Article

Research on Route Deviation Transit Operation Scheduling—A Case Study in Suburb No. 5 Road of Harbin

Xianglong Sun and Sai Liu *

School of Civil Engineering, Northeast Forestry University, Harbin 150040, China; sunxianglong001@163.com
* Correspondence: vivianliusai@163.com; Tel.: +86-187-0364-7862

Abstract: Route deviation transit is a flexible “door-to-door” service method that combines the efficiency of conventional public transport modes and the flexibility of demand response modes, meeting the travel needs of people with low travel density and special groups. In this paper, the minimum value of the sum of vehicle operating cost and passenger travel cost was the optimal goal, and the RDT multi-vehicle operation scheduling model was constructed. Taking the available relaxation time as the control parameter of the RDT system and considering the insertion process of the random travel demand of the passengers during the operation process, we used a heuristic search algorithm to solve the scheduling model. This paper took Suburb No. 5 Road of Harbin as an example, using MATLAB to simulate the RDT operation scheduling model to verify the stability and feasibility of the RDT system under different demands. The results showed that under different demand conditions, the system indicators such as passenger travel time, waiting time, and vehicle mileage in the RDT system fluctuated very little, and the system performance was relatively stable. Under the same demand conditions, the per capita cost of the RDT system was 5.9% to 10.8% less than that of the conventional bus system. When the demand \( \rho \) is 20–40 person/hour, the RDT system is more effective than the conventional bus for the 5 bus in the suburbs of Harbin.

Keywords: route-offset bus; bus dispatch; control station; optional station; Harbin City

1. Introduction

With the acceleration of urbanization and the rapid expansion of urban boundaries, the population structure and spatial layout of urban areas have also undergone tremendous changes. The demand for public transportation has shown the characteristics of scale and diversification, and the relationship between transportation supply and demand has gradually become a complex system. In order to increase the proportion of public transportation in urban transportation, some cities have adopted measures such as increasing the frequency of bus lines and opening branch buses to alleviate the travel problems of residents in areas with low travel density. However, the increase in operating expenses of bus companies has followed, and the passenger load factor of buses has not increased [1]. Conventional public transport can no longer meet the needs of residents for diversification and individualization of travel modes. There is an urgent need for a new public transport model to ensure the daily travel of residents in these areas and increase the share of public transport.

In response to the lack of flexibility of traditional public transportation systems, European and American countries took the lead in putting forward the concept of “flexible public transportation systems”, which sought to solve the travel needs of passengers in the last mile, and then Demand Responsive Transit System was born [2]. Regarding the last mile issue, Marlon et al. proved that the first/last mile access/exit mode is an important tool to improve the ability of public transportation to provide work access by studying the important relationship between the entry and exit of a station or parking station and the fairness of traffic accessibility [3]. Francesco Bruzzone et al. pointed out that in practice, the
last mile problem has a series of key issues such as high cost, high safety requirements, and
time sensitivity, making it fragmented, uncoordinated, and unattractive [4]. Silvio Nocera
et al. gave a detailed introduction to the identification of the first/last mile, the problematic
scheme and cost analysis, the definition of the stakeholder participation process, and the
identification of key aspects of the process, and determined the best strategy to reduce
costs, reducing the negative impact of liquidity for planners [5]. The scheduling problem
of flexible transportation is regarded as a complex NP problem [6]. Jaw et al. proposed a
time-constrained heuristic algorithm for many-to-many DART problems. This algorithm
describes the Advanced Dial-a-Ride Time Window Problem (ADARTW) with quality of
service constraints and can determine the feasibility of passenger insertion in the vehicle’s
work schedule [7]. Barr et al. provided reporting guidelines for computational experiments
using heuristic methods [8]. Later, Campbell and Savelsbergh developed an efficient “plug-
in heuristic” for vehicle routing and scheduling problems. This method is fast in calculation
and can easily handle complex constraints [9]. Nadia Giaffreda et al. used a model cali-
ibrated on the basis of real data of a geographic information system (GIS) to find the best
configuration from the perspective of transportation operators and communities, indicating
that the path selection strategy is important for finding the cost between operators and
users. Balance is essential [10]. The route-offset buses are the most common route layout
form of demand-responsive buses [11]. Madsen constructed a route-offset bus dynamic
optimization model with line time windows and designed a plug-in algorithm [12]. Cortes
designed a heuristic algorithm to improve the efficiency of path offset system operation
scheduling, and the feasibility was verified through simulation experiments [15]. Dra-
biakowski proposed a hybrid scheduling model, including static scheduling and dynamic
scheduling, and designed a hybrid algorithm for real-time scheduling of the system [14].

At this stage, the research on variable route bus dispatching algorithms is mainly
divided into two categories. One is a heuristic algorithm with simple design. The algorithm
is simple and easy to apply in practice, but it only starts from the local optimum and
cannot guarantee the overall solution quality; the other is classed as a heuristic algorithm
based on intelligent algorithm, which considers global optimality, but the algorithm is
relatively complex and takes a long time to solve, making it difficult to apply in practice.
This article explores the theory and method of route-offset bus system operation scheduling
from the perspectives of both operators and users. Taking five buses in the suburbs of
Harbin as an example, we constructed a multi-vehicle operation scheduling model, and the
available relaxation time was used as the control parameter to design a heuristic search
algorithm to solve the model. This is also the expansion and improvement of urban public
transportation system planning and design theories and methods.

2. RDT Operation Dispatching Model

During the entire operation of the RDT, the vehicle needs to stop at all control stations
according to the driving plan, and the departure time of the vehicle from the control station
needs to meet the station departure schedule [15]. When RDT vehicles are traveling on
the reference route, they can only travel in one direction, and cannot turn back to respond
to passengers’ travel requests. Travel requests that pass through the service area are not
accepted while driving.

2.1. Model Assumptions

In RDT operation scheduling, the vehicle meets the travel needs of passengers in the
service area. The scheduling platform adjusts the driving route in real time, responds, and
feeds back real-time information according to the passenger’s request information while
meeting the vehicle’s slack time. Suppose the content is as follows:

(1) Assuming that the number of travel requests of passengers is not greater than the
maximum load capacity of the vehicle, that is, there is no problem of denying travel
requests of passengers due to overcrowded vehicles.
(2) The study in this section adopts one-way driving, assuming that the vehicle passes only once at each station, and each station (except the first and last station) has only one incident route and one exit route.

(3) It is assumed that passengers in the service area on the entire route will not change their travel modes due to changes in the operating mode, that is, the number of passengers will not decrease.

(4) It is assumed that the driving speed of the vehicle is uniform and constant, and it is not affected by traffic control facilities such as traffic lights and external forces.

2.2. Modeling

We divided passengers into four categories on the basis of where they get on and off, namely, PD (boarding at the control station), PND (boarding at the control station, getting off at the optional station), NPD (boarding at the optional station, getting off at the control station), and NPND (get off at the optional station) [16]. If the vehicle was parked at the control station, it was marked as $i = 1, \ldots, T_c$, if it was parked at the optional station, it was marked as $i = T_c + 1, \ldots, T_s$, where $S$ is the total number of vehicles parked. In order to simplify the calculation results, we divided the NPD and NPND passengers into separate travel needs, that is, their travel needs did not occur at the same alternative station.

This article considered both the system vehicle operating cost and the passenger travel cost, and established a dispatch model.

(1) Vehicle operating cost.

This term expresses the running cost of the vehicle in terms of time cost [17], that is, the running time cost of the vehicle, and the expression is as shown in Formula (1).

$$\sum_{(i,j) \in A} \left( t_{(i,j)} x_{ijv} \right)$$

(2) Passenger travel time cost.

In the RDT bus system, we believed that the time for passengers to board the bus at each stop was equal to the vehicle start time, and the time to get off the bus was equal to the vehicle parking time, and thus the passenger’s travel time cost expression was as shown in Equation (2).

$$\sum_q \left[ (d_q - p_q) \cdot \delta_{qv} \right]$$

(3) Passenger walking and waiting time costs

In the RDT bus system, when a passenger sends a travel request to the dispatching platform, the dispatching platform responds to this request and sends feedback to the passenger, and the passenger goes to the station to wait; then, the passenger’s walking and waiting time cost expression is as shown in Equation (3).

$$\sum_{q \in Q} \left[ (p_q - \tau_q) \cdot \delta_{qv} \right]$$

Thus, the system operation scheduling model is as shown in Formula (4):

$$\min \sum_{v=1}^{V} \left\{ \omega_1 \sum_{(i,j) \in A} \left( t_{(i,j)} x_{ijv} \right) + \omega_2 \sum_q \left[ (d_q - p_q) \cdot \delta_{qv} \right] + \omega_3 \sum_{q \in Q} \left[ (p_q - \tau_q) \cdot \delta_{qv} \right] \right\}$$

$t_{(i,v)}$—the departure time of the vehicle; $t_{(i,v)}'$—when the vehicle arrived at the station, the first station had no arrival time; $p_q$—the boarding time of passenger travel demand $q$; $d_q$—passenger travel demand $q$ alighting time.

$x_{ijv} = \{0, 1\} (\forall (i, j) \in A)$ represents the (0,1) variable; if the vehicle $v$ was driving on the road segment $(i, j)$, $x_{ijv} = 1$; otherwise, $x_{ijv} = 0$. $\delta_{qv} = \{0, 1\} (\forall v \in V)$ represents the
(0,1) variable, if the vehicle $v$ can provide passengers with the control station getting on and off service, $\delta_{qv} = 1$; otherwise, $\delta_{qv} = 0$.

The constraints of this model are as follows:

$$\sum_{i} x_{jiv} = 1, \forall j \in N_{(k)} / \{I_{(k)}\}, \forall v \in V$$

(5)

$$\sum_{j} x_{jiv} = 1, \forall i \in N_{(v)} / \{T_{(v)}\}, \forall v \in V$$

(6)

In terms of route constraints, it was assumed that except for PD passengers, other types of passengers were independent of each other when getting on and off the bus at optional stations [18]. Constraints (5) and (6) indicate that in each vehicle operation, except for the first and last stations, each station (including control station and optional station) had one and only one route through, that is, there was only one incident route and one exit route.

$$t_i = \theta_i, \forall i \in N_{0(v)}$$

(7)

$$p_q = t_{ps(q)}, \forall q \in Q_{(k)}/Q_{PND(v)}$$

(8)

$$d_q = t'_{ds(q)}, \forall q \in Q_{(k)}/Q_{NPD(v)}$$

(9)

Constraint (7) is to limit the departure time of the control station. The departure time of the vehicle must be in accordance with the departure timetable of the control station. Restriction (8) means that except for PND passengers, the vehicle will leave the station immediately after other passengers get on the bus. Assuming that when the loaded vehicle arrives at the station, the passengers get off immediately. Constraint (9) indicates that the PD, PND, and NPND passengers got off the station when the vehicle arrived at the station.

$$p_q \geq \tau_q, \forall q \in Q_{(v)}$$

(10)

$$d_q > p_q, \forall q \in Q_{(v)}$$

(11)

Constraint (10) indicates that the boarding time of each type of passenger was no earlier than the time it took to arrive at the boarding station from the location. Constraint (12–15) indicates that each type of passenger got on and then got off.

$$p_q \geq t_{pc(q)} - M(1 - \delta_{qv}), \forall q \in Q_{PND(v)}, \forall v \in V$$

(12)

$$p_q \leq t_{pc(q)} + M(1 - \delta_{qv}), \forall q \in Q_{PND(v)}, \forall v \in V$$

(13)

$$d_q \geq t'_{dc(q)} - M(1 - \delta_{qv}), \forall q \in Q_{NPND(v)}, \forall v \in V$$

(14)

$$d_q \leq t'_{dc(q)} + M(1 - \delta_{qv}), \forall q \in Q_{NPND(v)}, \forall v \in V$$

(15)

Constraints (12) and (13) indicate that if $\delta_{qv} = 1$, the vehicle left the station immediately after each PND passenger got on the bus. Constraints (14) and (15) indicate that if $\delta_{qv} = 1$, NPD passengers got off immediately when the vehicle arrived. Among the four constraints, in order to ensure that the constraint can be invalid when $\delta_{qv} = 0$, M must be large enough [19].

$$\sum_{v=1}^{V} \delta_{qv} = 1, \forall q \in Q_{HYB(v)}$$

(16)

$$V \leq V_{\text{max}}$$

(17)

Regarding the vehicle $v$ constraint, constraint (16) means that each passenger can only travel in a unique vehicle, and cannot change vehicles halfway through the entire RDT bus system. Constraint (17) means that the number of running vehicles was not greater than the system’s maximum number of vehicles $V_{\text{max}}$, which can effectively save operating costs.
not only causing waste of vehicle resources, but also meeting the travel needs of passengers and improving service levels.

\[
t'_i \geq t_i + t_{(i,j)}x_{ij} - M(1 - x_{ij}), \forall (i,j) \in A
\]

(18)

\[
t_i \geq t'_i + b_i, \forall i \in N(v) / \{I(v)\}, \forall v \in V
\]

(19)

Constraint (19) is the core constraint of this model and also a priority constraint. Constraint (18) means that at \(\delta_{qv} = 1\), the time for the vehicle to arrive at stop \(j\) was not less than the sum of its departure time from the stop and the travel time. Moreover, at this time, \(M\) must be large enough. This ensures that each operating line does not include an inner loop and is a one-way path from the first station to the end station. Constraint (19) represents vehicle arrival time constraints.

3. Algorithm Optimization

In the bicycle scheduling model algorithm, the most common one is the plug-in heuristic algorithm. However, in a multi-vehicle dispatching system, the objective function is often to balance the running cost of multiple vehicles running online at the same time and the travel time cost of passengers, so as to find the optimal solution of the objective function. On the basis of the plug-in algorithm proposed by Quadrifogli et al. [20] for real-time dynamic travel demand under single-vehicle conditions, this paper used relaxation time as a control parameter to improve the algorithm.

3.1. Control Parameter

The establishment of the slack time is a time constraint that is preset for vehicles to deviate from the limit when they go to the service area to provide travel services for passengers. It is one of the key parameters of the RDT bus system [21].

The expression for the initial available relaxation time is as follows:

\[
st_{c,c+1,p} = s_{c,c+1,p}^{(0)} (\forall c = 1, \cdots, T_{c-1})
\]

(20)

The available slack time \(s'_{c,c+1}\) is related to the passenger travel demand \(q\) between the continuously controlled stations \(c\) and \(c + 1\). When the travel demand \(q\) is large, the available slack time \(s'_{c,c+1}\) is smaller, and the number of services that can be provided will gradually decrease; when \(q\) is smaller, the available relaxation time \(s'_{c,c+1}\) is larger, and the number of services the vehicle can provide will gradually increase. The slack time \(s_{c,c+1,p}\) between the control stations is determined and does not affect the change of \(s'_{c,c+1}\), and there is \(s'_{c,c+1} \leq s_{c,c+1,p}\) for the demand \(q\).

The expression of vehicle slack time \(\pi_{c,c+1}^{(0)}\) between two adjacent control stations \(c\) and \(c + 1\) in section \((c, c + 1)\) is as follows:

\[
\pi_{c,c+1}^{(0)} = \frac{W / v_{speed} + h_q}{s_{c,c+1,p}^{(0)}}
\]

(21)

where \(W\) is the service width between two adjacent control stations, and \(h_q\) represents the passenger service time of two adjacent control stations. As the value of \(\pi_{c,c+1}^{(0)}\) decreases, the more slack time of vehicle \(v\) runs between two adjacent stations, the greater the probability that the vehicle can provide services to passengers at alternative stations, and therefore the value of \(\pi_{c,c+1}^{(0)}\) needs to be set as small as possible. However, if \(\pi_{c,c+1}^{(0)}\) is too low, the scheduling algorithm cannot be used.
The relaxation time control coefficient of two adjacent control stations \( c \) and \( c + 1 \) in the interval \( (c, c + 1) \) is denoted by \( \pi_{c,c+1} \). \( q_{c,c+1,v}^{low} \) is the expected demand variable in the interval, and its expression is as follows:

\[
\pi_{c,c+1} = 1 + \left( \frac{\pi_{c,c+1}^{(0)} - 1}{q_{c,c+1,v}^{low}} \right) q_{c,c+1,v}^{low}
\]  

(22)

The relaxation time values of two adjacent control stations \( c \) and \( c + 1 \) in section \( (c, c + 1) \) change from moment to moment. Vehicle \( v \) at time \( t \) can be represented by \( s_{t,c,c+1,v}^{u} \), and its expression is as follows:

\[
s_{t,c,c+1,v}^{u} = \begin{cases} 
\pi_{c,c+1}^{(0)} + s_{t,c,v}^{(0)} & t_{now} < t_{c,v} \\
1 + (\pi_{c,c+1}^{(0)} - 1) \left( 1 - \frac{t_{now} - t_{c,v}}{t_{c,v} - t_{c,v}^{min}} \right) s_{t,c,c+1,v}^{u} & t_{c,v} \leq t_{now} \leq t_{v,v}^{min} \\
s_{t,c,c+1,v}^{u} & t_{now} > t_{v,v}^{min}
\end{cases}
\]  

(23)

As shown in Figure 1, before time \( t_{c,v} \), the vehicle deviates from the reference route to provide services for passengers. The slack time can only use the minimum available slack time \( s_{t,c,c+1,v}^{u} = \pi_{c,c+1}^{(0)} + s_{t,c,v}^{(0)} \), which can avoid the occurrence of blocked passenger demand \( q \) due to unreasonable slack time arrangements. If the vehicle needs to stop at the optional station \( a \) near the control station \( c + 1 \), the dispatch platform will generally reject the travel reservation response of the untraveled section in the new section \( (c, c + 1) \). According to the driving plan, the vehicle can have more remaining slack time (if there is only one travel reservation in section \( (c, c + 1) \), then the slack time can be used as the maximum slack time) to provide services to passengers who can choose stop \( a \).

![Figure 1. Available relaxation time function curve.](image)

If the vehicle is driving in the service area, the road network in the area is a broken road (that is, the road does not form at least one loop with other roads), and the backtracking distance of the vehicle in this type of road section needs to be limited [22]. The maximum allowable backtracking distance for the vehicle to travel between two consecutive control stations is represented by the control parameter \( BACK > 0 \). Obviously, only when \( BACK > L \) can any backtracking be allowed between control sites.

3.2. Algorithm Establishment

3.2.1. Problem Description

\( a_{s,v} \) represents the current position of the vehicle. Then, the problem can be described as follows: by checking the current position \( a_{s,v} \) of vehicle \( v \) and the departure time \( t_{d,v}(\forall s_{v} > t_{v,v}^{min}) \) and arrival time \( t_{a,v}(\forall s_{v}) \) of vehicle \( v \), we can obtain the optimal solution of the objective function of the model under the constraint of “getting on and then getting off”.
3.2.2. Feasibility

When choosing whether to respond to passenger travel requests, one must judge the feasibility of inserting this request in the travel plan, that is, the feasibility of inserting a new demand site $s = q$ between two known adjacent sites $a$ and $b$. Insert the extra time as follows:

$$\Delta st_{a,q,b} = \frac{d_{a,q} + d_{q,b} - d_{a,b}}{v_{speed}} - h_q$$

(24)

The algorithm can calculate the available slack time $st_u$ from the above formula. In this algorithm, the multi-vehicle operating system adopts the principle of “no retrograde nearest insertion point”. At the same time, there is no retrograde vehicle in the multi-vehicle system, and therefore the backtracking distance is used as the judgment condition. In summary, if the conditions such as Formula (25) are met, it is feasible to insert $q$ between $a$ and $b$.

$$\begin{cases} \Delta st_{a,q,b} \leq \min (st_{c,c+1,v}, st^u_{c,c+1,v}) \\ b_{d_{a,q}} \leq BACK \\ b_{d_{q,b}} \leq BACK \end{cases}$$

(25)

3.2.3. Cost Function

According to the driving plan before the vehicle departs in a static environment, the system cost function expression can be obtained as follows:

$$\Delta st_{a,q,b} \leq \min (st_{c,c+1,v}, st^u_{c,c+1,v})$$

(26)

For each feasible insertion point (station) of travel demand $q$, the expression of the insertion cost function can be obtained as follows:

$$COST = \omega_1 \times \Delta st_{a,q,b} + \omega_2 \times \Delta RT + \omega_3 \times \Delta WT$$

(27)

$$\Delta st_{a,q,b}$$—the amount of slack time consumed by travel demand; $\Delta RT$—additional ride time for passengers; $\Delta WT$—the sum of all waiting times.

According to different commuting conditions and traffic conditions, one can adjust the weight values of $\omega_1$, $\omega_2$, and $\omega_3$ at any time to change the consumption of available slack time. The operating cost is emphasized during the peak period, and the waiting time and walking time cost of the passengers are emphasized during the off-peak period [23].

3.2.4. Search Domain

Considering the driving plan, each control site $c$ is adjusted to be stopped by each vehicle multiple times, with a different stop index $s(r,c,v)$ (the parking index of the $r$ control site $c$ in the vehicle schedule), depending on the size of the fleet and the number of driving plans $R$ [24].

In order to facilitate the marking of the parking index in the dispatch plan, for each intermediate control station, $c = 2, \cdots, C - 1$ and each $v \in V$ parking index $s(r,c,v)$, we calculate them in the order shown in Formula (28):

$$s(r,c,v) = 1 + (C - 1)(r - 1) + \frac{(C - 1) + (-1)^{(c - 1)}[(C - 1) - 2(c - 1)]}{2} + (v - 1)TC_0$$

(28)

In the formula, $\forall r = 1, \cdots, R \forall v = 1, \cdots, |V|$.

For terminal control stations 1 and $C$, since their frequency of occurrence is halved, the calculation sequence is as follows ((29) and (30)):

$$s(r,1,v) = 1 + 2(C - 1)(r - 1) + (v - 1)TC_0$$

(29)
In the formula, \( \forall r = 1, \cdots, R/2 \) \( \forall v = 1, \cdots, |V| \).

\[
s(r, C, v) = C + 2(C - 1)(r - 1) + (v - 1)TC_0 \tag{30}
\]

In the formula, \( \forall r = 1, \cdots, 1 + R/2 \) \( \forall v = 1, \cdots, |V| \).

For each control station \( c \) and each \( v \) in \( V \), the search areas of \( c \) and \( v \) are part of the driving plan, which is defined by the same car’s two consecutive appearances of \( c \), that is, all the stops \( s \) in the current driving plan, so that \( a[s(r, c, v)] \leq a(s) \leq a[s(r + 1, c, v)] \).

The definition of the search domain for NPND passengers needs to be slightly modified. The calculation sequence to determine the appearance of any terminal control station \((c = 1 \text{ or } C)\) is as shown in Formula (31):

\[
s(r, 1 \text{ or } C, v) = 1 + (C - 1)(r - 1) + (v - 1)TC_0 \tag{31}
\]

For NPND passengers, the search area represents all stops \( s \), and for any allowed \( r \), as described in the equation \( a[s(r, 1 \text{ or } C, v)] \leq a(s) \leq a[s(r + 1, 1 \text{ or } C, v)] \).

3.2.5. Insert Program

From the travel request of the passengers, it is possible to clarify the control station sections \((c_1, c_1 + 1)\) and \((c_2, c_2 + 1)\) where the pick-up and drop-off points are located. Then, the following three situations are not affected by the algorithm: the vehicle has passed the stop point \( q_1 \) at time \( t_{q_1} \); the vehicle \( t_{q_1} \) is not in the adjacent control station \((c_1, c_1 + 1)\); the vehicle \((c_1, c_1 + 1)\) is not in the adjacent control station \((c_2, c_2 + 1)\).

Search for the feasibility of NPND in at most two consecutive control sites. The algorithm will start to check the feasibility of NPND in the first site. At this time, the terminal control site \( c = 1 \text{ or } C \) needs to meet \( s(r', 1 \text{ or } C, v) = \min_{r,p} s(r, 1 \text{ or } C, v) \) and \( t_{s(r, 1 \text{ or } C, v)} \geq t_{\text{now}} \). The point with the least insertion cost is the target result.

If no NPND feasibility is found, the algorithm will check two consecutive shifts at a time and increase the scope of inspection by a search domain (1/2 of the search domain, then 2/3, \ldots, and \( i + 1 \) of the search domain) in each step. We only need to check ND insertion in search field \( i + 1 \). This process will continue until at least one feasible insertion of NPND is found.

The general assumption when performing the insertion process is that the RDT system will not reject the passenger’s reservation [25]. Therefore, generally speaking, the pending request will not be rejected, but will be postponed, and the next vehicle is recommended for passengers to choose from. However, in a static environment where the planned service itinerary is very small, there are too few feasible insertion points, and passenger requests are more likely to be rejected, but this still occurs with only a small probability.

3.2.6. Correction of Relaxation Time

When the optimal feasible insertion point is determined, at this time, whether it is to pick up or get off at the optional station, the new stop is in the control station section \((c, c + 1)\), forming a new driving plan, and inserting it between stations \( A \) and \( B \). At this time, due to changes in the driving plan, the original system variables (available slack time) need to be corrected [26].

The correction method of relaxation time is shown in Formula (32):

\[
st_{c,c+1} = st_{c,c+1} - \Delta t_{a,b} \tag{32}
\]

The departure time and arrival time of the vehicle have also changed. The correction methods are as shown in Equations (33) and (34):

\[
t_c = t_c + \Delta t_{a,b} \quad \alpha(c) \in [\alpha(b), \alpha(m + 1)] \tag{33}
\]
\[ t'_c = t'_c + \Delta t_{a,q,b} \quad \alpha(c) \in [\alpha(b), \alpha(m+1)] \]  

Passengers get on the bus after the new insertion point \( q \) and get off before the control station \( c+1 \). The passenger’s boarding and boarding time will be extended, and all need to be corrected. Assuming that a vehicle \( v \) is assigned to passengers, the earliest departure time \( et_{q,v} \) from \( q \) is calculated as Equation (35):

\[ et_{q,v} = t_{a,v} + d_{a,q} / v_{speed} + h_q \]  

In the formula, \( t_{a,v} \)—the current departure time from the parking station \( a \) of vehicle. \( q \)'s departure time \( t_{q,v} \) is also initialized, and the expression is as shown in Formula (36):

\[ t_{q,v} = t_{a,v} + d_{a,q} / v + h_q = et_{q,v} \]  

It can be easily proved that \( et_{q,v} \) is the lower limit of the correction value of \( t_{q,v} \) at any time.

The algorithm calculates the latest departure time of \( lt_{q,v} \) according to \( q \), as shown in Formula (37):

\[ lt_{q,v} = et_{q,v} + st_{m,m+1,v} \]  

It can be proved by contradiction theory that \( lt_{q,v} \) is the upper limit of \( t_{q,v} \).

If the passenger accepts the result, he will provide the customer with \( et_{q,v}, lt_{q,v}, et'_{q,v}, \) and \( lt'_{q,v} \). Please note that their actual time \( t_{q,v} \) and \( t'_{q,v} \) will be subject to the following constraints:

\[ et_{q,v} \leq t_{q,v} \leq lt_{q,v} \]
\[ et'_{q,v} \leq t'_{q,v} \leq lt'_{q,v} \]  

When the request for boarding \( P \) at the control station meets \( et_{p,v} = t_{p,v} = lt_{p,v} \), the request for getting off at the control station \( D \) will meet A. Obviously, NP and ND requests also need to meet the following constraints:

\[ et_{N,P,v} \leq t_{N,P,v} \leq lt_{N,P,v} \]
\[ et'_{N,P,v} \leq t'_{N,P,v} \leq lt'_{N,P,v} \]  

In this paper, heuristic search algorithm is adopted, relaxation time is used as the control parameter, and the heuristic information of the problem is used to simplify the calculation amount of the scheduling model and narrow the search scope.

4. Case Analysis
4.1. Route Selection

The first and last stations of Suburb No. 5 Road are Harbin East Station (Sankeshu Passenger Transport Station) and Yongyuan Crossing, with a total length of 27 kilometers and a total of 49 fixed stations. The bus running time is 4:55–16:50, and the departure timetable is shown in Table 1; there are 13 departures, and the driving route is shown in Figure 2.

**Table 1. Departure timetable of Harbin Suburb No. 5 Road.**

| Station | Departure Times |
|---------|-----------------|
| HES | 6:30 7:30 8:00 9:00 10:20 11:10 12:10 13:50 15:15 16:25 17:15 18:10 |
| YC | 4:55 5:30 6:30 7:00 7:55 8:55 9:40 10:15 12:30 13:20 14:10 15:50 16:50 |
This article takes the service area of the No. 5 bus on the outskirts of Harbin as an example research object, mainly from the following perspectives:

1. Passenger travel demand

The passenger travel demand on the suburban bus route No. 5 is 29.3 people per hour. Except for the first and last stations, the passenger travel demand rate is not high. The RDT bus system uses small and medium-sized service vehicles, mainly to provide services for passengers in areas with low travel demand density.

2. Bus Station

There are 49 stations on this line, but most of the stations have less passenger flow, which is a waste of resources. The number of RDT bus control stations is small, and the driving plan is adjusted in real time according to demand, which is more flexible than conventional buses.

3. Service area

According to the survey of passenger information at each station in the suburban 5 bus, the pedestrian distance perceived by passengers is counted, and the maximum value is used as the service radiation radius of the station, combined with the actual road network to obtain the approximate service area of the route. The service radius of this article is 500 m, and the specific situation is shown in Figure 3.
4.2. Site Selection of Bus Stops

4.2.1. Control Station

Combined with the above-mentioned control station, the service radiation radius is 0.5 km, the service area deviation width is set to \( W = 1 \) km, and the reference route is used as the axis to deviate from 0.5 km on both sides. The area of the service area is \( L \times W = 27 \) km \( \times 1 \) km = 27 km\(^2\).

A total of 75 stations are involved in the section from Harbin East Station to YongYuan Crossing. The distribution of these bus stations is shown in Figure 4. According to the distribution of stations, these stations can be simply divided into 10 gathering areas.

![Figure 4](image1.png)

Figure 4. Location distribution map of fixed stations in the service area.

K-means clustering analysis was performed on each site in the service area: the number of categories was \( K = 10 \), and the clustered sites in each area were obtained. The clustering results are shown in Figure 5.

![Figure 5](image2.png)

Figure 5. K-means site clustering results.
The cluster center coordinates need to be corrected according to the weight of the passenger flow of each station, and the correction results are shown in Table 2.

**Table 2.** The corrected latitude and longitude coordinates of the cluster centers.

| Site Number | Longitude | Latitude | Site Number | Longitude | Latitude |
|-------------|-----------|----------|-------------|-----------|----------|
| 1           | 126.809448 | 45.789110 | 6           | 126.907870 | 45.794061 |
| 2           | 126.717145 | 45.797045 | 7           | 126.983718 | 45.782834 |
| 3           | 126.939738 | 45.790607 | 8           | 126.774467 | 45.795076 |
| 4           | 126.851818 | 45.794266 | 9           | 126.872808 | 45.790934 |
| 5           | 127.021983 | 45.782570 | 10          | 126.833767 | 45.791498 |

The geographic locations of some sites are not on the actual road network, and these sites need to be finalized on the basis of the actual road network. The final distribution results of the control sites are shown in Figure 6.

**Figure 6.** Control site location distribution map.

4.2.2. Optional Station

The optional stations in the RDT system refer to the non-controlled stations distributed within the service area and outside the reference route. The passenger submits an appointment, and the vehicle deviates from the reference route to respond to the request.

The system parameters are set as follows:

1. The service area is \( L = 27 \) km in length and \( W = 1 \) km in width, and the service radius of the site is 500 m.
2. The passenger boarding time is set to 3.5 s per person, and the vehicle service time is 16 s.
3. The running speed of the vehicle is constantly set to \( v = 30 \) km/h, and the average walking speed of passengers is \( v_{w} = 3.6 \) km/h.
4. Passenger demand A is 30 people per hour, and passenger travel demand is uniform and random.
5. Passenger travel demand ratio PD:PND:NPD:NPND = 0.2:0.35:0.35:0.1.
6. The unit time value coefficient of each time cost \( \alpha_1 = 0.1, \alpha_2 = 0.1, \alpha_3 = 0.4, \alpha_4 = 0.4 \)

Potentially optional stations are pre-arranged in each service area according to the size of the service radius. The number of potential optional stations is shown in Table 3.

**Table 3.** Distribution of the number of potential optional stations.

| Station Interval | (1,2) | (2,3) | (3,4) | (4,5) | (5,6) | (6,7) | (7,8) | (8,9) | (9,10) |
|------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Interval length  | 2.1   | 3.8   | 2.9   | 3.9   | 2.2   | 2.1   | 3.3   | 3.7   | 3.0   |
| Number of potential stations | 2     | 4     | 3     | 4     | 2     | 2     | 3     | 4     | 3     |
The passenger travel demand of each potentially selectable station is the sum of the demand of all fixed stations covered by it, and the station impact index $\theta_i$ of each station is used. The results are shown in Table 4. The feasibility of optional site layout is determined according to the site layout judgment criteria.

### Table 4. Site impact index $\theta_i$ of potential alternative sites.

| Site Number | $\theta_i$ | Site Number | $\theta_i$ | Site Number | $\theta_i$ |
|-------------|------------|-------------|------------|-------------|------------|
| 1           | 8.47       | 10          | 3.37       | 19          | 7.38       |
| 2           | 5.61       | 11          | 1.23       | 20          | 6.46       |
| 3           | 4.53       | 12          | 5.41       | 21          | 6.27       |
| 4           | 5.61       | 13          | 5.43       | 22          | 6.31       |
| 5           | 6.37       | 14          | 5.29       | 23          | 4.29       |
| 6           | 4.41       | 15          | 5.36       | 24          | 2.23       |
| 7           | 2.68       | 16          | 2.34       | 25          | 4.28       |
| 8           | 5.42       | 17          | 5.41       | 26          | 5.36       |
| 9           | 5.43       | 18          | 6.26       | 27          | 6.45       |

When $5 \leq \theta_i \leq 15$, the potential sites can be reserved. From the above table, it can be seen that the number of optional stations was 18. The layout of optional stations in the RDT system was closely related to passenger demand. The location coordinates were optimized according to the actual road network and the site selection principles of optional stations. The specific latitude and longitude coordinates are shown in Table 5.

### Table 5. Site coordinates that can be selected.

| Site Number | Longitude | Latitude | Site Number | Longitude | Latitude |
|-------------|-----------|----------|-------------|-----------|----------|
| 1           | 126.715664| 45.793166| 10          | 126.790044| 45.796823|
| 2           | 126.70855 | 45.794297| 11          | 126.80783 | 45.786542|
| 3           | 126.715844| 45.799977| 12          | 126.875527| 45.791117|
| 4           | 126.724252| 45.797766| 13          | 126.937114| 45.786793|
| 5           | 126.737259| 45.796257| 14          | 126.980736| 45.775479|
| 6           | 126.744805| 45.80043 | 15          | 126.975418| 45.77553 |
| 7           | 126.755369| 45.798758| 16          | 126.946601| 45.789659|
| 8           | 126.76579 | 45.794335| 17          | 126.910525| 45.799362|
| 9           | 126.778438| 45.792072| 18          | 126.888031| 45.780357|

### 4.3. Scheduling Analysis

This paper used MATLAB to use the heuristic search algorithm to simulate the operation and dispatch of RDT bus system to verify the feasibility of the algorithm.

#### 4.3.1. Simulation System Description

In the simulation experiment, the evaluation of the RDT bus operation was mainly reflected in the operating cost and service level of the system. The expressions defining the performance indicators of the bus system are as follows:

$$ P = \beta_1 \times S / (v \times N_T) + \beta_2 \times T_p + \beta_3 \times T_w + \beta_4 \times T_k $$

(40)

In the formula, $T_p$, $T_w$, and $T_k$ represent the average travel time of passengers, the average waiting time of passengers, and the average walking time of passengers, respectively. $S$ represents the total mileage of the vehicle, and $N_T$ represents the total number of passengers. $\beta_1$, $\beta_2$, $\beta_3$, and $\beta_4$ represent the unit time value coefficient of various time costs, and $\beta_1 = 0.1$, $\beta_2 = 0.1$, $\beta_3 = 0.4$, $\beta_4 = 0.4$.

#### 4.3.2. Simulation Results

This paper carried out a 100 h simulation experiment. Case 1 uses the RDT multi-vehicle scheduling model of this paper, case 2 is the dynamic demand vehicle scheduling.
The model used in the literature [20] mentioned in the third chapter of the algorithm optimization, and case 3 represents the use of conventional bus operation mode, and the related parameters of conventional bus are based on previous research. The simulation results under these three conditions are shown in the table below.

The results in Table 6 show that the total cost of the RDT multi-vehicle dispatching system was 10.8% less than the total cost of the conventional bus system. In addition, under the same passenger trip volume, the system performance index using the RDT multi-vehicle scheduling model in this paper was lower than the simulation results using the dynamic vehicle scheduling model in the literature [20]. This is enough to show that the RDT multi-vehicle dispatching system is more advantageous on the 5 bus lines in the suburbs.

Table 6. Example simulation comparison results.

| System Indicators | RDT          | Traditional Bus |
|-------------------|--------------|-----------------|
|                   | Case 1       | Case 2          | Case 3          |
| ρ                 | 30.00        | 30.00           | 30.00           |
| Tp (min)          | 27.10        | 29.00           | 20.00           |
| Tw (min)          | 1.57         | 1.92            | 5.00            |
| Tk (min)          | 5.74         | 6.83            | 7.50            |
| (min)             | 74.15        | 74.53           | 54.00           |
| S (km)            | 32.62        | 32.78           | 27.00           |
| Per capita cost P | 13.67        | 14.91           | 15.34           |

As shown in Figure 7, about 61% of the optional stations deviated from the distance less than 0.2 km, indicating that the reference path selection and control site selection are reasonable and can meet most of the travel needs in the service area.

Figure 7. RDT multi-vehicle dispatching route simulation diagram at ρ = 30. a and b represent two adjacent control stations, c and d represent adjacent optional stations between control stations a and b. The vehicle starts from the control station a and deviates from the reference route according to the driving plan to respond to the passenger travel demand at the optional station c. At this time, the new demand is generated in the service area at the optional station d.

The passenger travel demand density in the service area is not fixed. Under the current system parameter conditions and the number of stations, to test the stability of the RDT bus operation scheduling model, one must analyze the system indicators of the RDT bus
under different demand conditions, verifying the feasibility of the system. The results are shown in Table 7.

Table 7. System indicators under different demand.

| Demand | RDT | Traditional Bus |
|--------|-----|-----------------|
|       | 20  | 25  | 30  | 35  | 40  | 30  | 35  | 40  |
| \( \rho \) (people/hour) | 26.54 | 27.36 | 27.10 | 26.80 | 27.20 | 22.56 | 22.64 | 22.61 |
| \( T_p \) (min) | 1.51 | 1.54 | 1.57 | 1.50 | 1.48 | 7.50 | 7.50 | 7.50 |
| \( T_w \) (min) | 5.62 | 5.73 | 5.74 | 5.82 | 5.85 | 7.69 | 7.48 | 7.55 |
| \( T_k \) (min) | 74.25 | 73.65 | 74.15 | 73.89 | 74.19 | 54.00 | 54.00 | 54.00 |
| \( S \) (km) | 32.67 | 32.35 | 32.62 | 32.49 | 32.63 | 27.00 | 27.00 | 27.00 |
| Per capita cost \( P \) | 13.41 | 13.53 | 13.67 | 13.99 | 14.10 | 15.34 | 15.12 | 14.98 |

Under the circumstance that the location of the control station and the optional station remain unchanged, the average ride time, average waiting time, vehicle travel time, and mileage of passengers in the RDT system does not change much and fluctuates within a certain range; the average walk of passengers in terms of time is positively correlated with demand. Demand \( \rho \) increased from 20 to 40, and the average waiting time increased by 4.1%, which was relatively small. Therefore, the RDT system performed relatively stable under demand. Under the same demand, the average ride time of the RDT system was 18% to 20% slower than the conventional bus system, its average walking time was 22.1% to 25.3% faster than the conventional bus system, and its average waiting time was faster than the conventional bus system at 79% to 80%, making the per capita cost of the RDT system lower than that of the conventional bus system by 5.9% to 10.8%. Therefore, the RDT system is more reasonable and reliable to operate when the demand \( \rho \) is 20–40.

5. Conclusions

On the basis of the principle of vehicle driving, this paper took the minimum sum of vehicle operating cost and passenger travel cost as the objective function, considering constraints such as time window, establishing a multi-vehicle operation scheduling model of the RDT system. Taking the available relaxation time as the control parameter of the system, we used a heuristic search algorithm to design the algorithm of the scheduling model. Taking Suburb No. 5 Road in the suburbs of Harbin as the case object and using MATLAB to simulate the operation and scheduling of the RDT system, we found that, compared with conventional bus services, the biggest feature of RDT is to reduce the walking distance and waiting time of passengers, but the price is that the passenger time in the vehicle is higher than that of conventional bus services. With the increase in passenger travel volume, the average value of the performance indicators of the RDT system increased, while the performance indicators of conventional buses remained basically stable. This is also one of the important differences between the two bus modes. Under the same demand conditions, the system performance index of the RDT multi-vehicle scheduling model was found to be significantly lower than that of the conventional dynamic vehicle scheduling model. Moreover, the per capita cost of the RDT system was 5.9% to 10.8% lower than that of the conventional bus system. When the demand is 20–40 people/hour, the RDT system is more effective than the conventional bus.

Author Contributions: Conceptualization, X.S. and S.L.; methodology, S.L.; software, S.L.; validation, S.L.; formal analysis, S.L.; investigation, S.L.; resources, S.L.; data curation, S.L.; writing—original draft preparation, S.L.; writing—review and editing, X.S.; visualization, X.S.; supervision, X.S.; project administration, X.S.; funding acquisition, X.S. All authors have read and agreed to the published version of the manuscript.
Funding: This research was funded by the Ministry of Education of Humanities and Social Science project (no. 17YJCZH152), National Natural Science Foundation of China (no. 71901057), Fundamental Research Funds for the Central Universities (no. 2572021BJ03), and Heilongjiang Natural Science Fund (no. QC2017039).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zheng, Y.; Li, W.; Feng, Q.; Cao, X. Flexible Transit Services: Choosing Between Route Deviation and Point Deviation Policy. In Proceedings of the Transportation Research Board 97th Annual Meeting, Washington DC, USA, 7–11 January 2018.

2. Li, X.; Quadrifoglio, L. Optimal zone design for feeder transit services. Transp. Res. Rec. 2009, 2111, 100–108. [CrossRef]

3. Francesco, B.; Federico, C.; Silvio, N. The integration of passenger and freight transport for first-last mile operations. Transp. Policy 2021, 100, 31–48.

4. Silvio, N.; Giuseppe, P.; Francesco, B. How to evaluate and plan the freight-passengers first-last mile. Transp. Policy 2020, preprint.

5. Boarnet, M.G.; Giuliano, G.; Hou, Y.; Shin, E.J. First/last mile transit access as an equity planning issue. Transp. Res. Part A 2017, 103, 296–310. [CrossRef]

6. Chandra, S.; Quadrifoglio, L. A model for estimating the optimal cycle length of demand responsive feeder transit services. Transp. Res. Part B 2013, 51, 1–16. [CrossRef]

7. Jaw, J.J.; Odoni, A.R.; Psaraftis, H.N.; Wilson, N.H.M. A heuristic algorithm for the multi-vehicle advance request dial-a-ride problem with time windows. Transp. Res. Part B 1986, 20, 243–257. [CrossRef]

8. Alrukaibi, F.; Alkheder, S. Optimization of bus stop stations in kuwait. Sustain. Cities Soc. 2020, 25–40. [CrossRef]

9. Cunha, C.; Cortes, C.S. Sistema de apoio à decisão baseado em planilha eletrônica para otimização da programação de entrega de concreto pronto. J. Transp. Lit. 2014, 8, 125–158. [CrossRef]

10. Crainic, T.G.; Errico, F.; Malucelli, F.; Nonato, M. Designing the master schedule for demand-adaptive transit systems. Ann. Oper. Res. 2010, 194, 151–166. [CrossRef]

11. Madsen, O.B.G.; Ravn, H.F.; Rygaard, J.M. A heuristic algorithm for a dial-a-ride problem with time windows, multiple capacities and multiple objectives. Ann. Oper. Res. 1995, 60, 193–208. [CrossRef]

12. Huang, D.; Tong, W.; Wang, L. An Analytical Model for the Many-to-One Demand Responsive Transit Systems. Sustainability 2020, 12, 298. [CrossRef]

13. Alrukaibi, F.; Alkheder, S. Optimization of bus stop stations in kuwait. Sustain. Cities Soc. 2018, 44, 726–738. [CrossRef]

14. Drabikowski, M.; Nowakowski, S.; Tuiryn, J. Library of local descriptors models the core of proteins accurately. Proteins Struct. Funct. Bioinform. 2010, 69, 499–510. [CrossRef] [PubMed]

15. Frei, C.; Hyland, M.; Mahmassani, H.S. Flexing service schedules: Assessing the potential for demand-adaptive hybrid transit via a stated preference approach. Transp. Res. Part C Emerg. Technol. 2017, 76, 71–89. [CrossRef]

16. Quadrifoglio, L.; Dessouky, M.M.; Palmer, K. An insertion heuristic for scheduling Mobility Allowance Shuttle Transit (MAST) services. J. Sched. 2007, 10, 25–40. [CrossRef]

17. Zheng, Y.; Li, W.; Qiu, F. A slack arrival strategy to promote flex-route transit services. Transp. Sci. 2014, 8, 369–378. [CrossRef]

18. Drabikowski, M.; Nowakowski, S.; Tuiryn, J. Library of local descriptors models the core of proteins accurately. Proteins Struct. Funct. Bioinform. 2010, 69, 499–510. [CrossRef] [PubMed]

19. Chandra, S.; Quadrifoglio, L. A model for estimating the optimal cycle length of demand responsive feeder transit services. Transp. Res. Part B 2013, 51, 1–16. [CrossRef]

20. Drabikowski, M.; Nowakowski, S.; Tuiryn, J. Library of local descriptors models the core of proteins accurately. Proteins Struct. Funct. Bioinform. 2010, 69, 499–510. [CrossRef] [PubMed]

21. Qiu, F. Two-stage model for flex-route transit scheduling. J. Southeast Univ. (Nat. Sci. Ed.) 2018, 44, 1078–1083.

22. Zheng, Y.; Li, W.; Qiu, F. A slack arrival strategy to promote flex-route transit services. Transp. Res. Part C Emerg. Technol. 2018, 92, 442–455. [CrossRef]

23. Zheng, Y.; Li, W.; Qiu, F. The benefits of introducing meeting points into flex-route transit services. Transp. Res. Part C Emerg. Technol. 2019, 106, 98–112. [CrossRef]

24. Alshalalafah, B.; Shalaby, A.S. Sensitivity of Flex-Route Transit Service to Design and Schedule-Building Characteristics. In Proceedings of the Transportation Research Board Meeting, Washington, DC, USA, 9–13 January 2008.

25. Zheng, Y.; Gao, L.; Li, W. Vehicle Routing and Scheduling of Flex-Route Transit under a Dynamic Operating Environment. Discret. Dyn. Nat. Soc. 2021, 202, 1–10. [CrossRef]

26. Jiang, S.; Guan, W.; Yang, L. Feeder Bus Accessibility Modeling and Evaluation. Sustainability 2020, 12, 8942. [CrossRef]