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Research Article

Study on the Selection Model of Staying Adjustment Bus Lines along Rail Transit

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To fully achieve effective rail transit, prevent the waste of conventional bus capacity along a rail transit line, and relieve the urban traffic congestion problem, it is necessary to screen for the adjustment of conventional bus lines prior to the operation of rail transit to provide a basis for further optimization of bus lines. Based on the analysis of spatial relationships between a rail transit line and conventional collinear bus lines and considering the time advantage characteristics of rail transit in rush hours, a model of the generalized travel time costs and travel time savings proportion in the collinear section of rail transit and bus was proposed. To evaluate the utility of rail transit relative to conventional bus collinear lines, the conventional bus lines to be adjusted were determined. Taking Xiamen as an example, the bus lines of Hubin East Road Station as the endpoint of metro line 1 were employed to calculate the model using GPS data of the buses, and the bus lines to be adjusted in the Hubin East Road were determined. The results show that the model is effective in the elastic selection of conventional bus lines that need to be adjusted and provides decision-making support for urban comprehensive public transport planning.

1. Introduction

In the process of continuous urbanization, the urban scale and population keep expanding, and the demand for long-distance and large-volume transportation keeps growing. However, limited by urban road resources, traffic congestion is formed. Therefore, the development mode of "public transport priority" emerged at a historic moment [1]. Rail transit, with its advantages of large volume, fast speed, and punctuality, occupies a dominant position in the public transport system and is widely considered as the main way to solve urban traffic problems. Because rail transit needs to carry the main flow of urban passenger flow, line alignment is usually repeated with the layout of dense urban main and secondary trunk lines of conventional bus lines. To achieve a large volume after the operating of rail transit and prevent the waste of conventional bus capacity, the optimization and adjustment of conventional bus lines along rail transit need to be evaluated prior to the operation of a rail transit system.

After the operating of rail transit, passengers of conventional buses along the line are attracted, which requires some conventional bus lines to be adjusted and reorganized before the rail transit is operated. Public transportation system after the introduction of rail transit has been widely studied, mainly focusing on the network integration of the metro bus system, the evacuation planning of rail interruption, and the social benefits of the metro bus system [2–7]. However, the optimization and adjustment of rail transit and bus network mostly consider their coordinated operation. Some scholars determined the lines that need to be adjusted by studying the regions where passenger flows competed between rail transit and bus [8, 9]. This paper starts with the collinearity characteristics of rail transit and conventional bus, evaluates the utility of rail transit and conventional bus of the collinear channel, and adjusts the conventional bus lines before the rail transit is operated, so as to avoid the waste of conventional bus capacity.

Whether from the traffic demand or direct policy initiatives, urban public transport system with rail transit as the main and conventional bus as the auxiliary has become an inevitable trend [10]. To ensure a large capacity of rail transit and avoid the waste of conventional bus capacity, it is necessary to optimize and adjust the conventional bus lines along the rail transit line in advance before the rail transit is put into operation. Since the problem of traffic congestion in rush hours need to be improved first after the rail transit is introduced, this paper first considers the time advantage brought by the rail transit in rush hours and the time utility of the rail transit and conventional bus in collinear channel. Based on this evaluation, the conventional bus lines to be adjusted are determined, which provides a basis for further formulating adjustment measures.

2. Literature Review

With the large-scale development of rail transit, most scholars have focused on the integration of metro and bus system from the perspective of public transport network. The complementary capacity of bus services to the metro network can be improved by optimizing the connectivity between the two systems, which mainly concentrates on the construction of metro bus integrated network and their coordinated operation level. Jin et al. [2] focused on introducing localized integration with bus services. A two-stage stochastic programming model was developed to assess the intrinsic metro network resilience as well as to optimize the localized integration with bus services. Song et al. [4] determined the lines of ridership reduction under the influence of the metro and evaluated different bus service patterns using a pivot point demand model to "feed" various metro stations. Sun et al. [5] took the integrated network of rail transit and bus lines as the subject of study and build a multi-objective programming model for bus network optimization and adjustment to adjust the route direction and operation parameters. Qin and Zhou [8, 9] determined the collinear length of bus lines that need to be adjusted (above 6 km) by evaluating the length of passenger flow competition interval generated by bus and rail transit. In addition, as a mode of transportation with large volume, evacuation planning for rail transit is an important consideration. Zhang et al. [6] determined the initiation time of substitute bus services for metro disruption management, especially under uncertain recovery time by trading-off their initiation cost and passenger delay cost, thereby minimizing the total system cost. Lv et al. [3] developed an evacuation planning model based on the interval chance-constrained integer programming (EICI) method in response to bus–subway corridor incidents. With the rapid development of metro bus system, scholars have begun to pay attention to its social benefits. Zolnik et al. [7] explored who benefits from metro bus system according to the rider and the commuter data sources, respectively, as well as how they benefit, taking Lahore's new metro bus system as an example.

The optimization and adjustment of conventional bus lines mostly consider the integration of line network, and seldom study it from the perspective of passenger's travel utility. Due to the different attributes of travel time and cost of rail transit and conventional bus, the travel utility of rail transit and bus in the collinear channel is different, and passengers' choices of travel modes are different. In previous studies, the generalized travel cost has contained important travel characteristic information and is usually used as an evaluation index of travel utility in studies of travel mode choice [11–14]. For example, Feng and Yang [12] took the generalized travel cost as the travel utility, improved the traditional logit model, and predicted the sharing rate of travel modes. In this paper, the concept of the generalized travel time cost is introduced by referring to the study of generalized travel cost, and the travel utility of bus and rail transit of the collinear section is evaluated, followed by determining whether most passengers will choose rail transit during peak hours to identify the conventional bus lines that need to be adjusted before the rail transit is operated. In general, the generalized travel cost includes the costs of travel time, travel cost, and travel comfort [12, 14, 15]. Additionally, some scholars have also considered the travel time uncertainty [13, 16]. The indicators of travel time are usually based on traffic survey data [12–14] or a conversion between the travel distance and average speed of transportation modes [17]. The index of travel cost has usually been measured by the fare level of the mode of transportation [12, 13]. However, the measurement indicators of travel comfort have mostly used the degree of crowding [13], travel time [14], travel distance [15], etc. In the actual process, travel comfort is difficult to quantify, and there is no unified quantitative algorithm at present. To facilitate the calculation, the generalized travel costs in existing studies were converted into costs [12–15]. For value conversion between time and cost, the production method, income method, and disaggregate model are the most prevalent methods used for calculating the travel time value [12, 13, 17–19]. Referring to the generalized travel cost, this paper mainly evaluates the travel utility of bus and rail transit in the collinear channel. To highlight the time utility of rail transit during peak periods, the generalized travel cost is converted into time for calculations. Meanwhile, since the travel time of conventional buses is extremely unstable due to the impact of road congestion in rush hours, this paper uses vehicle GPS data to conduct a statistical analysis of the travel time of conventional buses, including time uncertainty factors, to obtain a more stable and accurate time utility. For the value conversion between time and cost, this paper adopts the income method and production method, respectively. Moreover, the travel comfort is related to personal physical exertion and the perceived degree of congestion, which is difficult to evaluate for the majority of passengers. While travel congestion during rush hours leads to little difference in the comfort between conventional buses and rail transit, comfort is not considered in this paper. In summary, this paper introduces the concept of the generalized travel time, evaluates the travel time and travel cost of conventional bus and rail transit in the collinear channel, builds a model of the generalized travel time cost and travel time savings proportion, and determines the conventional bus lines along the rail transit that need to be adjusted.

The adjustment of conventional bus lines along the rail transit takes place after the rail transit is put into operation, so the adjustment of conventional bus lines lags behind [2, 4, 8, 9, 10]. In practice, most cities have applied an experience value of the uniform index of greater than a collinear length

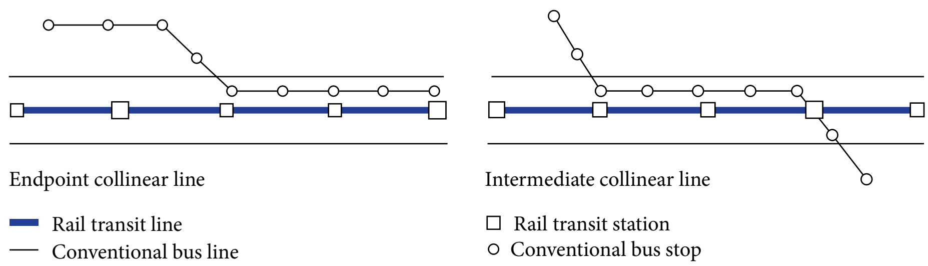

Figure 1: Diagram of the collinear relationship between bus lines and rail transit line.

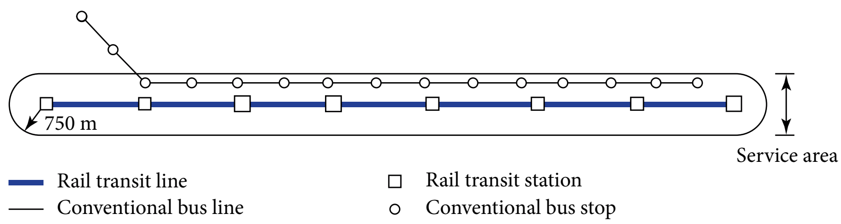

Figure 2: Diagram for determining the range of collinear lines.

of above 6 km in China [10], and the utility of rail transit relative to conventional bus along the line was not considered for targeted adjustment. In this paper, the time advantage of rail transit is taken into consideration first. On the basis of analyzing the spatial relationship between rail transit and bus lines, a generalized travel time cost and travel time savings proportion model is established for the rush hours of the collinear section of bus and rail transit. The model considers the road traffic conditions during rush hours, the transfer time of conventional bus and rail transit, the distance between two stations, the rail transit station design and other factors, which flexibly screens the conventional bus lines to be adjusted. The model provides a basis for further optimization of conventional bus lines in the collinear section of the rail transit. This research provides decisional support for urban integrated public transport planning.

3. Study Area

3.1. Concept of Collinear Lines. In the same passenger flow corridor, when the direction of a conventional bus line is similar to that of a rail transit line and within the service area on both sides of the rail transit line, both lines are collinear. Collinear lines can be classified as follows: fully collinear line, intermediate collinear line, and endpoint collinear line [21]. Due to the different services provided by rail transit and conventional bus transit, no fully collinear line exists. As a result, the intermediate collinear line and the endpoint collinear line are the main subjects in this paper (as shown in Figure 1).

The study area of the collinear line depends on the service radius of the rail transit affected by the service radius of the rail transit station, which can be considered as the direct service area of the rail transit. According to the "Guidelines for Planning and Design of Urban Rail Areas" [22] issued by the Ministry of Housing and Urban-Rural Development, the influence area of a rail transit station refers to an area that is approximately 500–800 m from the rail transit station, in which the station entrance can be accessed within approximately 15 min of walking and is closely related to the rail transit function. According to the urban practice experience in China, the direct-attractive range of the station is an area that is perpendicular to a rail transit line within 750 m on each side. At the end of the line, the range is a radius of 750 m from the station [23]. Therefore, this paper employs 750 m as the research range of the collinear line (as shown in Figure 2).

3.2. Spatial Relationship between Collinear Bus Lines and Rail Transit Line. For the endpoint collinear line, due to the existence of a breakpoint point between the conventional bus line and the rail transit line, the original conventional bus passengers will transfer once in the collinear section when moving to rail transit, and the research object can be abstractly described as the "point-line" spatial mode. However, two breakpoints exist between the conventional bus line and the rail transit line in the collinear section of the intermediate collinear line. The original conventional bus passengers will transfer twice in the collinear section when moving to rail transit, and the research object can be abstractly described as the "point-line-point" spatial mode (as shown in Figure 3).

3.3. Factors Affecting the Adjustment of Bus Lines along Rail Transit. After operation of the rail transit commences, travel time is saved due to the advantage of fast speed. To screen the conventional bus lines to be adjusted to be collinear with the rail transit, the influencing factors of the travel utility of passengers between rail transit and conventional buses in the collinear section should be analyzed.

3.3.1. Travel Demand during Peak Hours. Peak hours are the most prominent period of urban traffic conflicts. Whether conventional bus lines need to be adjusted after placing the rail transit into operation depends on the services provided by

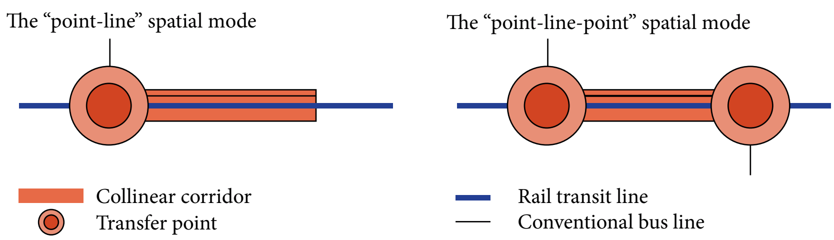

Figure 3: Conceptual diagram of the spatial relationship between collinear bus lines and rail transit line.

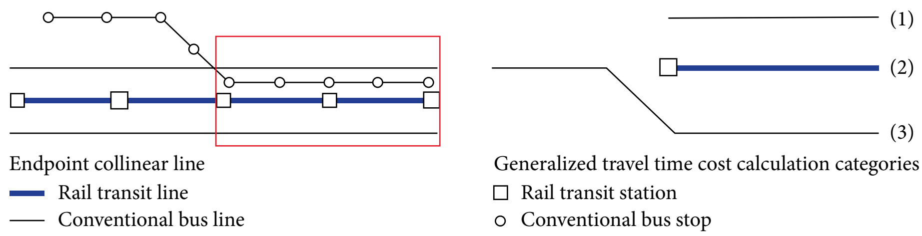

Figure 4: Schematic of the "point-line" space mode.

different modes of transportation within the same passenger flow corridor during peak hours, so as to satisfy the travel needs of passengers.

3.3.2. Generalized Travel Time Costs. Public transportation during peak hours primarily consists of the mass commuter group. Usually, the production method and the income method are used to calculate the travel time value. With the popularity of global positioning systems, using big data to obtain traffic status has been widely applied. In this paper, when comparing the travel utility of rail transit and conventional buses in a collinear section, the advantage of time savings of rail transit is first considered, which is converted into the time cost and used as the evaluation index of comprehensive utility. The aggregate model of the travel time and the time conversion value of the travel cost of the collinear section are established using the GPS data of buses.

3.3.3. Travel Time Saving Proportion. Among the changes in travel time before and after the travel mode transfer, the proportion of travel time savings within 10% can be considered as no travel time savings [20]. The proportion of travel time savings refers to the proportion of the time saved after transferring to rail transit relative to the original bus travel time. Therefore, in this paper, the proportion of time saved by choosing rail transit in the collinear section is defined as less than 10% of the total travel time of the conventional bus line, which indicates that the rail transit has no time advantage in the collinear section, that is, the time services provided by the two modes in the transport corridor are equal.

4. Model Construction

4.1. "Point-Line" Space Mode. The "point-line" space mode diagram is shown in Figure 4. When passengers choose rail transit in the collinear section, they need to have a transfer, that is, a transfer from the conventional bus to rail transit. By calculating the generalized travel time costs of conventional bus and rail transit in the collinear section and the proportion of travel time saved by rail transit to account for the average travel time of the original bus line, the proportion of travel time savings is determined.

4.1.1. Generalized Travel Time Costs

(1) Generalized Travel Time Costs of Conventional Buses

(i) Travel Time. During peak hours, due to the congestion of urban roads, the speed of each bus and the stop time at each stop differ. The average travel time of the vehicles in the collinear section also differs. Therefore, this paper uses the real-time GPS trajectory data sent by the floating vehicle equipped with GPS equipment to dynamically acquire information such as the time, vehicle terminal ID, latitude and longitude coordinates, instantaneous speed, direction, and calculates the average travel time of the collinear vehicles in peak hours to obtain the conventional bus travel time T_B.

(ii) Time Conversion Value of the Travel Cost. By the investigation and study of conventional bus fares in China, most cities such as Foshan, Wuxi and Jinan have adopted a transfer discount system. This paper adopts a discount system of transfers, and the model is constructed according to the actual travel processes of residents in terms of the public transport fare expenditure. The travel cost of conventional buses in collinear section M_B can be expressed as follows:

$$M_B = m \times [1 + (a - 1)P]. \tag{1}$$

In the equation, m is the fare level for a conventional bus (yuan/ride); P is the discount rate of transferring for the conventional bus; and a is the number of bus rides on one trip. The original conventional bus travel cost only calculates the travel costs of the passengers on collinear lines. No transfer occurs, that is, only one bus ride, $a = 1$.

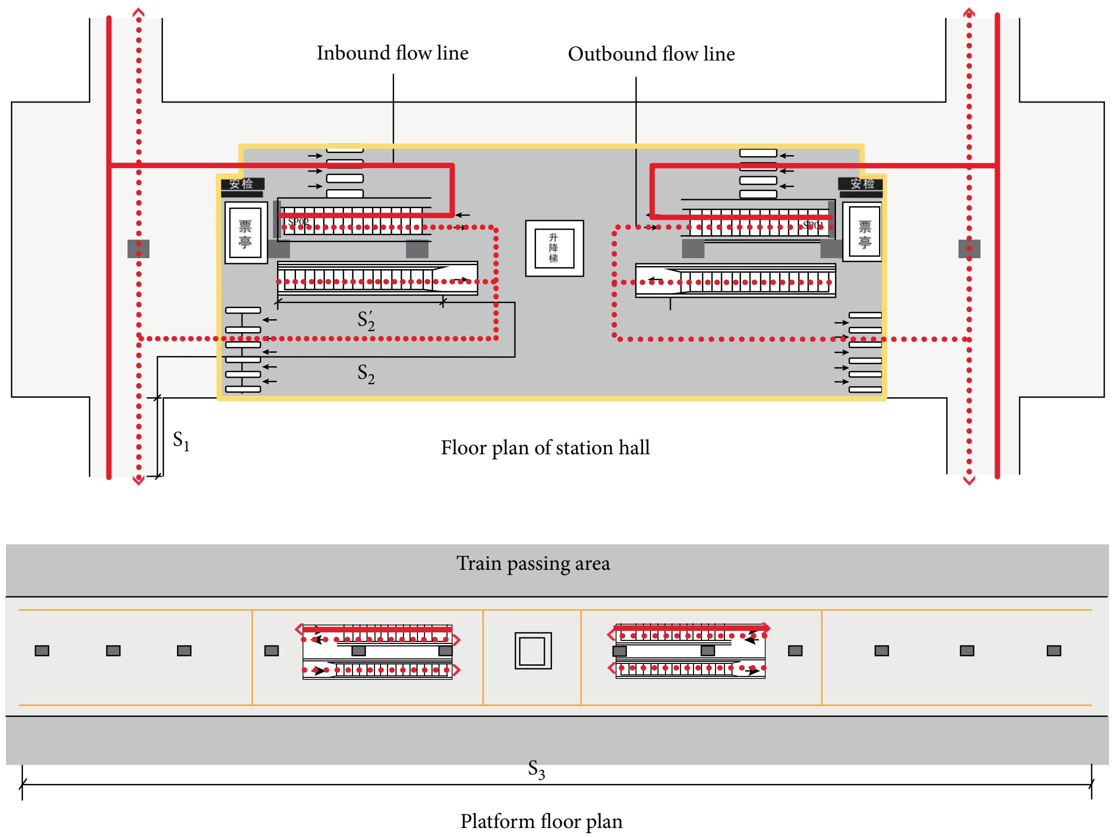

FIGURE 5: Diagram of the passenger flow line at the rail transit station.

According to the calculation results of the passenger's value of the time unit λ (yuan/min), the time conversion value T_M^B (min) of the travel cost after conversion can be expressed as follows:

$$T_M^B = \frac{M_B}{\lambda}. \tag{2}$$

In this equation, M_B is the travel cost of conventional bus transit, and λ is the value of the hour unit.

The generalized travel time cost of the conventional bus in the collinear section is equal to the sum of the travel time and the time conversion value of the travel cost, which can be expressed as follows:

$$C_B = T_B + T_M^B = T_B + \frac{m \times [1 + (a-1)P]}{\lambda}. \tag{3}$$

(2) Generalized Travel Time Costs of Rail Transit

(i) Travel Time. The travel time of rail transit in the collinear section includes the average travel time and the transfer time from bus to rail transit in the collinear section. The transfer time includes the walking time to the station, the walking time in the rail transit station and the waiting time in the rail transit station. The travel time of the rail transit collinear section T_{R^0} can be expressed as follows:

$$T_{R^0} = T_R + T_T = T_R + t_p + t_d + t_w. \tag{4}$$

In the equation, T_R is the average travel time of rail transit in the collinear section; T_T is the transfer time from the conventional bus to rail transit; t_p is the walking time to the station during transferring; t_d is the walking time in the rail transit station; and t_w is the waiting time in the rail transit station.

The average travel time of the rail transit in the collinear section can be converted according to the total running time of the rail transit line and the proportion of collinear line mileage. The waiting time in the station can be defined according to the maximum tolerance time of passengers, which is usually the average travel time of the two stations with the minimum distance on the rail transit line. The passenger's walking time is determined by the standardized design of the rail transit station. According to the Metro Design Code [24], the space for walking primarily includes the entrance and exit, the station hall (passage, stairs or escalator), and the platform (as shown in Figure 5). The walking time to the station t_p and the walking time in the station t_d during the transfer process are defined according to the total distance traveled and the average walking speed of a passenger in the station, as shown in Equations (5) and (6).

$$t_p = \frac{s_0}{v_0}, \tag{5}$$

$$t_d = t_1 + t_2 + t_3. \tag{6}$$

In the equations, s_0 is the walking distance to the station; v_0 is the walking speed of an ordinary adult; t_1 is the walking time of the station exit/entrance; t_2 is the walking time on the passage, stairs or escalator; and t_3 is the walking time on the platform.

The passenger's transfer walking time t_1, t_2, and t_3 inside the station can be estimated according to the design of the station, as shown in Equations (7), (8), and (9). According to the graphic design of the station, the walking distance of the exit/entrance, the plane distance of the entrance stairs or the escalator, the walking distance of the hallway, the plane distance of the stairs or escalators in the hall, and the plane distance of the platform when waiting can be measured, and expressed as s_1, s'_1, s_2, s'_2, and s_3, respectively. In addition, in the design of a transfer station, there are usually multiple stairs or escalators (stairs for descending passengers, and stairs and escalators for ascending passengers). The farthest distance from the stairs where the passenger chooses to get on and off the platform is the ratio of the platform distance to the number of stairs, and the number of stairs is defined as n.

$$t_1 = \frac{\sqrt{s_1'^2 + d^2}}{v_2} + \frac{s_1}{v_1}, \tag{7}$$

$$t_2 = \frac{s_2}{v_1} + \frac{\sqrt{s_2'^2 + d^2}}{v_2}, \tag{8}$$

$$t_3 = \frac{s_3}{n \times v_1}. \tag{9}$$

In the equations, v_1 is the average walking speed of a passenger in a straight channel of the station when in a crowd; v_2 is the speed of the escalators in the rail transit station; v_3 represents the average walking speed when descending stairs; v_4 is the average speed when ascending stairs; and d is the designed height of each floor in the station.

(ii) Time Converting Value of Travel Cost. Usually, rail transit employs a segment billing system and a mileage billing system. The mileage billing system sets a basic starting price and then increases the travel cost according to the increase in the travel distance. M_R is the travel cost of rail transit, which can be expressed as follows:

$$M_R = m_0 + (L - L_0)\tau. \tag{10}$$

In the equation, M_R is the travel cost of rail transit in the collinear section; m_0 is the starting price of rail transit; L_0 is the farthest distance that the rail transit starting price can afford (km); L is the travel distance of the passenger (km); and τ is the charge of the rail transit distance unit (yuan/km).

The travel cost of the original conventional bus refers to the cost of choosing a bus to complete a trip. Travelers who choose rail transit in the collinear section will choose the conventional bus first and then transfer to the rail transit or choose the rail transit first and then transfer to the conventional bus to complete a trip. Therefore, in the calculation of the travel cost of rail transit, the travel cost of conventional bus should be calculated. The method of converting the travel cost into a time value is the same as that described above, and the time conversion value of the travel cost of passengers who choose to transfer to rail transit is T_M^R, which can be expressed as follows:

$$T_M^R = \frac{M_R + M_B}{\lambda}. \tag{11}$$

The generalized travel time cost of the collinear section of rail transit C_R is equal to the sum of the travel time and the time conversion value of the travel cost of rail transit, which can be expressed as follows:

$$C_R = T_R + T_T + T_M^R = T_R + t_p + t_d + t_w + \frac{M_R + M_B}{\lambda}. \tag{12}$$

4.1.2. Travel Time Savings Proportion. Usually, travelers who can save more travel time by transferring to rail transit are more willing to choose rail transit. Assuming that a travel time savings proportion within 10% indicates that travel time is not saved, then the travel time savings proportion k can be expressed as:

$$k = \frac{T_B - T_R - T_T}{T_{B^0}} \times 100\%. \tag{13}$$

In the formula, T_{B^0} is the average running time of the entire trip on a conventional bus collinear line.

A conventional bus line is identified to be adjusted if the generalized travel time costs $C_R < C_B$, and $k > 10\%$.

4.2. "Point-Line-Point" Space Mode. In the "point-line-point" space mode, when passengers choose rail transit in the collinear section, they need to have two transfers, that is, a transfer from the conventional bus to rail transit and then a transfer from rail transit to the conventional bus. Increasing the transfer time of the other transfer point and redetermining the generalized travel time costs and the proportion of travel time savings is necessary, as shown in Figure 6.

4.2.1. Generalized Travel Time Costs. Compared with the "point-line" space mode, the generalized travel time costs of the conventional bus in the collinear section does not change. However, the generalized travel time costs of rail transit changes due to the need to consider two transfers—the travel time needs to be increased by an additional transfer time from rail transit to the bus. The transfer time includes the walking time to the bus stop and the waiting time at the bus stop.

$$T'_T = T'_p + T'_w. \tag{14}$$

In the equation, T'_T is the transfer time from rail transit to the conventional bus; T'_p is the walking time to the bus stop when transferring; and T'_w is the waiting time at the bus stop.

In the transfer time from rail transit to bus, the walking time to the bus stop T'_p is measured using the method in Section 4.1.1. However, the waiting time at the bus stop T'_w is half of the average departure interval of conventional bus lines, referring to existing research [25]. In terms of travel cost, when choosing rail transit, there will be a transfer in the conventional bus itself, which requires increasing the fare of the conventional bus. Therefore, the generalized travel time costs of rail transit C_R can be expressed as:

$$C_R = T_R + T_T + T'_T + T_M^R. \tag{15}$$

In the formula, T'_T is the time of the second transfer, and the number of bus rides $a = 2$.

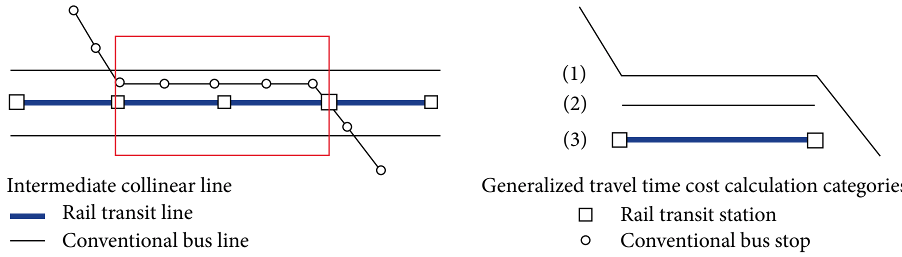

Figure 6: Schematic of the "point-line-point" space model.

4.2.2. Travel Time Savings proportion. The longer the travel time, the more time can be saved by choosing rail transit. Since the "point-line-point" space mode has increased the transfer time compared with the "point-line" space mode, the travel time savings proportion k can be expressed as follows:

$$k = \frac{T_B - T_R - T_T - T_T'}{T_{B^0}} \times 100\%. \quad (16)$$

5. Case Analysis

The Hubin East Road Station of Xiamen Metro Line 1 is selected as a case study. All conventional bus lines within a 750-m service range perpendicular to each side of this station's line are included in the case study. According to the direction and stop information of bus lines, 29 conventional bus lines in the collinear section are determined, as shown in Figure 7, and the conventional bus lines to be adjusted are screened using the above model.

5.1. Data Sources. To determine the average travel time of conventional buses during peak hours, the study extracted the vehicle GPS information of the collinear lines with Hubin East Road Stop as the endpoint within two weeks working days from July 24, 2017, to August 6, 2017, including the vehicle number, line information, stop information, and arrival time.

5.2. Model Verification. In this paper, the conventional bus line 44, which has 9 collinear stops with Xiamen Metro Line 1 is selected for the calculation.

5.2.1. Generalized Travel Time Costs of Conventional Bus Transit. The total length of conventional bus line 44 is 12.44 km, and the fare is 1 yuan for the whole journey, which is 8.32 km of the collinear section with rail transit. It belongs to the "point-line-point" spatial mode mentioned above, and the collinear section of the conventional bus transit is located between the Green Community Station and the Gaoqi Station. The generalized travel time cost of line 44 is divided into two parts: the average travel time and the time conversion value of the travel cost. According to the Xiamen Urban Transport Development Annual Report [26], the early peak-hour period is 7:30–8:30. Vehicle GPS information from July 24, 2017 to August 6, 2017 of line 44 is selected to calculate the average travel time of the collinear section. The average travel time T_B is 35.80 min. According to the fare of line 44, m is equal to 1 yuan. The value of the travel time unit is calculated by the income method. The annual per capita salary in Xiamen in 2016 was 68,586 yuan [27] according to weekdays, at 250 days per year and 8 h per day, and the value of the time unit is calculated to be 0.57 yuan/min. The generalized travel time cost of conventional bus transit is:

$$C_B = T_B + T_M^B = 35.80 + \frac{1}{0.57} = 37.55\ \text{min}. \quad (17)$$

5.2.2. Generalized Travel Costs of Rail Transit. The collinear section of the rail transit is located between the Hubin East Road Station and the Gaoqi Station, and the generalized travel time costs of the rail transit in the collinear section includes the average travel time of the rail transit in the collinear section, the time required for two transfers, and the time conversion value of the travel cost. Xiamen Metro Line 1 has a total length of 30.3 km, and the total transit time is approximately 50 min. Hubin East Road Station and Gaoqi Station are taken as transfer stations from the collinear section, with a length of 8.50 km. According to the proportion of mileage, the average travel time of the rail transit in the collinear section T_R is 14.03 min.

The walking speed decreases as the passenger flow density increases. The values of walking speed in each case are described as follows [28]. The average walking speed of passengers walking to the station v_0 is 4.68 km/h. The average walking speed of passengers in the channel where the flow of passengers is more concentrated in the rail transit station v_1 is 3.6 km/h. The average walking speed of passengers descending the stairs in the station v_2 is 2.74 km/h, and the average walking speed of passengers ascending the stairs v_3 is 1.02 km/h. The running speed of the escalator v_4 is 2.34 km/h.

The station type of the Hubin East Road Station of Xiamen Metro Line 1 is double-layer island, and three transfer stairs are set up in the station hall and station platform. According to Equations (5)–(9), the walking distance to the station is s_0, the walking distance of the entrance/exit is s_1, the plane distance of the entrance stairs or the escalator is s_1', the walking distance in the hall is s_2, the plane distance of the stairs of the station hall or the escalator is s_2', and the plane distance of the platform when waiting is s_3. According to the design of the Hubin East Road Station, the indicators s_0, s_1, s_1', s_2, s_2', and s_3 are calculated as 95 m, 36.80 m, 19.86 m, 47.77 m, 4.74 m, and 112.99 m, respectively. The waiting tolerance time of the passengers at the Hubin East Road station is defined by the minimum distance between the adjacent rail transit stations. The distance between the two adjacent stations of Hubin East Road Station and Lianban station is 0.67 km. According to the ratio

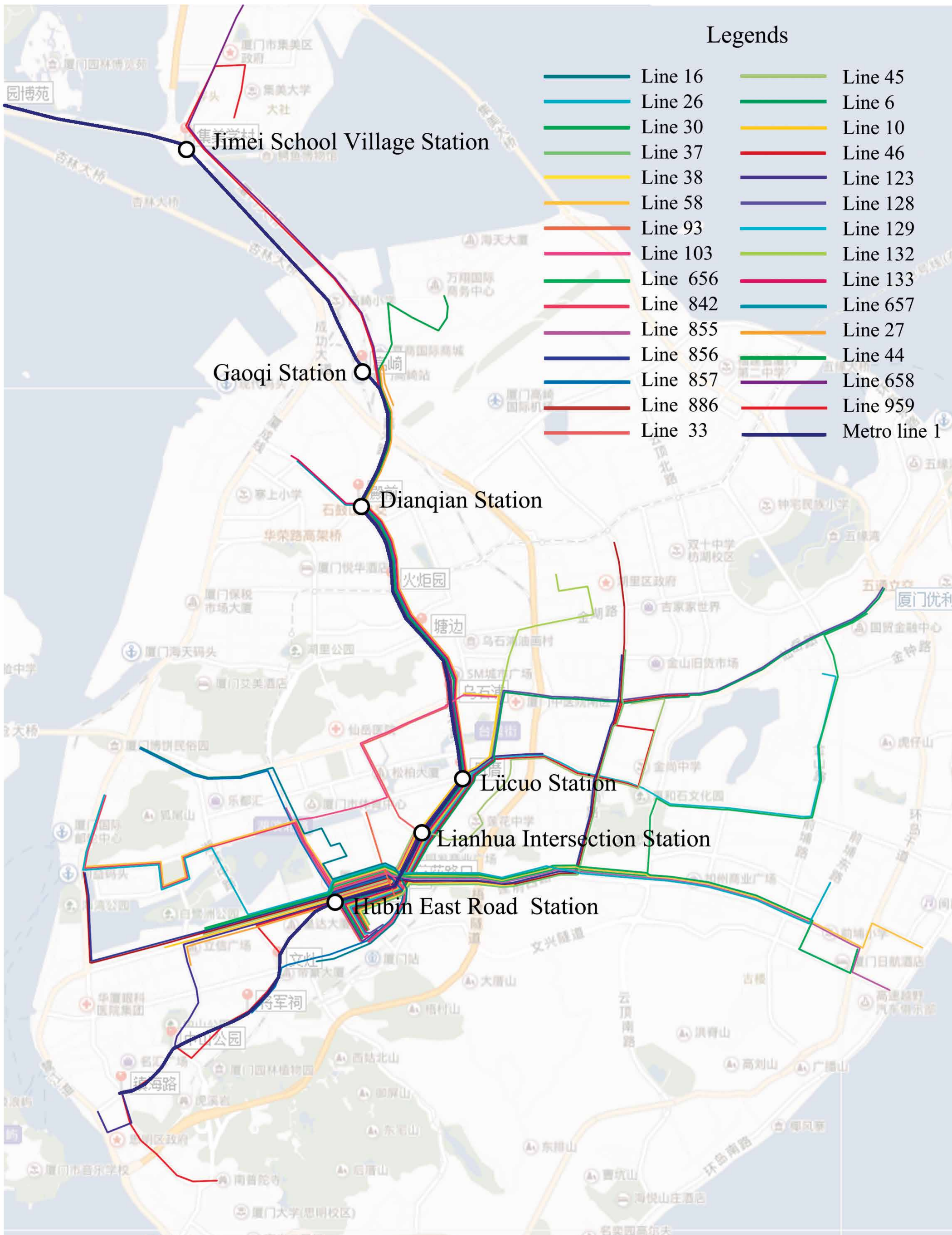

FIGURE 7: Diagram of the collinear bus lines of Hubin East Road at the transfer station of metro line 1.

of the distance between the stations to the mileage of the entire line, the waiting time in the station t_w is 1.11 min. The walking time to the station t_p, the walking time between the entrance of the station t_1 and the exit of the station t_1, the walking time of the station hall and the stairs or escalators t_2, the walking time at the platform t_3, the walking time in the rail transit station t_d, and the transfer time of the rail transit T_T are calculated as follows:

$$t_p = \frac{s_0}{v_0} = \frac{95 \times 60}{4.68 \times 1000} = 1.22 \text{ min} \tag{18}$$

$$t_1 = \frac{\sqrt{s_1'^2 + d^2}}{v_2} + \frac{s_1}{v_1} = \frac{\sqrt{19.86^2 + 6^2} \times 60}{2.74 \times 1000} + \frac{36.80 \times 60}{3.6 \times 1000} = 1.07 \text{ min} \tag{19}$$

$$t_2 = \frac{s_2}{v_1} + \frac{\sqrt{s_2'^2 + d^2}}{v_2} = \frac{47.77 \times 60}{3.6 \times 1000} + \frac{\sqrt{4.74^2 + 6^2} \times 60}{2.74 \times 1000} = 0.96 \text{ min} \tag{20}$$

$$t_3 = \frac{s_3}{n \times v_1} = \frac{112.99 \times 60}{3 \times 3.6 \times 1000} = 0.63 \text{ min} \tag{21}$$

$$t_d = t_1 + t_2 + t_3 = 1.07 + 0.96 + 0.63 = 2.66 \text{ min} \quad (22)$$

$$T_T = t_p + t_d + t_w = 1.22 + 2.66 + 1.11 = 4.99 \text{ min}. \quad (23)$$

Similarly, the second transfer time $T_T^{'}$ can be calculated as 5.30 min. The travel cost of the rail transit refers to the Shenzhen rail segment pricing system. The metro line has 2 collinear segments, and the cost M_R is 3 yuan. To transfer to rail transit, conventional bus must be selected before and after the transfer. The cost M_B is 2 yuan. Since transfer discount information in Xiamen is temporarily unavailable, the transfer discount rate is not considered in the calculation process, and the time conversion value of the travel cost calculated by the income method is:

$$T_M^R = \frac{M_R + M_B}{\lambda} = \frac{3+2}{0.57} = 8.77 \text{ min}. \quad (24)$$

The generalized travel time costs of the rail transit in the collinear section is:

$$\begin{aligned} C_R &= T_R + T_T + T_T' + T_M^R \\ &= 14.03 + 4.99 + 5.30 + 8.77 = 33.09 \text{ min}. \end{aligned} \quad (25)$$

By the income method, the general travel time costs difference between the bus line 44 conventional bus collinear line and the metro line is calculated to be 4.46 min. The generalized travel time costs difference is 4.44 min, as calculated by the production method. This paper also applies the production method and income method to calculate the general travel time costs of other collinear lines. The results show that the difference between the two methods is very small. Therefore, this paper uses the income method to calculate the travel time conversion value. With regard to the comprehensive utility of the generalized travel time costs, the income method is used to convert it to the difference in generalized travel time costs, which is calculated to be 4.46 min. The uniform conversion to the cost calculation reveals that the generalized travel costs difference of the bus line 44 collinear section is 2.55 yuan. The general travel time costs of all conventional bus collinear lines were calculated and converted into cost; the model results were not affected. To reflect the time utility of rail transit, because the results of calculating the travel time with location data is more accurate, this paper uniformly converted to time for calculation.

5.2.3. Travel Time Savings Proportion. The travel time savings proportion for bus line 44 after transferring to rail transit in the collinear section is:

$$\begin{aligned} k &= \frac{T_B - T_R - T_T - T_T'}{T_{B^0}} \times 100\% \\ &= \frac{35.80 - 14.03 - 4.99 - 5.30}{41.00} \times 100\% = 27.99\%. \end{aligned} \quad (26)$$

Therefore, bus line 44 is selected for adjustment.

The generalized travel time cost difference between conventional bus transit and rail transit corresponds to 29 collinear bus lines, and the travel time savings proportion is calculated using the method mentioned above. The results are listed in Table 1.

5.3. Results Analysis. Table 1 lists the model results of the generalized travel time cost difference for the collinear section of conventional bus and rail transit and the travel time savings proportion after transferring to rail transit. The generalized travel time costs of lines 133, 27, 44, and 959 are larger than that of the rail transit in the collinear section, and the travel time savings proportion after transferring to rail transit is greater than 10%. The effect of rail transit in the collinear section is larger than that of the conventional bus lines. The passengers on the conventional bus lines will consider transferring from conventional bus to rail transit when they are in the collinear section, which determines that the 4 lines are conventional bus lines to be adjusted. According to the experience value of the original research (a collinear length exceeding 6 km), lines 133, 657, 27, 44, 658, and 959 are the conventional bus lines to be adjusted. Although lines 657 and 658 satisfy the conditions, they are not conventional bus lines to be adjusted in the research model of this paper. The main reason is that line 657 has a small proportion of collinear section with rail transit, and passengers undertaking long-distance travel by bus will not obtain large travel utility if they transfer to rail transit in the collinear section. Line 658 has a large distance between transfer stops, which reduces the travel utility of rail transit in the collinear section. The model results show the effectiveness of determining the line to be adjusted by evaluating the utility of the rail transit in the collinear section relative to the conventional bus line. Compared with the traditional empirical value screening method of collinear lines, this approach is more targeted, and the line characteristics can be better reflected.

The difference between the general travel time costs of conventional bus and rail transit indicates that the collinear length is the same, whereas the generalized travel time costs differ, and those of lines of 658 and 959 are more notable. Since the relative positions of the stations differ when transferring from bus to rail transit, on one hand, the road conditions between the collinear conventional bus stops differ, and the average travel time between the conventional bus collinear stops calculated by vehicle GPS data differ. For example, the average travel time difference in the collinear section of lines 658 and 959 is 6 min. On the other hand, the distance from the bus stop to the rail transit station and the walking time to the rail transit station during the transfer process differ. The walking time to the station for lines 658 and 959 differs by 1.81 min. Regarding the travel time savings proportion after the transfer from conventional bus to rail transit in the collinear section, the collinear length is the same, but the travel time savings proportion is significantly different, as is the case for lines 133 and 657. The main reason is that the proportion of collinear section for each conventional bus line differs. For instance, the total lengths of bus lines 133 and 657 are 12.75 km and 45.53 km, respectively, and the entire running time of the two lines differs by 118 min. Passengers with longer travel distances on line 657 may not choose rail transit because a smaller proportion of time is saved.

Table 1: Model results of bus lines of Hubin East Road as the transfer station of metro line 1.

Num	Line	Collinear section of rail transit	Collinear station number	Collinear ratio (%)	Generalized travel time costs difference (min)	Travel time savings proportion (%)
1	16	Hubin East Rd—Lianban	2	7.96	−11.32	−30.85
2	26	Hubin East Rd—Lianban	2	3.75	−18.48	−28.35
3	30	Hubin East Rd—Lianban	2	4.27	−9.77	−15.41
4	37	Hubin East Rd - Lianban	2	4.45	−16.30	−29.10
5	38	Hubin East Rd—Lianban	2	7.03	−16.06	−40.89
6	58	Hubin East Rd—Lianban	2	3.75	−11.37	−16.30
7	93	Hubin East Rd—Lianban	2	7.18	−7.97	−17.26
8	103	Hubin East Rd—Lianban	2	4.05	−11.22	−17.21
9	656	Hubin East Rd—Lianban	2	1.38	−9.90	−4.33
10	842	Hubin East Rd—Lianban	2	3.00	−7.90	−7.40
11	855	Hubin East Rd—Lianban	2	3.03	−10.57	−10.88
12	856	Hubin East Rd—Lianban	2	2.71	−9.07	−7.62
13	857	Hubin East Rd—Lianban	2	2.35	−9.87	−6.71
14	886	Hubin East Rd—Lianban	2	2.71	−9.77	−8.35
15	33	Hubin East Rd—Lianhua Intersection	3	14.88	−6.04	−12.24
16	45	Hubin East Rd—Lianhua Intersection	3	10.94	−5.12	−7.00
17	6	Hubin East Rd—Lücuo	4	17.98	−7.04	−11.01
18	10	Hubin East Rd—Lücuo	4	20.95	−2.34	−1.42
19	46	Hubin East Rd—Lücuo	4	23.85	−7.51	−15.99
20	123	Hubin East Rd—Lücuo	4	15.96	−5.84	−7.56
21	128	Hubin East Rd—Lücuo	4	17.82	−4.83	−6.98
22	129	Hubin East Rd—Lücuo	4	24.51	−2.53	−2.20
23	132	Hubin East Rd—Lücuo	4	19.85	−6.41	−9.50
24	133	Hubin East Rd—Dian-qian	8	52.55	*1.44*	*11.79*
25	657	Hubin East Rd—Dianqian	8	14.72	*2.56*	*3.80*
26	27	Hubin East Rd—Gaoqi	9	32.40	*5.15*	*12.38*
27	44	Hubin East Rd—Gaoqi	9	68.33	*4.46*	*27.99*
28	658	Hubin East Rd—Jimei school village	10	33.47	*2.78*	*6.44*
29	959	Hubin East Rd—Jimei school village	10	47.11	*10.98*	*15.47*

6. Discussion and Conclusions

This paper studies the adjustment of conventional bus lines along a rail transit line, and the time utility brought by rail transit is taken into consideration first. A model of the generalized travel time costs and travel time savings proportion is established to evaluate the utility of a collinear section between conventional bus and rail transit, and then the conventional bus lines to be adjusted are screened. The adjustment of conventional bus transit along a rail transit line is usually based on an empirical value (a collinear length that exceeds 6 km), which indicates that the conventional bus lines to be adjusted and the rail transit have certain commonalities in space. Based on the time utility of rail transit, especially during rush hours of commuting, the time utility of the collinear section is evaluated by means of aggregate analysis, and the conventional bus lines that need to be adjusted are screened. To highlight the time utility of rail transit, the conventional bus lines of Hubin East Road station, which is relatively congested in Xiamen, are selected to verify the model. Since the selected case is not the first or last station of the rail or conventional bus transit, the collinear lines of conventional bus are all in the "point-line-point" spatial mode, with two transfers, which makes the verification of the case special. However, for the whole bus network, there are transfers once and twice between rail transit and conventional bus lines. The model can be analyzed according to the specific situations of collinear sections, which makes it universal. Therefore, it can provide a basis for the adjustment of bus lines before the operation of urban rail transit.

The model of the generalized travel time costs and the travel time savings proportional model are constructed to evaluate the time utility of the collinear channel. In the process of evaluating generalized travel costs, the studies of [12–15] have uniformly converted time into costs for research. To highlight the time utility of rail transit in the peak period and reduce the conversion loss, the cost is uniformly converted into time for calculation. For the estimated value of travel time, most studies have utilized the state preference (SP) data of passengers [12–14, 18]. Here, the aggregate model is mainly used to evaluate the time utility of the collinear channel. To avoid the instability of the travel time of conventional bus in the peak period, the travel time of a conventional bus is calculated using the GPS data of the bus to obtain the accurate travel time in the peak period. Regarding the transfer time between conventional bus and rail transit using passenger survey statistics [20, 29], this paper takes into account factors such as the distance between conventional bus and rail transit transfer stations and the design of rail transit station, and makes an objective evaluation of the time required for the transfer process. By evaluating the time utility of rail transit and conventional bus in the collinear channel, the bus lines that need to be adjusted along the rail transit are determined. According to the passenger flow distribution and the corresponding transfer intention, the adjustment principle of the conventional bus lines to be adjusted will be further determined in the future.

This paper analyses the factors that affect the adjustment of conventional bus lines along rail transit. By considering whether passengers in the collinear section will shift during peak hours, the model of the generalized travel time costs and the travel time savings proportion is established based on the GPS data of the conventional bus, and the conventional bus lines to be adjusted can be screened flexibly, so as to prejudge the adjustment of conventional bus lines before the rail transit is put into operation. The model provides a basis for further optimization of the conventional bus lines in the collinear section of the rail transit. Since the study analyzes only two weeks of GPS data via the continuous analysis of GPS data, a more accurate travel time during peak hours can be obtained to calculate the travel time savings proportion, and the conventional bus line to be adjusted can be screened. Combined with card data, the passenger flow distribution of the "transfer once" and "transfer twice" conventional bus lines and the corresponding transfer intention research can be calculated, and the adjustment principle of cancels, retentions, and mergers for the conventional bus collinear section and the noncollinear section can be formulated. At the end of this paper, the calculations demonstrate the rationale of establishing the model, which provides a scientific basis for the elastic adjustment of the conventional bus line of a rail transit collinear section. This research provides decisional support for urban integrated public transport planning.

Data Availability

The GPS data used to support the findings of this study were supplied by Xiamen GNSS Development & Application Co., Ltd. under license and so cannot be made freely available.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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