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Modeling and Simulation of coordination relationship between rail and bus lines

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Modeling and Simulation of coordination relationship between rail and bus lines

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轨道交通与常规公交线路协调关系建模与仿真

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摘要：*通过分析轨道交通线路和常规公交线路之间共线部分的协调关系，将考虑互补和竞争的协调关系定义为最大化资源利用率和能力匹配的目标。基于对协调与竞争作用的分析，提出了协调指标的计算方法。考虑线网干扰对协调性影响，提出了公交线路的调整方法。*以武汉公交网络的一部分为例进行仿真，结果表明，调整后的交通系统协调性较高，服务指标均在合理范围内。考虑干扰的轨道交通线路与常规公交线路之间协调关系的分析可为线网优化提供依据，有助于提高运行效率。

关键词：轨道交通；常规公交；协调指标；互补指标；竞争指标
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Introduction

In urban areas, the demand for mass transit has increased rapidly. More and more people use public transit system for work or for other travel purposes. Both rail transit and bus transit play an important role in alleviating the traffic congestion. In comparison, rail transit system is an essential travel mode with larger capacity and higher punctuality rate. However, bus is widely used and can serve the local area. Therefore, the coordination of rail and bus can

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maximize their advantages and it's vital for enhancing the efficiency of the public transit system.

The network structure coordination is the basis of the coordination problem. In previous studies, the feeder bus was always designed to cover residential areas, gathering transit demand and feeding main transit system in specific transfer points with the objective of a minimum of the total cost, or the total travel time [1]. Chien and Yang[2] design the feeder bus network aiming at minimizing the total cost of the operators and the passengers. The problem to be solved is that the uncertain demand and traffic condition make the transfer coordination become difficult[3]. Chien[4] optimizes the total cost of an intermodal transit system based on the bus arrival time distribution. Ting and Schonfeld[5] add the slack time to reduce the probability of missed connections. Tuzun and Yilmaz[6] think that the change of the homogeneous headway can improve the transfer coordination but has adversely impact on the initial waiting time. They focus on the trade-off between the transfer waiting time and the initial waiting time to minimize the total waiting time. The potential value of the economic coordination is to fully consider the interests of users, regulators and operators and to seek the maximization benefit of the three sites[7]. Peng and Xin-ping[8] propose the passenger-oriented evaluation indexes, the enterprise-oriented evaluation indexes and the government-oriented evaluation indexes to evaluate the level and the degree of the operation coordination.

This paper focuses on the structural coordination which is the first and basic step of the whole coordination, including the complementation and the competition existing in these parallel edges. Being different from the researches above of concentrating on one or two objectives, this paper comprehensively considers maximizing the resource utilization and the degree of capacity matching, in order to improve the service performance and the economic aspect. Furthermore, this paper proposes the computational method of the structural coordination coefficient to define the bus lines need to be adjusted. Especially, whether the bus system can supply to the rail system under the disruption is also the evaluation standard of the coordination. Then, reasonable range of the coordination of the collinear edges is measured for determining which parts of the bus lines should be re-planned, followed by the coordination strategy to adjust the bus lines. Finally, the transit network before and after adjustment is evaluated for the validation of effectiveness.

1 Modeling on the coordination among the collinear edges

Determining the degree of competition in the collinear edges makes it easier to take full use of the public transit resource. Therefore, this paper will focus on the coordination analysis including the complementation and the competition. In addition, in contrast to previous studies about the coordination of the transit systems or transit lines, this paper will concentrate on the edges.

The coordination analysis from the transit systems aspects or the transit lines aspects can find the degree of the coordination of the whole system or every two transit lines. However, these studies can't reflect which areas of the whole system or which segments of the transit lines are good coordination or poor coordination and the level of the coordination can determine whether the area or the segment need to be adjusted. Analysis from the edge aspect can obtain the coordination degree of every edge of the collinear lines and further can determine which parts of the parallel bus lines need to be modified. As shown in Fig. 1, each collinear edges can be measured from the coordination aspect. Based on these values, an initial set of edges requiring to be adjusted can be generated. Taking the efficiency of the public transit system into account, the total travel time and the loss of the passengers ought to be considered as the constraint with further determining whether the edges need to be adjusted. After the adjustment, the redundant edges can be adjusted and the necessary edges could be retained. The public transit system with a higher coordination becomes more effective and efficient.

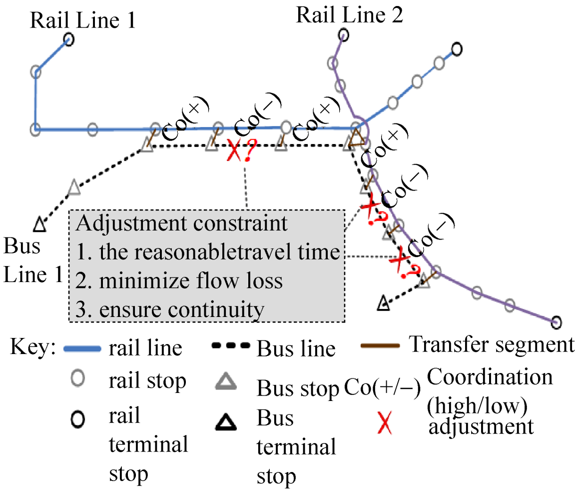

Fig. 1 Coordination among the collinear edges

In order to model the coordination relationship between the two transit modes, the integrated transit network is modeled by the nodes and the edges. The nodes represent the metro or bus stops, and the edges represent the connection between any two stops. Let (S, E) be an undirected graph, which denotes the infrastructure structure of the integrated transit network. $S=\{S^r,S^b\}$ represents the set of the nodes, where S^r denotes the set of the rail stops and S^b denotes the set of the bus stops. $E=\{E^r,E^b,E^t\}$ represents the set of the edges which connects any two stops, where E^r denotes the set of the rail travel edges, E^b denotes the set of the bus travel edges, and $E^t=\{E^{tr},E^{tb},E^{trb}\}$ gives the set of transfer edges which is divided into three types. E^{tr} denotes the transfer edge within the rail system, E^{tb} denotes the transfer edge within the bus system and E^{trb} denotes the transfer edge between the rail system and the bus system.

1.1 Modeling on the coordination coefficient between the collinear edges

Both the complementation and competition can exist in the collinear lines[9]. As shown in Fig. 2, if the passengers cannot get to the destination by one transit line, they have to transfer to another transit mode to complete their travel. There are complementary relationship between these two lines[10]. That means, if one edge becomes over-crowded, the passengers have to go to another transit edges to reach the destination represented by f_1 or the passengers must transfer between the two collinear edges to finish their travel represented by f_2, the passenger flow of the transfer edges reflects the complementation level of the two collinear edges. Furthermore, the transfer flow has directions. Overload passenger flow at stop S_2^r (stop S_2^b) will transfer to the connected stop S_2^b (stop S_2^r) and then scatter along the edge e_{12}^b (edge e_{12}^r) and the edge e_{23}^b (edge e_{23}^r). The transfer flow at edge e_{23}^{trb} shifts to the edge e_{23}^b and the edge e_{23}^r is a component of the complementary coefficient. Passengers that must across the transfer edge e_{22}^{trb} in one direction come from the edge e_{12}^r (edge e_{12}^b) and then transfer to the edge e_{23}^b (edge e_{23}^r). In the opposite direction, the passengers travel by the transfer edge e_{22}^{trb} from the edge e_{23}^r (edge e_{23}^b) to the edge e_{12}^r (edge e_{12}^b). The passenger flow passing by the transfer edge to the edge e_{23}^r (edge e_{23}^b) is another component of the complementary coefficient. It is assumed that half of the transfer flow at edge e_{23}^{trb} is contributed by the collinear edges e_{23}^{r} and edge e_{23}^{b}. Generally, both the two ends of collinear edges have the transfer edges which can reflect the complementation level. Thus, we calculate the average value of the two transfer edges' passenger flow to measure the complementation level of the collinear edges.

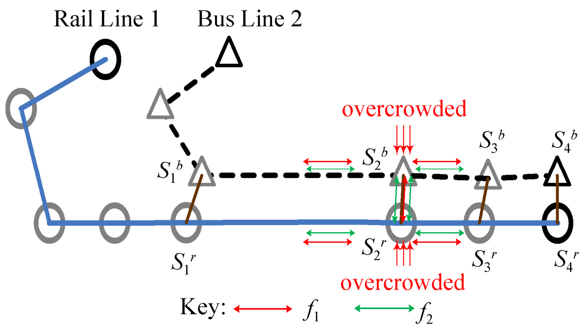

Fig. 2　Two Complementary Bus Line and Rail line

If there is no transfer flow between two travel edges, the coordinated coefficient is defined as 0. If collinear edges' passenger flow is contributed by the two transfer edges, the coordinated coefficient is defined as 1. If the transfer flow is part of the collinear edges' passenger flow, the coordinated coefficient is defined as:

$$\delta_{e_{i^r j^r}, e_{i^b j^b}} = \frac{\frac{1}{2}\left(ft_{i^r j^r} + ft_{i^b j^b}\right)}{f_{i^r j^r} + f_{i^b j^b}} \tag{1}$$

Where, $\delta_{e_{i^r j^r}, e_{i^b j^b}}$ is complementation coefficient between rail edge $e_{i^r j^r}$ and bus edge $e_{i^b j^b}$; $f_{i^r j^r}$ and $f_{i^b j^b}$ are the passenger flow of rail edge $e_{i^r j^r}$ and bus edge $e_{i^b j^b}$, respectively; $ft_{i^r i^r}$ and $ft_{j^b j^b}$ are the transfer flow of the transfer edges $e_{i^r i^r}^{t}$ and $e_{j^r j^r}^{t}$. Eq. (1) gives the contribution of the complementary passenger flow of the transfer edges to the collinear edges' flow to estimate the complementation level of the two collinear edges.

When passengers have multiple transit lines to choose for travel, there is a competitive relationship between these lines[11]. For the collinear edges, that is, the passenger flow competition between the collinear edges reflects the competitive relationship. The passenger competition is the natural competition which can be analyzed from two aspects. If the majority of the passengers select one mode, while the rest travel on the parallel transit mode, the mode carrying more passengers has more advantages in the passenger competition[12]. Thus, the difference of the sharing rates between two edges can be one of the factors to measure the competition level. If the difference of the sharing rates of the collinear edges is bigger, the competition degree of the collinear edges is higher.

However, as shown in Fig.3, when there is a small difference in the sharing rates, the collinear edges can also have the competition relationship. If the redundancy capacity of the rail edge calculated by the difference between capacity and flow $\left(c_{i^r j^r} - f_{i^r j^r} = 1000 - 500 = 500\right)$ can accommodate all the passenger flow ($f_{i^b j^b} = 400$) of the parallel bus edge, it can be assumed that the rail edge can also meet the passenger flow even without the parallel bus edge. That means, operating collinear edges are both inefficient and cause the waste of resources. Therefore, the absorptive capacity of the redundancy should be taken into consideration when analyzing the competition relationship. If the absorptive capacity of the redundancy is stronger, the competition level of the collinear edges is higher. The competitive coefficient is defined as:

$$\lambda_{e_{i^r j^r}, e_{i^b j^b}} = \alpha \lambda^{1}_{e_{i^r j^r}, e_{i^b j^b}} + \beta \lambda^{2}_{e_{i^r j^r}, e_{i^b j^b}}$$

$$\lambda_{e_{i^r j^r}, e_{i^b j^b}} = \alpha \frac{\left| f_{i^r j^r} - f_{i^b j^b} \right|}{f_{i^r j^r} + f_{i^b j^b}} + \beta \frac{c_{i^r j^r} - f_{i^r j^r} - f_{i^b j^b}}{c_{i^r j^r} - f_{i^r j^r} + f_{i^b j^b}} \tag{2}$$

Where, $\lambda_{e_{i^r j^r}, e_{i^b j^b}}$ is the competitive coefficient between rail edge $e_{i^r j^r}$ and bus edge $e_{i^b j^b}$; $c_{i^r j^r}$ is the capacity of the rail edge $e_{i^r j^r}$; $\lambda^1_{e_{i^r j^r}, e_{i^b j^b}}$ is the difference of the collinear edges' sharing rates; $\lambda^2_{e_{i^r j^r}, e_{i^b j^b}}$ presents the passenger flow accommodation of the rail edge in terms of the parallel bus edge' s passenger flow. $\alpha, \beta (0 \leqslant \alpha, \beta \leqslant 1$, and $\alpha + \beta = 1)$ are the weighted coefficient of the competition.

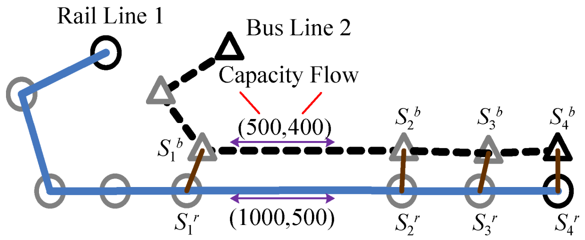

Fig. 3 Two Competitive Bus Line and Rail line

The coordination contains both complementation and competition. Complementation and competition reflect edges' coordination degree from different aspects. In reality, planners always want to strengthen the complementation level and reduce the competition level. Therefore, in order to reflect the role of the complementation in the coordination, the coordination level of the collinear edges can be represented by.

$$Co_{e_{i^r j^r}, e_{i^b j^b}} = \frac{\delta_{e_{i^r j^r}, e_{i^b j^b}}}{\sqrt{\delta_{e_{i^r j^r}, e_{i^b j^b}}^{\ 2} + \lambda_{e_{i^r j^r}, e_{i^b j^b}}^{\ 2}}} \tag{3}$$

Where, $Co_{e_{i^r j^r}, e_{i^b j^b}}$ is the coordination degree between rail edge $e_{i^r j^r}$ and bus edge $e_{i^b j^b}$. According to Eq. (3), the range of the coordination degree $Co_{e_{i^r j^r}, e_{i^b j^b}}$ is: $0 \leqslant Co_{e_{i^r j^r}, e_{i^b j^b}} \leqslant 1$; when $Co_{e_{i^r j^r}, e_{i^b j^b}} = 0$, there is no coordination relationship between the collinear edges; when $Co_{e_{i^r j^r}, e_{i^b j^b}} = 1$, it is a complete coordination relationship; A higher value of $Co_{e_{i^r j^r}, e_{i^b j^b}}$ indicates a stronger coordination between the collinear edges.

1.2 Adjustment strategy of the lines

The aim of the bus lines' adjustment concerning the rail system is to reduce the waste of resources caused by the repeated construction as well as keeping the high operational efficiency. As shown in Fig. 4, the coordination coefficient is firstly assessed for maximizing the resource utilization to determine the candidate set of the edges to be adjusted. However, only focusing on the resource utilization may cause more transfers or longer travel time. For example, the coordination between one bus edge and its parallel rail edge is poor. But in fact, many passengers select the fastest routes including the bus edge to complete their travels. Finally, the adjustment of the bus edge may increase the transfers and the travel time. Therefore, it is based on the candidate set of the edges.

To be adjusted, the importance of these edges must be measured to further determine which edges should be modified. The importance of the edge can be defined as the number of the shortest routes crossing the edge [13]. The more important the edge, the less likely it is adjusted. The importance of the edge can be represented by.

$$(e_{i^b j^b}) = \sum_{o \neq d \in S} \Psi_{od}(e_{i^b j^b}) \tag{4}$$

Where $\Psi_{od}(e_{i^b j^b})$ is the number of the shortest routes between stop S_o^b and stop S_d^b which cross the edge $e_{i^b j^b}$.

After the measure of the importance of the candidate bus edges, the determining set of the edges to be modified can be generated. According to the different circumstances of the results of the edges requiring to be adjusted, the adjustment strategy of the bus line can be divided into the translation motion, the site consolidation, the lines' truncation and the lines' cancellation and rerouting.

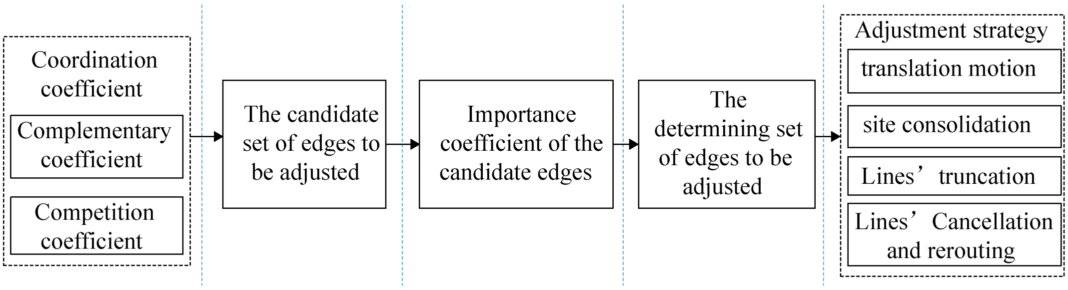

Fig. 4 The adjustment process of the public transit system

The results have three types. Tab. 1 presents the different adjustment strategies from the three types. Firstly, a plurality of continuous edges of a bus line needs to be adjusted. That means, the repetition rate of the bus lines and the rail lines is high. In this case, if the bus line is long and across different areas, the strategy of the translation motion can be used for changing the bus line to the parallel main street. If the bus line is within one area, the bus line can be cancelled and rerouted to the feeder rail line.

Tab. 1 The adjustment strategy under different conditions

	Adjustment strategy	
First type	across different areas (bus line) translation motion	within one area (bus line) Cancellation and rerouting
Second type	Too long (bus line) truncation	Short (bus line) reroute
Third type	Site consolidation	

Secondly, one continuous edge of a bus line should be modified. That is, in some sections, the rail line and the bus line are along the same corridors. If the bus line is too long, these edges can be cut off. When the bus line is short, the line can be rerouted to the feeder rail lines.

Finally, the edge in the middle of the high coordinated edges has poor coordination. In such a situation, the strategy of the site consolidation can be adopted to consolidate the stops which connect the poor-coordinated edge into the neighboring bus stops to shorten the stop time.

2 Simulation of coordination degree under different conditions

The simulation model is applied to analyze the lines' coordination degree of the parts of Wuhan (China) rail and bus network. The integrated transit network topology is shown in Fig. 5. In order to provide better analysis of the lines' coordination, the influences of the disruptions on the coordination are taken into consideration. According to the disruptions in the network, the failure of the critical nodes or edges in the rail network, and the different traffic congestion degrees in the bus network is included.

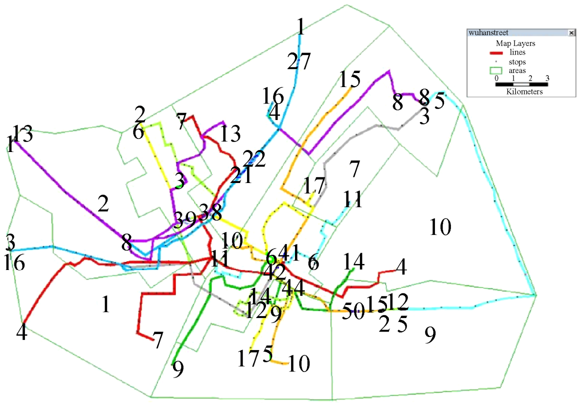

Fig. 5 The central area of the Wuhan intermodal transport network

The congestion on the bus network can extremely increase the travel time and further alter the passengers' selection. Finally, the change of the passenger flow can affect the coordination of the collinear edges. Therefore, the buffer time is added to the bus edge' travel time caused by the congestion. The weight coefficient $\rho, 0 \leqslant \rho \leqslant 1$ reflects the degree of the congestion. In this paper, $\rho = 0.5$. The travel time of the bus edge can be calculated as follow:

$$T'_{i^b j^b} = E\left(T_{i^b j^b}\right) + \rho * \sigma\left(T_{i^b j^b}\right) \qquad (5)$$

where $E(T_{i^b j^b})$ is the expected value for all the possible travel time of the bus edge $e_{i^b j^b}$. $\rho * \sigma(T_{i^b j^b})$ is the buffer time considering the traffic congestion on the road and $\sigma(T_{i^b j^b})$ is the variance of the possible travel time of the bus edge $e_{i^b j^b}$.

The failures on the rail network not only influence the distribution of the passenger flow but also change the topology structure of the integrated transit network. Hence, it's vital to define the critical nodes and edges which may cause the worst disruption in the rail network to see the coordination ability of the collinear lines.

In this paper, the clustering coefficient is defined to measure the average degree of the transitivity. The higher transitivity the stop has, the more critical the stop is[14]. The formula is:

$$V_i = \frac{e_i}{k_i * (k_i - 1) / 2} \qquad (6)$$

Here the degree k_i of stop S_i is the number of the stops in the set of the neighborhood NS_i of stop S_i. The $k_i * (k_i - 1) / 2$ gives the total number of the edges between any two stops in the set of the neighborhood NS_i.

If an edge failure lead to the greatest increasing of the travel length, then the edge is the critical edge. The important degree of the edge $I(e_{i^b j^b})$ in the network can reflect the criticality.

In our computational experiments, six node/edge failures scenarios are simulated to measure the changes of the coordinated degree of the collinear edges under the certain traffic condition $(\rho = 0.5)$ to provide more reasonable analysis under the normal and disruptive traffic conditions and finally to generate the candidate set of bus edges to be adjusted.

The considered integrated transit network consists of 489 stops and 637 edges connecting the different stops, thereof 75 being travel edges in the rail network, 399 being travel edges in the bus network, 102 being transfer edges within one transit mode, and 61 being transfer edges between two transit modes. The integrated transit network has 5 stops connecting 7 lines, 8 stops connecting 6 lines, one stop connecting 5 lines, 17 stops connecting 4 lines, 48 stops connecting 3 lines, and 105 stops connecting 2 lines. Of the 17 lines making up the network, 3 lines (line 1, 2, 3) are the rail lines and the rest are the bus lines. The node list, the edge list, the length list, the possible travel times of the bus edges and their probability distribution list, line capacity list and vehicle frequency list, as well as the OD matrix (as shown in Tab. 2) are provided by the operator. The travel time matrix of the bus edges and the transfer edges are obtained from the shortest routes. The weighted coefficient is $\alpha = 0.7, \beta = 0.3$. All the calculations in this section are performed with MATLAB in a computer with 2 Gb RAM and 2.30 GHz CPU.

2.1 Simulation of Coordination degree under normal traffic condition

After the transit simulation, based on the calculations proposed in the section 2, we can obtain the complementation, the difference of the share rates, the absorptive capacity, the competition, and the coordination of each collinear edges. As shown in Tab. 3, we can conclude from the edges whose coordination coefficient is higher than 0.5 that only when the complementary coefficient is higher, the coordination relationship is stronger. Even though when the complementation is weaker, the coordination coefficient of some collinear edges is over 0.5, but only slightly over than 0.5. Thus, the complementation plays a dominant role in the coordination analysis.

Tab. 2　The OD matrix of the integrated transit network

OD	1	2	3	4	5	6	7	8	9	10
1	0	6 988	5 940	8 123	9 084	12 141	349	6 289	699	87
2	6 988	0	6 800	9 300	10 400	13 900	400	7 200	800	100
3	5 940	6 800	0	7 739	8 655	11 567	333	5 992	666	83
4	8 123	9 300	7 739	0	12 377	16 543	476	8 569	952	119
5	9 084	10 400	8 655	12 377	0	18 879	543	9 779	1 087	136
6	12 141	13 900	11 567	16 543	18 879	0	777	13 983	1 554	194
7	349	400	333	476	543	777	0	317	35	4
8	6 289	7 200	5 992	8 569	9 779	13 983	317	0	710	89
9	699	800	666	952	1 087	1 554	35	710	0	9
10	87	100	83	119	136	194	4	89	9	0

Tab. 3　The coordination of the collinear edges under normal situation

Rail edge	Rail line	Bus edge	Bus line	complementation	competition	coordination
(7,8)	1	(211,212)	551	0	0.789 0	0
(8,9)	1	(212,213)	551	0.446 0	0.858 4	0.461 0
(7,8)	1	(446,445)	707	0	0.502 5	0
(8,9)	1	(445,444)	707	0.442 2	0.270 9	0.852 7
(19,20)	1	(327,328)	621	0.026 0	0.227 1	0.113 8
(20,21)	1	(328,329)	621	0.014 7	0.250 1	0.058 5
(21,22)	1	(329,330)	621	0.036 9	0.250 1	0.146 1
(22,23)	1	(330,332)	621	0.051 6	0.272 6	0.185 9
(23,24)	1	(332,335)	621	0.014 7	0.249 5	0.058 7
(24,25)	1	(335,337)	621	0	0.3	0
(25,26)	1	(337,338)	621	0	0.3	0
(26,27)	1	(338,339)	621	0	0.3	0
(43,44)	2	(102,101)	413	0.009 3	0.950 3	0.009 8
(43,44)	2	(249,250)	576	0	0.999 2	0
(44,45)	2	(250,252)	576	0	0.999 1	0
(45,46)	2	(252,253)	576	0.032 6	0.999 1	0.032 6
(44,46)	2	(398,401)	702	0.051 7	0.891 2	0.057 9
(46,50)	2	(401,407)	702	0.036 7	0.984 1	0.037 2
(47,50)	2	(297,291)	613	0	0.998 6	0
(48,49)	2	(365,369)	625	0.079 2	0.997 7	0.079 1
(49,50)	2	(369,371)	625	0.079 2	0.882 8	0.089 3
(53,54)	4	(416,418)	707	0	0.3	0
(54,55)	4	(418,419)	707	0	0.3	0
(55,56)	4	(419,421)	707	0.184 5	0.287 0	0.540 8
(56,57)	4	(421,423)	707	0.095 8	0.137 9	0.570 7
(59,60)	4	(425,426)	707	0.760 2	0.347 0	0.909 7
(59,60)	4	(95,96)	413	0.084 7	0.661 8	0.127 0
(62,63)	4	(272,273)	578	0.032 1	0.993 3	0.032 3
(68,69)	4	(396,394)	702	0.081 6	0.817 1	0.099 3
(69,70)	4	(394,393)	702	0.008 1	0.827 0	0.009 9
(70,71)	4	(393,392)	702	0.011 8	0.810 5	0.014 5
(70,71)	4	(485,486)	777	1	0.712 8	0.814 3

The bus lines 511, 707, and 621 are parallel with the rail line 1. Among the three bus lines, only the edge $e_{445,444}$ of the bus line 707 has the coordination coefficient higher than 0.5. The complementation of edge $e_{445,444}$ is very high comparing with other collinear edges and the difference of the share rate is lower. Even though the absorptive capacity of the rail 1 is over 0.5, the competitive flow of the bus line mostly contributes to complement the rail line 1. Thus, the coordination of the edge $e_{445,444}$ is high. Both the line 551 and the line 621 have poor coordination comparing with the rail line 1. None of the edges of the two lines has the coordination coefficient higher than 0.5. What's more, two edges of the line 551 and three edges of the line 621 have no coordination relationship with the collinear rail edges. Although the complementation of edge $e_{212,213}$ is the highest, the difference of the share rates and the absorptive capacity is too high leading to the higher competition which is stronger than the complementation. Consequently, the coordination coefficient is lower than 0.5.

The bus lines 413, 576, 702, 613, 625 are parallel with the rail line 2. The coordination coefficients of these lines are all lower than 0.1 because of the poorer complementation and the stronger passenger competition.

Among the bus lines 707, 413, 578, 702, and 777 which are collinear with the rail line 4, the edges $e_{419,421}$, $e_{421,423}$, $e_{425,426}$ of the bus line 707 and the edge $e_{485,486}$ of the bus line 777 have stronger coordinated relationship with the rail 4. The edge $e_{419,421}$ and the edge $e_{421,423}$ have ower complementation coefficients. Meanwhile, the absorptive capacity of the two edges and the difference of the share rates of them are also weaker. That means both the bus edges $e_{419,421}$, $e_{421,423}$ and the rail edges $e_{55,56}$, $e_{56,57}$ have a large number of the passengers flow. In the case of the large cardinal number, there are also many passengers of the edge $e_{419,421}$ and the edge $e_{421,423}$ contributing to complement to the rail line 4. Thus, the coordination coefficients of the edges $e_{419,421}$, $e_{421,423}$ are higher than 0.5.

Except the edge $e_{445,444}$, $e_{419,421}$, $e_{421,423}$, $e_{425,426}$, and $e_{485,486}$ whose coordination coefficients are higher than 0.5, other bus edges parallel with the rail edges are all included in the candidate set of the edges which should be adjusted.

2.2 Simulation of Coordination degree under disruptions

The change of the distribution of the passenger flow and the network structure has huge influence on the coordination analysis. Thus, based on the integrated transit network with the certain traffic congestion, $\rho = 0.5$, four node/edge failure scenarios are considered to test the coordinated capacity of the collinear edges reacting to the external disruptions. Before simulating these disruption scenarios, the principal requirement is to define the critical nodes and edges. Tab. 4 shows the critical nodes and Tab. 5 presents the critical edges. We select the most critical node S_{44}, the random node S_{27}, the most critical edge $e_{38,39}$, and the random edge $e_{21,22}$ to be a failure.

Tab. 4 The critical nodes

node	degree	stop
44	7	Zhongnan Road
50	6	Guanggu Square
13	5	Xunlimen
43	4	Hongshan Square
7	3	Xuzhou village

Tab. 5 The critical edge

edge	degree	stops
38-39	7	Xunlimen-Jianghan Road
39-40	7	Jianghan Road-Jiyu Bridge
40-41	7	Jiyu Bridge-Pangxiejia
41-42	6	Pangxiejia-Xiaoguishan
42-43	6	Xiaoguishan-Hongshan square

The coordination coefficients under the normal and the disruptive situation have been shown in Tab. 6. The closure of the most critical stop S_{44} leads to the closure of the rail edges $e_{43,44}$, $e_{44,45}$ and the transfer edges $e_{44,101}$, $e_{44,250}$, $e_{43,398}$. The bus edges $e_{102,101}$, $e_{252,253}$ supplement much to the failure rail edges $e_{43,44}$, $e_{45,46}$ and finally increase the coordination coefficient of the edges $e_{102,101}$, $e_{252,253}$ up to more than 0.5. The bus edges $e_{249,250}$, $e_{102,101}$ and the bus edges $e_{250,253}$, $e_{398,401}$ are also collinear to the rail edge $e_{43,44}$ and the rail edge $e_{44,46}$, respectively. However, under the normal condition, the coordination coefficients of the edges $e_{102,101}$, $e_{43,44}$ and the edges $e_{250,253}$, $e_{44,46}$ are higher than the edges $e_{249,250}$, $e_{43,44}$ and the edges $e_{398,401}$, $e_{44,46}$. Once the disruptions happen upon the nodes S_{43}, S_{46} , the passengers on the failed node will firstly choose the better coordinated edges $e_{102,101}$, $e_{250,253}$. Thus, the coordination coefficient is lower to 0. In addition, the closure of the node S_{44} also has impact on other edges, causing the increasing coordinated degree of the edges $e_{212,213}$, $e_{365,365}$, $e_{396,394}$ and the decreasing coordinated degree of the edges $e_{445,444}$, $e_{419,421}$, $e_{421,423}$.

The node S_{27} is at the end of the collinear edges of the rail line 1. What's more, there is no passenger flow crossing the stop S_{27} under the normal condition and the disruptive condition. Therefore, the coordination of the bus edges and collinear rail edges which connect the stop S_{44} makes no difference. Besides, the failed node S_{27} increases the coordination degree of the edges $e_{212,213}$, $e_{250,252}$, $e_{396,394}$ and decreases the coordination degree of the edges $e_{445,444}$, $e_{421,423}$. There are no bus lines parallel with the critical edge $e_{38,39}$ of the rail line 2. Nevertheless, the failure of the rail edge $e_{38,39}$ affects other edges in the integrated network. The coordination coefficients of five bus edges $e_{212,213}$, $e_{330,332}$, $e_{332,335}$, $e_{250,252}$, $e_{396,394}$ are up over 0.5, while the bus edges $e_{445,444}$, $e_{421,423}$ drop below 0.5.

Under the circumstance of the failure of the edge $e_{21,22}$, the coordination coefficient of the parallel bus edge $e_{329,330}$ increases to 0.5426. It means that the parallel bus edges can play an important role in assisting to scatter the crowded people under the disruptions.

After the coordination analysis in the different transit situations, the coordination coefficients of the bus edges $e_{425,426}$, $e_{485,486}$ are all above 0.5 under the five scenarios. The edges $e_{212,213}$, $e_{396,394}$ contribute much of the supplement to the rail edges when there are disruptions. The coordination coefficient of these two edges is higher than 0.5 under four failure scenarios, followed by the edge $e_{250,252}$ with the coordination coefficient greater than 0.5 under three failure scenarios, the edges $e_{330,331}$, $e_{419,421}$ under two scenarios, 7 edges under one scenarios. The rest of edges are put into the candidate set of the edges needing to be adjusted.

The parallel bus lines play an important role in relieving the crowded in the rail lines under the disruption. Therefore, it's necessary to take the disruptions into consideration when analyzing the coordination of the rail system and the bus system.

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Tab. 6 The coordination coefficients under different transit situations

Rail edge	Bus edge	normal	Dn1	Dn-random	De1	De-random
(7,8)	(211,212)	0	0	0	0	0
(8,9)	(212,213)	0.461 0	0.602 1	0.602 1	0.551 5	0.840 8
(7,8)	(446,445)	0	0.074 3	0.082 1	0	0
(8,9)	(445,444)	0.852 7	0.081 8	0.081 8	0.067 5	0
(19,20)	(327,328)	0.113 8	0.229 5	0.229 5	0	0
(20,21)	(328,329)	0.058 5	0	0	0	0.346 6
(21,22)	(329,330)	0.146 1	0.065 4	0.091 7	0.196 9	0.542 6
(22,23)	(330,332)	0.185 9	0.251 9	0.251 9	0.505 9	0.643 9
(23,24)	(332,335)	0.058 7	0.221 8	0.221 9	0.615 7	0
(24,25)	(335,337)	0	0	0	0	0
(25,26)	(337,338)	0	0	0	0	0
(26,27)	(338,339)	0	0	0	0	0
(43,44)	(102,101)	0.009 8	0.675 1	0.016 3	0.012 6	0.016 3
(43,44)	(249,250)	0	0	0.001 7	0.001 6	0.001 7
(44,45)	(250,252)	0	0	0.879 6	0.879 6	0.707 1
(45,46)	(252,253)	0.032 6	0.712 2	0	0	0
(44,46)	(398,401)	0.057 9	0	0	0	0
(46,50)	(401,407)	0.037 2	0	0	0	0
(47,50)	(297,291)	0	0.133 1	0.066 3	0.076 8	0
(48,49)	(365,369)	0.079 1	0.605 8	0	0	0
(49,50)	(369,371)	0.089 3	0.008 1	0	0	0
(53,54)	(416,418)	0	0	0	0	0
(54,55)	(418,419)	0	0	0	0	0
(55,56)	(419,421)	0.540 8	0.481 8	0.569 7	0.300 5	0.292 7
(56,57)	(421,423)	0.570 7	0.307 4	0.214 9	0.422 8	0.215 0
(59,60)	(425,426)	0.909 7	0.738 7	0.741 9	0.753 6	0.741 9
(59,60)	(95,96)	0.127 0	0	0	0	0
(62,63)	(272,273)	0.032 3	0	0	0	0
(68,69)	(396,394)	0.099 3	0.873 0	0.577 7	0.963 3	0.936 0
(69,70)	(394,393)	0.009 9	0.165 5	0.039 4	0.471 9	0.538 6
(70,71)	(393,392)	0.014 5	0.132 5	0.038 2	0.029 5	0.047 0
(70,71)	(485,486)	0.814 3	0.958 2	0.843 8	0.786 7	0.857 1

3 Simulation of lines’ adjustment

3.1 The adjustment strategy

In order to keep the high operation efficiency, the transfers and the travel time must be in a reasonable range. The importance of the transit edges is measured to make sure the shortest routes can be retained. Tab. 7 presents the importance of each candidate edge. As long as there is one shortest route crossing the edge, that edge should be preserved. Thus, the determining set of the edges needs to be adjusted as shown in Tab. 8.

Tab. 9 presents the adjustment strategies of the bus lines. The edges $e_{335,337}$, $e_{337,338}$, $e_{338,339}$ are the continuous terminal edges of the line 621. There are only a few passengers passing by these three edges under the five scenarios. Hence, considering the resource utilization, the three edges $e_{335,337}$, $e_{337,338}$, $e_{338,339}$, which not only cannot afford the traffic flow, but also cannot coordinate to the rail lines, should be cut off.

Tab. 7 The importance of the candidate edges

Bus edge	Importance	Bus edge	Importance
(212,213)	1	(401,407)	0
(446,445)	2	(297,291)	0
(327,328)	3	(369,371)	1
(328,329)	3	(416,418)	0
(335,337)	0	(418,419)	0
(337,338)	0	(95,96)	0
(338,339)	0	(272,273)	0
(249,250)	0	(394,393)	1
(398,401)	2	(393,392)	1

Tab. 8 The determining set of edges needs to be adjusted

Bus edge	Bus line	Bus edge	Bus line
(335,337)	621	(297,291)	613
(337,338)	621	(416,418)	707
(338,339)	621	(418,419)	707
(249,250)	576	(95,96)	413
(401,407)	702	(272,273)	578

Tab. 9 The result of the adjustment

Bus line	Bus edges	Adjustment strategy
621	$e_{335,337}$ $e_{337,338}$ $e_{338,339}$	lines' truncation
576	$e_{249,250}$	site consolidation
702	$e_{401,407}$	lines' truncation
613	$e_{291,297}$	translation motion
707		lines' truncation
413	$e_{95,96}$	site consolidation
578	$e_{272,273}$	site consolidation

The edge $e_{410,417}$ is a large section of the bus line 702. The edge $e_{410,417}$ is at the end of the bus line 702. In the ground bus system, there are other edges $e_{297,291}$, $e_{365,371}$, $e_{401,407}$ parallel with the rail edge $e_{46,50}$, which cause a higher repetition rate. The bus edge $e_{365,371}$ has a stronger coordinated relationship with the rail lines, and comparing to the edge $e_{401,407}$ no-coordinated to the rail edges, the edge $e_{297,291}$ has a certain supplementary capacity to the rail system under the disruption. This proves that the edge $e_{401,407}$ is non-competitive among the three collinear bus edges. Therefore, the edge $e_{401,407}$ should be cut off to relieve the congestion.

The edge $e_{297,291}$ is at the middle of the bus line 613. Even though the edge carries a few passenger flow, in order to maintain consistency, the edge $e_{291,297}$ can be changed to the parallel main street. The edge $e_{291,297}$ crosses the node Guanggu Square, the node Youkeyuan, the node Wujiawan, the node Science and Technology Convention Center, the node Majiazhuang, the node Zhuodaoquan middle school, and the node Guangbutun railway station. There are two routes along the main road from the node Guanggu Square to the node Guangbutun railway station. The first route is along the Lumo Road to the Bayi Road, then crossing the Bayi Road,r eaching the Guanggu Bridge, passing by the Guanggu Bridge to the Zhuodaoquan Road, finally entering the Luoyu Road arriving at the node Guangbutun railway station. The second route is along the National Road to the Xiongchu Avenue, then passing by the Xiongchu Avenue, entering the Zhuodaoquan Road, finally reaching the Luoyu Road to the node Guangbutun railway station. Compared to the two routes, the former is too long, but the lines' repetition rate is lower. The latter is shorter, but the lines' repetition rate is high in the National Road and the Xiongchu Avenue. What's more, the congestion rate of the two road is very high from current situation. Even though the first route is too long, the bus lines along the route are very few in relative to the surrounding university and attractions. Thus, in order to attract more potential passenger flow, the edge $e_{297,291}$ is rerouted along the first route. The site setting is that: Guanggu Square, China University of Geosciences, Nanwangshan, Shawan Village, and Guangbutun railway station.

The edges $e_{416,418}$, $e_{418,419}$ are the continuous terminal edges of the line 707. The edges $e_{419,421}$, $e_{421,423}$ connected to the edge $e_{418,419}$ have a higher coordination coefficient of the rail edges. Therefore, the edges $e_{416,418}$, $e_{418,419}$ which have no passenger flow should be cut off.

The edge $e_{249,250}$, $e_{95,96}$, $e_{272,273}$ is in the middle of the line 576, line 413, and line 578. The adjacent edges $e_{250,252}$, $e_{252,253}$ of the edge $e_{249,250}$ have a higher coordination coefficient. The edge $e_{95,96}$ and the edge $e_{272,273}$ have some passenger flow under normal situation. Thus, the stops S_{249}, S_{250}, the stops S_{95}, S_{96}, and the stops S_{272}, S_{273}can be consolidated into the neighboring bus stops S_{248} , S_{251}, stops S_{94}, S_{98}, and the stops S_{271}, S_{274} to shorten the stop time.

3.2 Simulation results

In order to test the validity of the adjusted integrated transit network, the comparative analysis of the coordination coefficient and the service performance of the transit system are given.

Tab. 10 presents the comparison of the coordination coefficient. After the truncation, the translation motion and site consolidation of the bus lines, only the remaining collinear edges need to calculate the coordination coefficient. As we can see from Tab. 10, the coordination coefficients of all the adjusted collinear edges are at least not less than the original collinear edges. The average value of the coordination coefficients of the integrated transit system increase from 0.232 to 0.292. Especially the bus edges $e_{102,101}$, $e_{365,369}$, $e_{369,371}$, paralleling with the adjusted bus edges, whose coordination coefficient is obviously improved.

Tab. 10 The comparison of the coordination coefficients

Rail edge	Bus edge	before	after
(7,8)	(211,212)	0	0
(8,9)	(212,213)	0.461	0.461
(7,8)	(446,445)	0	0
(8,9)	(445,444)	0.852 7	0.854 7
(19,20)	(327,328)	0.113 8	0.154 4
(20,21)	(328,329)	0.058 5	0.074 3
(21,22)	(329,330)	0.146 1	0.186 9
(22,23)	(330,332)	0.185 9	0.242 1
(23,24)	(332,335)	0.058 7	0.128 7
(43,44)	(102,101)	0.009 8	0.302 7
(44,45)	(250,252)	0	0.031 6
(45,46)	(252,253)	0.032 6	0.102 6
(44,46)	(398,401)	0.057 9	0.143 9
(48,49)	(365,369)	0.079 1	0.368 7
(49,50)	(369,371)	0.089 3	0.381 7
(55,56)	(419,421)	0.540 8	0.540 8
(56,57)	(421,423)	0.570 7	0.570 7
(59,60)	(425,426)	0.909 7	0.936 6
(68,69)	(396,394)	0.099 3	0.099 3
(69,70)	(394,393)	0.009 9	0.009 9
(70,71)	(393,392)	0.014 5	0.014 5
(70,71)	(485,486)	0.814 3	0.814 3
Average coordination coefficient		0.232	0.292

Tab. 11 gives the comparison of the service performance of the integrated transit network. Even though the five indicators of the adjusted network are worse than before, all the indicators are still in the reasonable range, owing to the adjusted edges redundant to the whole network.

In a word, the proposed coordination coefficient can be used to adjust and optimize the layout of the integrated transit system. The adjusted transit network has a higher coordination degree, lower waste of the resources. The organic combination of the rail system and the bus system can finally improve the operation efficiency.

Tab. 11 The comparison of the service performance

Indicators	Average edge length	Connectivity	Network density	Average travel time	Average transfers
before	0.863 0	0.436	2.405	52.3	1.927
after	0.892 3	0.437	2.393	53.67	2.07

4 Conclusion

This paper concentrates on the qualitative and quantitative analysis of the coordination of the collinear edges between the rail lines and the bus lines. From the aspect of resource utilization and the capacity matching degree, the definition of the coordination is given. Then, the role of the complementation and the competition in the coordination is defined. After that, this paper proposes the reasonable calculation of the complementarity coefficient, the competitive coefficient, and the coordination coefficient. Based on that, a series of adjustment methods are applied to the bus edges whose coordination degrees are weak.

The process of the coordination analysis and the lines adjustment is based on the transit simulation. The applicability of the proposed analysis and adjustment is illustrated on the parts of Wuhan (China) intermodal transit network. The complementation plays a leading role in the coordination. Lower complementation with lower competition may show higher coordination, but only the high complementation can lead to the extremely strong coordination. Of course, both the complementation and the competition can influence the coordination.

The disruption on the rail system can have huge effect on the degree of the coordination, especially in the failed sites, with which the bus lines parallel show a stronger coordination relationship. Thus, it’s important to consider the influence of the disruption in coordination analysis.

The adjusted bus system displays a better coordination relationship with the rail system. What’s more, service indicators of the adjusted transit network are all within a reasonable range. Consequently, the coordination analysis applied to the adjustment of the bus lines can greatly improve the operation efficiency and the level of comprehensive service to the integrated transit network.

In general, there are several bus lines parallel with the rail lines, and the traffic flow can shuttle among these collinear lines. Thus, in the future, we will consider the interrelationship of the collinear transit lines and further study and extend the proposed quantitative method.

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