GREEN TRANSPORTATION DESIGN OF CHANGZHI CITY

Qi Yu, Lin Xiaohan, Lin Zhizhi,

Zhang Xinqi, Zhao Haocheng, Zhou Ziyi

2023-6-24

TSINGHUA UNIVERSITY

FINAL PROJECT OF GREEN TRANSPORTATION SYSTEM

Abstract: Under the guidance of the concept of green transportation, we design a transit system for Changzhi city. In this paper, we'll introduce basic information about Changzhi and how we achieve the data we need in part 1. Part 2 shows what kind of model we choose, how to do quantified analysis and how to implement the design into reality. Part 3 discusses whether our system will be more efficient if combined with BRT. The rationality of our design will be proved in this paper.

Key words: Green transportation; Changzhi city; Hybrid system; BRT

Content

Part 1 Data Collection 3

1.1 Region Characteristics 3

1.1.1 District Size: 3

1.1.2 Road Network Layout： 3

1.2 Vehicle Characteristics 4

1.2.1 Changzhi maximal cruising speed V_m 4

1.2.2 Lost time per stop t_s 4

1.2.3 Passenger walking speed V_w 5

1.2.4 Value of user time β 5

1.2.5 Operating cost C_m 5

1.3 Demand Characteristics 6

Part 2 Network Design 7

2.1 Model Selection 7

2.1.1 Why to choose the bus? 8

2.1.2 Why to use hybrid system? 9

2.1.3 Why to divide the grid system into two? 10

2.1.4 Why to use "walking transfer"? 10

2.2 Quantitative model analysis 11

2.2.1 The Grid system 11

2.2.2 The Corridor system 13

2.2.3 Theoretical solution 14

2.3 Implementation of the design 15

2.3.1 Deploying bus routes on the main roads 16

2.3.2 Matching with line spacing 17

2.3.3 Considering real road conditions 17

2.3.4 How to deploy corridors 18

2.3.5 Principles for selecting bus stops 19

Part 3 Further improvement: BRT 23

3.1 System with BRT 23

3.2 System without BRT (ordinary situation) 26

3.3 Comparison and Conclusion 28
Part 4 Division of labor 29

Part 1 Data Collection

1.1 Region Characteristics

1.1.1 District Size:

Changzhi City is located in the southeast of Shanxi Province. It is about 150 kilometers long from east to west and 140 kilometers wide from north to south, with Taihang Mountain lying on the east. Changzhi City borders Hebei and Henan provinces in the east, Linfen City in the west, Jincheng City in the south and Jinzhong City in the north. The total area of Changzhi is 13,955 km^2, accounting for 8.90% of the province's total area. The location of Changzhi is shown in Figure 1.

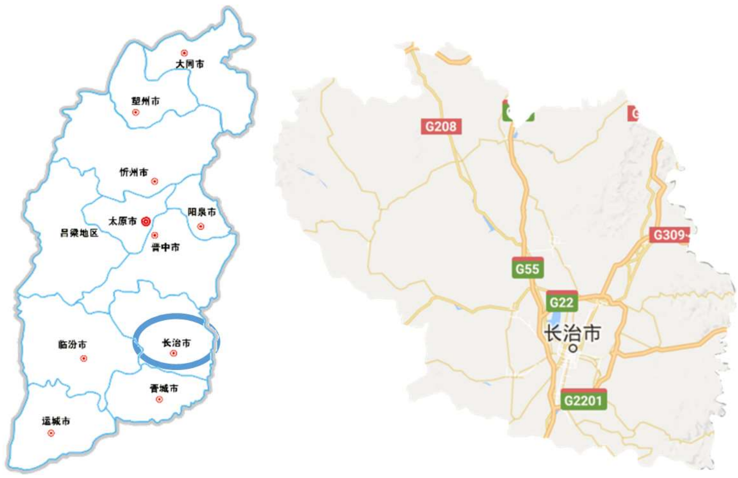

Figure 1 The location of Changzhi

With the help of CAD drawing of Changzhi, we could discover that the downtown area(S) is about 70280232 m^2. The length of side(Φ) approximates the square root of S, which is 8383 m.

1.1.2 Road Network Layout：

By comparing the information from the website, remote sensing images of Ama and CAD drawings, we could find the main roads of Changzhi and mark them with lines in different colors on the CAD drawing with legend. We've discovered a total of 25 main roads. The layout of the traffic zones and the road network are shown in Figure 2.

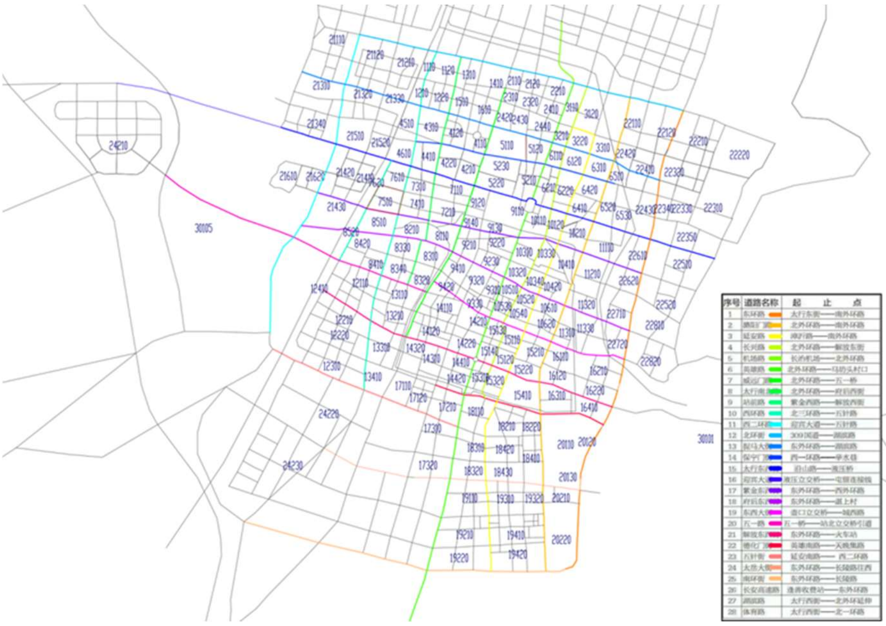

Figure 2 The road network layout of Changzhi

1.2 Vehicle Characteristics

1.2.1 Changzhi maximal cruising speed V_m

Data source:

Amap

changzhi.gongjiao.com

Derivation process:

According to the data from Amap and changzhi.gongjiao.com, Bus No.9 is from Chengnan Ecological Garden to Jingxin Garden and the total length is about 7km. There is little traffic jam throughout the day, and it takes 32 minutes for a bus to cover the whole route. Therefore, the cruising speed is 7km/32min = 14km/h.

Bus No.8 starts at Taihang Hotel and ends at Wangqiao and its total route length is 40 km. It takes about 1 hour and 40 minutes to cover the whole route, so the cruising speed is 40km/100min = 24km/h.

Bus No. 6 ,whose route is 7 km, runs from Hukou to Changzhi Railway Station, with a total cruising time of 25min and speed of 17km/h.

According to other official data, reasonable peak cruising speed of buses in ordinary cities without special planning should be about 15kph.

To sum up, the running speed of urban area is about 21km/h, and that of suburban area is about 30km/h. As Amap tends to overestimate the travel time, it can be regarded as peak operating speed. Off-peak operating speed is 24km/h in urban areas and 35km/h in suburban areas.

We design our traffic system based on data during rush hours in urban areas. Therefore, V_m = 21 km/hr.

1.2.2 Lost time per stop t_s

Data source:

https://patents.google.com/patent/CN105678036A/zh

http://www.xml-data.org/GDGYDXXB/html/20190405.htm

https://patents.google.com/patent/CN103903429B/zh

Derivation process:

Assuming that it takes 1.8 seconds for each person to get on and off the bus, and 5 seconds for drivers to open and close the bus. The acceleration and deceleration of the bus are 1.2m/s^2. If a bus runs at 21kph (5.8m/s), acceleration and deceleration will take 10 seconds in total.

Therefore, the estimated loss time is 5+10x+1.8y, where x is the number of buses parked at the station, which generally equals 1, and y is the number of queuing people.

If there are six people queuing to get on and off the bus, the lost time is about 26 seconds.

So, during peak hours, t_s approximates 30s.

1.2.3 Passenger walking speed V_w

Data source:

Changzhi City Statistics Bureau, Bulletin of the seventh national population census of Changzhi City[R], 2021.

Yunlong Ma, Hui Xiong, et al. Analysis of Influence of Pedestrian Character on Walking Behavior[J]. Traffic & Transportation, 2009(01):98-101.

Derivation process:

The literature points out that if the proportion of the elderly (≥65 years old) in the walking section is no more than 20%, V_w can be 1.22m/s, or 1.01m/s is recommended if the proportion is more than 20%. The average walking speed for men is 1.26 m/s, and 1.22 m/s for women.

In Changzhi, the male population is 1618349, accounting for 50.88% of the whole population and female population accounts for the rest 49.12%. Among the city's permanent residents, the 0-14 year old population is 524264, accounting for 16.48% of the whole population; the population aged 15-59 is 2,047,350, accounting for 64.36%; the population aged 60 or above was 609,270, accounting for 19.15%, of which 412,263 were 65 or above, accounting for 12.96% (less than 20%).

If we calculate the weighted average of walking speed according to the gender and age composition of Changzhi, we could find that V_w = 1.23m/s.

1.2.4 Value of user time β

Data source:

https://www.changzhi.gov.cn/xxgkml/zfxxgkml/szfgzbm/czstjj/czsrmzf/tjxx_1188/tjgb/202208/t20220817_2623929.shtml

Derivation process:

The average annual income of employees is 78282 yuan in 2020. According to labor law, working hours per week should not exceed 44 hours

Therefore, β= 78282/(52*44) = 34.2 yuan/hour

1.2.5 Operating cost C_m

Data source:

https://www.sohu.com/a/499613898_360824

https://www.ahsz.gov.cn/public/2655601/193177731.html

Derivation process:

Since the data of Changzhi is difficult to find, pinch estimation using the information of Beijing and Suzhou is used.

In 2020, the total annual mileage of buses in Beijing is 1.068 billion kilometers. The total expenditure is 18.630 billion yuan.

北京市公共电汽车运营企业成本费用表	
报告单位：公交集团	单位：万元
项目	2020年度
一、主营业务成本	1,697,062.71
（一）人工成本	1,031,658.32
1、工资	792,492.60
2、相关费用	239,165.73
（二）业务成本	665,404.39
1、行车燃料费	148,015.24
2、电车电力费	57,272.19
3、车辆修理费用	208,632.51
4、车辆折旧费用	642.92
5、线网维修费用	3,805.28
6、营运业务费用	53,428.31
7、营运间接费用	187,242.33
8、行车事故费	6,365.62
二、期间费用	165,976.51
（一）管理费用	165,640.55
（二）财务费用	335.96
三、成本费用合计	1,863,039.22
四、客运量（万人次）	182,567.11

Figure 3 The total operation cost of buses in Beijing in 2020

C_m = Sum of costs which increased with mileage / annual mileage = (fuel cost + electric charge+ repair cost + network maintenance cost) / total mileage = (148015.24+57272.19+208632.51+3805.28) / 10.68/10^4 = 3.911 yuan/km

Do the calculation again in Suzhou, and find that C_m = 2.803 yuan/km.

Considering that Changzhi is more similar to Suzhou in all aspects, we take 3 yuan/km. So, C_m = 3 yuan/km.

1.3 Demand Characteristics

Data source:

"OD Demand of Changzhi City.xlsx"

Result:

We divide the whole area into 26 sections, according to the first and second digit of the region number. For each section, add OD up and divide it by the area, and we get demand density. The unit of y axis is pax/hr/m^2.

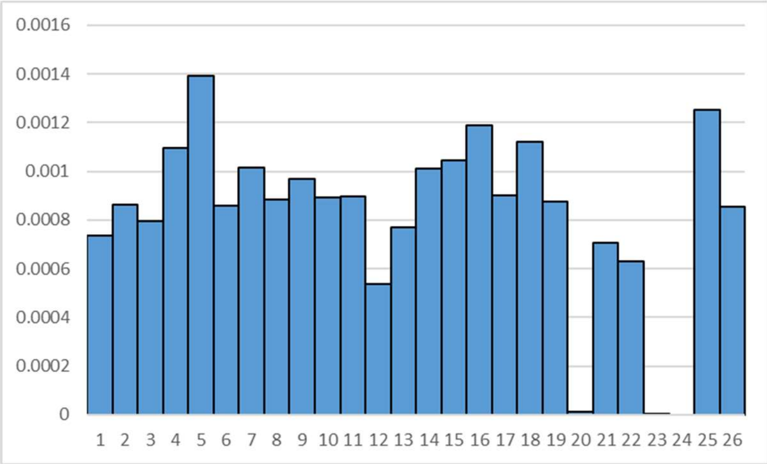

Figure 4 Generation demand density

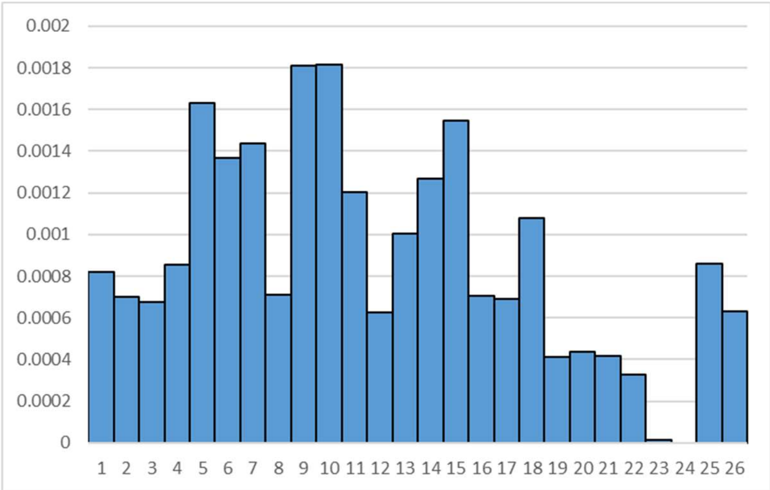

Figure 5 Attraction demand density

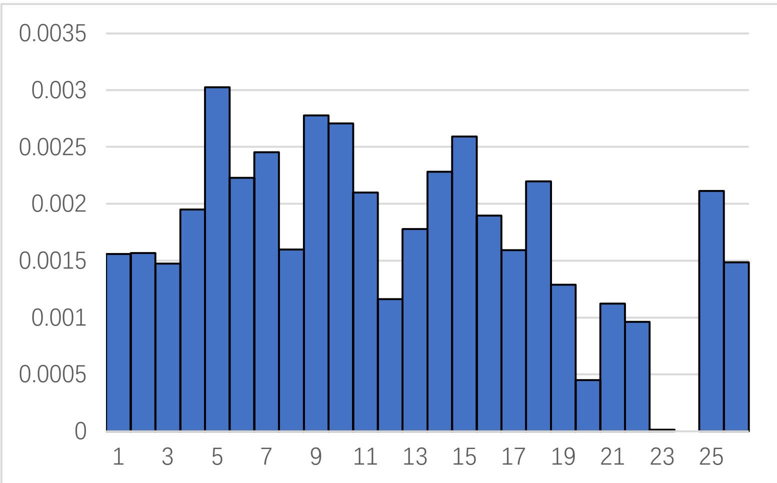

Figure 6 Total demand density

Part 2 Network Design

2.1 Model Selection

As figure 7 shows, we choose hybrid transit system. The system contains two grid systems which lie at the center of the city, and are marked by red and orange color in the figure. In the peripheral area, we use corridor systems. In this section, we try to explain why we choose bus as our mode of traffic, why we select hybrid system and divide grid system into 2 parts.

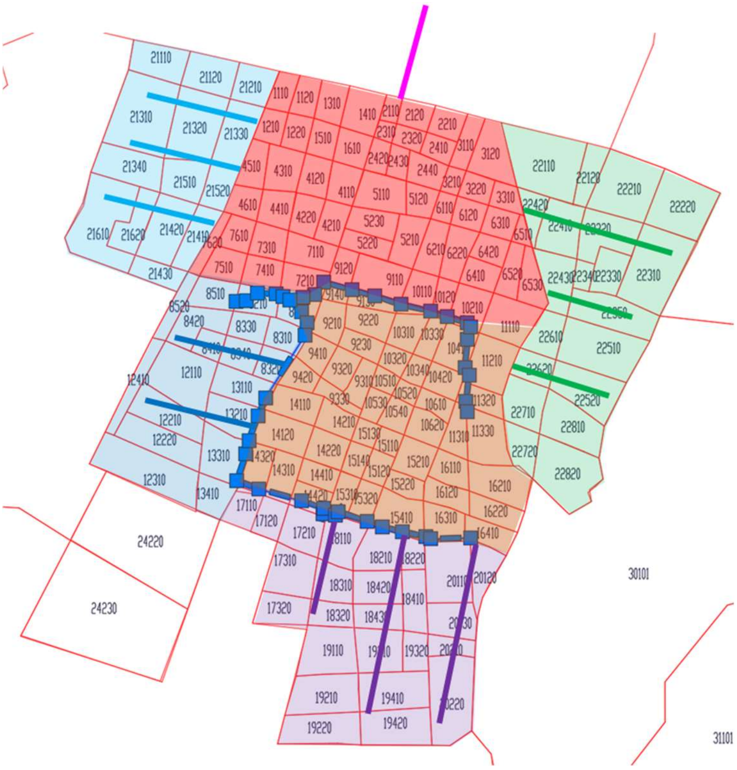

Figure 7 The design of hybrid system

2.1.1 Why to choose the bus?

In the green transportation system, the bus is one of the most important parts. Compared with private cars, taxis and other "non-green" travel modes, the advantage of buses is that they can carry more passengers. From the perspective of energy, each passenger does not necessarily consume less energy than private cars, but the high carrying capacity of buses can greatly improve commuting efficiency. As a medium-sized city with dense population, Changzhi has a large traffic demand, especially in the central area of the city. The use of buses will help avoid road congestion. If people can give priority to the bus as a mode of travel, through the coordination of signal lights and public transport, or improve the priority of bus operation, the use of BRT and other ways to commute, we will be able to further reduce unnecessary congestion and energy waste.

Compared with rail transit, buses are more flexible and need less investment. Subway and light rail need to spend a lot of money and time in construction, and the operation cost is relatively high. In small and medium-sized cities, it is likely to make ends meet. According to relevant data, the heavy rail system in the United States needs 1646 thousand US dollars for each station and 1044 thousand US dollars for each kilometer of track. If Changzhi uses rail transit as the main commuting mode, it will cause a huge financial burden. A large amount of investment in fixed assets has violated the premise of "green". However, if rail transit is to ensure efficiency, the distance between stations cannot be too close. If public transportation is to be spread throughout the city, buses are also needed for ferry and transfer. Therefore, it is unrealistic to focus on rail transportation.

Item	All bus		Heavy rail		Regional rail		LRT & streetcar		Demand responsive	
Infrastructure & facilities										
guideway (million$)	215.6	5%	2,344.4	38%	1,276.9	42%	2,569.4	73%	0.0	0%
Stations (million$)	443.8	10%	1,718.5	28%	339.2	11%	307.7	9%	22.4	4%
Admin & maintenance facilities (million$)	756.6	17%	224.6	4%	190.5	6%	130.4	4%	83.9	14%
Subtotal (million$)	1,416.1	31%	4,287.4	70%	1,806.6	60%	3,007.6	86%	106.3	18%
Directional route length (km)	428,024		2,610		14,389		2,553		—	
Station count	0.5		898.1		88.7		1,006.3		—	
Unit guideway cost (1,000$/km)	—*		1,044		1,296		887		—	
Unit station cost (1,000$/station)	—		1,646.1		261.7		346.9		—	
Vehicle										
Subtotal (million$)	2,361.9	52%	441.1	7%	780.2	26%	312.1	9%	412.3	69%
Available vehicle count	71,139		10,380		7,369		2,387		68,559	
Unit vehicle cost (1,000$/vehicle)	33.2		42.5		105.9		130.7		6.0	
Average purchase price (1,000$/vehicle)**	486.8		2,254.4		2,444.6		3,300.0		77.6	
Other										
Subtotal (million$)	746.4	16%	1,428.4	23%	437.8	14%	195.1	6%	81.4	14%
Total	4,524.4	100%	6,156.9	100%	3,024.6	100%	3,514.8	100%	600.0	100%

Source: Neff and Dickens (2015).

Figure 8 US transit capital costs in 2013

Compared with bicycles and walking, buses are more friendly to the elderly, children and other vulnerable groups. In this design scheme, the average distance between the stations we designed is about 400 meters, and the grid is used in areas with high traffic demand such as downtown to ensure that people can take buses nearby. According to statistics, at present, more than 35.6 percent of children under the age of 14 and people over the age of 60 in Changzhi City, a relatively high proportion. For the elderly and children who can not ride bicycles, establishing a dense bus network is the best solution.

Comprehensive road carrying capacity, financial revenue, vulnerable groups and other needs, we use the general public transport network as the core of this design. At the same time, we are actively exploring the possibility of other options, such as using skip-stop or BRT to upgrade existing systems. Generally speaking, no matter which scheme is adopted, it is inseparable from the bus as a means of transportation.

2.1.2 Why to use hybrid system?

During the modeling process, we analyzed the OD requirements of different regions. The results show that the traffic demand in some areas is very small, such as #8,#12,#21,#23, etc., and these areas are generally in the suburbs; while the traffic demand in some areas is very large, these areas are generally in the city center. The theory suggests that, with the same resource input (e. g., number of sites), Grid is more suitable for regions with higher demand, while other networks, such as Corridor, should be considered for regions with lower demand.

At the same time, the road network density in the city center is also much higher than that in the suburbs. When Grid is used to establish the public transportation system, the optimal solution of the station spacing is about 450m, which is exactly the distance of one block. The optimal solution for the distance between transfer stations is about 900m, which is exactly the distance between two stations. The road network in the suburbs is sparse, extending roughly in four directions relative to the city center. Both theoretical calculations and actual road networks show that the combined use of downtown Grid and suburban Corridor is the most appropriate solution.

2.1.3 Why to divide the grid system into two?

The investigation found that there is a river running through the center of Changzhi in the east-west direction. Ba'yi Square, Tai'hang Park, Bin'he Park, Botanical Garden, etc. are adjacent to the riverside, which generally leads to the city center being divided by a low population density area (river and park), resulting in two centers, north center and south center. Analysis of OD demand also shows that #5 on the north side and #9 and #10 on the south side are the areas with the highest demand.

Figure 9 Grid Design

There is also a certain asymmetry on both sides of the river. The area with higher demand is not a complete rectangle, but two rectangles are spliced along the river. If you only use a square Grid, you will not be able to avoid low-demand areas while including all high-demand areas, such as #4 and #10. At the same time, the number of bridges and traffic carrying capacity limit the traffic on both sides to a certain extent. Based on the above reasons, we take the river as the boundary, divide the urban area into two parts, and design two Grid systems.

2.1.4 Why to use "walking transfer"?

We may find that every bus stop in the city center is shared by a large number of bus lines. We believe that it’s partly because the bus route is designed without considering the future network expansion and urban expansion in a global way, and the system is limited to the single station transfer of Hub & Spoke, and a large number of lines share a single station. On the other hand, in order to transfer at the same station, different bus routes must converge on the same station. In reality, in order not to make too many unnecessary turns, two buses that can transfer to each other must have a large straight line that is completely repeated. Due to the above two reasons, a large number of bus lines reuse the same station and the same section of the route, resulting in a waste of resources; the design of the route must also take into account these repetitions, which is not simple and clear enough.

Our design adopts the method of walking transfer and non-same station transfer. Each stop serves only one route, and the two bus lines intersect at the intersection, with separate stops on both sides of the intersection. The characteristics of this approach are as follows: First, it can ensure that the public transport network is simple and clear. Since there is no need to transfer at the same station, our bus routes do not need to overlap. All bus routes are in the north-south direction or the east-west direction. There is no need to turn when the bus is running, which can improve the ride comfort and safety. If it can cooperate with the signal system, or adopt the form of bus priority, the running speed can be greatly improved. Secondly, it can improve efficiency. There will be no duplication of bus routes. There will not be a large number of bus congestion at the same bus stop. There will be no "whether to squeeze this bus" entanglement, because there is only one line through this station. Thirdly, it can facilitate scheduling. The headway can be adjusted by simply increasing or decreasing the number of buses on the line. Since it is only necessary to judge the traffic situation on one road, the timetable can also be made more accurately, which is convenient for passengers to plan.

In order to realize this system, we design a pair of stations on both sides of the intersection, that is, the east-west direction of the intersection. Set another pair of stations in the north-south direction. The reason for placing the station at the intersection is to minimize the distance passengers need to walk. Through another green transportation mode, namely walking, connecting different bus lines, the integration of the two green transportation systems is realized.

2.2 Quantitative model analysis

2.2.1 The Grid system

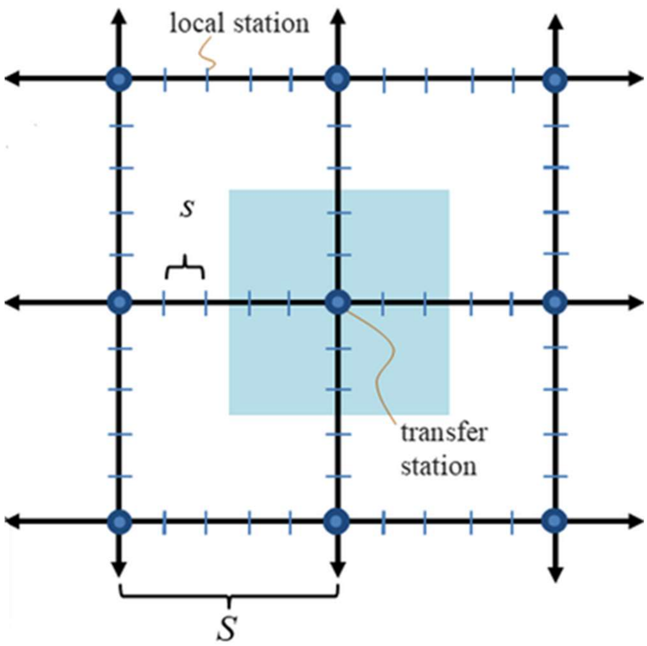

Figure 10 The grid system

Decision variables in the grid system include headway(H), line spacing(S) and stop spacing(s). The demand density in this area is λ pax/hr/km^2. The unit operation cost caused by moving and stopping is C_d \$/km and C_s (\$/stop). For the blue area in the figure above:

——$Number\ of\ passengers = \lambda S^2 H$

——$Total\ vehicle\ stops = 4\frac{S}{s}$

——$Total\ vehicle\ distance\ = \ 4S$

——$Agency\ cost\ per\ capita\ \$ = \frac{4C_d S + 4C_s \frac{S}{s}}{\lambda S^2 H} = \frac{4}{\lambda S H}\left(C_d + \frac{C_s}{s}\right)$

Passenger travel time consists of waiting time(WT), access time(AT), in-vehicle-travel-time(IVTT) and transfer time(TT).

——$Total\ travel\ time\ T\ =\ WT\ +\ AT\ +\ IVTT\ +\ TT$

In our model, transfer time is quantified. For passengers travelling within the grid system, they need to transfer only when they have to move in the perpendicular direction, just as the following figure shows.

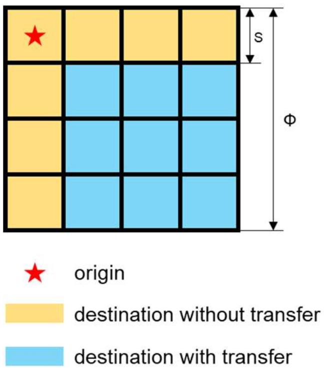

Figure 11 Transfer time

Blue squares are destinations which passengers have to reach with transfer. Their area is $(\Phi - S)^2$. Therefore, assuming that the destinations of passengers are uniformly distributed, the possibility for a passenger to transfer is $\frac{(\Phi-S)^2}{\Phi^2}$. If the passenger doesn't know the schedule of the bus, the transfer time equals to the waiting time. Therefore, in the average case, the transfer time $TT\ =\ \frac{(\Phi-S)^2}{\Phi^2}H$, while in the worst case, $TT\ =\ H.$

In the average case:

——$Waiting\ time\ WT\ =\ H$

——$Access\ time\ AT = \frac{S+s}{2v_w}$

——$In - vehicle\ travel\ tme\ IVTT = \frac{l}{v_{max}} + \frac{l}{s}t_s$

——$Transfer\ time\ TT = \frac{(\Phi - S)^2}{\Phi^2}H$

——$Total\ travel\ time\ T =\ WT\ +\ AT\ +\ IVTT\ +\ TT = H + \frac{S+s}{2v_w} + \frac{l}{v_{max}} + \frac{l}{s}t_s + \frac{(\Phi-S)^2}{\Phi^2}H$

In the worst case:

——$Waiting\ time\ WT\ =\ H$

——$Access\ time\ AT = \frac{S+s}{v_w}$

——$In-vehicle\ travel\ tme\ IVTT = \frac{l}{v_{max}} + \frac{l}{s}t_s$

——$Transfer\ time\ TT = H$

——$Total\ travel\ time\ T\ =\ WT\ +\ AT\ +\ IVTT\ +\ TT = 2H + \frac{S+s}{v_w} + \frac{l}{v_{max}} + \frac{l}{s}t_s$

The Lagrangian function under the average case is:

——$Lagrangian\ function\ z\ =\ \$\ +\ \beta T\ \approx\ \frac{4C_d}{\lambda SH}\ +\ \beta[H + \frac{S+s}{2v_w} + \frac{l}{v_{max}} + \frac{l}{s}t_s\ +\ \frac{(\Phi-S)^2}{\Phi^2}H]$

Stop spacing(s) can be determined via basic inequality.

——$Stop\ spacing\ s = \sqrt{2lt_s v_w}$

To determine line spacing(S) and headway(H), we should let the derivative of H and S equal to zero:

$$\frac{\partial z}{\partial H} = -\frac{4c_d}{\lambda SH^2} + \beta\left(1 + \frac{(\Phi - S)^2}{\Phi^2}\right) = 0$$

$$\frac{\partial z}{\partial S} = -\frac{4c_d}{\lambda S^2 H} + \frac{2(S-\Phi)}{\Phi^2}\beta H + \frac{\beta}{2v_w} = 0$$

$$\Rightarrow H = \frac{1}{2v_w}\frac{S\Phi^2}{2\Phi^2 - S^2} \quad (1)$$

$$\Rightarrow -\frac{16c_d}{\lambda\Phi^4}v_w^4(2\Phi^2 - S^2)^2 + \beta\left(1 + \frac{(\Phi - S)^2}{\Phi^2}\right)S^3\ =\ 0\ \ (2)$$

Equation (2) can be solved numerically with the help of calculator. Then just plug S into equation (1) and we can get H.

It should be noted that sometimes S is smaller than s, which, according to the textbook, is a normal phenomenon. If that happens, just let S equals to s and do the calculation again:

——$Lagrangian\ function\ z' = \frac{4c_d}{\lambda SH} + \beta\left[H + \frac{S}{v_w} + \frac{l}{v_{max}} + \frac{l}{S}t_s + \frac{(\Phi - S)^2}{\Phi^2}H\right]$

$$H = \frac{\Phi}{\Phi - s}\sqrt{\frac{4C_d}{\lambda S\beta}}\ (3)$$

$$\frac{4(\Phi + S)c_d}{\lambda(S-\Phi)S^2} + \beta\left(\frac{1}{v_w} - \frac{lt_s}{S^2}\right)\frac{\Phi}{\Phi - s}\sqrt{\frac{4c_d}{\lambda S\beta}}\ =\ 0\ \ (4)$$

Again, we can use numeric approach to solve equation (3) and (4) and determine H and S.

2.2.2 The Corridor system

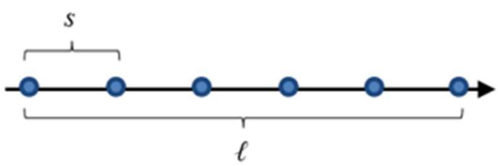

Figure 12 The corridor system

Decision variables in the corridor system include headway(H) and stop spacing(s). The demand density is distributed along the corridor and equals to λ pax/hr/km. The unit operation cost caused by moving and stopping is C_d \$/km and C_s (\$/stop). For a s-H space:

$$——Agency\ cost\ per\ capita\ \$ = \frac{C_d s + C_s}{\lambda s H} = \frac{1}{\lambda s H}(C_d s + C_s)$$

In the average case:

$$——Total\ travel\ time\ T = WT + AT + IVTT = H + \frac{s}{2v_w} + \frac{l}{v_{max}} + \frac{l}{s}t_s$$

In the worst case:

$$——Total\ travel\ time\ T = WT + AT + IVTT = H + \frac{s}{v_w} + \frac{l}{v_{max}} + \frac{l}{s}t_s$$

The Lagrangian function under the worst case is:

$$——Lagrangian\ function\ z = \$ + \beta T \approx \frac{C_d}{\lambda H} + \beta(H + \frac{s}{v_w} + \frac{l}{v_{max}} + \frac{l}{s}t_s)$$

H and s can be determined through basic inequality:

$$——Stop\ spacing\ s = \sqrt{l t_s v_w}$$

$$——Headway\ H = \sqrt{\frac{C_d}{\lambda \beta}}$$

2.2.3 Theoretical solution

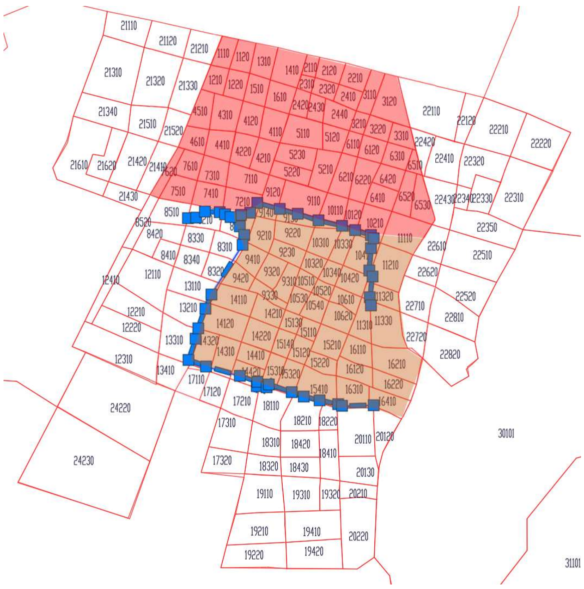

Figure 13 The grid system

For the Grid system, the length of side(Φ) equals to square root of the area. Demand density for transit is 15% of the whole demand density. Average travel distance l = 2Φ/3.

For Grid 1 (the red area in the figure above):

Φ = 4.222 km, λ = 15% * 1076 = 161.4 pax/km^2/hr, l = 2*4.222/3 = 2.815km.

β = 34.2yuan/hr, V_w = 4.428 km/hr, C_d = 5.28 yuan/km, t_s = 0.008333s.

Plug these parameters into the equations mentioned earlier:

$s* = \sqrt{2lt_s v_w}$ = 455.77 m, S* = 890.95 m, H* = 3.087min

For Grid 2 (the orange area in the figure above):

Φ = 4.151 km, λ = 15% * 1076 = 151.5 pax/km^2/hr, l = 2*4.222/3 = 2.767km.

β = 34.2yuan/hr, V_w = 4.428 km/hr, C_d = 5.28 yuan/km, t_s = 0.008333s.

Again, plug these parameters into the equations:

$s* = \sqrt{2lt_s v_w} = 451.92$ m, $S^* = 911.32$ m, $H^* = 3.163$min

Table 1 Theoretical results for the grid system

	Φ (km)	λ (pax/km^2/hr)	H (min)	S (m)	s (m)
Grid 1	4.222	161.4	3.087	890.95	455.77
Grid 2	4.151	151.5	3.163	911.32	451.92

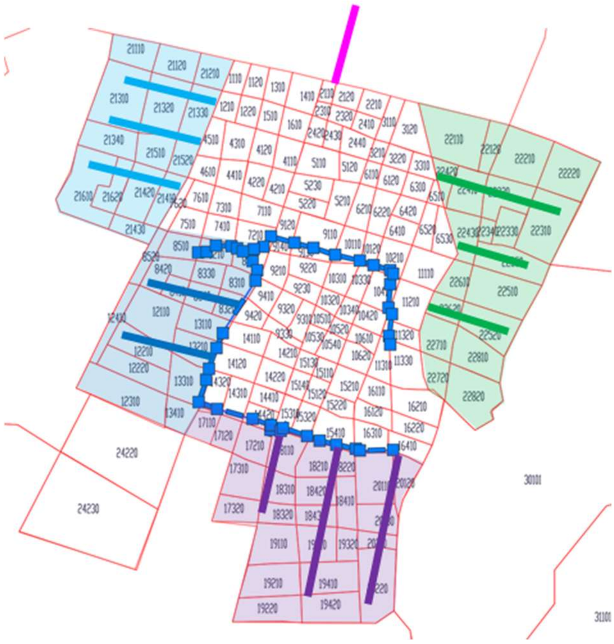

Figure 14 The corridor system

For the corridor system, the length of side(Φ) roughly equals to square root of the area. Demand density for transit is 15% of the whole demand density. The worst travel distance l = the length of corridor ≈ Φ/2.

$\beta = 34.2$yuan/hr, $V_w = 4.428$ km/hr, $C_d = 5.28$ yuan/km, $t_s = 0.008333$s.

Plug these parameters into $s = \sqrt{lt_s v_w}$ and $H = \sqrt{\frac{C_d}{\lambda\beta}}$.

The parameters and results for 4 corridor areas are shown as follows.

Table 2 Theoretical results for the corridor system

	Φ (km)	l (km)	λ (pax/km/hr)	H (min)	s (m)
#22	16.128	8.064	19.262	5.371	545.49
#21	11.314	5.657	21.854	5.043	456.88
#8/12/13	11.927	5.964	18.609	5.464	469.10
#17/18/19/20	14.475	7.238	23.252	4.889	516.78

2.3 Implementation of the design

When matching the theoretical model with the existing road, we should take some realistic factors into account. In this section, we'll focus on the difference between the model and reality.

2.3.1 Deploying bus routes on the main roads

Based on the research findings and mathematical modeling results discussed earlier, we have chosen to deploy bus routes on the main roads of Changzhi City. This decision is mainly based on the following two considerations:

Firstly, laying bus lanes on the main roads has a relatively smaller impact on the overall road network, in comparison with non-main roads. Due to the occupation of bus lanes, non-main roads may even be reduced to extreme situations where only two lanes remain for two-way traffic. Such conditions, if happening, would significantly worsen traffic congestion in the urban area.

Secondly, the spacing between the main roads in Changzhi City is approximately 700m to 1000m, which roughly aligns with the optimal S requirement we obtained in the previous section (approximately 900m). Moreover, the main roads effectively connect the two "grids" we designed and can serve as "tentacle-shaped" corridors extending to the surrounding areas of the grids.

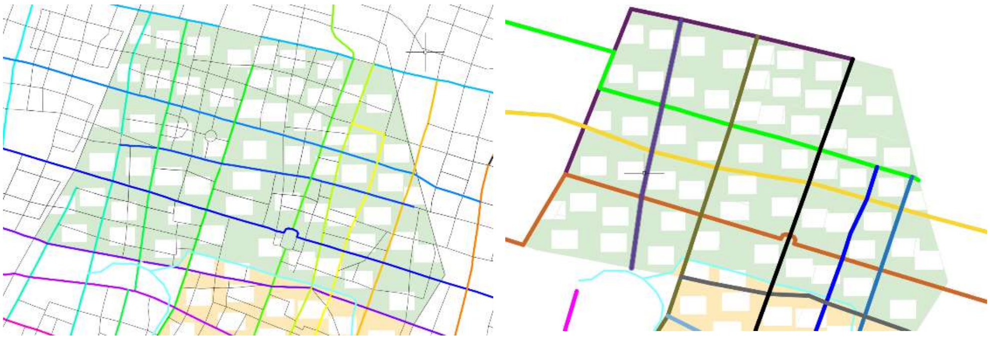

Figure 15 The comparison between the main road network (left image) and the bus route network (right image)

In addition, the influence of rivers also plays a crucial role in the selection of bus routes. The rivers surrounding the southern part of Changzhi City act as natural barriers, dividing many traffic behaviors. For instance, when you want to go to the other side of the river, route selection is not as free as on flat ground. You cannot simply seek the "shortest line segment between two points" path. Instead, you need to find the nearest bridge from your starting point to cross the river and then circle back to your destination. Recall that one of the main criteria for dividing the two grids was based on the presence of rivers, and bridges serve as vital links between the two grids. Therefore, it is necessary to maximize the utilization of the highways where bridges are located by laying bus routes, as they serve as connecting lines between the two grids. Fortunately, several important main roads on the map correspond precisely to the roads that meet these requirements.

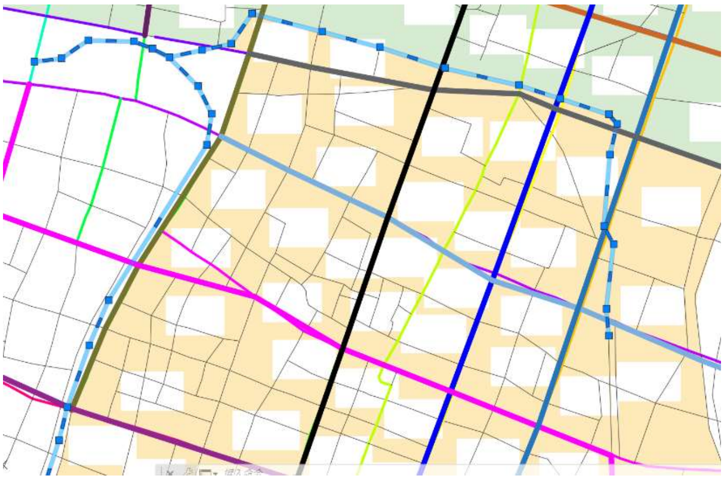

Figure 16 Bus routes across the river

2.3.2 Matching with line spacing

In practical implementation, we have found that the main roads sometimes limit the selection of routes that meet the requirements. For example, in Grid1, the distances between the five east-west main roads and Taihang West Street from the southernmost road are as follows: 0, 600-900m, 1300m, 1800m, and 2700m (estimated). Choosing the above routes does not guarantee that the spacing between each bus route strictly adheres to the 900m requirement. However, we can take an average within a certain area. For instance, within the overall north-south distance of 2700m, we can construct four east-west bus routes—resulting in an average distance of approximately 900m between any two routes. Additionally, we should densely deploy routes near District 5 and District 6, where there is a higher demand according to the OD demand table. This led to the creation of Bus Routes 1, 2, 3 and 4 as shown in the diagram.

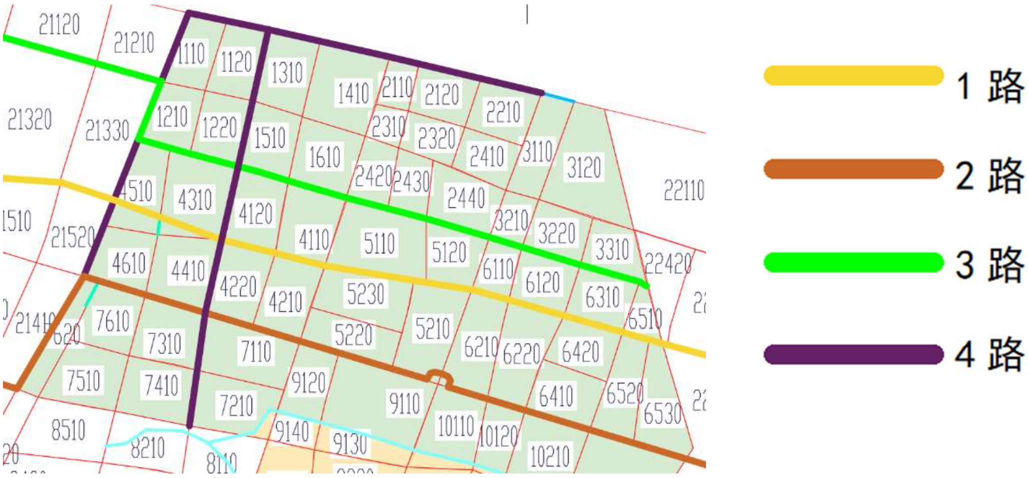

Figure 17 Bus Routes 1,2,3 and 4

2.3.3 Considering real road conditions

During the actual deployment of routes, it is essential to make detailed adjustments based on the actual situation in Changzhi City. For example, Route 9 undergoes two corrections during the design process. The interrupted section is due to the discovery in real-time remote sensing images that the road does not continue after Weiyuanmen South Road, and it can only detour via Jiefang West Street to Xihuan Road. The sharp turn below, changing from a right angle to following the Erxi Line, is because the remote sensing images showed that the original planned route corresponds to a rural dirt road or no road at all.

Figure 18 Adjustment of Bus Route 9

2.3.4 How to deploy corridors

In some areas surrounding the grids where demand is relatively low, it is assumed that the traffic demand is distributed along the routes to construct a corridor model. These corridors generally extend from the bus routes within the grid but are not necessarily laid out on the main roads. Each corridor extends into the surrounding areas along the original route direction, covering the demand area as much as possible, without intersecting with other corridors.

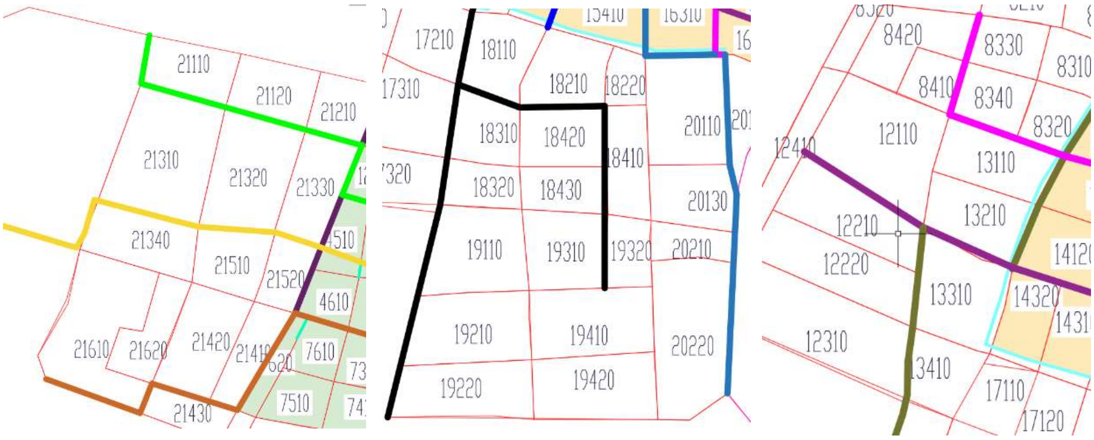

Figure 19 Detailed design of corridors

One notable aspect worth criticizing is that between District 5, which has the highest demand in the city, and District 9, which has the second highest demand, there is only one main road connecting them along the east-west boundary. There is even a lack of interconnected main roads within each of the two districts, making the rivers a significant obstacle that cannot be ignored for internal transportation. This is a major problem we have identified in the current road infrastructure development in Changzhi City...

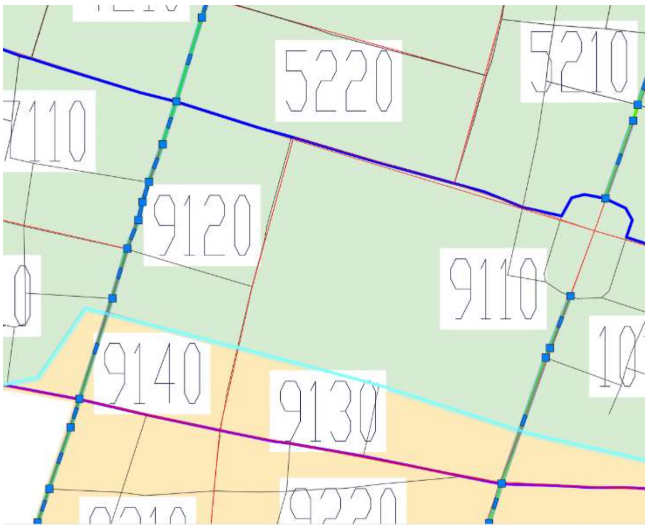

Figure 20 Limited main roads between #5 and #9

2.3.5 Principles for selecting bus stops

Firstly, based on the calculated S values from Unit 2.2, preliminary selection of points is done on the CAD map. The selected bus stops are then compared with the bus stops listed on the official "Changzhi Public Transit" app to assess their distances. It is found that the selected density of bus stops is relatively reasonable.

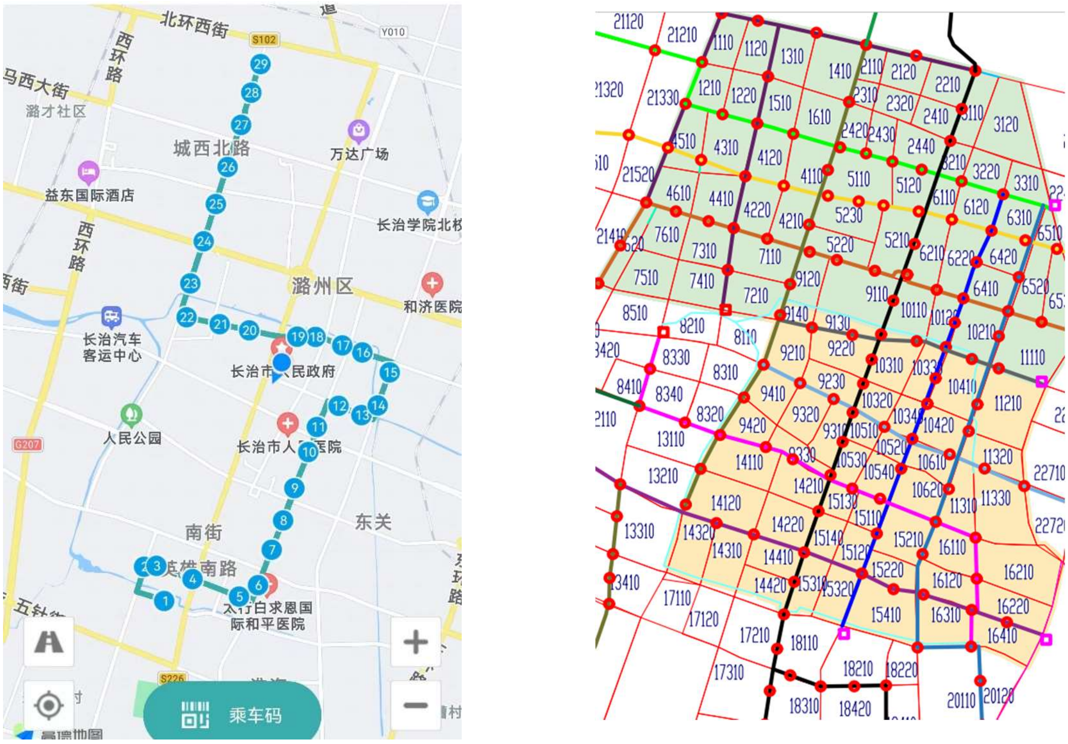

Figure 21 Comparison between actual routes and designed routes

The locations of important places in Changzhi City, such as Changzhi Railway Station and Changzhi East Station, should also be taken into considerations for setting bus stops. For example, when designing bus routes to reach Changzhi East Station, even though the location is not on a main road, we can set the terminal station near Changzhi East Station. At the same time, fewer bus stops are set in the suburban areas along the route to ensure efficient shuttle service.

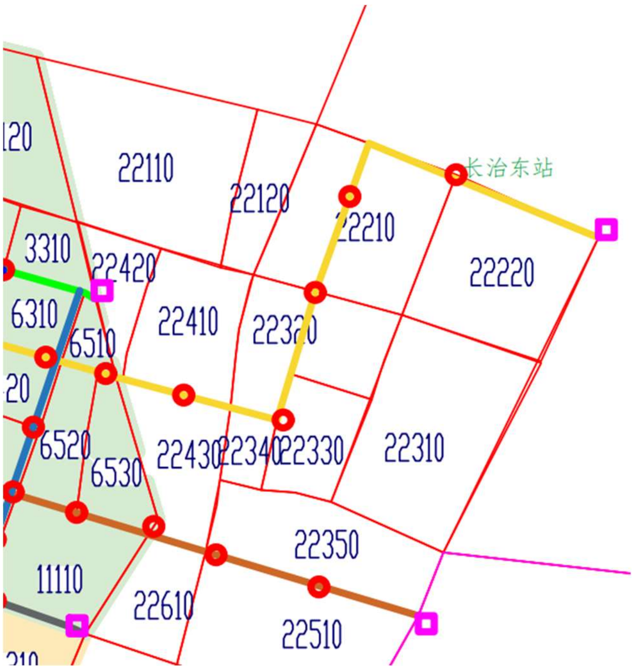

Figure 22 Adjustment of bus route to reach Changzhi East Station

At the same time, during the process of selecting bus stops, we implemented the innovative concept of "walking transfer" as proposed in Unit 2.1. We explain this principle through the following analysis.

When designing bus routes, especially within the grid, we have established a network of intersecting routes on the main roads, minimizing the number of required turns. This approach can improve the efficiency of bus operations to some extent and reduce route duplication. Moreover, through transfers, passengers can also minimize unnecessary detours and travel distances.

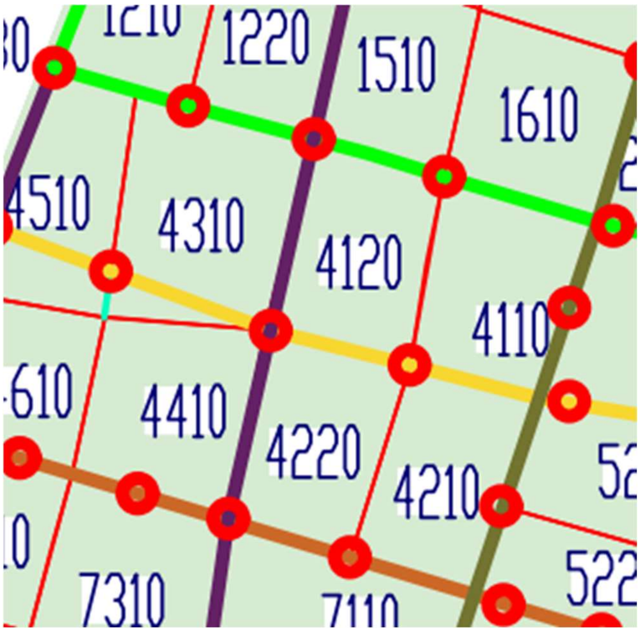

Figure 23 Intersecting routes

It is worth noting that in the CAD map, we have marked many bus stops at intersections for the sake of simplicity in the illustration. However, we are fully aware that it is highly dangerous and contributes to road congestion to have buses stop at busy intersections. Therefore, in reality, bus stops are not placed in the middle of intersections. Instead, we indicate the placement of two pairs of bus stops near the intersections. Buses traveling in different directions stop at their respective dedicated stops near the intersection. The distance between these two sets of stops is relatively short, allowing for quick transfers on foot. In practice, overlapping bus routes occur at the same stop during transfers. By utilizing walking transfers and setting up dedicated stops, efficiency can be significantly improved. The following diagram clearly demonstrates this design.

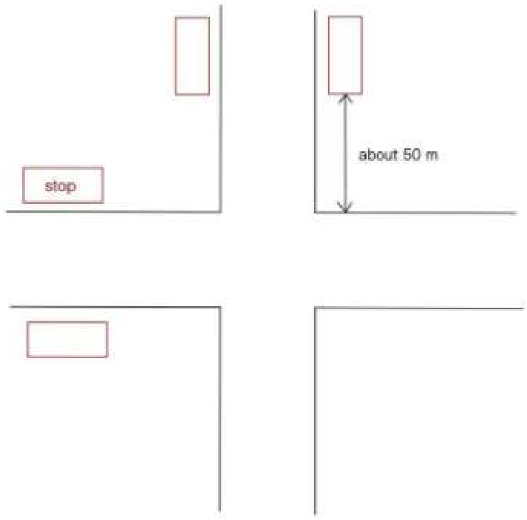

Figure 24 Design of walking transfer

In this way, we have established the bus route network in Changzhi City and set up actual bus stops. After cross-referencing with the actual place names in the remote sensing images of Changzhi City, we have assigned bus route numbers and provided their real originating and terminating station

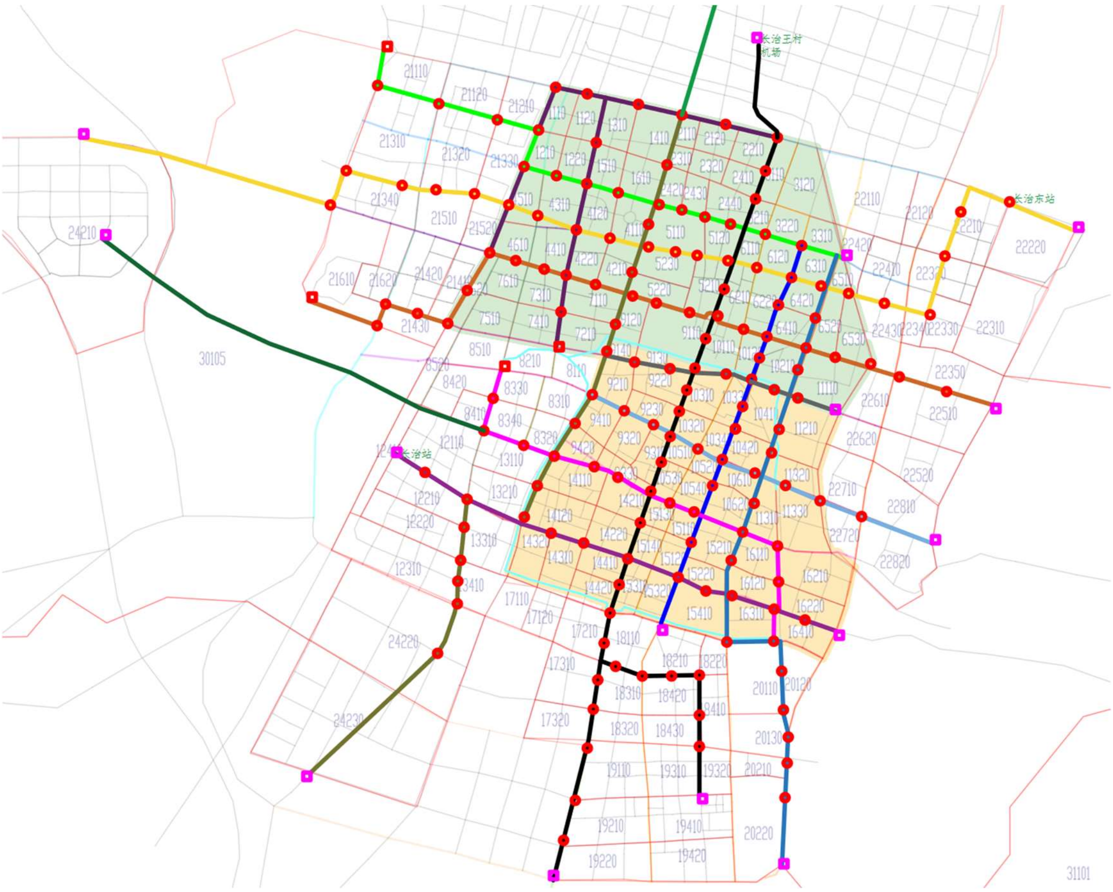

Figure 25 Final result of the implementation of the design

Figure 26 Origins and destinations of each route

Part 3 Further improvement: BRT

3.1 System with BRT

Bus Rapid Transit (BRT) is a new type of public transport system, with the characteristics of high speed, efficiency and environment-friendliness and has been used in many cities in China. For routes among grid 1, grid 2 and other areas, we replace the original corridors with BRT shuttles, calculate the average time and compare it with that in the original scheme.

In order to analyze the problem, we simplify the original region as figure 28 shows and each region is treated as a rectangular shape, as shown in the figure below.

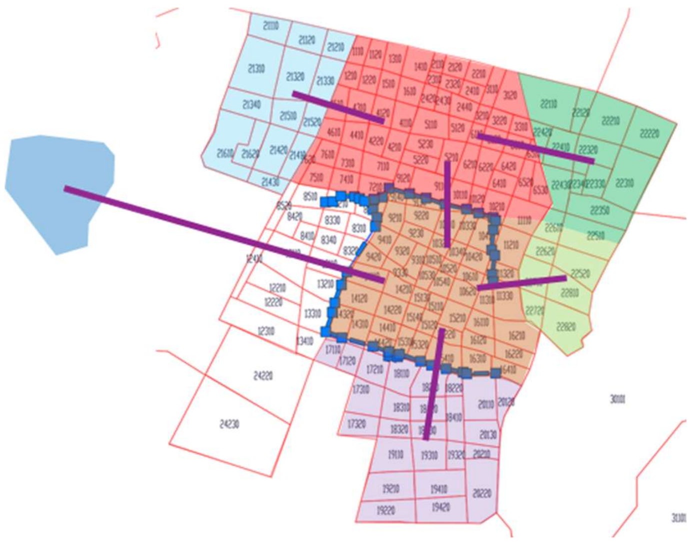

Figure 27 BRT Track Layout

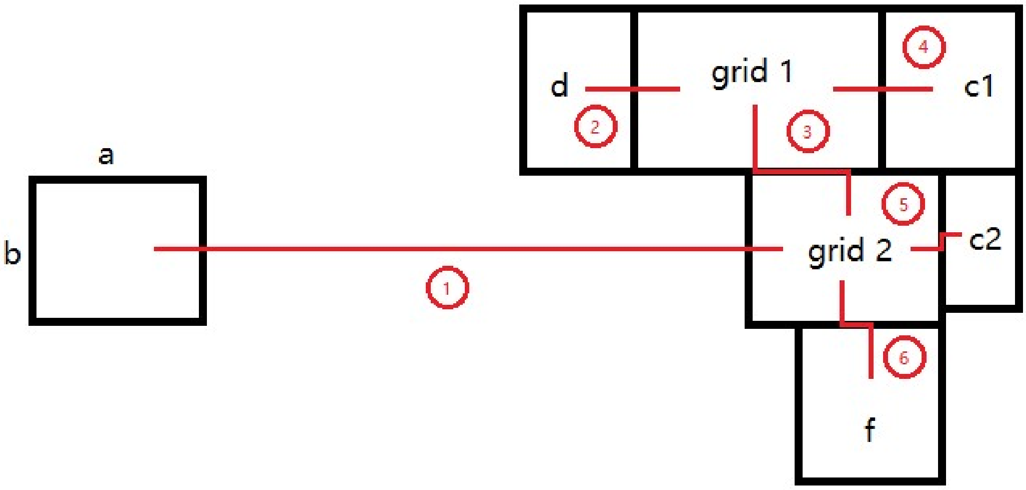

Figure 28 Simplified BRT Track Layout

Region	Transverse Length	Longitudinal Length
Grid 1	5000m	3600m
Grid 2	4500m	3500m
c1	2700m	3600m
c2	1500m	2100m
d	2200m	3600m
f	3000m	3700m
h	2000m	1700m

Figure 29 Transverse and Longitudinal Length of Each Region

Figure 27 is the original map. Figure 28 is the simplified abstract map and Figure 3 is the transverse length and longitudinal length of each region corresponding to the simplified rectangle. The lines in the middle of the regions are the BRT tracks and are numbered.

Firstly, we calculate the length of the track. Considering a model as shown in the figure below, we are going to get an x that minimizes the total time for passengers in the area to walk to the start of the BRT and travel in BRT within the area. Such x serves as the length of the BRT track in the area.

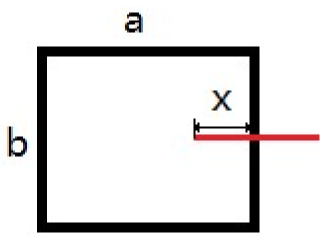

Figure 30 The Model Used to Calculate x

The average longitudinal walking distance is b/4. The average transverse walking distance is $\frac{1}{a}(\int_0^{a-x} y\,dy + \int_0^{a} y\,dy) = \frac{a}{2} - x + \frac{x^2}{a}$. The in-vehicle travel distance within the area is x.

Assuming that the walking speed is v_1, and the BRT speed is v_2, the average travel time in the whole area is:

$$\frac{x^2}{av_1}+\left(\frac{1}{v_2}-\frac{1}{v_1}\right)x+\frac{a}{2v_1}+\frac{b}{4v_1}$$

Therefore when $x=\frac{a}{2}\left(1-\frac{v_1}{v_2}\right)$, the average time is the shortest in the whole region.

Using this model, we can calculate the length of each BRT track. Consult the data and apply the conclusions obtained above, $v_a=1.23m/s$, $v_{BRT}=8.3m/s$. It should be noted that in the grid area, v_a should not be the walking speed v_w, but should be corrected with the v_{grid} after using the grid system. The correction is calculated as follows:

$$t=\frac{S+s}{2v_w}+\frac{\frac{1}{3}(a+b)}{v_{max}}$$

$$v_{grid}=\frac{\frac{1}{3}(a+b)}{t}$$

By substituting the related data of grid1 and grid2 obtained above, we can get $v_{grid1}=2.32m/s$, $v_{grid2}=2.23m/s$. For each track, length of it = x1 in the first area + x2 in the second area. Using the above formula, the length of the six tracks can be obtained:

Table 3 Length of 6 BRT tracks

Number	1	2	3	4	5	6
Length(m)	9027	2765	4327	2978	2984	3587

Finally according to the above conclusions, the average total time between grid 1 and grid 2 is calculated using the following formula:

$$T=\frac{L_{BRT}}{v_{BRT}}+\sum_{grid\ 1}^{grid\ 2}\left[H+\frac{S+s}{2v_{grid}}+\frac{l_{grid}}{v_{max}}+\frac{l_{grid}}{s}t_s+\frac{(\Phi-S)^2}{\Phi^2}H\right]$$

l_{grid} takes the average value:

$$l_{grid}\to\overline{l_{grid}}=\frac{2x^2-2xa+a^2}{2a}+\frac{b}{4}$$

Calculate the average total time between grid areas and other areas using the following formula:

$$T=\frac{l}{v_a}+\frac{L_{BRT}}{v_{BRT}}+H+\frac{S+s}{2v_{grid}}+\frac{l_{grid}}{v_{max}}+\frac{l_{grid}}{s}t_s+\frac{(\Phi-S)^2}{\Phi^2}H$$

l takes the average value:

$$l\to\bar{l}=\frac{2x^2-2xa+a^2}{2a}+\frac{b}{4}$$

The average total travel time of the six paths is calculated in the following table:

Table 4 Travel time between different areas by BRT

BRT route	1	2	3	4	5	6
Total Time(min)	55.7	50.9	59.9	59.3	46.7	47.7

3.2 System without BRT (ordinary situation)

Next, we will estimate the average door-to-door time of people who travel from a region to one of the 2 grids, who just use the original bus network instead of using BRT shuttles connecting the areas mentioned above.

Let's also consider the previous 6 cases but just using original bus network.

1. Region h to grid 2

Combined with the actual bus network designed, we can simplify Region h and grid 2 into rectangles and their position relationship and dimensions can be simplified as figure below:

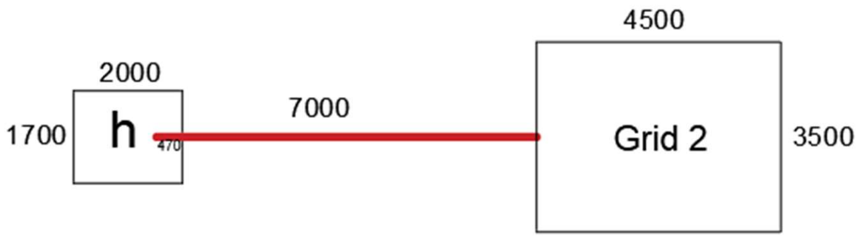

Figure 31 The Case of Region h to Grid 2

The red line denotes the bus corridor (in this case, the bus doesn't stop halfway). Based on the simplified graph above, we can calculate the door-to-door time in average case as below:

$$T_1 = \frac{\frac{1}{4} \times 1700 + 765 \times 0.765 + 235 \times 0.235}{v_w} + \frac{7000}{v_{max}} + H + \frac{(\phi - S)^2}{\phi^2} H + \frac{S + s}{4v_w} + l(\frac{1}{v_{max}} + \frac{t_s}{s})$$

In the equation above, l denotes the average Manhattan distance travelling in grid 2.

$$l = \frac{1}{4} \times 3500 + \frac{1}{2} \times 4500 = 3125 \text{ m}$$

T_1 can be calculated by plugging in other values:

$$T_1 = 3392\text{s} = 56.5 \text{ min}$$

2. Region d to grid 1

We can simplify Region d, grid 1 and the bus routes as below. According to the actual bus network designed, there are 3 routes as shown in the simplified figure.

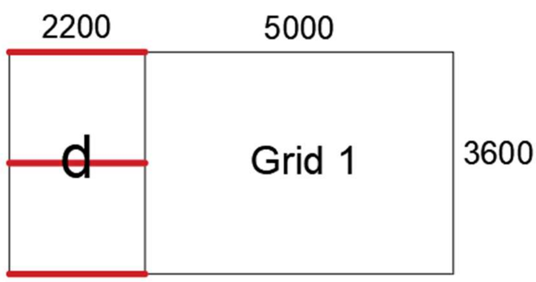

Figure 32 The Case of Region d to Grid 1

Based on the simplified graph above, we can calculate the door-to-door time in average case as below:

$$T_2 = \frac{\frac{1}{8}\times 3600}{v_w} + +H + \frac{(\phi - S)^2}{\phi^2}H + \frac{S+s}{4V_w} + (\frac{1}{2}\times 2200 + l)(\frac{1}{v_{max}} + \frac{t_s}{s})$$

$$l = \frac{1}{2}[(\frac{1}{2}\times 5000 + \frac{1}{4}\times 3600) + (\frac{1}{2}\times 5000 + \frac{1}{2}\times 3600)] = 3850m$$

The value of T_2 is :

$$T_2 = 2115s = 35.3 \text{ min}$$

3. Region c1 to grid 1; Region c2 to grid 2; Region f to grid 2

The simplified figures are as shown below:

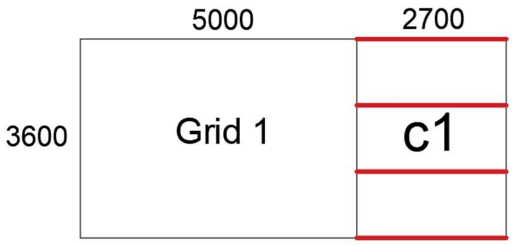

Figure 33 The Case of Region c1 to Grid 1

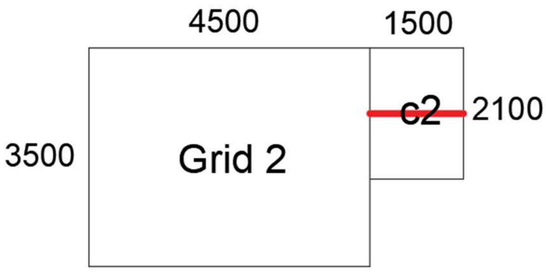

Figure 34 The Case of Region c2 to Grid 2

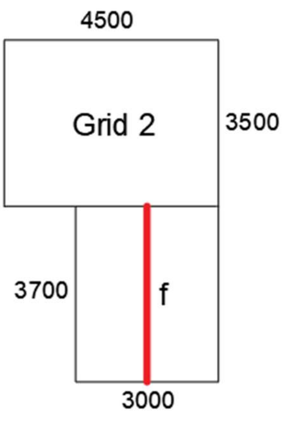

Figure 35 The Case of Region f to Grid 2

T_4, T_5 and T_6 respectively denotes the door-to-door time from region c1 to grid 1, region c2 to grid2 and region f to grid2. Using methods similar to methods used in Region d to grid 1, we can get the values of T_3, T_4 and T_5 as showned below:

$$T_4 = 2032s = 33.9 \text{ min}$$
$$T_5 = 1964s = 32.7 \text{ min}$$
$$T_6 = 2100s = 35.0 \text{ min}$$

4. Grid 1 to grid 2

The simplified figures are as shown below:

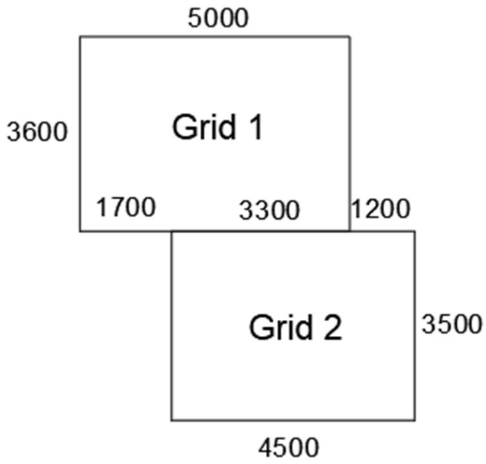

Figure 36 The Case of Grid 1 to Grid 2

In this case, let's think of grid 1 and grid 2 as one new bigger grid as the calculated values of S and s in grid 1 and grid 2 are almost the same and these 2 grids has direct bus lines to connect with each other. The new parameters we can esitimated as below:

$$\phi = \sqrt{{\phi_1}^2 + {\phi_2}^2} = \sqrt{4.222^2 + 4.151^2} = 5.921 \text{ km}$$

$$S = 900\text{m}, \qquad s = 450\text{m}, \qquad H = 3.1 \text{ min}$$

$$T_3 = H + \frac{(\phi - S)^2}{\phi^2} H + \frac{S + s}{4v_w} + l\left(\frac{1}{v_{max}} + \frac{t_s}{s}\right)$$

The simplified graph is as follows:

We can calculate the average traveling distance l from grid 1 to grid 2(or grid 2 to grid 1) by the method of partitioning:

$$l = \frac{1200}{4500} \times \left(\frac{1200 + 2500}{2}\right) + \frac{3300}{4500} \times \frac{3300}{5000} \times \left(\frac{3300}{3}\right) + \frac{3300}{4500} \times \frac{1700}{5000} \times 2500 = 2550 \text{ m}$$

So we can get $T_3 = 1476\text{s} = 24.60 \text{ min}$

3.3 Comparison and Conclusion

Next let's compare the results calculated with the results with BRT. They are juxtaposed in the table below.

Table 5 Comparison between system with BRT and without BRT

Route	1	2	3	4	5	6
Total Time(min) with BRT	55.7	50.9	59.9	59.3	46.7	47.7
Total Time(min)	56.5	35.3	24.6	33.9	32.7	35.0

with original bus network						

From the table above, we can find that the total travel time with BRT is almost always longer than the total time cost with original bus network. We get these insights: using BRT shuttle even with H=0 to realize the connection between a region and a grid, or between a grid to another grid, is not better than the method that relies on grid system combined with corridors to connect the regions around the 2 grids, and uses direct bus lines to connect grid 1 with grid 2. This is because many corridors can be extended from the grid and provide people more alternatives to travel from one region to the grid, which is more flexible than the BRT shuttle. Besides, it will cost much more to build BRT system.

This shows the strength and rationality of our designed ”gird+corrider” bus network. However, for No.1 connection, the total time with BRT is less. So when we want to connect the downtown with a suburb region far away, BRT is a possible option.

Part 4 Division of labor

Qi Yu(Group leader):

Operating cost estimation(1.2.5) Model Selection(2.1) **Quantitative model analysis(2.2)** and Calculation.

Lin Xiaohan:

Region characteristics(1.1) Model Selection(2.1) **Implement of the design(2.3)** Charting

Lin Zhizhi:

Value of user time estimation(1.2.4) **Further improvement(3)** PPT & Charting

Zhang Xinqi:

Demand characteristics(1.3) Model Selection(2.1) **Further improvement(3)**

Zhao Haocheng:

Lost time per stop& maximal cruising speed estimation(1.2.1&1.2.2) **Model Selection(2.1)** Implement of the design(2.3)

Zhou Ziyi:

Passenger walking speed(1.2.3) **Data collection(1)** PPT

(Work in bold text means that the person takes charge of this work and writes corresponding parts in this report)