7:10	7:15	7:21	7:26
	7:33	7:43	7:51		

Table 9 – Departure timetable between 7:00-8:00 am (average boarding time = 4s/p)

Strategy	Timetable				
All-stop	07:05	07:14	07:24	07:34	07:44
	07:54				
Short-turn	07:05	07:11	07:15	07:20	07:25
	07:29	07:34	07:40	07:47	07:49
	07:54				

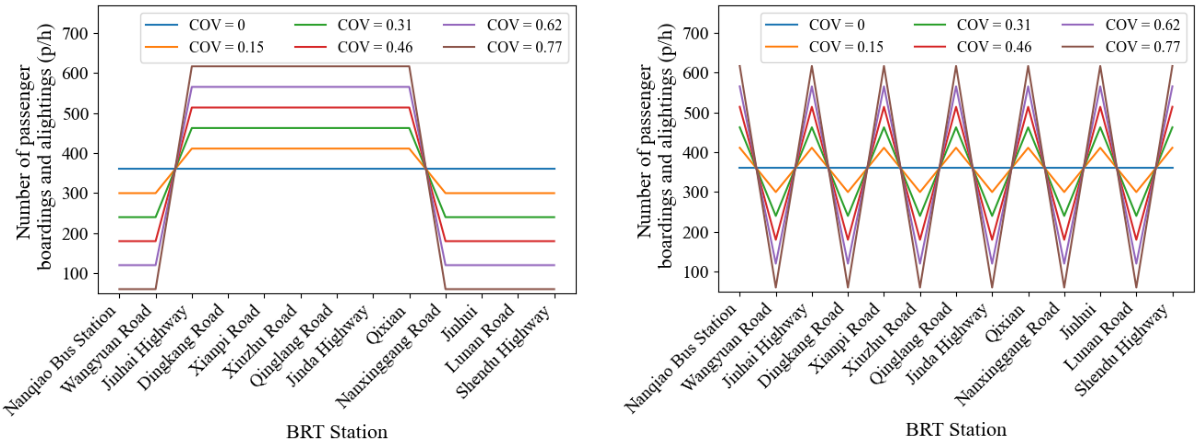
Table 10 – The optimised total passenger travel time (hours) with variations of average boarding and alighting time

Alighting / Boarding	4 s/p	3.5 s/p	3 s/p	2.5 s/p	2 s/p	1.5 s/p	1 s/p
4 s/p	1152.98	1148.72	1147.33	1146.63	1146.53	1146.36	1145.93
3.5 s/p		1118.36	1117.56	1116.29	1115.27	1114.19	1113.32
3 s/p			1066.32	1064.51	1063	1062.33	1062.3

Table 10 exhibits the total travel time of passengers with varying average boarding and alighting time. The average boarding time has a greater influence on total passenger travel time compared to the alighting process. As indicated in *Table 10*, under the same average boarding time, the total passenger travel time shows a mild decrease with the reduction of average alighting time. In contrast, under the same average alighting time, the total travel time of passengers decreases by 3-5% with the 0.5-second reduction of boarding time. By jointly analysing *Tables 7-10*, we could tell that the holding time of BRT vehicles increases as passengers' average boarding time and alighting time increase, which results in longer enroute time for BRT vehicles and in-vehicle travel time for passengers.

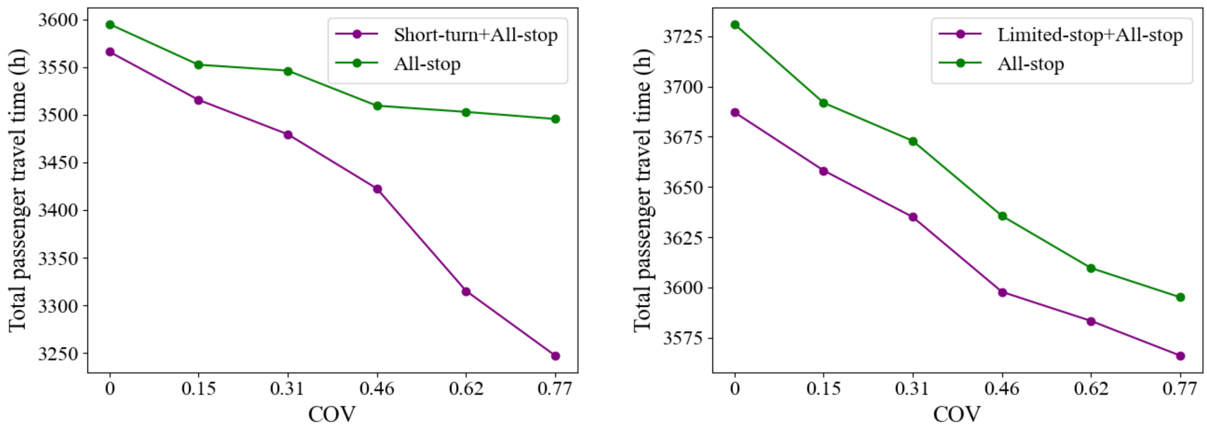
2) OD profile

Two typical OD profiles for short-turn and limited-stop strategies are created. Differences in OD distributions along BRT stations are enlarged from the baseline to analyse the impacts on optimisation results. *Figure 8* illustrates the passenger volume distribution and the corresponding coefficient of variance (COV) for BRT stations, i.e. the standard deviation divided by the mean of passenger volumes. Results of the total passenger travel time for the proposed combinatorial strategy and all-stop-only strategy are compared, as shown in *Figure 9*.



(a) (b)

Figure 8 – Two OD profiles used for combinatorial strategies: a) OD Profile 1; b) OD Profile 2



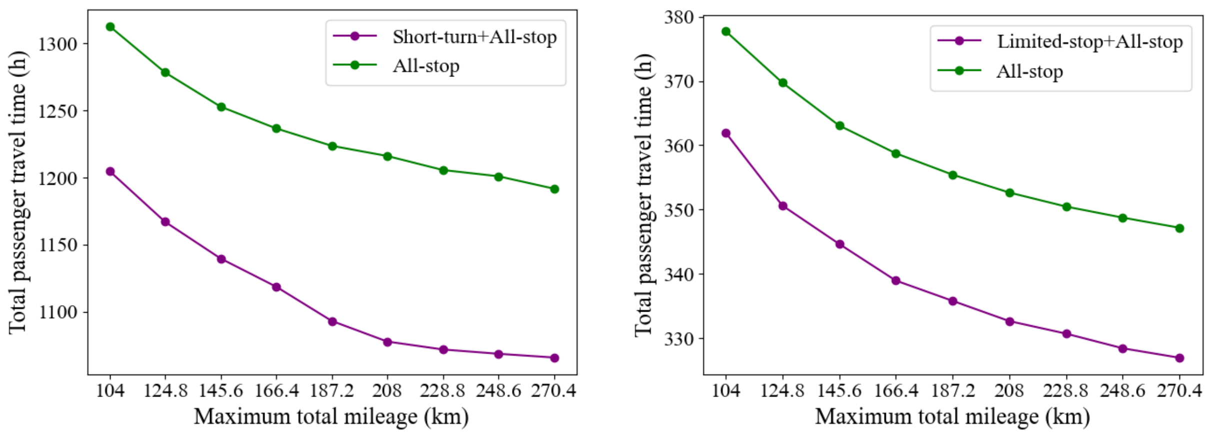
(a) *(b)*

Figure 9 – Changes of total passenger travel time with varying OD distributions: a) OD Profile 1; b) OD Profile 2

As indicated in *Figure 9*, in general, the combinatorial strategy is more effective than all-stop services. Under OD Profile 1, where the passengers' boardings and alightings are more suitable for short-turn combined with all-stop services, the combinatorial operational strategy gets more effective as the COV of passenger volume increases. Total passenger travel time shows 1-7% greater reductions compared to an all-stop strategy only. Under OD Profile 2, as shown in *Figure 9b*, the total passenger travel time of the combinatorial strategy is 1% less than that of all-stop only strategy, and the difference remains relatively stable under varying COV levels.

3) Maximum total mileage

The current OD demands of Fengpu Express BRT line during 7:00-8:00 and 17:00-18:00 are used for integrating all-stop and short-turn as well as all-stop and limited-stop, respectively. The maximum number of all-stop vehicle journeys that could be dispatched, R_{max}, is increased from 5 to 13 (the maximum total mileage ranging from 104 km to 270.4 km). The results of total passenger travel time are shown in *Figure 10*.



(a) *(b)*

Figure 10 – Changes of total passenger travel time under different maximum total mileage limits: a) Short-turn combined with all-stop versus all-stop only; b) Limited-stop combined with all-stop versus all-stop only

The total passenger travel time in response to the variations of maximum total mileage is analysed in *Figure 10*. As the maximum total mileage increases, total passenger travel time is reduced under all three strategies. From *Figure 10a*, when the maximum total mileage increases, the total passenger travel time of short-turn combined with all-stop strategies shows 8% to 11% higher decreases than that of all-stop only strategy. A threshold of 208 km is observed for a short turn combined with an all-stop strategy, beyond which the reduction in total passenger travel time slows down. As indicated in *Figure 10b*, the effectiveness of the limited-stop combined with the all-stop strategy varies with the maximum total operating mileage. When the maximum total operating mileage increases from 104 km to 270.4 km, the limited-stop combined with the all-stop strategy achieves 4-6% greater reductions in total travel time compared to the all-stop strategy only.

6. CONCLUSION

This paper presents an optimisation model of integrating multiple operational strategies including all-stop, short-turn and limited-stop services to improve the efficiency and effectiveness of BRT operation. A rule-based heuristic algorithm is proposed to solve the optimisation model. The proposed model enables detailed descriptions of the interactions between successive BRT vehicle journeys and the influence of passenger arrivals, boardings and alightings on BRT operation. In addition, the interdependencies between multiple time periods are involved. Stopping patterns and departure timetables are decision variables, and the objective is to minimise the total travel time of passengers taken by BRT vehicle journeys during the analysis period. The developed method is validated through a case study of a BRT line in Shanghai, China. Sensitivity analyses of key inputs and parameters are made to better understand and apply the presented model and algorithm.

Using the proposed method integrating multiple operational strategies for BRT routes, total passenger travel time is decreased by 18.72% and 17.83% compared to the current timetable and conventional all-stop strategy, respectively. The multi-operational strategy enables improving transit quality of service under the same operational cost levels. Therefore, through optimisation, transit agencies could better balance OD distribution, save passenger travel time and improve service efficiency. Moreover, the designed algorithm demonstrates better performance in computational time compared to existing GA algorithms. Additionally, the optimised stopping pattern, timetable and total travel time vary with changes in average boarding and alighting times, OD profiles and maximum total mileage.

1) The average boarding time of passengers has a greater impact on the optimised timetable and total travel time than alighting time. By improving the ease of boarding for passengers along BRT routes, total passenger travel time could be saved.
2) Under typical OD profiles, the combinatorial strategies achieve lower total passenger travel time compared to the all-stop-only strategy. Short-turn services show a growing advantage over an all-stop strategy as variations of OD distribution increase. This indicates that the multi-operational strategy becomes increasingly efficient as the imbalance in OD distribution grows, especially for the designed short-turn service.
3) For both all-stop-only and combinatorial strategies, total passenger travel time is decreased as the maximum total mileage grows. There is a threshold for short-turn combined with an all-stop strategy, beyond which the reduction in total passenger travel time slows down. Therefore, transit agencies could consider increasing budgets on operational costs in order to reduce total passenger travel time. However, it is recommended to control the investment within a reasonable threshold, as exceeding it could reduce cost-effectiveness.

The proposed method could be implemented utilising historical data on passenger demand and BRT vehicle trajectories. It is suggested that the stop patterns and combinatorial dispatch plans be regularly updated, for instance, on a seasonal basis. Predefined vehicle and crew scheduling plans are subsequent tasks essential for the smooth execution of the optimised timetable. For all-stop combined with limited-stop strategies the terminals are the same, so that vehicle scheduling plans can be generated through varying trip times based on existing methods. For short-turn strategy the terminals are different, vehicle scheduling could be on its own or optimised together with all-stop journeys. Additionally, timetables and dispatching plans should be made accessible via mobile applications and displayed at BRT stations to ensure ease of use for passengers.

Future research in line involves the stochastic optimisation of timetables integrating multiple operational strategies, taking into account the variations in bus running times along segments and the interactions between passengers and buses across time periods. Service reliability considerations, such as fluctuations in passenger journey times, could be embedded in the optimisation objective. Furthermore, it is essential to explore emerging technologies while developing multi-operational strategies, including modular buses and reservation-based systems. Modular buses, which enable coupling and decoupling, introduce more flexibility in stopping patterns [47,48]. Reservation-based systems, on the other hand, could significantly reduce passenger waiting times and the additional delays associated with failure to board [49]. Therefore, incorporating these innovations would facilitate saving operational costs and improving service quality.

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一种融合全站停靠、区间车和大站快车的快速公交时刻表设计方法

摘要
快速公交 (BRT) 拥有专属道路环境、专用站台及先进的技术装备，与传统公交相比，能够提供更高质量的服务。然而，乘客需求在时间和空间上的不平衡分布导致 BRT 系统浪费严重。为了提高运营效率，本文提出了一种基于时刻表的优化方法，该方法集成了多种运营策略，包括全站停、区间车和大站快车，并在此基础上开发基于规则的启发式算法，生成分析时间段内的停车模式和发车时刻表解决方案。本文所提出的模型和算法能够考虑连续 BRT 班次之间的相互作用，乘客在车站的上下车过程，以及多个服务时间之间的相互依赖关系。最后基于上海市奉浦快线的实际案例对所提出的算法予以验证，并针对不同乘客需求分布、平均上下车时间和最大总里程参数进行敏感性分析。结果表明，融合多种运营策略的时刻表设计方法在相同运营成本下减少了乘客的总行程时间，是一种经济高效的快速公交运营优化方法。

关键词
快速公交，多种运营策略，启发式算法，区间车，大站快车，全站停靠