

Research Article

Optimization of Bus Rerouting to Alleviate the Impact of Rail Transit Construction

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In urban areas, rail transit construction affects the travel time and the efficiency of bus lines along the surrounding roads. To ensure service qualities, this study proposes a two-stage optimization method for bus rerouting to alleviate the impact of rail construction. In the first stage, the effect of the construction on bus operation is evaluated based upon one indicator, namely the increased rate of bus turnaround time. The affected lines that need rerouting are sifted by the indicator. For each rerouting line, we design two adjustment patterns and associated candidate alternative rerouting sets. In the second stage, the bus network alteration optimization model is developed to maximize the number of passengers served. The model considers several practical constraints, including service connectivity, rationality of bus travel time, and budget for building new bus stops. It realizes a systematic optimization of bus rerouting lines affected by rail transit construction. The proposed method is applied to Ning-Ma intercity railway in Ma'anshan, China to analyze the impact of construction on the surrounding bus lines and obtain the optimal adjustment scheme. The results show that the proposed method is capable of effectively reducing the negative effects caused by rail transit construction and meantime guaranteeing bus service quality.

1. Introduction

Bus is a basic mode of urban transit, which establishes the initial network structure for a city's public transport system (e.g., Ibarra-Rojas et al., 2015; [1–6]; among many others). With the advancement of urbanization, rail transit is now being rapidly constructed in many large cities so as to relieve the pressure of passenger flow. Rail transit routes are usually constructed along the passenger corridors to ensure attracting sufficient passengers when they are in operation [7]. Nevertheless, the daily demand of these passenger corridors still needs to be served by bus lines before rail transit routes are constructed.

The construction of rail transit generally forms several work zones, which occupy the road resource and influence the operation of ground transportation [8]. As the construction period lasts for a long time, it brings troubles to the

operations of bus lines which pass through road segments with work zones. Passengers who originally take bus lines nearby work zones may switch to other bus lines or other modes of transport due to dust, noise, and congestion resulting from rail transit construction. Numerous studies have been conducted to analyze the impact of work zone on ground transportation. Some of these studies discussed the influence of work zone from the perspective of improving safety [9, 10]. Some authors studied the heterogeneous behaviors of drivers when passing the work zone [11, 12]. Furthermore, the optimization of project schedule for rail transit and traffic flow organization have also been investigated to reduce traffic delay and travel cost resulting from the disturbance of work zones [13–15]. Generally, travel behavior and traffic flow organization are focused more in the existing studies. However, identifying the affected bus service due to rail transit construction and optimizing

associated bus lines have not been studied particularly. Thus, it is imperative to identify bus lines that are greatly affected and take active measures to improve the quality of bus service so as to maintain passenger flow.

In this paper, the impact of rail transit construction on bus operation relates to the relationship between bus and rail transit, and there are a number of studies addressing this problem. Most of them pay attention to the coordination between two modes and optimization of passenger transfer [16–18], for the coordination between bus schedule and rail transit timetable has major economic importance to both operators and passengers [19–24]. Existing studies reported many interesting findings on the cooperation of bus service and rail transit in operation. However, the role of bus lines pertinent to rail transit is apparently different when rail transit is under construction.

During the rail transit construction period, bus lines may be influenced in terms of both travel time and efficiency when passing the road segments nearby work zones. Bus rerouting is an active measure by adjusting bus lines and associated stops to reduce negative impacts of rail transit construction. However, relevant studies that explicitly explore the effects of rail transit construction and bus routing scheme are limited. The only related paper is the work of Huang et al. [25]. It proposed a method to evaluate the performances before and after the implementation of the bus routing scheme. However, it is not capable of generating the set of candidate rerouting plans for affected bus lines and meantime optimize the bus rerouting scheme of these lines, which is addressed in this study.

The primary objective of this study is to propose a two-stage optimization method to generate a bus rerouting scheme and alleviate the impact of rail construction. In the first stage, bus rerouting lines are sifted using one indicator, namely the increased rate of bus turnaround time. For each rerouting line, we design two adjustment patterns and associated candidate alternative rerouting sets. In the second stage, a bus network alteration optimization model is developed to maximize the number of passengers served. The model considers several practical constraints, including service connectivity, rationality of bus travel time, and budget for building new bus stops.

The remainder of this paper is organized as follows. Section 2 describes the bus rerouting problem during the rail transit construction period. Sections 3 and 4 present the two-stage optimization method. In Section 5, a numerical example is adopted to verify the efficiency of the method. Finally, conclusions are provided in the Section 6.

2. Problem Description

Rail transit route is usually located along the passenger corridor to ensure serving sufficient passengers. Such passenger corridors densely distribute several bus lines. As a result, the rail transit construction may undermine the operational quality of these lines when bus vehicles pass road segments with work zones. Surely, if the work zone fully blocks the road, stop-skipping will also be an infeasible pattern. In that case, all affected lines need to reroute with migration. Yet, the road fully blocked is an extremely rare

scenario, and the more common scenario is that the work zone occupies partial lanes with the remaining lanes open. We illustrate the latter scenario in this study using a road with three lanes in each direction as an example.

As shown in Figure 1(a), vehicles run regularly with three lanes in each direction before rail transit construction. In Figure 1(b), rail transit is under construction, one work zone is formed along one side of the road segment which occupies two vehicle lanes. As the number of vehicle lanes decreases from 6 to 4, travel time along this road segment inevitably rises even though the traffic flow is identical. Therefore, the operating time of buses passing the road segment containing the work zone will be longer, which affects bus operations.

2.1. Two-Stage Optimization Method. To alleviate the impact of construction, a two-stage optimization method is developed for actively rerouting affected bus lines. To illustrate the relations among the following sections, Figure 2 shows the structure of the two-stage optimization method, and each step in the flowchart is linked to the corresponding section. In Stage I, we employ one evaluation indicator to estimate whether one bus line needs to be adjusted. Then, bus rerouting lines are sifted. According to the degree of influence, these bus rerouting lines are further classified into two patterns, namely the stop-skipping pattern and the migration pattern. The appropriate pattern is selected by the bus operating time within the affected section, which is illustrated in Section 3.2. For each rerouting line, it has one particular adjustment pattern and candidate alternative rerouting set, which contains candidate alternative plans. In Stage II, we propose an optimization model to obtain the optimal alternative plans by maximizing the number of passengers served. For ease of concise interpretation, we summarize the notations used in the two-stage optimization method in Table 1.

2.2. Concept Identification. In general, the construction of rail transit forms several work zones, which affects the operation of bus lines when passing the road segments with work zones. Hereafter, the bus line section that overlaps road segments with work zones is termed as the affected section. Specifically, the affected section refers to the minimum bus line section bounded by two bus stops on the bus line and containing the overlapping road segments with work zones. Note that if there are two or more affected sections along one bus line, we will optimize these affected sections independently.

As mentioned in Figure 2, one adjustment pattern is chosen between stop-skipping and migration for each rerouting line. The stop-skipping pattern allows vehicles to skip some stops within the affected section, such as stop 4 and stop 6 are skipped in Figure 3(a). For the migration pattern, some alternative plans adjacent to the affected section need to be selected. The stops in the alternative plan can be selected from the existing stops or by building new bus stops, which incorporates practical road conditions. Each affected section corresponds to at least one alternative



(a)



(b)

FIGURE 1: Rail transit construction and work zone; (a) road segment before rail transit construction; (b) road condition under rail transit construction.

plan, and finally, there is one and only one alternative plan selected. The segment replaced by an alternative plan is called the migration section. Each migration section needs to be completely replaced by an alternative plan. It is

noteworthy that for the same affected section, different alternative plans correspond to different migration sections. It is because some stops cannot be served even if they are not in the affected section. For further illustration, the original bus

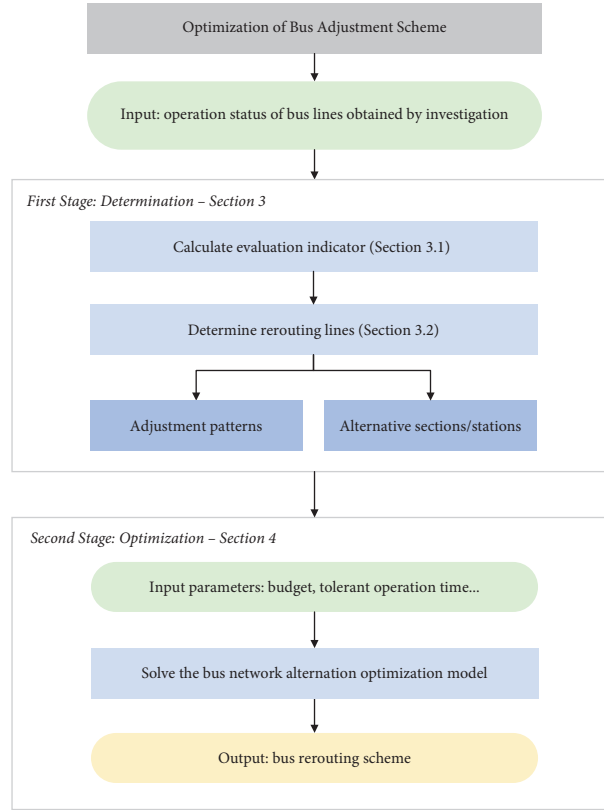


FIGURE 2: Flowchart of the two-stage optimization method.

TABLE 1: Illustration of the notations.

Parameters

N . Set contains all bus lines.

N' . Set contains all rerouting lines. $Z' = N_1 \cup N_2$, where N_1 is the line set containing rerouting lines with stop-skipping and N_2 is the line set containing rerouting lines with migration.

P_0 . The rerouting criterion value of increased rate.

P_n^t . The increased rate of turnaround time*

T_n . The average turnaround time before construction.

T_n' . The average turnaround time during construction.

t_n . The average time when buses travel within the affected section during construction.

t_n' . The average operation time by skipping half of the stops within the affected section.

t_n^0 . The average time when buses travel within the affected section during construction with skipping all stops.

t_s^0 . The average time when buses travel within an alternative plan $s \in S_n$ of line $n \in N_2$ during construction with skipping all stops.

R_n . Set contains stops in the affected section of line $n \in N_1$, stops ordered in sequence.

S_n . Set contains all alternative plans of line $n \in N_2$.

V_n^s . Set contains stops in an alternative plan $s \in S_n$, stops ordered in sequence.

R_n^s . Set contains stops in a migration section (which corresponding to V_n^s), stops ordered in sequence.

V . Set contains alternative stops of all line $n \in N_2$. $V = \{V_n^s | n \in N_2, s \in S_n\} = V_e \cup V_b$, where set V_e contains all the existing stops in the alternative stop set, and V_b is the new stops set.

w_n . The maximum tolerant operation time of the rerouting line $n \in N'$ within the affected section.

δ_n . The average increase in the operating time for each additional stop of line $n \in N_1$ in the affected section.

δ_s . The average increase in the operating time for each additional stop within an alternative plan $s \in S_n$ of line $n \in N_2$.

a_n^k . The potential passenger flow can be attracted by alternative stop k of line $n \in N'$.

c . The cost of building a new stop.

W . represents the total budget for building new stops.

Decision variables

x_n^k . 0-1 variable, when line $n \in N'$ after adjustment visits stop k , the variable equals 1.

y_n^k . 0-1 variable, when new stop k is selected to be built, the variable equals 1.

z^s . 0-1 variable, it equals 1 when alternative plan $s \in S_n$ of line $n \in N_2$ is selected.

*Turnaround time: the operation time that a bus spends on completing a whole single trip.

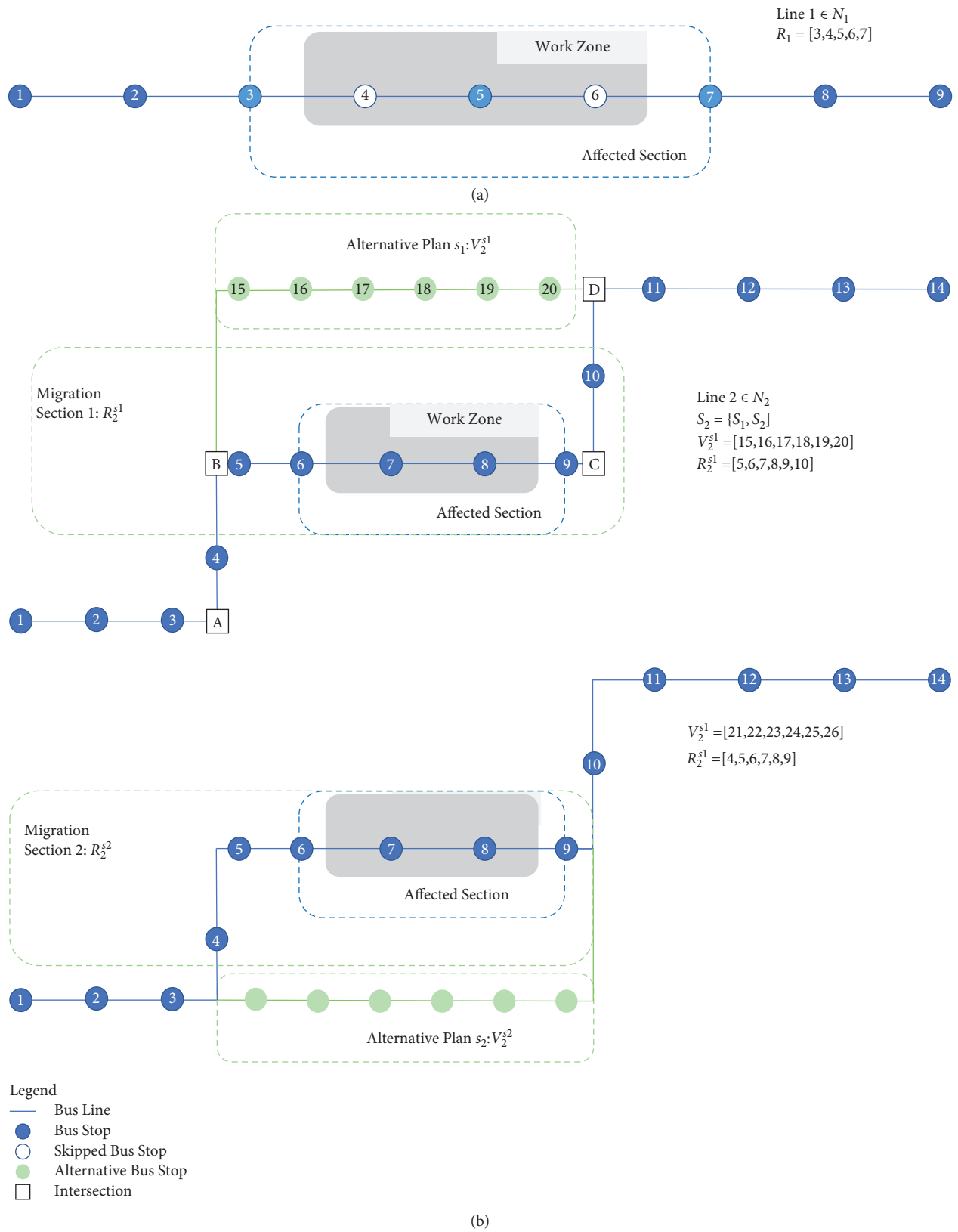


FIGURE 3: Illustration of the two adjustment patterns. (a) Stop-Skipping pattern and (b) Migration pattern.

line in Figure 3(b) passes four intersections A, B, C, and D (marked in the black box). Its affected section is the road segment between stop 6 and stop 9. For its alternative plan 1 going straight on at intersection B, stops 5 and 10 cannot be visited any more. As a result, the two stops are contained in the corresponding migration Section 1, although they are not in the affected section. Similarly, stops 4 and 5 are contained in migration Section 2.

3. Stage I: Determinization

The lines intersecting the construction work zone called “affected lines” are obtained from field investigation of operation status and GPS data. Construction affects the operation of these bus lines, while its influences on each line may have a different extent. It is unnecessary to adjust all these lines because the adjustment is costly and inconvenient to passengers. For these reasons, we should determine whether a bus line needs adjustment, and further how to enhance its service quality via rerouting.

3.1. Evaluation Indicator. For each bus line, to determine whether it needs adjustment, we utilize an evaluation indicator to estimate the operation status of bus vehicles during the rail transit construction. The travel time is usually regarded as the most important factor dominating mode choice, and travelers’ willingness mainly depends on the time costs of different modes [26]. Turnaround time denotes the operation time that a bus spends on completing a whole single trip. It is a key factor indicating the quality of bus service, which is easy to be measured before and after rail transit construction. In this study, we choose the increased rate of turnover time as the evaluation indicator. For line $n \in N$, the increased rate of turnaround time P_n^t is defined as

$$P_n^t = \frac{T_n' - T_n}{T_n}. \quad (1)$$

The rerouting criterion P_0 is the maximum tolerant increased rate of the operation time chosen by the bus company. When P_n^t exceeds P_0 , it means the impact of rail construction on line $n \in N$ cannot be ignored that the line n is necessitating to be adjusted. All bus lines that satisfy $P_n^t > P_0$ are sifted and denoted by set N' , which are called rerouting lines.

3.2. Two Adjustment Patterns. There are two adjustment patterns provided for each rerouting line, namely stop-skipping and migration, and which one to be chosen is determined according to the operation time within the affected section. For a bus line $n \in N'$, let L_n represent the total length of the bus line. Let l_n represent the length of the affected section. Under the criterion value P_0 , the maximum tolerant operation time within the affected section is set as $w_n = l_n/L_n T_n + P_0 T_n$. The setting of parameter P_0 depends on the local circumstances, for example the value of time for passengers in different areas may be distinct. Questionnaire survey and survival analysis can be employed to understand

the maximum acceptable time increase of the local residents, and hence determine the suitable setting of parameter P_0 .

In order to promise the service quality, we require that at most half of the stops within the affected section can be skipped if the stop-skipping pattern is chosen. With parameters t_n and t_n^0 , the average time for each additional stop in the affected section δ_n can be calculated, and further we procedure the average operation time by skipping half of the stops within the affected section t_n' . Therefore, if t_n' satisfies

$$t_n' \leq w_n. \quad (2)$$

It indicates that stop-skipping can effectively mitigate the construction impact on the bus line operation, i.e., stop-skipping is chosen as the adjustment pattern for this affected section. If t_n' satisfies

$$t_n' > w_n. \quad (3)$$

migration will be chosen as the adjustment pattern.

After determining adjustment patterns for each line, we need to select some appropriate alternative plans for rerouting lines with migration. An appropriate alternative plan shall have high similarity with the migration section, which can facilitate bridging the unchanged section and attracting passenger flow. For the Fréchet distance often used to measure spatial similarity [27, 28], it is applied to measure the rationality of alternative plans. Equation (4) requires that the Fréchet distance between the selected alternative sections and the corresponding migration section not exceed the maximum tolerant distance D .

$$\begin{aligned} & \inf_{i: [0, m] \rightarrow [0, |\mathbf{V}_n^s|]} \max_{t \in [0, m], t \in \mathbb{Z}} d_{i(t), j(t)} \leq D, \\ & j: [0, m] \rightarrow [0, |\mathbf{R}_n^s|] \end{aligned} \quad (4)$$

$$\forall m = \max(|\mathbf{V}_n^s|, |\mathbf{R}_n^s|), \quad s \in S_n, n \in N_2.$$

It constrains that the change before and after the adjustment should be within a tolerant range. A smaller distance between the affected section represents higher similarity. Furthermore, it restricts the maximum access distance of passengers originating from affected section to fetch the rerouting line. Readers can refer to Agarwal et al. [29] for details on the Fréchet distance.

4. Stage II: Optimization

With the selected rerouting lines and their patterns, the second stage formulates a bus network alteration optimization model to obtain the optimal bus adjustment scheme. The adjustment of bus lines is a strategic transit network planning problem aimed to determine network layout at the macro level. Since the bus network layout influences the efficiency of services, which is reflected by passenger demand [22], the selections of bus stops and routes need to maximize patronage. Passengers’ demand may be affected by many factors [30–32], and during rail construction, they pay more attention to the in-vehicle time (i.e., the operation time of the bus line). As a result, the model in Stage II is formulated as



FIGURE 4: Ning-Ma intercity railway under construction.

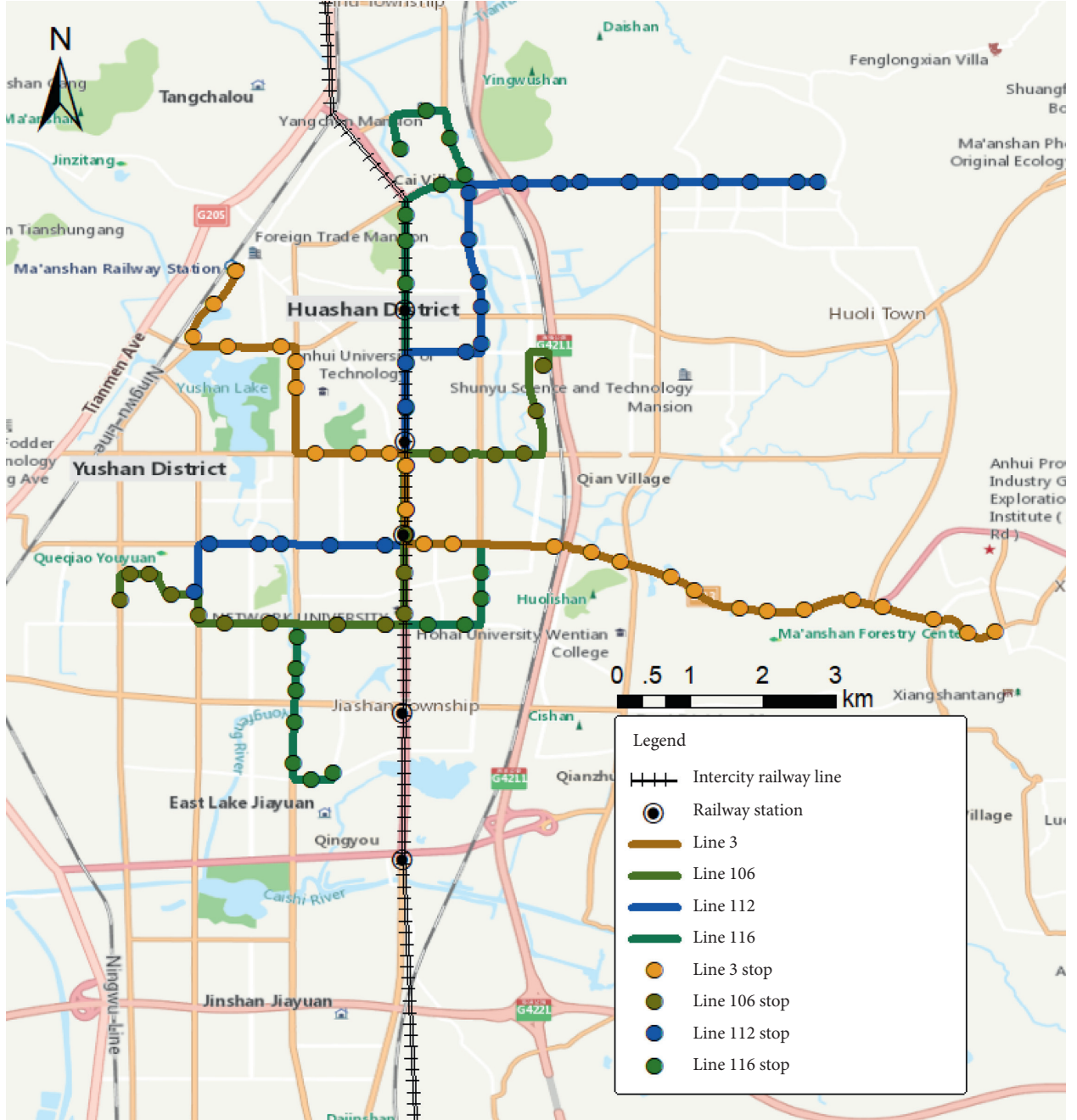


FIGURE 5: Ning-Ma intercity railway and affected bus lines.

$$[M]: \max \sum_{n \in N_2} \sum_{s \in S_n} \sum_{k \in V_n^s} a_n^k \cdot x_n^k - \sum_{n \in N_1} \sum_{k \in R_n} a_n^k \cdot (1 - x_n^k) - \sum_{n \in N_2} \sum_{s \in S_n} \sum_{k \in V_n^s} z^s \cdot a_n^k \quad (5)$$

$$t_n^0 + \delta_n \sum_{k \in R_n} x_n^k \leq w_n, \quad \forall n \in N_1, \quad (6)$$

$$t_s^0 z^s + \delta_s \sum_{k \in V_n^s} x_n^k \leq w_n, \quad \forall n \in N_2, s \in S_n, \quad (7)$$

$$\sum_{k \in V} c y^k \leq W, \quad (8)$$

TABLE 2: Operational parameters of the four bus lines.

Bus line	L_n (km)	l_n (km)	T_n (min)	T'_n (min)	t_n (min)	t_n^0 (min)	δ_n (min)	t'_n (min)
Line 3	13.9	1.5	52	64	20	15	3	18
Line 106	11.5	2.8	48	61	32	19.5	3	25.5
Line 112	13.3	3.1	60	75	29	13	3	22
Line 116	14.5	5.6	46	60	34	18	2	26

TABLE 3: Determine the adjustment patterns for the bus lines.

Bus line	P'_n	Reroute or not	w_n (min)	Adjustment pattern
Line 3	0.231	Reroute	16.01	Migration
Line 106	0.271	Reroute	21.29	Migration
Line 112	0.250	Reroute	25.98	Stop-skipping
Line 116	0.304	Reroute	26.97	Stop-skipping

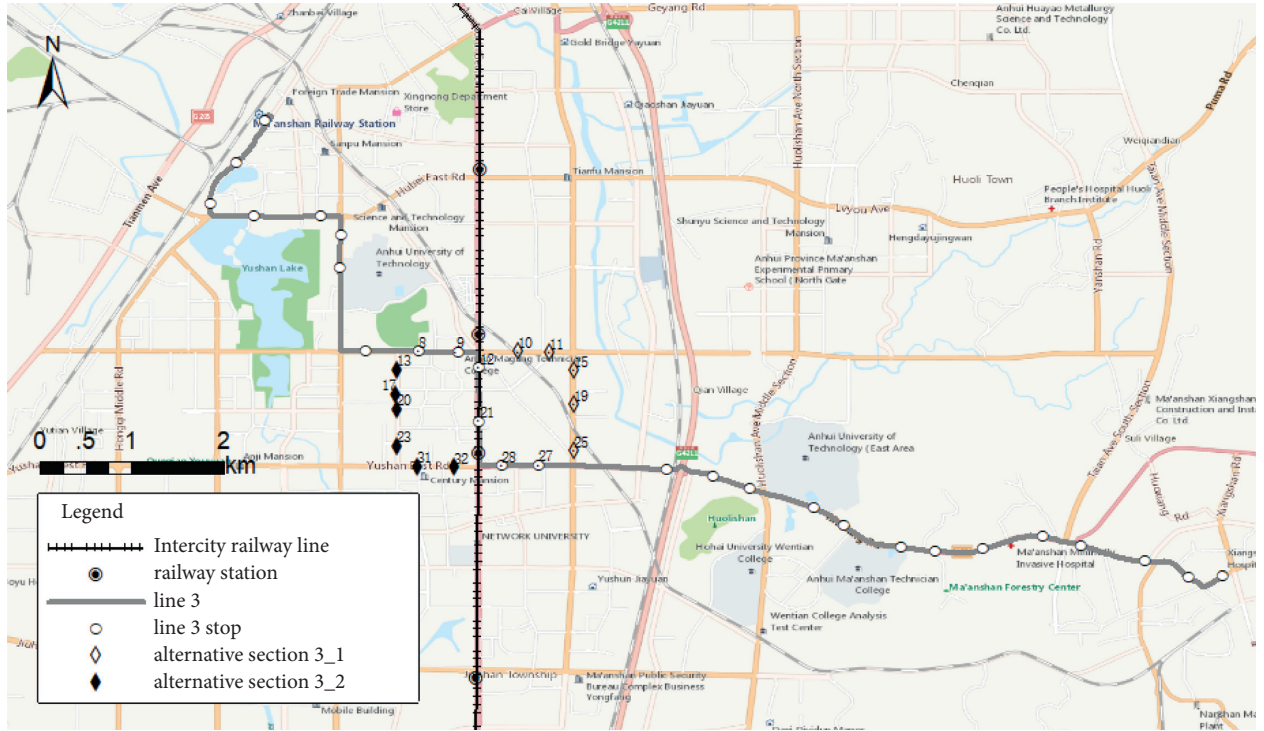


FIGURE 6: Alternative plans and stops of line 3.

$$\sum_{s \in S_n} z^s = 1, \quad \forall n \in N_2, \quad (9)$$

$$x_n^k \leq z^s \leq \sum_{k \in V_n^s} x_n^k, \quad \forall n \in N_2, s \in S_n, k \in V_n^s, \quad (10)$$

$$x_n^k \leq y^k \leq \sum_N x_n^k, \quad \forall n \in N_2, k \in V_b, \quad (11)$$

$$x_n^k \in \{0, 1\}, \quad \forall n \in N_1, k \in \{R_n | n \in N_1\} \cup \{V_n^s | n \in N_2, s \in S_n\}, \quad (12)$$

$$y^k \in \{0, 1\}, \quad \forall k \in V_b, \quad (13)$$

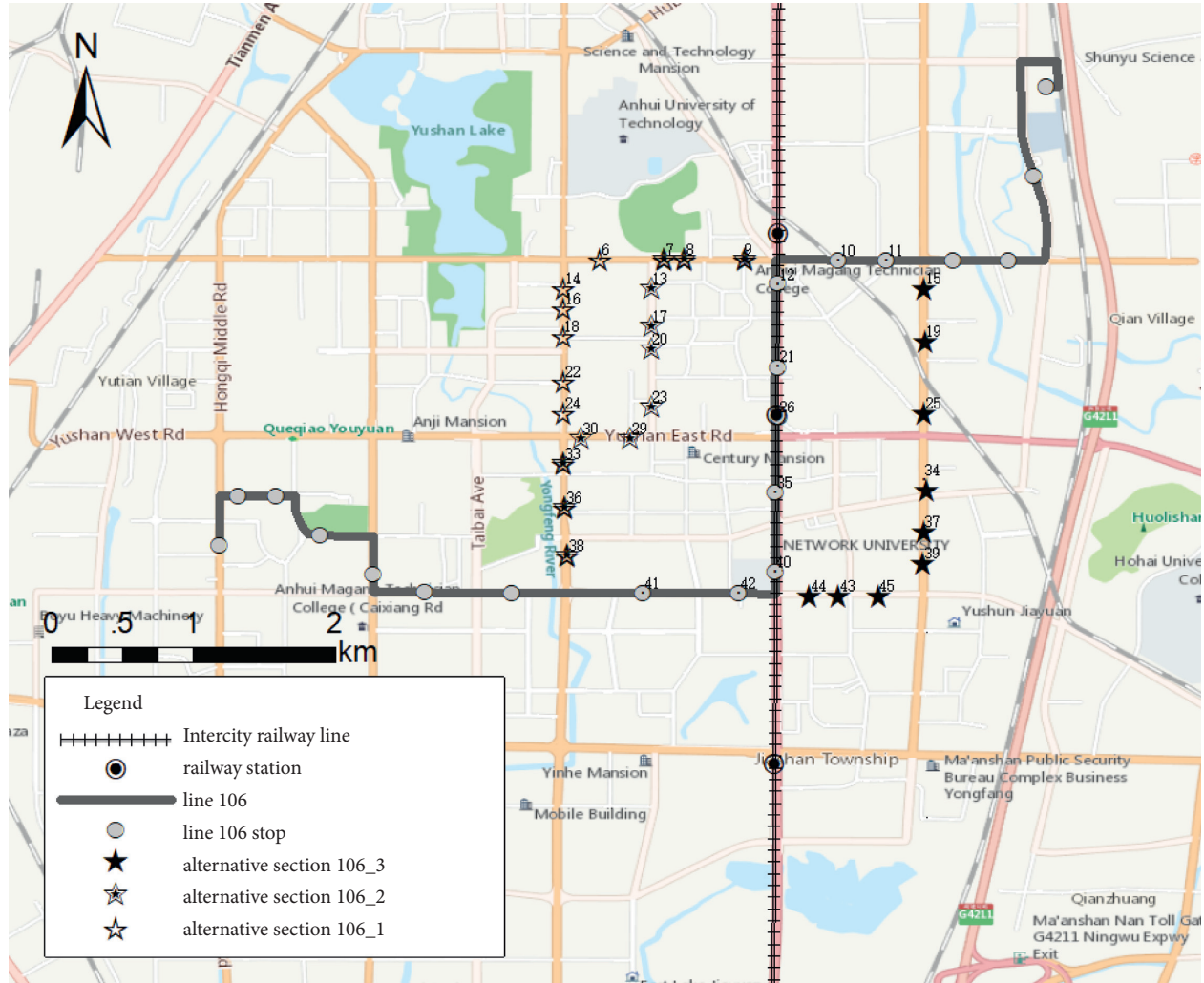


FIGURE 7: Alternative plans and stops of line 106.

$$z^s \in \{0, 1\}, \quad \forall n \in N_2, s \in S_n. \quad (14)$$

Parameters associated with passenger demand and operation status, i.e., a_n^k , t_n^0 , δ_n , t_s^0 , δ_s , are obtained by investigation. The potential passenger flow a_n^k can be acquired by analyzing the street network, land uses, and population density data in the range of the acceptance access distance with geographic information system tools.

The objective of model [M] is to maximize the number of passengers served by the adjustment scheme. Since the number of passengers before conducting the adjustment scheme is fixed, the objective can be modified as the variation of passenger flow before and after conducting the adjustment scheme. The first item of the objective function (5) is the number of passengers attracted by the selected alternative stops, the second item is the number of passengers lost because of stop-skipping, and the third item is the number of passengers lost because of migration. If the objective value is positive, it means that more passengers

choose to use bus rerouting lines. In such case, the objective function being 0 means “no passengers lost” with the optimal adjustment scheme. It should be pointed out that the effect of bus capacity is not considered in this paper, and bus frequencies are assumed to be sufficiently large that all the passengers at each stop can successfully board the buses.

Constraints (6) and (7) indicate the operation time within each affected section should not exceed the tolerance. It reduces agency costs by limiting the operating time of bus lines. Constraint (8) indicates the total cost of building new stops cannot exceed the budget. Constraint (9) indicates there is one and only one alternative plan selected for each rerouting line with migration. Constraints (10) and (11) indicate the relationship between decision variables. The above integer linear programming (ILP) with a polynomial number of variables could be solved by the off-the-shelf ILP solvers, such as Gurobi.

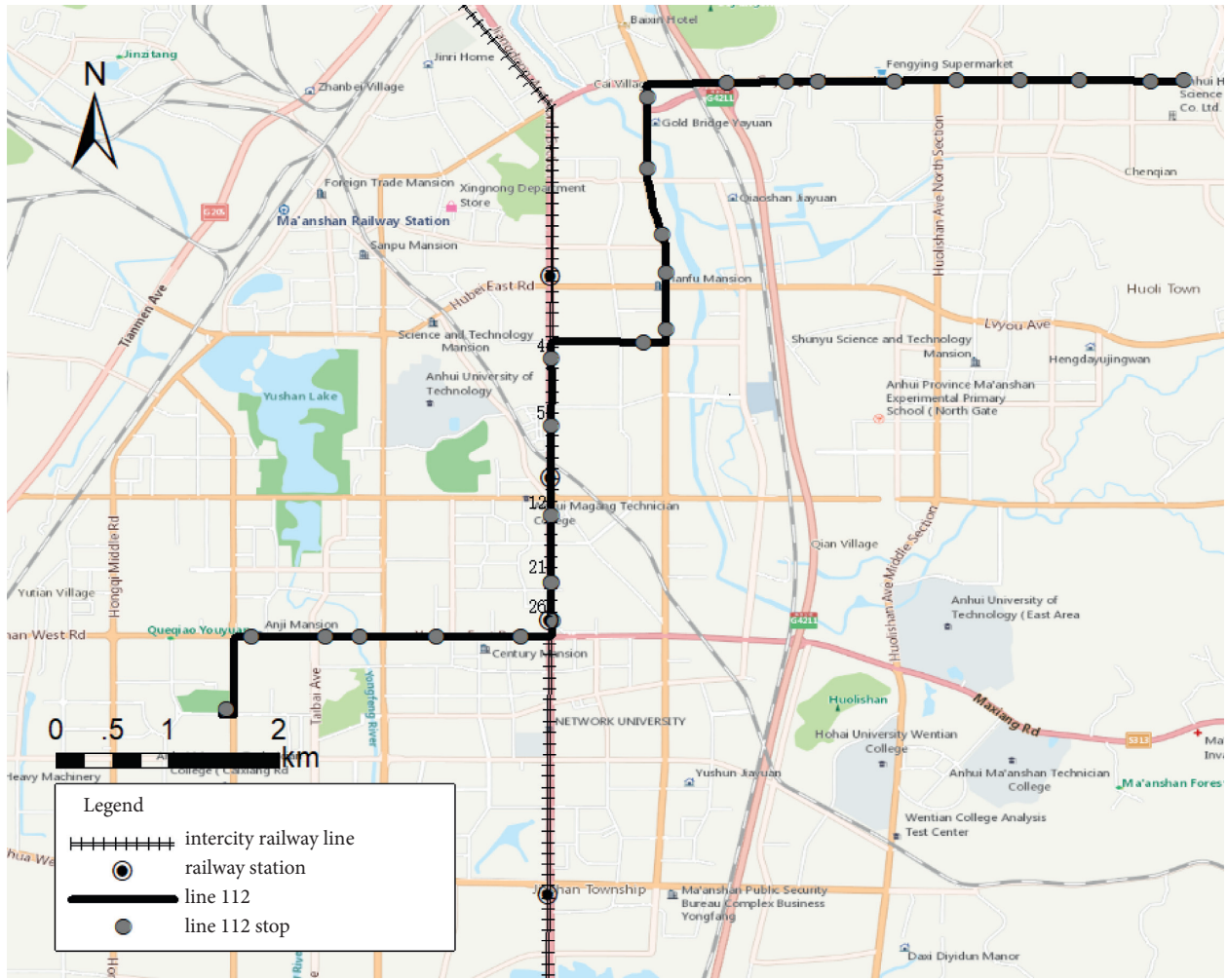


FIGURE 8: Alternative plans and stops of line 112.

5. Numerical Experiments

5.1. Case Study. In this section, we apply the proposed two-stage method to a numerical instance to verify its effectiveness and practicability. Ning-Ma intercity rail transit route in Ma'anshan, Anhui Province, China, and associated bus lines are taken as an example. The location of the Ning-Ma intercity rail transit is shown in Figure 4, and the bus lines include bus lines 3, 106, 112, and 116. The location of these four bus lines and their relationship with the rail transit route are shown in Figure 5. Although the bus operation is divided into two directions, the stops in different directions are symmetrical. So, in this section, we only take one direction of each bus line to illustrate the proposed method.

The operational parameters of bus lines 3, 106, 112, and 116 were obtained from historical data, as shown in Table 2.

Depending on the local circumstance, the criterion values are set as $P_0 = 0.2$. Then, we determine whether these

four bus lines need adjustment, and further choose an adjustment pattern for each line, as shown in Table 3.

According to the results in Table 3, all these four bus lines need adjustment. Bus lines 3 and 106 need reroute by migration, while bus lines 112 and 116 need reroute by stop-skipping, i.e., $N_1 = \{112, 116\}$, $N_2 = \{3, 106\}$, and $N^i = \{3, 106, 112, 116\}$. Considering the condition of the surrounding road network, the maximum tolerant distance of the Fréchet distance is set as $D = 2$ km. Under this circumstance, alternative plans and stops of these bus lines are given in Figures 6–9 respectively. Other related parameters obtained by the investigation are shown in Table 4.

As shown above, two alternative plans are selected for bus line 3 and three for bus line 106. In Table 4, all the stops in column V_n^s constitute the alternative stop set V , among which stops 7, 19, 31, 36, and 43 are the new stops, i.e., $V_b = \{7, 19, 31, 36, 43\}$. Table 5 shows the potential passenger flow attracted by some stops.

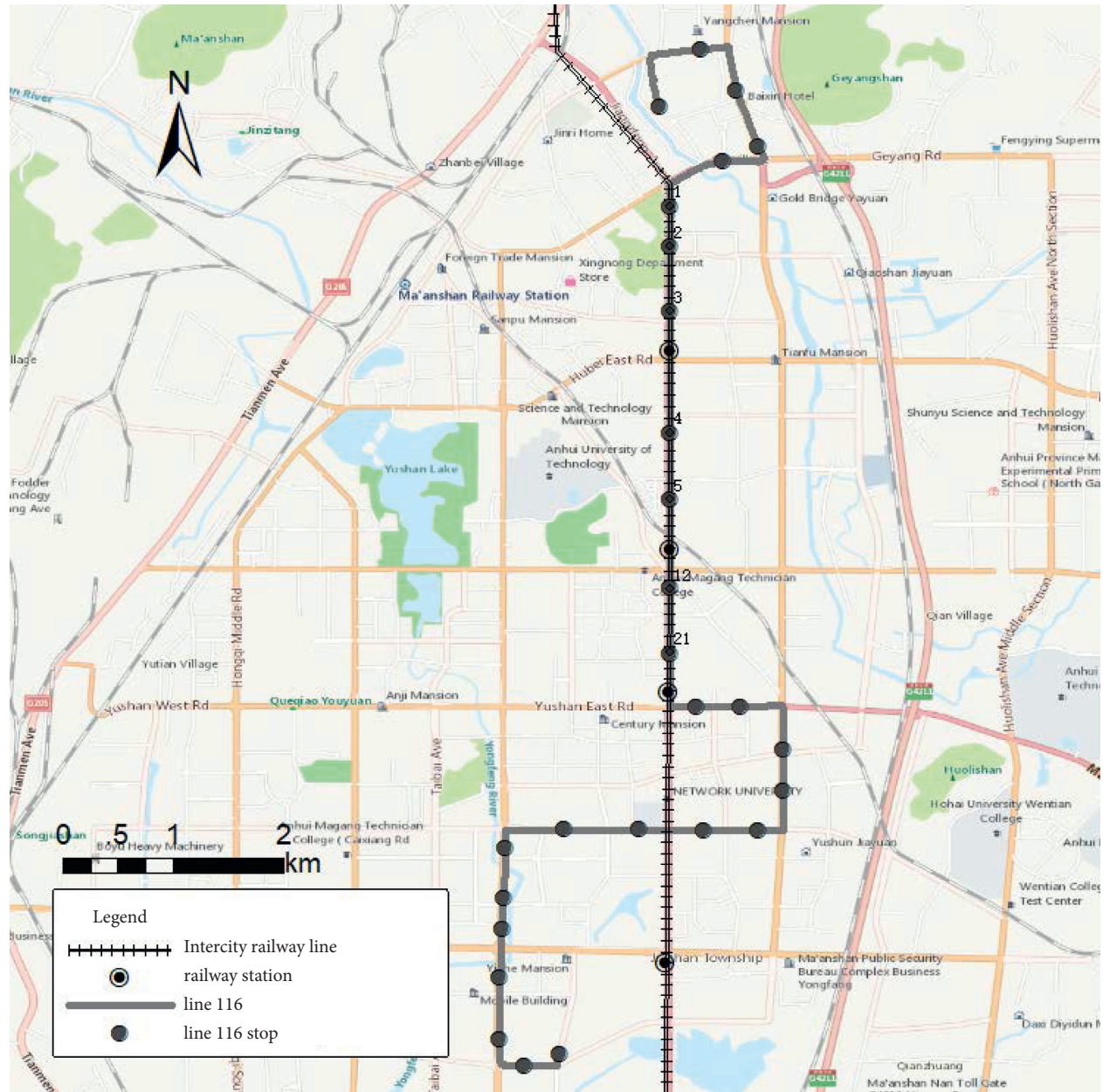


FIGURE 9: Alternative plans and stops of line 116.

TABLE 4: Information of the rerouting lines.

Bus line	Adjustment pattern	S_n	V_n^s	R_n^s/R_n	Fréchet distance (km)	$t_s^0 (t_n^0)$ (min)	$\delta_s (\delta_n)$ (min)
Line 3	Section migration	1	[10,11,15,19,25]	[12,21,28,27]	1.21	8	1.5
		2	[13,17,20,23,31,32]	[8,9,12,21]	1.37	9	1.5
Line 106	Section migration	1	[9,8,7,6,14,16,18,22,24,33,36,38]	[12,21,26,35,40,42,41]	1.78	12	1.5
		2	[9,8,7,13,17,20,23,29,30,33,36,38]	[12,21,26,35,40,42,41]	1.54	13	1.5
		3	[15,19,25,34,37,39,45,43,44]	[11,10,12, 21,26,35,40]	1.21	12	1.5
Line 112	Stop-skipping	—	—	[4,5,12,21, 26]	—	13	3
Line 116	Stop-skipping	—	—	[1,2,3,4,5,12,21]	—	18	2

TABLE 5: The number of passengers attracted by the stop.

Stop number	Potential passenger flow a_n^k (persons/h)			
	Line 3	Line 106	Line 112	Line 116
4	—	—	6	7
5	—	—	5	5
8	6	10	—	—
9	6	6	—	—
10	5	10	—	—
11	8	4	—	—
12	2	7	5	5
21	5	3	4	6

TABLE 6: Optimal adjustment scheme of bus under the effect of Ning-ma intercity railway.

Bus line	Adjustment pattern	Stops in adjustment section	Replaced stops
Line 3	Migration	[10,11,15,19,25]	[12,21,28,27]
Line 106	Migration	[9,8,14,22,33,36]	[12,21,26,35,40,42,41]
Line 112	Stop-skipping	[4,5,12,26]	[21]
Line 116	Stop-skipping	[2,4,12,21]	[1,3,5]

Furthermore, the values of c and W are set as 50,000 CNY and 100,000 CNY, respectively. The unit of these two parameters can be formed as “ten thousand CNY;” then, the values of c and W can be simplified to 5 and 10. With the results analyzed from the first stage, the optimized adjustment scheme generated by model [M] in Stage II is shown in Table 6. The optimal results of the case study can be obtained in less than 1 second using Gurobi 9.1 with default settings, running on a 1.6 GHz Quad Core PC with 8 GB of RAM.

In the optimized adjustment scheme, two new stops need to be built, i.e., stops 19 and 36. The value of the objective function is 0, which means “no passengers lost” with the optimal adjustment scheme; more precisely, the potential demand attracted by the adjustment sections fills the lost passengers. The result shows the adjustment scheme can fully compensate for the loss of passenger flow caused by rerouting.

5.2. Sensitivity Analysis. We first analyze how the adjustment pattern varies with the change of the rerouting criterion P_0 . Recall that the adjustment pattern is decided by $\omega_n = l_n/L_n T_n + P_0 T_n$, i.e., the maximum tolerant operation time within the affected section. As shown in Table 7, a smaller P_0 provides a tighter restriction on the operation time, and hence more bus lines need to be adjusted using the migration pattern. If the threshold value of P_0 is increased, there will be more lines that can reroute by the stop-skipping pattern, which is easier to implement than the migration pattern but may lose more passengers. If P_0

continuously increases, it indicates that the bus operator gets more tolerant of the additional operation time resulting from the rail transit construction. For instance, if P_0 attains 0.24, bus line 3 does not need be adjusted. Yet, the setting of too high a value for P_0 is inappropriate because it may apparently impair bus service quality due to the considerable in-vehicle time, which is unacceptable to most passengers. Furthermore, we conduct a sensitivity analysis on the effect of P_0 on the fleet size (i.e., number of employed vehicles) of bus lines, given that the rerouting criterion is set as P_0 . With Table 7, we can find that the operators need to reserve more available vehicles with the increase in P_0 because the prolongation of the operation time reduces the bus turnover rate.

In addition, the influence of P_0 on the objective value and fleet size of the four bus lines is discussed as well. Figure 10 depicts the variation of the objective value and the number of vehicles needed when P_0 varies from 0.18 to 0.30. As can be seen, the number of potential demands attracted (i.e., the value of objective function) fluctuates under different settings of P_0 . Meanwhile, the setting of P_0 influences the number of employed vehicles. As the increased rate of the turnaround time increases, the fleet size of the four bus lines experiences a growth from 51 to 53. To determine a reasonable P_0 , it is wise to ascertain the total number of vehicles available first; then, the local authorities can choose a value of P_0 to maximize the demand attracted with the given number of vehicles. For the numerical example we studied here, if the number of available vehicles is 52, the best P_0 equals to 0.23 according to Figure 10.

TABLE 7: The relation between the adjustment pattern and the value of P_0 .

P_0	0.15	0.16	0.17	0.18	0.19	0.2	0.21	0.22	0.23	0.24	0.25	0.26	0.27	0.28	0.29	0.3
Line 3	w_n (min)	13.41	13.93	14.45	14.97	15.49	16.01	16.53	17.05	17.57						
	Adjustment pattern Fleet size	12	13	13	13	13	13	13	13	13	13	13	13	13	13	13
Line 106	w_n (min)	18.89	19.37	19.85	20.33	20.81	21.29	21.77	22.25	22.73	23.21	23.69	24.17	24.65	No need for adjustment	
	Adjustment pattern Fleet size	12	12	12	12	12	12	12	12	12	12	12	13	13	13	13
Line 112	w_n (min)	22.98	23.58	24.18	24.78	25.38	25.98	26.58	27.18	27.78	28.38					
	Adjustment pattern Fleet size	14	14	15	15	15	15	15	15	15	15	15	15	15	15	15
Line 116	w_n (min)	24.67	25.13	25.59	26.05	26.51	26.97	27.43	27.89	28.35	28.81	29.27	29.73	30.19	30.65	31.11
	Adjustment pattern Fleet size	11	11	11	11	11	12	12	12	12	12	12	12	12	12	12

* Before rail construction, the fleet size for the operation of lines 3, 106, 112, 116, is, respectively 12, 10, 12, and 10; during rail construction, if they maintain operation without adjustment, the fleet size will increase to 14, 14, 16, and 12, respectively.

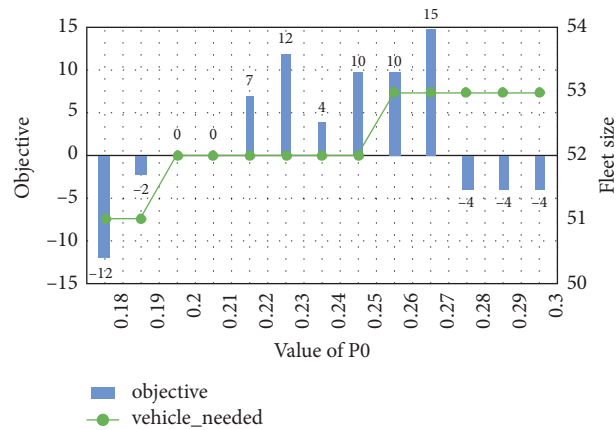


FIGURE 10: The objective and the fleet size change with P_0 .

6. Conclusions

This study proposed a two-stage optimization method to alleviate the impact of rail transit construction. By analyzing the characteristics of bus lines within the affected section, the first stage established an evaluation indicator to pick out bus lines that need adjustment. These selected lines are called rerouting lines, which were further divided into two patterns, i.e., stop-skipping and migration, and which pattern to be chosen was determined by their operation time within the affected section. Then, the second stage formulated a bus network alteration optimization model to optimize the adjustment scheme synergistically by maximizing the number of passengers. Constraints contained service connectivity, rationality of bus travel time, budget for building new bus stops, and many other realistic restrictions. A case study based on a Ning-Ma intercity rail transit route and four influenced bus lines in Ma'anshan, China was conducted to demonstrate the applicability of the proposed method. The results show that the obtained adjustment scheme ensures the coherence between the unchanged section and the adjustment section of bus lines. It also alleviates the negative impact of rail transit construction on the associated bus lines, especially decreasing the loss of passenger flow. Admittedly, our proposed method comes with some limitations, and the following improvements are suggested: (i) the value of time of various time components and the heterogeneous behaviors of passengers could be incorporated into the model; (ii) model formulations based upon different objective functions and associated algorithms could be systematically compared to solve the proposed problem in this study. The authors recommend that future studies focus on these issues.

Data Availability

The data presented in this study are available on request from the corresponding author.

Disclosure

Yiran Wang and Jingxu Chen are co-first authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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