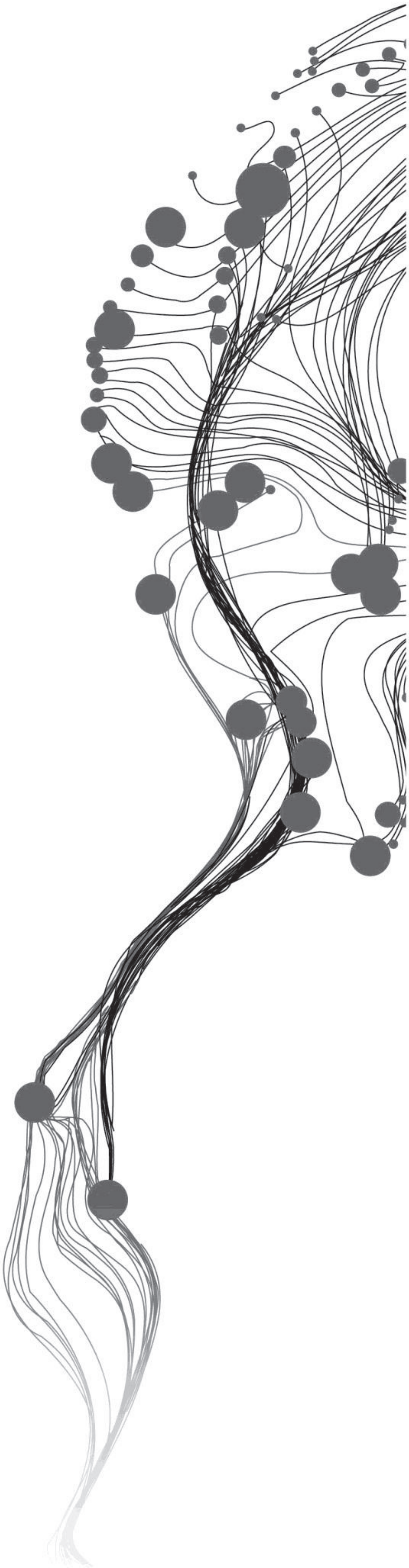
Bus Routes Optimization in Wuhan, China

ZHANG NING
March, 2011

SUPERVISORS:
Ing. F.H.M. Frans van den Bosch (ITC)
Prof. Dr. Huang Zhengdong (Wuhan University)



Bus Routes Optimization in Wuhan, China

ZHANG NING
Enschede, The Netherlands, March, 2011

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Urban Planning and Management

SUPERVISORS:
Ing. F.H.M. Frans van den Bosch (ITC)
Prof.Dr. Huang Zhengdong (Wuhan University)

THESIS ASSESSMENT BOARD:

ABSTRACT

With the expansion of urban area, urban bus transit plays an increasing important role in urban transportation. Reasonable network design is of great importance to the operation of bus transit system, while irrational layout of bus routes leads to the poor operation and a low service quality of bus transit system. For example, much overlapping among routes would lead to the traffic jam, and low network density reveals the low accessibility of bus in areas without routes passing by. Nowadays factors for bus network planning become more complex with the construction of rail transit in large cities of China. The integration of the bus and rail network is a new challenge in transit planning.

The objective of this research is to optimize the layout of bus routes in Wuhan using a GIS-based platform "TransitNet" to alleviate or solve the problems exposed from the layout of current existing bus routes in the city, such as reducing the route overlapping, enlarging the network coverage, and reducing the burden of main road. This research has employed a method for multi-modal transit route design based on stop, which treats certain rail routes as restriction. Genetic algorithm (GA) is applied to search for optimal combination of candidate routes. With the case of center area in Wuhan, two scenarios have been generated in the current situation with No.1 light rail and in the short-term situation with No.1, 2 and 4 rail routes. Evaluation based on the optimization results is generated to analyze that whether the expected improvements has been achieved, especially in the short-term situation.

Results indicate that great improvements can be achieved on the optimized network. Optimal network and routes displayed advantages at vacancy rate and coordination with rail. Also, the burden of main roads and two bridges crossing the Yangtze River have been reduced reasonably. Based on the optimized result, further improvement could be brought out by specific adjustment in the future. Research findings are summed up in the end, and future recommendation is discussed.

Keywords:
Bus transit; planned rail transit; bus routes optimization; genetic algorithm; GIS; TransitNet

ACKNOWLEDGEMENTS

First and foremost, I would like to extend my sincere gratitude to the Faculty of Geo-Information Science and Earth Observation of the University of Twente (ITC) and Wuhan University for providing me this precious opportunity to study in the Netherlands. It broadened my view and expanded my knowledge. The precious time together with you will have a special place in my heart.

I would like to express my sincere appreciation to my first supervisor, Frans van den Bosch (University of Twente), for his instructive advice and useful suggestions on my thesis, and his thorough and critical comments aiming to enhance and improve the research. I'm deeply grateful of his help in the completion of this thesis.

Special thanks go to my second supervisor, Prof. Huang Zhengdong (Wuhan University), for his constant encourgemnt and guidance. He has walked with me through all the stages of the research process. His profound ideology, comprehensive knowledge, solemn manner and kind mind deeply influenced me. Without his consistent and illuminating instruction and support in the hard times of this research, this thesis could not have reached its present form.

High tribute shall be paid to Dr. Richard Sliuzas, Dr. Mark Zuidgeest and Ms. Monika Kuffer, all from the University of Twente, for their constructive comments at the start stage of the research.

My sincere gratitude goes to the colleague both from ITC (Cheng Fangfang, Hao Pu, Mwehe Mathenge) and Wuhan University (Wei Xuebin, Zhou Jun, Yu Liang, Zhang Ying, Yang Ruqin and Zhang Yuanyuan) for the valuable experience with all of you which will be a never-to-be-fortotten period of my whole life.

Finally, my appreciation will not be complete without saying that I am forever grateful to my family, especially my parents and my maternal grandfather. Their encourgement, support and endless trust and love have been my driving force to continue my study and pursue my ideal. Thanks for all of you!

This research is supported by Chinese 863 Scientific Research Program "Optimization of Multi-modes of Public Transport in Wuhan, China", of which the core product "TransitNet" is a key technical environment for the operation of main parts in this research.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Research Background

Wuhan is a metropolitan city of China with a population of 8.29 million and approximate 8494 square kilometers area (WHSB, 2008), located in the geographic center of China, as Figure 1-1 shows. Wuhan is comprised of three towns Wuchang, Hankou and Hanyang, all separated by the rivers Yangtze and Han. For a long time, Wuhan has played a key role as the transport intersection of mainland in China, connecting the north, south, east and west.

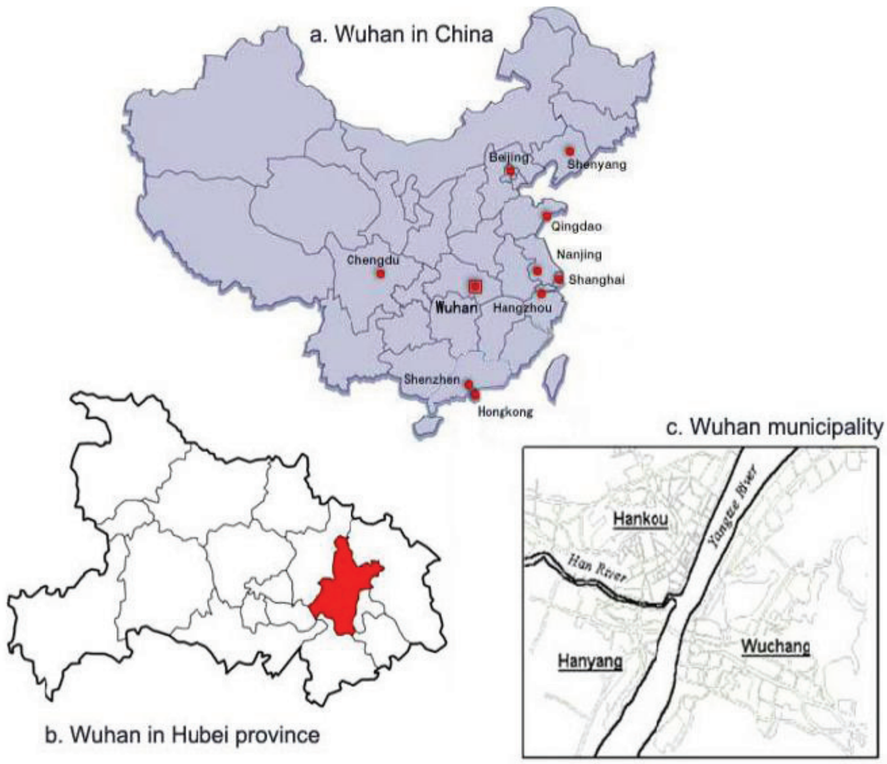


Figure 1-1 Location of Wuhan in China
(:: Source Xia,2009)

In recent years, Wuhan has maintained sustainable and rapid national economic development. Until the year of 2008, economic development in Wuhan has achieved the historical peak, with gross urban product of 396.01 billion yuan, 15.1% higher than that in 2007 (WTPI, 2009). Wuhan currently is an economic active city, with an increasing need for transportation (people as well as goods) and currently causing lots of traffic congestions in the city.

As a bus-oriented metropolis, Wuhan possesses 277 bus routes with total route network length of 1092 kilometers, operation length of 5,306 kilometers, bus stop number of 2,460, and six major transit hubs that cover an area of 6.6 hectare in the whole city, according to the statistic in 2008 (WTPI, 2009). However, with the rapid development of socio-economic in China, transport system of Wuhan has been confronted with serious problems: high population density and fast urban growth lead to a dramatic growth of travel demand which results in the increasing vehicle numbers. This change directly causes traffic bottlenecks, and stressed roadways, etc. All of these contribute to the bad transport situation of

Wuhan. To some degree, all the problems listed above can be triggered by the lack of development of public transport. Also, the central government and local authorities of Wuhan has invested huge human material and financial resources to construct the urban subway system to spur economic development and handle the crisis while enhancing the capacity of passenger transit, which consists of 8 routes and 119 subway stations, planned to be operational by 2020 (Wei, 2010).

Although the planned subway system can be taken as an effective solution of the problems, it still cannot change the fact that bus transit service is a major mode of public transport system in Wuhan, and this situation will last for a period of time in the city, as the Figure 1-2 shows. Bus transit system optimization or re-planning is still been considered as an essential solution of the problem in metropolises like Wuhan to contribute in the reduction of traffic bottlenecks. Therefore, optimization of bus system has been proposed by the central government, local authorities and institutes of the City Wuhan. An action plan, aiming to solve the traffic congestion problem by optimizing the transit network of the whole city, was published in 2009 (WTC). According to the plan, the whole transit system will own 368 bus routes with the total length of 5798 kilometers and the network length[1] of 1582 kilometers.

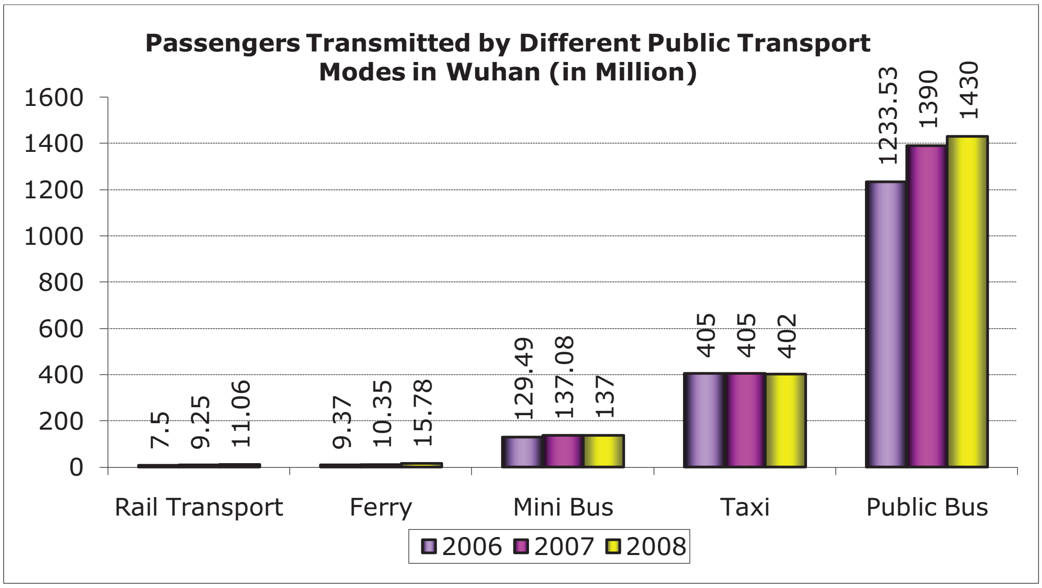


Figure 1-2 Passengers transmitted by different public transport modes in Wuhan
(:: adapted from WTPI, 2007, 2008, 2009)

1.2. Scientific Justification

Operational state of urban public transport closely interrelate to people's daily life and production, thus striving to develop urban public transport is a basic policy in China (Sun, et al., 2010). Nowadays, the speed of urbanization gets faster and faster, accordingly, the re-planning or optimization of urban public transport should follow this process of the development.

Wuhan is naturally separated by two rivers Yangtze and Han, and this led to the political subdivision into three sub-towns: Wuchang, Hankou and Hanyang. The urban development pattern caused by the rivers leads to the intrinsic flaws of the urban road network. Moreover, inadequate development strategies and operationalisation of public transportation system contributes to an over-concentration of the population flow on the main roads of the city. In the meantime, rail (including the light rail and metro) is still in its infancy with short routes, limited carrying capacity and inconvenience transfer. Therefore, bus routes

[1] **Network length:** The network length here means the length of road arcs that has the bus routes passed by it.

optimization is an important solution to alleviate the traffic problems exposed, and it is also an essential action to implement the bus priority strategy in the multi-mode transport environment.

Moreover, so far, not much attention has been paid to the problem of improving public transportation networks. In many cities these networks have been built sequentially and do not fit to the needs of the users any more , which is reflected in the long travel times and an unnecessarily high number of people who have to transfer (Mandl, 2003). Compared to other investments for improving the operational efficiency and the service level of public transportation systems, the costs of optimizing the bus routes are low and can highly improve the performance of the system, according to Mandl.

Now, a new public transit system--"TransitNet" of Wuhan is developed by the team of Professor Dr. Huang Zhengdong[2], supported by Chinese 863 Scientific Research Program[3] "Optimization of Multi-modes of Public Transport in Wuhan, China". In "TransitNet", multiple optimized bus route sets can be generated under different transit system conditions (including single mode and multi-mode) which are reflected by various initial values. The whole system aims to obtain the best urban transit system based on the optimal efficiency. It can be considered as an effective complement for current transit planning methods. All sets of the bus routes are optimized by using the genetic algorithm. During the optimization process, all the candidate bus routes follow the rule "survival of the fittest", shown as four different fitness functions which are separately described as bus stop coverage, route efficiency, stop effectiveness and road edge effectiveness. The four functions are chosen as "survival rules", aiming to obtain the corresponding optimized bus route sets. This system is a helpful tool that supports the bus route optimization.

1.3. Analysis and Statement of the Problem

Wuhan is chosen as the study area of this research. As a typical metropolis in central China, Wuhan is characterized by its high population density and large urban scale. For a long history, Wuhan has relied on bus system, and public bus service is still the major urban passenger transit mode of the city. As is shown in the Figure 1-2, it is clear that the bus system will still keep on being the most important and conventional public transit mode in Wuhan.

The current public bus system in Wuhan is confronted with severe problems shown as follows (L. M. Li, 2005):

- Rapid growth of vehicle number followed by the significant increase of traffic flow on the main roads, which makes the mismatch between the travel demand and road capacity increasingly prominent.
- Serious traffic congestion on two bridges of the Yangtze River.
- Serious traffic congestion in the urban center area.
- Poor convergence between the internal and external traffic of the city.

Problems revealed above are mainly caused by the irrational layout of the bus route network, such as too many long routes, highly route overlapping, low network density, and so on. According to the current problems exposed and future development of bus system, bus route optimization for Wuhan should be

[2] **Professor Dr. Huang Zhengdong**: Professor of School of Urban Design and Planning, Wuhan University. Wuhan, China.

[3] **Chinese 863 Scientific Research Program:** 863 Program, short of National High Technology Research and Development Program, is a high-tech development plan of the People's Republic of China. The scheme is a national program that is led by the government, and takes the limited areas as research objectives throughout the whole country.

executed. This research will try to explore a systematic approach for bus route optimization and give a preliminary evaluation based on the optimization results.

1.4. Research Objective

This research aims to optimize bus routes in Wuhan, China. According to the current existing problems and future development of bus system of Wuhan, bus route optimization will be implemented from the following several perspectives (WTC, 2009):

- Reduce the route overlapping, for the sake of reducing the burden for the main roads.
- Increase the route network coverage in order to reduce the coverage of regions without bus routes passing by.
- Reduce the overlapping and parallel length between the bus route and planned rail routes, and add the feeder routes for rail routes.
- Reduce the burden of the two bridges preliminarily.

Based on the main objective, several sub-objectives are confirmed in order to achieve the main goal gradually.

1.4.1. Main Objective

The objective of this research is to optimize the layout of bus routes in Wuhan with the consideration of layout of planned rail routes respectively in the current situation and short term situation, in order to solve or alleviate the problems of the current bus routes.

1.4.2. Sub-objectives

- **To analyze the problems of existing bus routes.**

By analyzing the problem of layout of existing bus routes both at the route network level and individual route level from the perspective of route design and service quanlity, the associated criteria (that avoid the problems exposed based on the analysis results) for candidate routes selection can be determined.

- **To filter the irrational existing bus routes.**

Filtration will be implemented based on the evaluation result at the individual route. Each existing route that cannot meet the certain requirements will be removed. Filtration is a preparing process for route optimization.

- **To generate candidate bus routes.**

A candidate route has to meet the requirement of previous defined criteria. The candidate route set is an important source for route optimization.

- **To generate the optimal bus route set by using genetic algorithm.**

The optimal bus route set is extracted from the candidate route set following a series of evolutionary principles.

- **To check whether the expected improvements has been achieved.**

To analyze that whether the optimized bus route set has shortened the gap exposed previously between the national (and local) standards and the newly proposed optimized bus route set.

1.5. Research Questions

- To analyze problems of existing bus route network of Wuhan.

Question 1: What factors should be considered when designing a bus route network?

- To collect data required.

Question 2: What data is required for candidate bus routes generation?

- To filter the irrational existing bus routes.

Question 3: What factors which are adequate to determine whether an existing bus route is rational should be taken into account?
Question 4: How to perform the filtration with respect of determined factors?

- To design a rational plan for optimization.

Question 5: What requirements should be satisfied in the optimization process?

- To test and verify that whether the expected improvements are achieved by route optimization.

Question 6: How to evaluate the optimized bus routes both at the network level and individual route level?

1.6. Conceptual Framework

According to the research objectives and questions, three stages including five research steps are constructed, as Figure 1-3 shows. They are evaluation for existing bus routes, data preparation, existing bus routes filtration, bus routes optimization, and evaluation for optimized bus routes.

1.7. Research Design

As is shown in the Figure 1-4, it outlines the operational plan based on which the entire study takes place. It incorporates three stages, including preparation for optimization, optimization process, and evaluation of optimization results. In each stage, each relative question will be solved by using a suitable method, and get a product to assist to answer and settle the following questions.

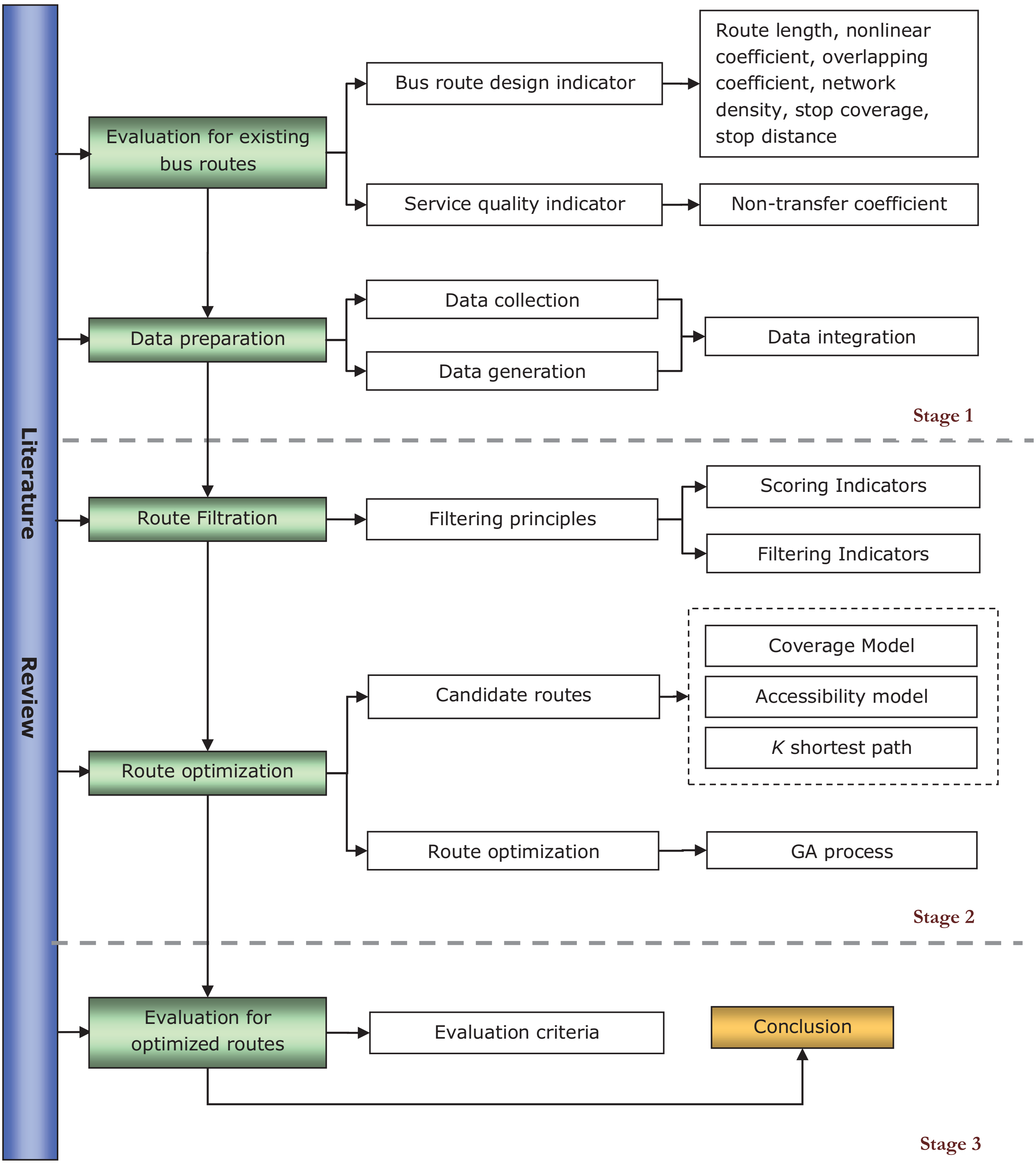


Figure 1-3 Conceptual framework

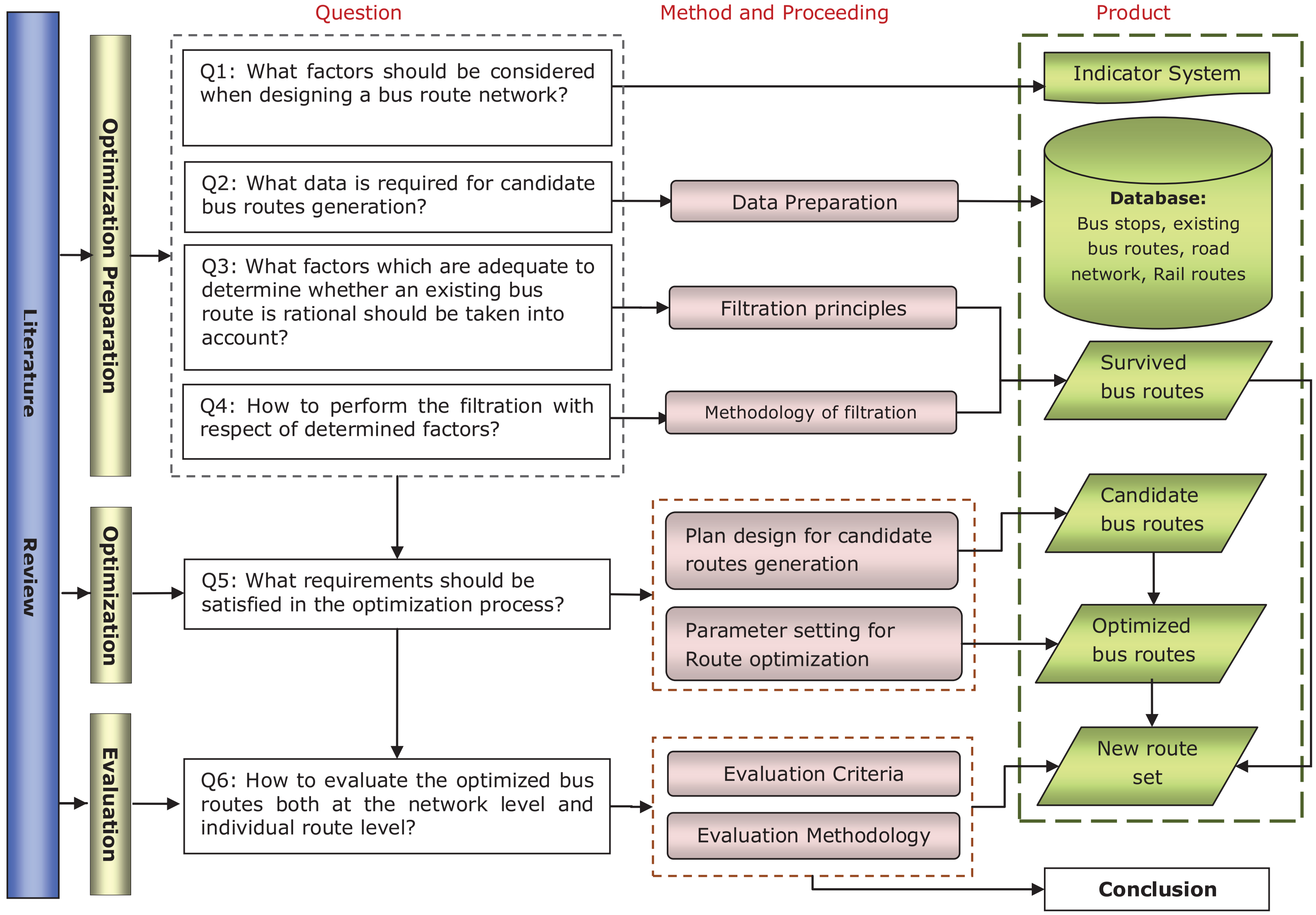


Figure 1-4 Operational plan

1.8. Thesis Structure

The thesis is organized into eight chapters which have been outlined as follows:

Chapter 1: Introduction

This chapter provides an introduction to the research and mainly address the research objective that optimization will be generated based on the existing bus routes to enlarge network coverage, reduce route overlapping, add feeder routes and reduce the burden of two bridges. In addition, the research problem, questions are also been identified. Finally, a research design is provided in order to show that how the research aims to achieve its intended objective.

Chapter 2: Literature Review

General reviews of theoretical background and previous studies on bus routes evaluation and optimization are summarized in this chapter.

Chapter 3: Background of Study Area

This chapter presents a brief introduction to Wuhan city, which is unfolded through the discussion of traffic operation characteristics and challenges of Wuhan.

Chapter 4: Basic Spatial Database – "Transit Multi Modal"

This chapter describes the secondary data collection and further data generation required to support the optimization process in this research.

Chapter 5: Research Methodology

The methodology of bus route optimization is described in this chapter, which comprises five specific steps, namely, evaluation for existing bus routes, bus route filtration, candidate routes generation, route optimization, and evaluation and discussion. Meanwhile, a brief introduction is made to TransitNet which is a helpful software employed in this research.

Chapter 6: Bus Route Optimization in Current Situation

In this chapter, optimization will be implemented with the consideration of layout of No.1 light rail route in the current situation.

Chapter 7: Bus Route Optimization in Short-term Situation

The optimization is carried out considering the restrictions of the No.1 light rail route and No.2 & 4 metro lines in short-term situation until 2013. This scenario development is implemented on the premise that no change would happen to population in the study area in the next three years.

Chapter 8: Conclusion and Recommendation

In this chapter, the research questions proposed before the optimization are answered, and some recommendations are offered.

2. LITERATURE REVIEW

2.1. The Key Role of Public Transport

Moving from location to location is a human activity and using public transport is a main alternative to do so. Public transport is an indispensable component of the social economy and plays a key role in spatial relations between locations. It represents a basic service and creates valuable connections among all the cities which provide diversified activities, economic vitality, socially and environmentally sound conditions (Rodrigue, et al., 2009; Vuchic, 2002). A city and its suburban areas must have a well functioning and attractive public transport system to provide high quality of life and stay in a long-term dynamic status.

The public transport can have a view advantages compared with private transport. Firstly, the service provision of public transport can enhance personal and economic opportunities which are demonstrated in various ways, such as access to work, school, visiting, and chance to new jobs for millions of people. According to the statistic of job analysis survey sponsored by American Public Transportation Association (APTA, 2009), about 450,000 jobs now provided by public transportation projects will put people to work building America's future. Secondly, public transportation can save fuel and reduce congestion, and then save money and time. For example, Americans living in the service area of public transportation can save approximately 646 million hours in travel time and 398 million gallons of fuel annually in congestion reduction alone (APTA, 2010). Finally, public transportation can provide a cleaner environment and make a better quality of life, which are realized by reducing gasoline consumption and carbon footprint. As Figure 2-1 shows, levels of air pollutants emissions of public transportation are only a small portion of those of automobiles.

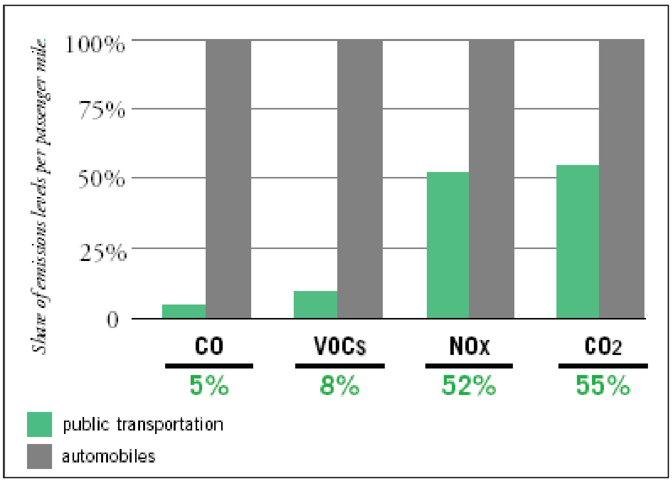


Figure 2-1 Public Transportation—A Cleaner Alternative
(:: Source APTA, PT, 2008)

These advantages can be partly realized by having a public transport system in place which performs well. In the following sections, optimization and performance evaluation is discussed focused on bus transit system as public tranpsort mode.

2.2. General Review of Transit Route Network Optimization

Optimization is a process or a technique to search for the best solution for a problem or a procedure as effective, perfect, or useful as possible (Zhao, Gan, 2003). The transit route network optimization problem may be started as the determination of a set of transit routes subject to a set of constraints to achieve the expected goals, according to Zhao and Gan. These goals can be set to minimize the overall cost of user and operator, the number of transfers, waiting time and so on. However, constraints are usually a series of strict conditions that must be satisfied, such as the maximum allowable bus headway, vehicle load factor, bus fleet size, maximum route length, number of routes, and the integrity restrictions on some or all the variables, as well as other requirements related to transit polices.

2.2.1. Previous Studies on Transit Route Network Design and Optimization

Transit route network (TRN) design is the single most important planning step in the urban transit planning process (Ceder, Wilson, 1986). A TRN optimization process attempts to find the optimal route network with different objectives, such as optimal transfer, route directness, and ridership coverage (Zhao, 2004).

Based on the proposed functional description and evaluation system, de Hsu and Surti (1975) have established a framework of route selection in bus network design considering the selection priority which is determined by several attributes at the neighborhood level, such as the connectivity of transfer nodes and the accessibility of the residential and activity nodes.

Pattnaik,et al. (1998) have employed the genetic algorithm as a search and optimization method to solve the route network design problem. The whole process consists of two stages which are candidate routes generation stage and the optimum route set selection stage.

For the sake of maximizing the direct unit passenger flow and minimizing the average travel time of direct travelers on each route in the meantime, an improvement route generation algorithm is proposed and implemented for bus network design (Mo, et al., 2008). Similar study for bus network optimization is also generated by using a parallel ant colony algorithm (Z. Z. Yang, et al., 2007). In order to get a better bus dispatching solution, a mathematical model for optimal selection of public transit route is develop by using the improved ant colony algorithm (Shi, et al., 2010). In addition, DNA algorithm is also an effective optimization algorithm to consider the shortest running distance by bus and the minimum interchange among the paths in the process of optimal path selection, according to Zhang, et al. (2009).

In the multi-mode transport environment, in order to build a better connection between bus routes and rail routes, the feeder bus network design problem is solved by using genetic algorithm and colony optimization (Kuan, et al., 2005). In this study, several test problems are generated randomly to evaluate the computational efficiency of the two meta-heuristics and the quality of solutions obtained by them. The test results have shown that both of these two algorithms almost have the same efficiency and effectiveness with the state-of-the-art algorithm such as simulated annealing and tabu search.

In sum, countless studies or researches are generated based on the bus route network design as well as optimization which involve determining a route configuration with a set of bus route and associated frequencies that achieve the desired objective.

2.2.2. Methods of Transit Route Network Optimization

A great deal of research has been conducted in the area of transit network optimization. The methods in the literature may be grouped into two categories: mathematical approaches and heuristic approaches (Zhao, 2004).

- An approach is taken as a mathematical approach if the problem is formulated as an optimization problem over a relatively complete solution search space (Zhao, 2004). For transit network design problems, mathematical optimization is usually formulated as constrained mixed optimization problems, which are usually combiantiorial problems (Zhao, Gan, 2003). Generic solution search methods used to obtain the optimal solution include various greedy type algorithms, hill climbing algorithms, and simulated annealing approadches, and so on. These mathematical search algorithms are introduced and explained in many articles, such as (Bertsekas, 1998), (Skalak, 1994) and (Zhao, et al., 2006).

- In transit network design, heuristic approaches are usually a combination of applications of guidelines and procedures for route selections and bus frequency/headway determination, based on criteria which are estabilished from past experiences, ridership and demand data, cost and feasibility constraints, intuition of the transit planners, as well as some policies out of ceratin social and/or political considerations (Zhao, Gan, 2003). Previous studies on transit network optimization by using various heuristic approaches can be found in (Axhausen, Smith Jr, 1984; Ceder, Wilson, 1986; Fan, Machemehl, 2004; Lampkin, Saalmans, 1967; Rea, 1972).

Among the various algorithms, the genetic algorithm (GA) has been extensively discussed. Genetic algorithm is search algorithm that is based on concepts of natural selection and natural genetics (Holland, 1992). A GA makes use of the genetic principle of "survival of the fittest" that the survived genes can be transferred from a generation to its sub generation through inheritance and mutation. The GA approach is distinguished from other search methods in that the transition scheme of GA is probabilistic, whereas tranditional methods use gradient information (Goldberg, 1989). Moreover, the only information used during optimization is the goodness that is in the form of objective function (Chakroborty, 2003). Furthermore, it is possible to incorporate problem-specific information and expertise during the optimization process, according to Chakroborty. Because of these features, genetic algorithms are used as general purpose optimization algorithms in many studies, such as (Zhao, et al., 2006) and (Kuan, et al., 2005).

2.3. Performance Evaluation of Public Transport System

Evaluation provides the basis for preparing the planning scheme and optimizing the layout of urban transit network throughout determining the relative merits of different planning alternatives. There are different performance measurement methods and approaches in the evaluation process for bus transit system. These methods may differ from each other depending upon the field they are applied to or the benefiting community they served or on the basis of the metrics or the data they use or the approach they employ, or even on their basic underlying assumptions (Sheth, 2003).

Effective performance evaluation is a significant means to promote the operation efficiency and service quality of urban transport system (Fielding, et al., 1985; Gomes, 1989). Before the real execution, two main issues need to be addressed to be able to choose proper measurement methods to implement them. First, the evaluation content and its branches are usually various and extensive, therefore a certain theme need to be determined. Second, the evaluation criteria and indicators are generally multiple, consequently a well-structured evaluation indicator system of multilevel hierarchies need to be developed.

2.3.1. Evaluation Indicator System

There are numerous performance criteria that can be utilized in the bus transit system evaluation process. These criteria initially serve as indicators that estimate performance of bus network structure, gauge the quality and quantity of service offered by a public transit system's bus routes, and operational efficiency of a whole network. Under each level, sub-indicators are followed in detail. For example, assessment of service quality can be unfolded in terms of safety, convenience, speediness, on-time performance, comfort, economy and efficiency (C. Q. Li, 2008). They also include a series of items that determine and reflect the manner in which transit systems offer service to the public, and often have a direct relationship with the costs of service provision (TRB, NRC, 1995).

Usually, the evaluation criteria are divided into the following five categories (TRB, NRC, 1995):

- Route design, of which the criteria (such as the location of services, the structure and configuration of transit routes) mainly relate to the basic structure and design of a transit system's route network.
- Schedule design, of which the criteria relate to the basic frequency and the hours and days in which a route will run.
- Economics and productivity, of which the criteria are used to monitor or evaluate the financial and ridership performance of individual bus routes.
- Service delivery monitoring, of which the criteria are used to measure service reliability.
- Passenger comfort and safety, of which the criteria are used to measure the ambiance that greets a rider using the bus transit system.

A survey of transit agencies in North American indicates that as many as 44 different evaluation criteria are currently used in the transit industry (TRB, NRC, 1995). These criteria cover activities related to bus route design and operation, ranging from location of bus stops to the hours of service. Based on results from the synthesis survey in North American, more transit agencies are formally using standards in the evaluation of bus routes, particularly larger systems with over 500 buses.

For example, the quality of a transit route network can be evaluted considering some network parameters, such as service coverage, network efficiency, and number of transfers required (Zhao, 2004). Service coverage refers to the percentage of the total estimated demand that potentially can be carried by the transit services based on a given transit route network. Network efficiency reflects the cost of providing transit services in this network. Number of transfers reveals the degree of incompetence of this network to supply direct service between all pairs of origins and destinations.

2.3.2. Previous Studies on Public Transportation Analysis and Evaluation

Urban transportation system can be measured and evaluated in many ways. Evaluation can be implemented by reflecting different perspectives concerning users, modes, land use, transport problems and solutions, as well as the means of measuring transport activity and the type of the used performance indicators (Pticina, 2008), as Figure 2-2 shows.

In recent years, some studies have been conducted to determine route design, schedule design, economics and productivity, service delivery monitoring and passenger comfort and safety using measures of quantitative and qualitative factors. The factors influencing service reliability have also been widely analyzed.

Kakimoto and Mizokami (2005) has developed a grouping evaluation method of business management condition for individual bus route in order to distinguish the subsidized bus route efficiently in both inside and outside environment. In the inside environment, productivity and management condition of bus route, the percentage of actual passenger number to potential demand (or attractiveness of passengers) are considered as indexes aiming to identify the inefficient bus routes and quicken the improvement of them. In the outside environment, potential demand and public of bus route are selected to show the significance of bus transit for daily life.

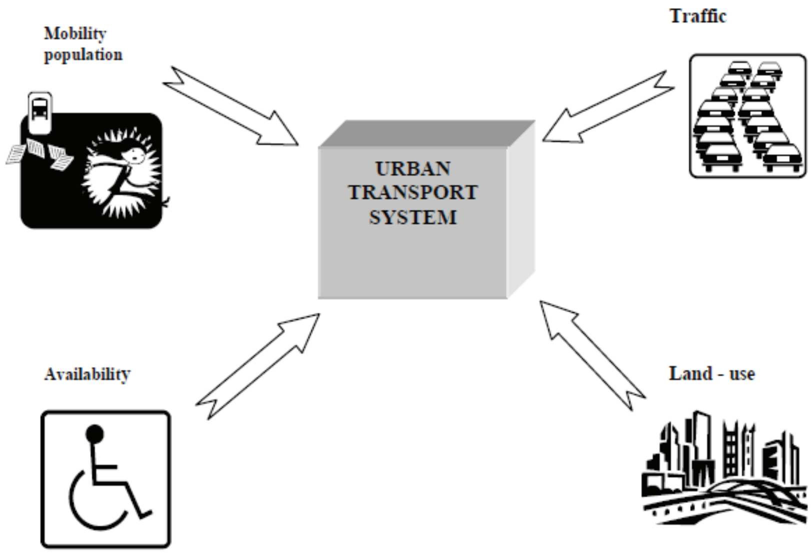


Figure 2-2 Different points of view on the estimation of the urban transport system
(:: Source Pticina, 2008)

To validate the new purchase need of 185 buses, Washington Metropolitan Area Transportation Authority (WMATA) and jurisdictional staff sponsored an bus network evaluation based on the need and efficiency of existing service, services that may exchange between WMATA and local operations, as well as new service that needs to be developed (WMATA, 2006).

The work of Chen, et al. (2009) presents an in-depth analysis of service reliability at the stop, route and network levels, based on bus operation characteristic in Beijing. In this research, from the perspective of passengers, they have considered three performance parameters, including punctuality index based on routes (PIR), deviation index based on stops (DIS), and evenness index based on stops (EIS), as well as the relationship among these parameters using a numerical example.

Lao Yong and Liu Lin (2009) combined data envelopment analysis (DEA) and geographic information systems (GIS) to evaluate the performance of individual bus route from the perspectives of both the operation efficiency and spatial effectiveness, based on a case study of Monterey-Salinas Transit (MST), a public transit bus system in Monterey County, California.

Also, the urban transit system can be estimated or evaluated from the perspectives of traffic, the mobility of the population, the accessibility and land-use (Pticina, 2008), as shown below:

- **Traffic-based** measurements evaluate the movement of vehicles;
- **Mobility-based** measurements evaluate the movement of individuals;
- **Land-use-based** measurements evaluate the efficiency of land-use;
- **Accessibility-based** measurements evaluate the accessible degree of people and business to desired goods, services and activities.

According to the "Urban Transport System Audit" (Pticina, 2008), several evaluation processes have been undertaken, following the transport system properties of mobility, accessibility and reliability. The urban transport audit is the estimation of conformity of the urban transport system and its subsystem to the purposes of stragety of the city development and requirements of the populaiton (Vaksman, Kochnes, 2007).

- Based on the analysis results of the Urban Mobility Report (Schrank, Lomax), estimation of congestion and mobility within an urban area has been developed in 2007. The audit method has yielded a quantitative evaluation of mobility level of the urbanized area, utilizing generally available data while minimizing the need of extensive data collection.

-The survey carried out by the Transportation Association of Canada (TAC) concerns conventional transit service and specialized transit service for the progress measurement in achieving sustainable transportation from both the point of view of the traffic and the point of view of expenses (2008).

-“Austroad National Performance Indicators” reports benchmarking performance data for the road system and road authorities in Australia and New Zealand (Austroads, 2007), and the indicators selected for the evaluation cover the economic, social, safety and environmental aspects.

-Analogue measurement sponsored by Europe Urban Audit (2000) employs indicators and indices that consider urban transport system more from the point of view of mobility of the population.

-In Russia, one of the variant of indices set is taken as one of the approaches to the analysis of the urban transport system, which characterizes urban transport system and consists of 7 groups including about 100 indices of planning, traffic, finance, transit, mobility, ratio of public and private transport, and influences of transport on an environment (Vaksman, Kochnes, 2007).

2.3.3. Methods and Models in Public Transport System Analysis

For a rigorous scientific evaluation, it is a critical step to ensure the evaluation content and select the reasonable targeted indicators. Meanwhile, effective methods and models are the indispensable elements to execute the evaluation process.

Overseas studies mostly focus on the perspectives of analysis of service quality, design of survey plan and qualitative analysis. However, domestic studies mainly focus on the indicator selection and method improvement of evaluation and application of GIS technology.

An evaluation method of grey entropy is introduced by Meng, et al. (2009) to generate a comprehensive evaluation that measure the balanced adjacent degree between the evaluation object and ideal catch. Evaluation based on this method can quantify the incertitude factors of decision-making and dispense with supplying other information.

An effective fuzzy multi-criteria synthesis evaluation method was employed by Yeh, et al. (2000) and Wang,et al. (2004) for performance evaluation of urban public transport systems. This method can solve the situations involving multiple criteria of multi-level hierarchies and subjective assessment of decision alternatives in the manner of modeling the subjectiveness and imprecision in the evaluation process as fuzzy numbers through the linguistic terms.

Liu, et al. (2008) has proposed a solution for the complete routing computing for traveling by public transport, through building the bi-level model of transit network and model of pedestrian network. The travel route plan will be chosen on the upper level of the transport network, while the lower level will solve the transfer stuff. The pedestrian network model is an effective connection between the transfer stops in the transfer area.

A novel and practical approach was proposed for evaluating transit network and its capacity by Yang, et al. (2010). The method was employed aiming at dealing with disequilibrium problems of district transport capacity by analyzing the matching degree between the network capacity and transit trip intensity in the analysis grids of the study area.

2.4. Conclusion

Bus transit system plays a key role in urban transportation system. With the development of a city, bus network as well as routes built sequentially does increasingly not fit to the needs of the users. The low cost and hign returns make bus route optimization become a top solution. Evaluation generated before optimization will effectively dig out the drawbacks of bus network which should be avoided on the optimized network. Rational selection of evaluation indicators will make the evalution results reliable and effective.

3. BACKGROUND OF STUDY AREA

3.1. City Profile

Wuhan is a metropolitan city of China with a population of 8.29 million population and approximate 8494 square kilometers urban area (WHSB, 2008), located in the superior center of China's economic geography circle (Figure 1-1). The administrative boundary of Wuhan is shown in Figure 3-1. It is known as the "thoroughfare of nine provinces". Wuhan is an important industrial base, scientific and educational base. Due to its geographic location, Wuhan is the integrated transport hub of China. Wuhan is naturally separated by the Yangtze River and Han River, and politically divided into three sub-towns, namely, Hankou, Wuchang and Hanyang. This kind of urban development pattern, as a result of the topology, leads to the intrinsic flaws of the urban road network. Therefore, daily river-crossed traffic mainly focuses on the two bridges crossing the Yangtze River, which leads to serious traffic congestion on these corridors and surrounding areas of riverside, especially during peak hours. According to Wuhan Transportation Annual Report (2009), the aggregate number of vehicles crossing the Yangtze River is up to 271,000 per day in 2008 with an significant growth by 8.8% compared with that in 2007, while the total number of vehicles crossing the Han River is 303,000 per day.

Figure 3-1 The administrative boundary of Wuhan
(:: Source liuliuzu, 2009)

3.2. Characteristics and Development of Wuhan Transportation

3.2.1. Mismatch between Potential Travel Demand and Transport Facilities

With the rapid development of industrialization and urbanization of Wuhan, a high travel demand is formed gradually due to the high population density, strong growth in economy (Figure 3-2) and rapid increase of vehicle number (Figure 3-3). According to the investigation in 2008 (WTPI, 2009), number of trips per head per day is 2.41 in the whole city and 2.32 in the central area within the third ring, which increases by more than 17.2% compared with 1998. Of all, the trips to work and school accounts for about 60% of the total number of trips, while the trips to business accounts for over 20%. All of the above interprets that the potential travel demand of citizens is gradually growing.

However, existing transport facilities can hardly meet the high travel demand due to the insufficient capacity. Inadequate development of public transportation contributes to the traffic passenger flow concentrating on the main roads of the city, especially in the city center, which is a dominant factor that leads to serious congestion. The actual travel speed of vehicle which reveals the serious congestion is shown in Figure 3-4. According to statistic, bus average running distance in Wuhan is only 8.18 km while the average route length is 21.42km, and bus average running speed per hour is only 22.5 km (Peng, Gong, 2009). In the meantime, rail including both light rail and metro is still in its infancy with short routes, limited carrying capacity and inconvenience transfer. Table 3-1 shows that development of road construction cannot match the increase of travel demand.

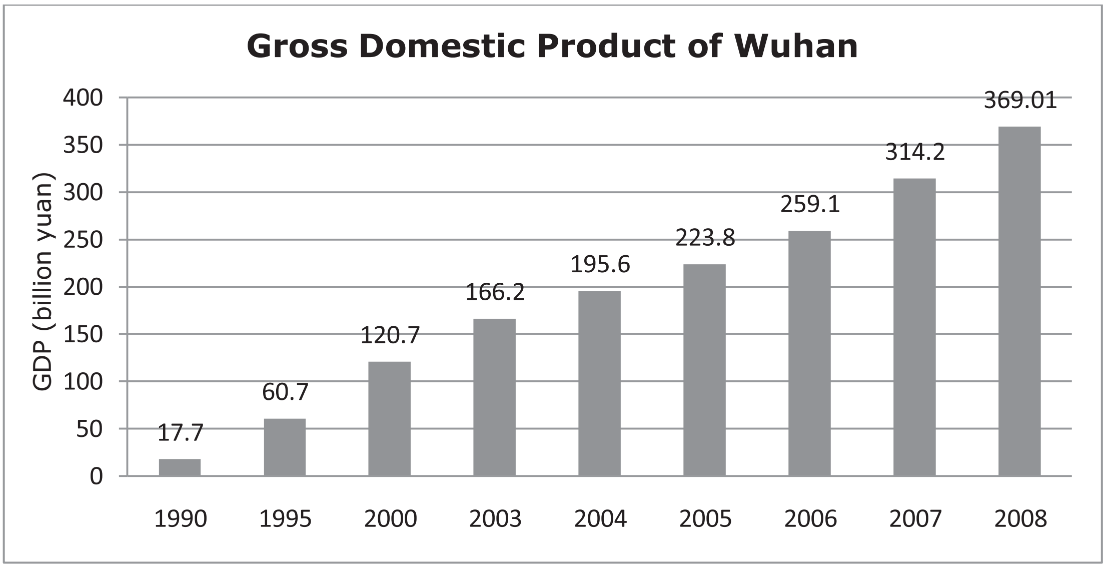


Figure 3-2 Gross Domestic Product of Wuhan
(::adapted from WTPI, 2009)

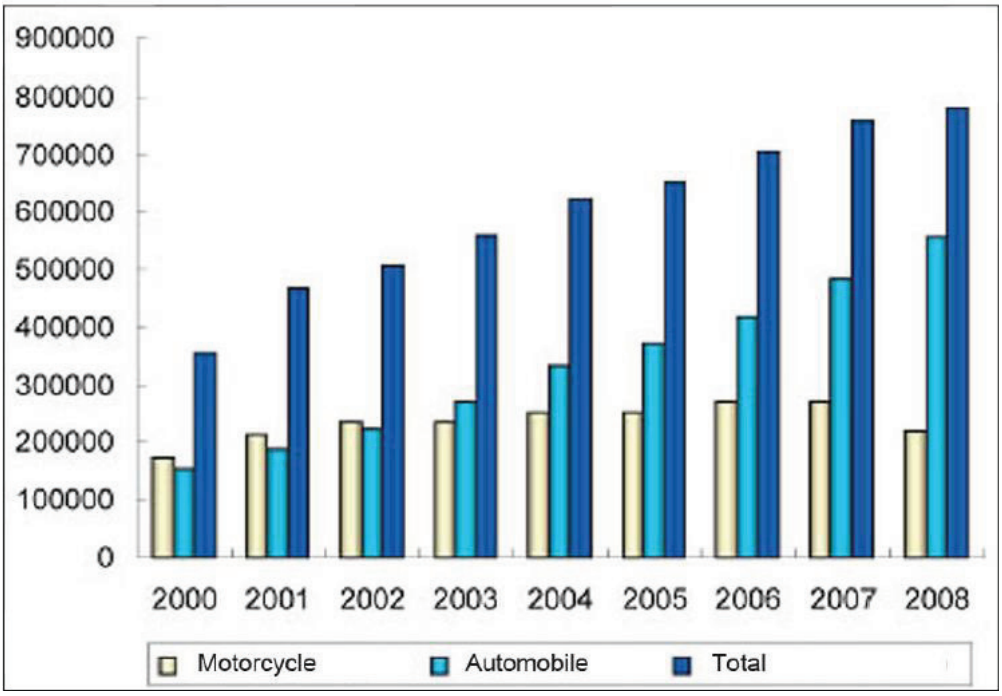


Figure 3-3 Number of Motor Vehicles of Wuhan
(:: Source WTPI, 2009)

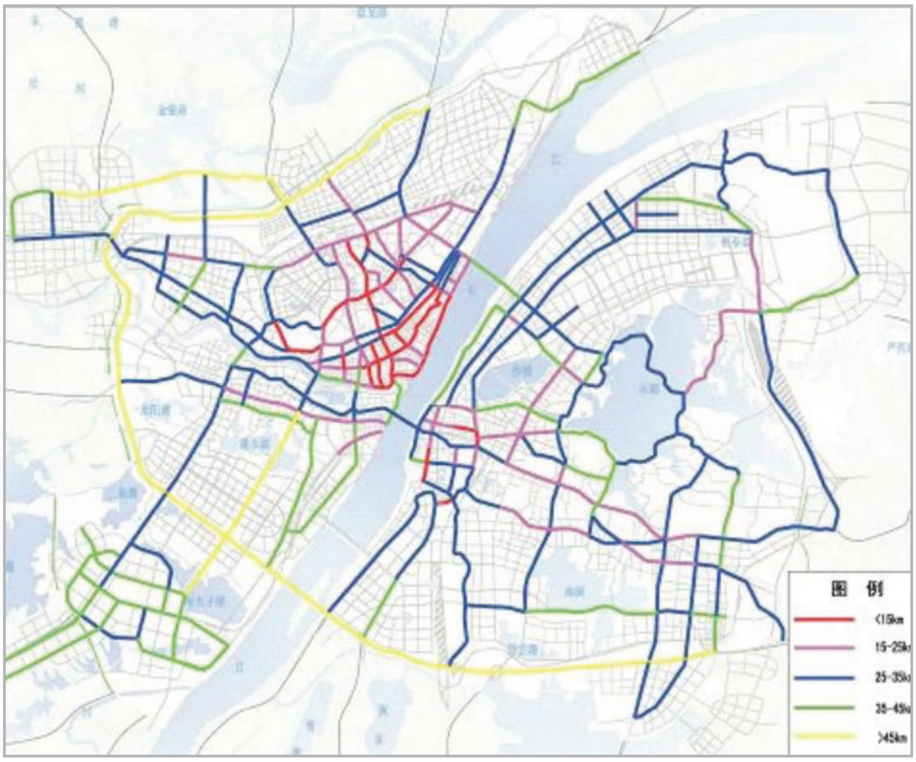


Figure 3-4 Vehicle Speed of Wuhan
(:: Source WTPI, 2009)

Table 3-1 Indicator Statistic of Urban Roads in Central Area (:: adapted from WTPI, 2006, 2007, 2008, 2009)

Year	Road length (km)	Road area (km^2)	Road area per head (m^2)
2004	2161	35.7	8.5
2005	2174	39.4	6.7
2006	2369	43.3	9.6
2007	2515	47.7	9.3
2008	3035	58.1	9.75

3.2.2. Low Proportion of Public Transport Travel

The low cost, regular coverage, big capacity and less environmental pollution of public transport make it an effective sollution to reduce road congestion, travel time, air pollution and energy consumption. Therefore, public transportation priority is the only way to solve traffic congestion.

However, public transport travel only accounts for 23.8 % of the total public travel in Wuhan. The proportion has only grown by 1.9% from 21.9% in 1998, which is lower than the national standard of 30% in the metropolises and medium-sized cities, according to the Ministry of Construction (L. M. Chen, 2010). Moreover, rail construction is lagging behind; therefore, mass public transportation has not yet played a dominant role in Wuhan transportation.

Therefore, to make great efforts to build rail tranpsort and optimized the conventional bus network is an effective solution to increase the proportion of public transport travel.

3.2.3. Bus Transit – Major Mode of Public Transport Travel

According to the investigation in 2008 (WTPI, 2009), number of passengers carried by public transport all year is approximately 2 billion with an increase by 2.5% compared to 2007. The number of passengers carried by bus in 2008 reaches 1.43 billion accounting for 71.7% of the total number, while 0.55% for rail transport, 6.9% for mini-bus, 20.1% for taxi and 0.79% for ferry, as Figure 1-2 shows. It illustrates that bus transit is still the main mode of public travel.

As a bus-oriented metropolis, Wuhan possesses 277 bus routes with total route network length of 1092 kilometers, operation length of 5,306 kilometers, bus stop number of 2,460, and six major transit hubs that cover an area of 6.6 hectare in the whole city, according to the statistic in 2008 (WTPI, 2009).

3.3. Challenges of Public Transport Development

The central government and local authorities of Wuhan have invested huge human material and financial resources to construct the urban subway system to spur economic development and handle the crisis while enhancing the capacity of passenger transit. According to the plans, the metro should consists in the end of 8 routes and 119 subway stations, planned to be operational by 2020 (Wei, 2010), as Figure 3-5 shows. Therefore, the coordinated operation among different transport modes, especially between bus and subway is the main challenge in transit planning in the near future. From the users' perspective, the transit system should meet the passengers' demand, such as comfort, punctuality, service coverage, and frequency with cheap and direct service. However, from the operator's perspective, the objective for the system is to make as much profit as possible. For this reason, conflict mitigation between operators and users is also another great challenge in transit planning for public transport development.

Figure 3-5 The planned subway system in Wuhan
(:: Source WHTPI)

4. BASIC SPATIAL DATABASE—"TRANSIT MULTI MODAL"

4.1. Data Collection

According to the actual needs of bus route optimization, and considering the availability of data, urban basic information including population data, land use pattern data and homo-zone data, urban road network data, and bus route network data of the study area were collected. The study area is the central area of Wuhan, including three road rings, with the built-up area of 474.46 km^2 and the urban population of 4.5 million heads. An overview of data collection of this research is given in Table 4-1.

Table 4-1 Data Description

<table>
<tr><th colspan="2">Data Category</th><th>Feature Type</th><th>Attribution</th><th>Purpose</th><th>Data Source</th></tr>
<tr><td colspan="6">Urban Basic Information</td></tr>
<tr><td colspan="2">Population</td><td>ASCII</td><td>Population</td><td rowspan="3">Trip production and attraction calculation</td><td rowspan="2">Wuhan Transportation Planning Institute</td></tr>
<tr><td colspan="2">Land use patterns</td><td>ASCII</td><td>Land use pattern and job number</td></tr>
<tr><td colspan="2">Homogeneous weight zones</td><td>ASCII</td><td>-</td><td>Product of Chinese 863 Scientific Research Program</td></tr>
<tr><td colspan="6">Road Network</td></tr>
<tr><td rowspan="2">Basic road network</td><td>Road arc</td><td>Polyline</td><td>Width, length, road hierarchy…</td><td rowspan="2">Bus route generation in TransitNet</td><td rowspan="4">Wuhan Transportation Planning Institute</td></tr>
<tr><td>Road node</td><td>Point</td><td>Location</td></tr>
<tr><td rowspan="2">Rail road network</td><td>Rail arc</td><td>Polyline</td><td>Length</td><td rowspan="2">Data base of rail routes</td></tr>
<tr><td>Rail node</td><td>Point</td><td>Location</td></tr>
<tr><td colspan="6">Transit Network</td></tr>
<tr><td colspan="2">Existing bus routes</td><td>Polyline</td><td>Length</td><td rowspan="2">Problem analysis; comparing with optimized bus routes</td><td rowspan="2">Field work</td></tr>
<tr><td colspan="2">Existing bus stops</td><td>Point</td><td>Location</td></tr>
<tr><td colspan="2">Rail routes</td><td>Polyline</td><td>Length</td><td rowspan="2">Restrict the layout of the optimized routes</td><td rowspan="2">Wuhan Transportation Planning Institute</td></tr>
<tr><td colspan="2">Rail stations</td><td>Point</td><td>Location</td></tr>
</table>

4.1.1. Urban Basic Information

Population data is key information for estimating the travel demand of bus mode, of which trip distribution determines the trend of traffic passenger corridors of the city. The data used in this research results from a population census in the year of 2000. Land use patterns, especially the distribution of residential and commercial land, mainly affects the direction of traffic flows by determining the trip generation and production. In addition, it contributes to the estimation of job distribution which is also an important basis that attracts the passengers all over the city. To get more detailed data at the micro level, existing population information needs a secondary processing. For this reason, population data was disaggregated from large statistical units into small raster units (30m× 30m) by employing a doubly weighted Monte Carlo simulation approach, based on land use and homogeneous weight zones (Z. D. Huang, et al., 2007). The homogeneous weight zone is applied in cases where the land-use classification is not detailed enough to differentiate local variations in density. The disaggregate result with the absolute number is shown in Figure 4-1.

4.1.2. Urban Road Network

Basic road network carries bus routes laying on it, and it is the skeleton of entire public transportation system of a city. Passengers access to the public transit system through the road network. Road network data is the vectorization result from the transportation map of Wuhan, and data is processed into the typical link-node structure which supports the network analysis in ArcGIS, as shown in Figure 4-2 and Figure 4-3. Road network provides basic condition for bus route optimization, and optimized bus stops are generated along the road.

4.1.3. Urban Rail based Network

Rail transportation network is independent of the basic road network, and network data used in this research consists of a light rail route and two metro lines, as Figure 4-4 shows. No.1 light rail has been put into operation in 2009, and No.2 metro line and No.4 metro line will be finished respectively in the year of 2012 and 2013. Rail routes are employed as layout constraints of bus route optimization in the current and short-term situations.

4.1.4. Urban Bus Route Network

There are three purposes of using existing bus routes: for analyzing the current defects of existing routes, for filtering the bad routes from the existing routes, and for making comparison with optimized routes to verify the improvements. Therefore, existing bus route network is a basis for route optimization. Existing bus routes are vectorized along the basic road network based on the field work result, as Figure 4-5 shows.

Because travel demand is estimated at the stop level, which is different from the conventional transit planning approaches, bus stops in this research is an essential access for route optimization. Bus stops used here are results from after-treatment of existing bus stops. Each pair of existing bus stops with the same name is merged and shifted to the closest road node. Consequently, all the bus stops are road nodes, as shown in Figure 4-5.

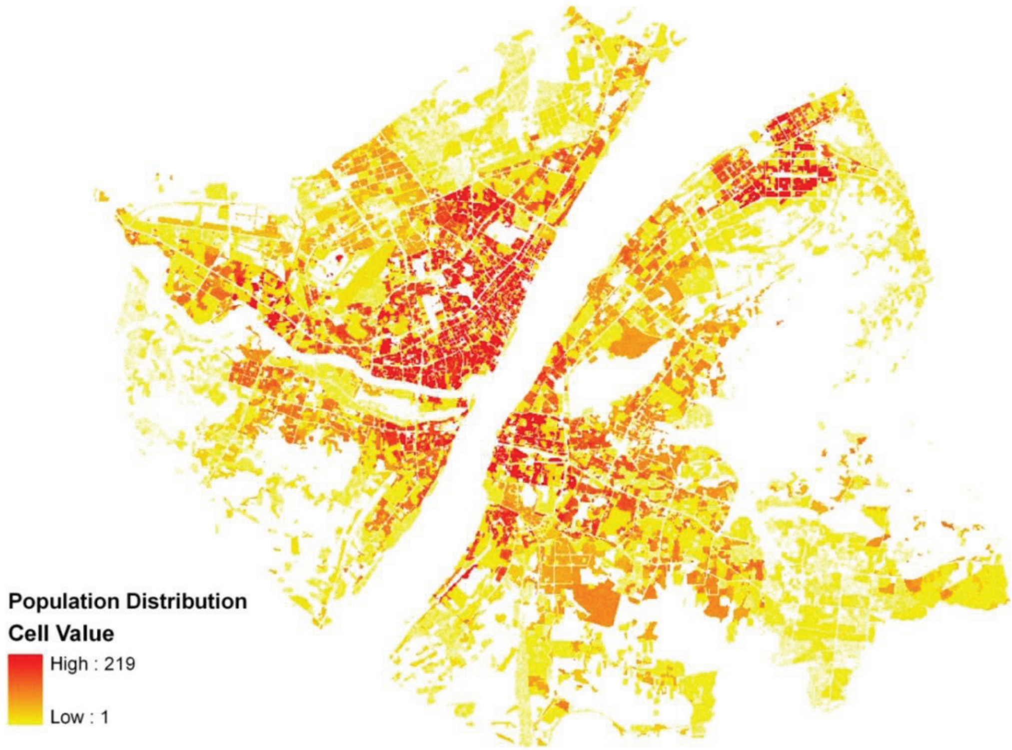


Figure 4-1 Population distribution in study area based on statistics of 2000

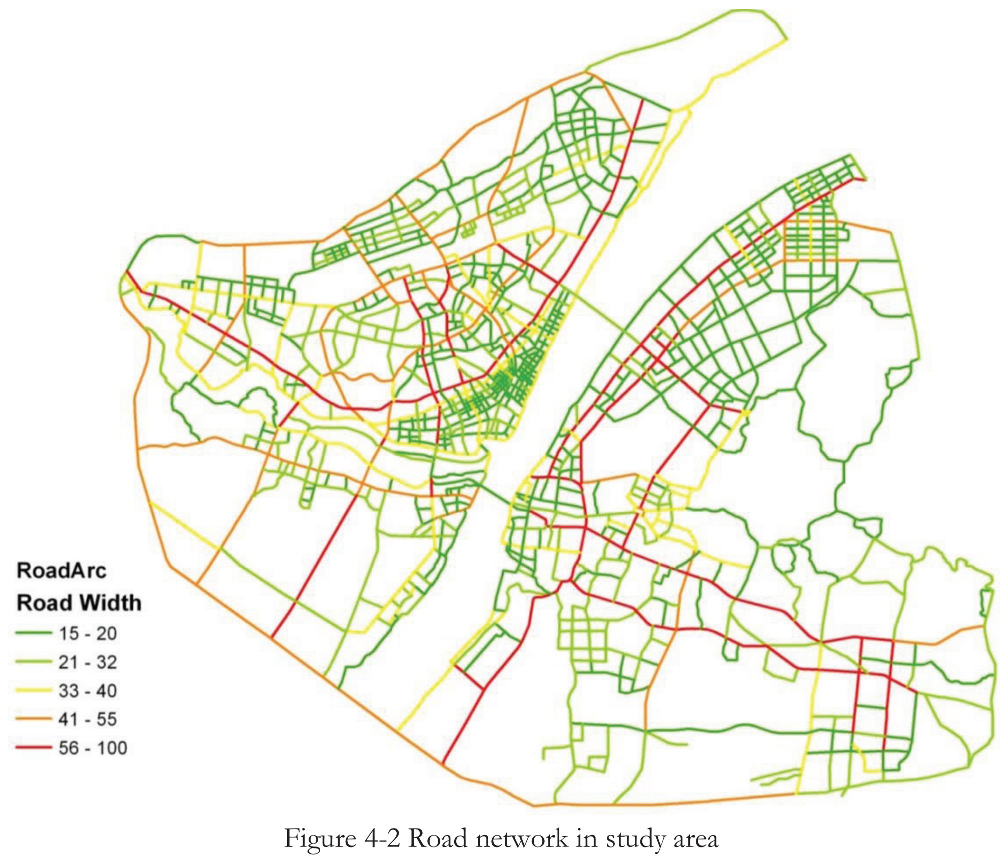


Figure 4-2 Road network in study area

Figure 4-3 Link-node structure of basic road network

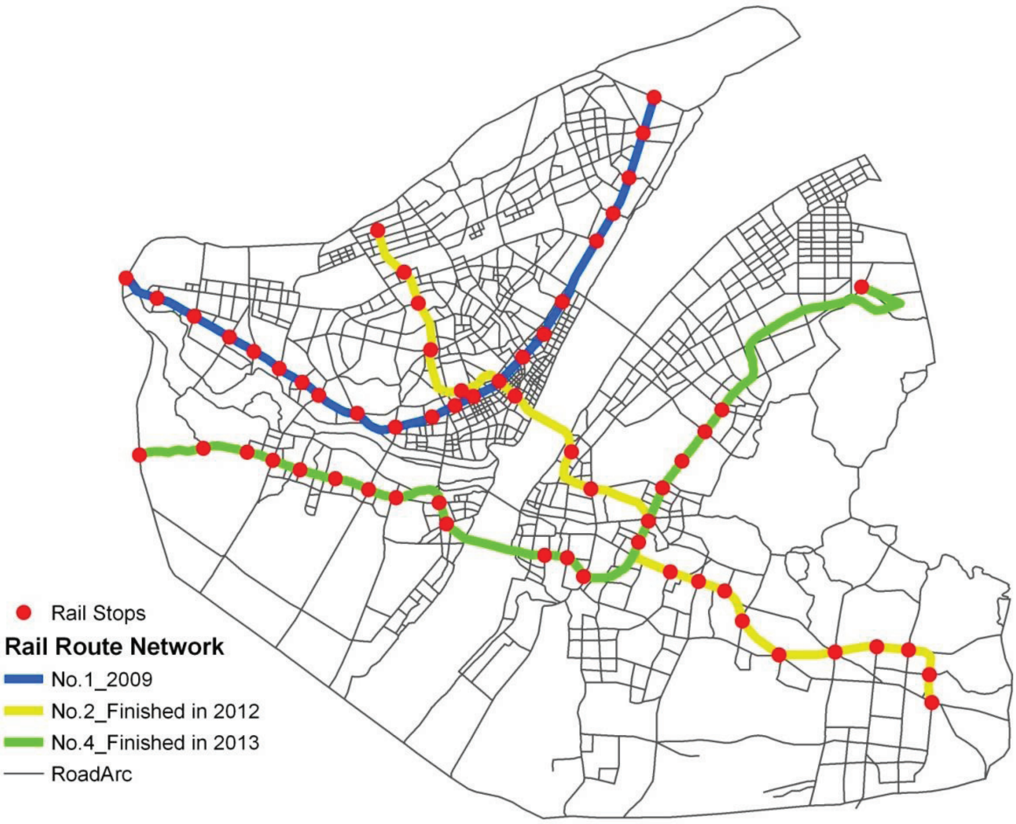


Figure 4-4 Planned rail route network of Wuhan

Figure 4-5 Existing bus routes and stops in study area

4.2. Additional Bus Terminals Selection and Locating in ArcGIS

The rational consideration of additional bus terminals is the feed function of bus routes for rail routes. In the multi-mode environment, well connection among different transport modes is a key factor in the whole transportation system. For this reason, the length of bus route needs to be reduced to enhance the feed function, and to increase terminal is a top solution for this problem.

There are 28 bus terminals optimized in the current planned transit system. This part aims to add another 12 new bus terminals for the whole transit system to continue the later analysis and evaluation. According to the data generation rule that all the bus stops must be part of nodes of basic road network, all the additional bus terminals should be extracted from the current data "RoadNode" in the spatial database "TransitMultiModal". The analysis process is carried out in ArcGIS, based on the road net data "RoadArc" of Wuhan, the flowchart shown as Figure 4-11.

4.2.1. Candidate Bus Terminals Selection and Locating in Polygon Domain

The locating and selection of candidate bus terminals are based on the current bus terminals[4], and locating process should follow two assumptions:

1) The best and optimal searching distance along the basic road network away from a bus terminal is 4 kilometers.
2) The location of additional bus terminals, as well as current optimized terminals, should roughly keep average spatial distribution. That is to say, the distance between any two terminals should be roughly equal.

[4] **Current bus terminals:** Here current bus terminals refer to the already optimized terminals generated from the previous researches, rather than the real bus terminals in the current transit system of Wuhan.

Although 4km is an expected searching distance, if it is set as the original searching value, the initial candidate terminals selection and next locating process would be greatly constrained. For this reason, selection area of the first two rounds is located within the certain buffer area around 4km. According to the several experiments, 200m and 500m are respectively two reasonable buffer radius values which can give more choices of candidate terminal selection and make the average distribution possible.

1. Searching and Selecting

Firstly, extract current optimized terminals and candidate terminals respectively as two distinctive shape files from the road nodes set. Here the candidate terminals are all the rest of road nodes except current terminals. Secondly, build network dataset for the basic road network. Do service area analysis, and find candidate sites located in the buffer area between 3800m and 4200m of current terminals along the road network. To keep the average distribution, the buffer area is merged into single part when it is built. In this process, 19 candidate nodes have been selected.

The problem is that there are still some nodes clustering in a small area that violate the average distribution rule, as shown in Figure 4-6. These 3 clusters need to be checked and only one or two candidate nodes can be picked out in each cluster.

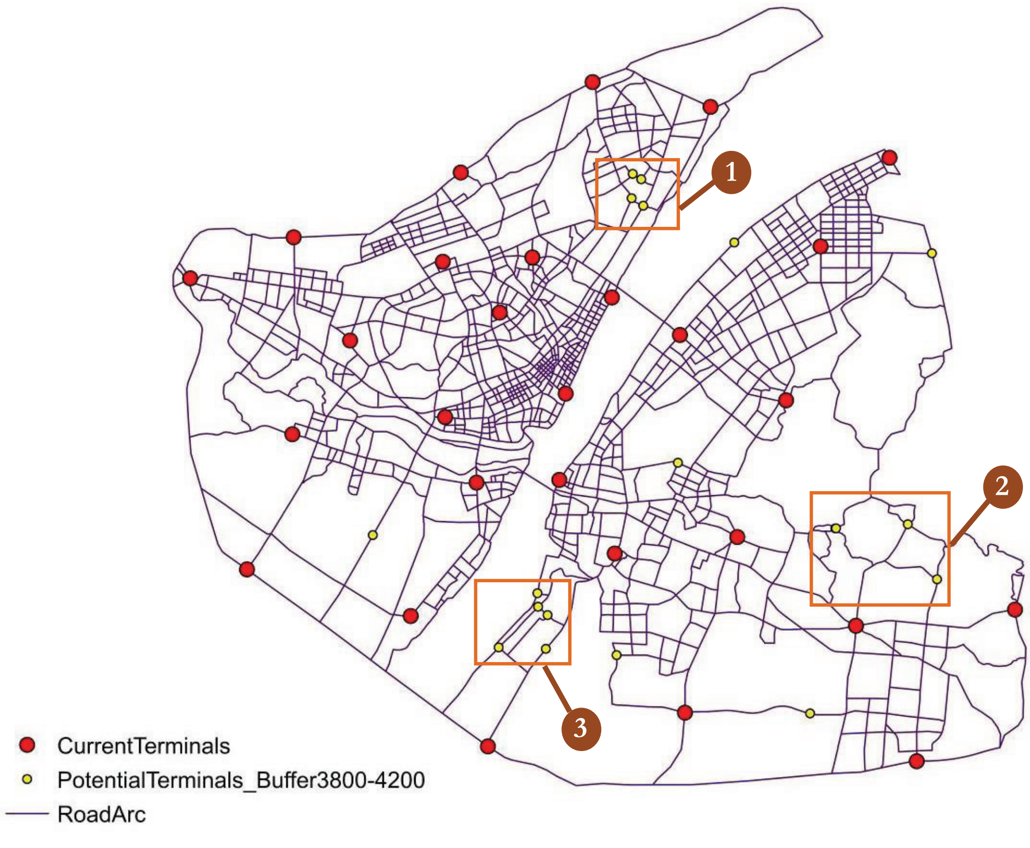


Figure 4-6 Candidate terminal clusters in the buffer area

2. Inverse Checking and Picking

In this part, it needs to carry out a second extraction from these 3 clusters. Do the closest facilities analyses, take the current terminals as facilities and potential candidate nodes in clusters as incidents, and find the several closest facilities for each incident. A constraint need to be set here, that the nodes in the same cluster must be served by the same several closest facilities for the sake of distance comparison.

Through the test and verification, it is rational to set 4 facilities to be found for clusters 1 and 2. For cluster 3 the number of facilities is set to 3. Based on the comparison of distance standard deviation among the chosen nodes in the same cluster, theoretically only one candidate node can be preserved as potential terminals. The function used is as follows,

$$\sqrt{\frac{\sum_{1}^{n}\left(D_i - E\right)^2}{n-1}}$$

Function 4-1

where E is given the value 4000, representing 4000 meters, D_i represents the distance from one candidate node to its *i*th closest current terminal in one cluster, and n means the number of current terminals in this cluster.

In the first round of selection, 10 potential terminals are chosen and picked in the buffer area between 3800m and 4200m, with two nodes picked out of cluster 2 due to the receivable distance between these two nodes. There are still two more terminals need to be selected. Therefore, the second round of selection is implemented in the buffer area between 3500m and 4500m, and the whole proceeding is identical with the analysis in buffer 3800m and 4200m.

4.2.2. Candidate Bus Terminals Selection and Locating on Line Domain

The unique feature in this round selection reflect in that the searching domain is no longer a polygon set but a line set which is a series of polygon edges of 4km buffer areas for current 28 bus terminals along the basic road network. In this part, the searching strategy and process procedure are a bit complicated compared with ones in polygon domain.

1. Initial Candidate Terminals Generation

In the network analysis environment, build separate service area of 4km buffer polygon without merging for each current terminal along the road network, and then extract the polygon edges of these service areas. After that, calculate and acquire the crossing points of road network and polygon edges. Actually, these crossing points have a low possibility to coincide with the road nodes, so further adjustment is needed. Carry out the closest facilities analysis, and find the closest road node for each crossing point. Consequently, these road nodes found compose the initial candidate terminals set.

2. Candidate Potential Terminals Generation

In fact, the nodes in the initial set generated in pre-section cannot be used directly due to two reasons: 1) it contains too many nodes which would affect the calculation time; and 2) most locations of these nodes disobey the rule of spatial average distribution, which is a direct result of the fact that most nodes satisfy the distance constraint for only one current terminal rather than most ones around them, as Figure 4-7 shows. So, further restriction needs to be done.

Utilize the service analysis again, and build separate buffer areas between 3800m and 4000m without merging for each current terminal. Make these independent buffer areas self-intersect, and reserve the segments that are intersected by at least two buffer segments. Extract the nodes located in these buffer segments, and manually delete the ones closely around the current terminals, which are apparently irrational and unnecessary.

3. Inverse Checking and Picking

The same situation as process in polygon domain, nodes cluster exists. Though the closest facilities analysis and distance standard deviation computation, 7 potential nodes are saved.

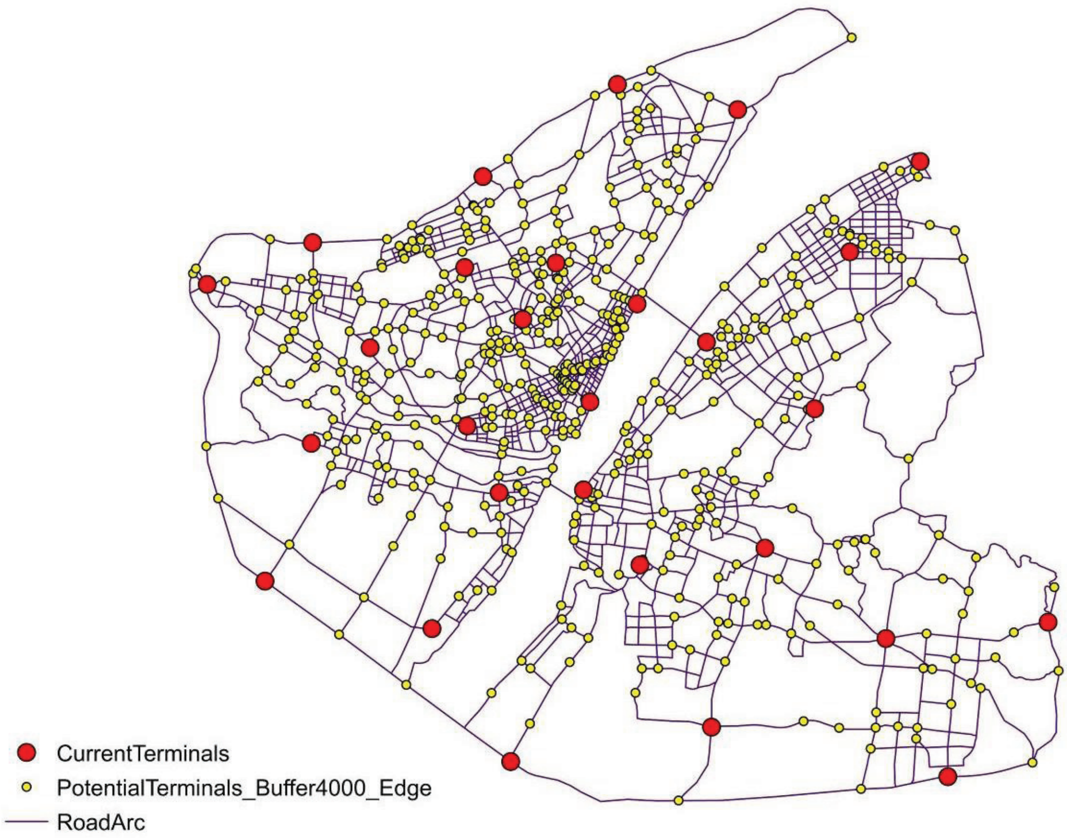


Figure 4-7 Initial candidate terminals based on 4000m buffer fringe

4.2.3. Comparison and Locating

In this part, two potential terminal groups (Figure 4-8) generated in two methods will compare with each other and place restrictions on each other on condition that population distribution and job number take effect at the same time.

In "TransitMultiModal", the essential information about land use is stored in dBASE file "DensWeight" which uses population and job number to reflect the potential trip production and attraction for each kind of land use in Wuhan. The land use cell codes are stored using ASCII in a TEXT file "Landuse" which can convert into raster file in ArcGIS.

Firstly, convert the ASCII data into raster data, and then vectorize the raster data in terms of joining the "DensWeight" to obtain population and job number for each cell of land use. Secondly, add these weight values into the two groups. Within the 200m buffer area of each potential terminal, pick out the total number of population and job number respectively. Assume that the population and job number (or trip production and attraction) have the equal effect on terminals locating, that is to say, each has a weight of 0.5. Finally, calculate the score for each potential terminal by function

$$\text{Score} = \text{Population} * 0.5 + \text{Job number} * 0.5 \qquad \textbf{Function 4-2}$$

200m of buffer radius shown up above is an experience value. The situation exists, that two potential nodes each from a different group could locate closely to each other, as shown in Figure 4-8. While the buffer value increases, the possibility grows accordingly of that total population and total job number within the buffer area of one node are both equal to the two values of the other one. In this way, these two nodes cannot distinct from each other quantitatively.

The final locating process still needs the manual work, while the scores of nodes are considered. First of all, compare the scores of each pair of adjoining nodes, and remove the one which gains the lower score (located in the blue circles in Figure 4-9). Then, according to the current situation in Wuhan, remove the nodes those disobey the rule of spatial average distribution while the score of each node is a secondary restriction, and keep 12 potential terminals. The final locating result is shown as Figure 4-10.

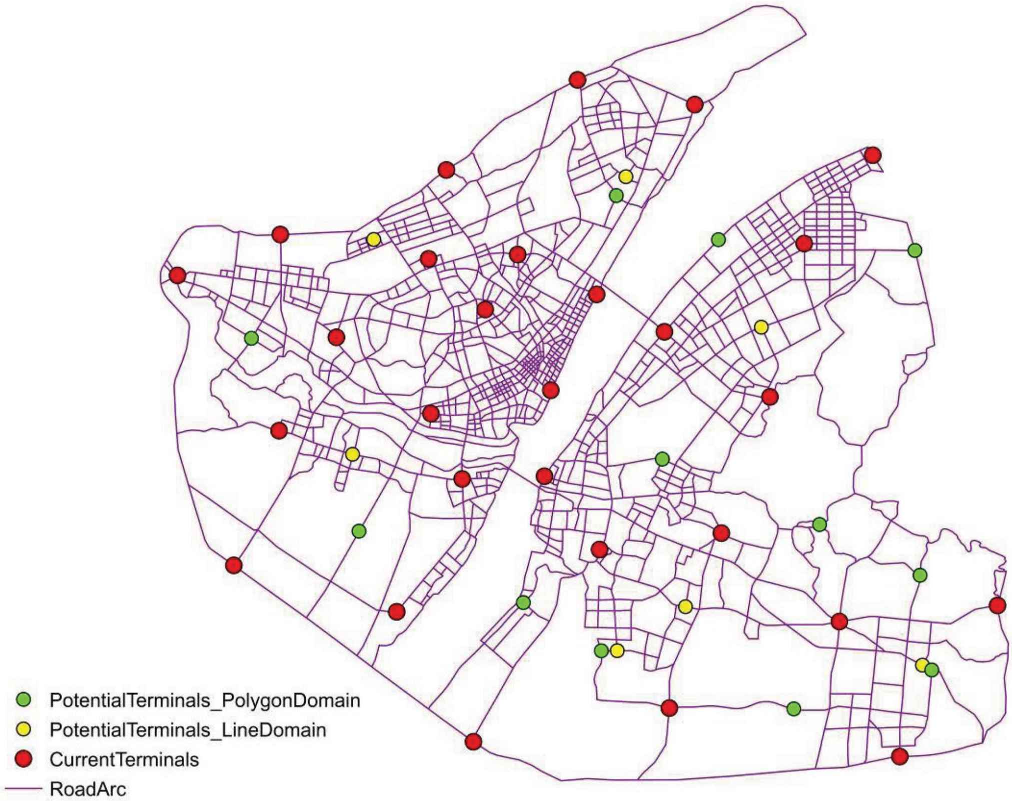


Figure 4-8 Potential terminals based on two searching methods

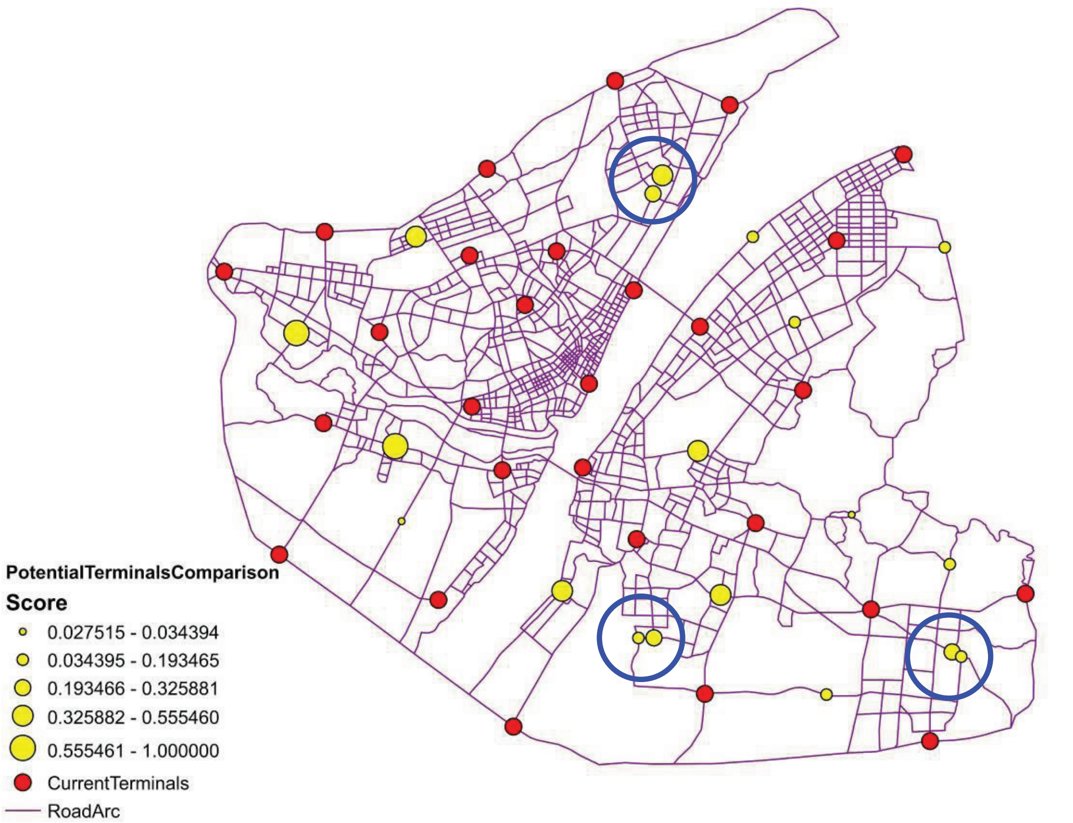


Figure 4-9 Score comparison for potential terminals in two groups

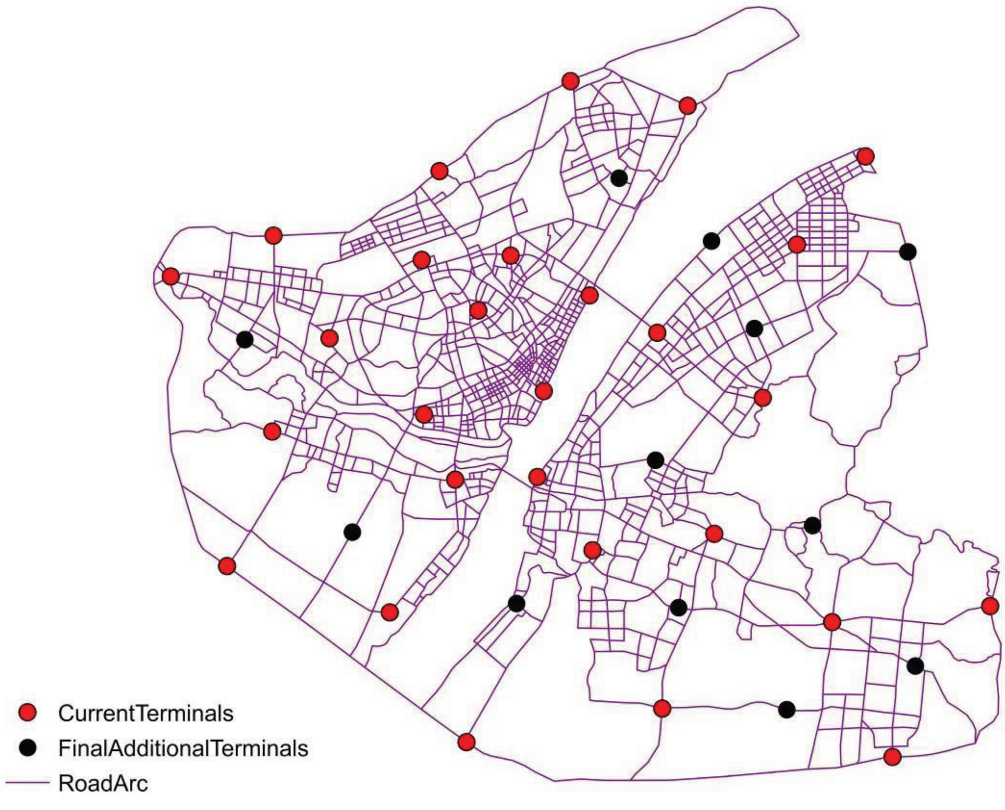


Figure 4-10 Final locating of additional bus terminals

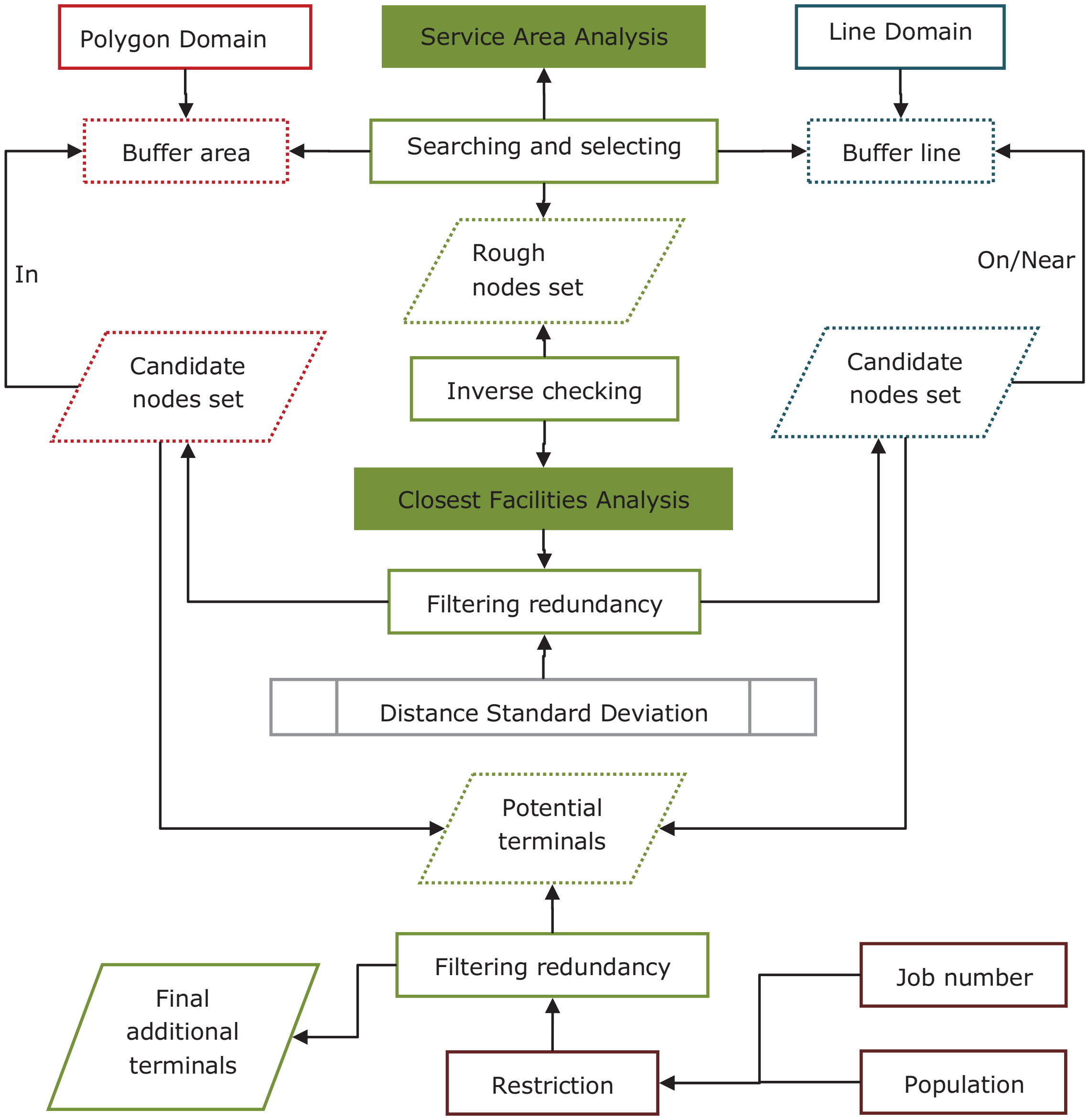


Figure 4-11 Process of additional terminals selection and locating

5. RESEARCH METHODOLOGY

In this chapter, a general methodology for bus route optimization is presented. There are three components of this methodoloy that are discussed in this chapter. The first component is mining the problems of current bus network layout in study area and selecting a group of good existing routes based on the result of comprehensive evaluation. The problems dug out are the key elements that should be avoided or alleviated in the optimized route set. Another component is generating candidate bus routes and extracting the best set of bus routes as an optimization solution by using genetic algorithm according to the optimization objective. Finally, an analysis of the optimized bus routes and a check considering that whether the expected improvements have been achieved will be carried out. A schematic of the whole process is shown in Figure 5-1.

5.1. Analysis of Current Problems

5.1.1. Evaluation for Existing Bus Routes

Evaluation of existing bus routes is carried out in two phases. In the first phase, evaluation aims to dig out the current problems of existing bus routes at the general level with the help of TransitNet. This network evaluation employs indicators especially from the point of view of route design level, such as nonlinear coefficient, overlapping coefficient, network density, and stop coverage as well as transfer rate (Table 5-1). The gap between existing routes performance and the national (or local) standard would be shown with corresponding indicator value. In addition, some further analysis and statistic will be carried out in GIS and spreadsheet calculations about the network accessibility and competing degree with No.1 light rail, which are also helpful for problems analysis and further optimization.

In the second phase, evaluation is carried out at the single route level, aiming to provide a basis for bus route filtration in the following step. In this phase, each route is developed with the consideration of route length limitation, number of stops, nonlinear coefficient, unit passenger flow, and route efficiency. According to the national standard and specific circumstances of study area, each indicator value is quantified and standardized rationally, and the weighted sum of these indicator values is taken as a score of individual route which reflects the comprehensive level of each route from the point of view of route design. Here, for different route length, the rational number range of stops is different. Unit passenger flow aims to reflect the carrying capacity per kilometer of a single route, while route efficiency reveals a possible mismatch between route production and attraction.

5.1.2. Bus Routes Filtration

Actually, bus routes filtration is a preparation for optimization. Of all existing routes, some needs to be kept while some removed in the competing process of "survival of the fittest". The filtering process consists of two phases which are respectively based on the comprehensive evaluation result of individual route in the previous section and additional filtering indicators. In the first phase, each route of which the comprehensive score is lower than the give threshold will be removed. In the next phase, routes that cannot meet the requirements of filtering indicators will be removed. Finally, the survived existing routes will be put into the optimization process.

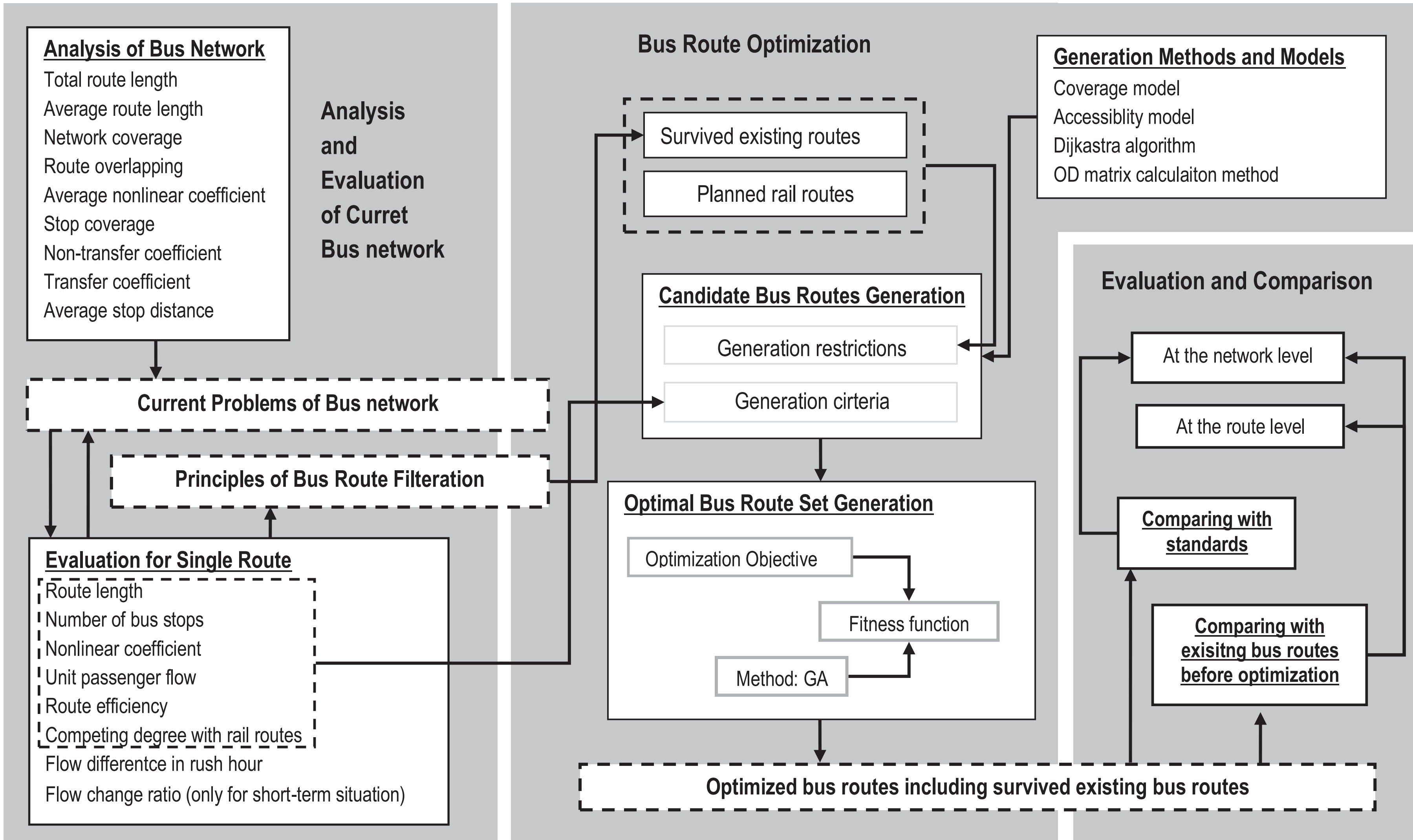


Figure 5-1 Schematic of bus routes optimization process

In the optimization process with restriction of No.1 rail route, two filtering indicators are considered, which are the number of shared adjacent stops and difference between the real passenger flow and assigned passenger flow in rush hour. Here, the real passenger flow is a forecasted result for individual route while the assigned flow is calculated based on the theoretical passenger flow of road segments passing by the corresponding route. One more filtering indicator is taken into account which is the possible passenger flow reduction with the restriction of No. 1, 2 and 4 rail routes in the optimization process of short-term situation in the year of 2013. Because when the number of rail routes increases, flow passenger of individual route would change greatly, and the change degree is mainly determined by the overlapping length and the parallel length between bus route and rail route in the service area of these rail routes. Therefore, reduction degree of passenger flow is an accepted filtering principle in the process.

5.2. Bus Routes Optimization

In this stage, routes generation and optimization are mainly implemented in TransitNet with the assistant of ArcGIS. The whole optimization process consists of candidate routes generation phase and routes optimization phase. Firstly, a brief introduction will be given to TransitNet, including the short explanation of several core models in this software. And then methodologies of bus route optimization follows.

5.2.1. The State of the Art--"TransitNet"

"TransitNet", is the latest system (including relative software product) of "Space Allocation and Optimization Technology of Multi-modal Public Transport Network in Metropolis", developed by the team of Professor Dr. Huang Zhengdong[1] of Wuhan University, supported by Chinese 863 Scientific Research Program "Optimization of Multi-modes of Public Transport in Wuhan, China". The software "TransitNet" is a secondary development on the platform of Microsoft Visual Studio.NET and GIS embedded component ArcEngine using C# programming language.

This software can automatically work out the production and attraction of bus stops, check the topology errors of route network, construct basic road network, allocate traffic flow for basic road network, generate the candidate bus routes, select the optimized bus routes based on genetic algorithm, and calculate the relative indicator value of route network under six transit modes, including bus, bus rapid transit, rail, bus & bus rapid transit, bus & rail, and bus & bus rapid transit & rail. In multi-modal transportation environment, only bus route network is the final optimized object while bus rapid transit and rail modes are the basic constraint elements for the passenger flow calculation.

Core Models and Methods in TransitNet are briefly introduced as follows:

- **Accessibility model**

A distinctive feature of TransitNet is that trip demand used for creating and validating candidate routes is estimated at the stop level rather than the TAZ level. Accessibility model used here aims to forecast travel demand by reflecting the phenomenon that activity intensity decrease with distance. This model intends to build a relationship between walking distance to stops and trip probability from each statistic cell of which each location is attributed with disaggregated population and access probability; therefore, transit demand can be estimated for each raster cell. Based on candidate stops distribution, a spatial allocation is implemented to generate the spatial coverage area of each stop. When the transit demand is computed for each raster cell, it is possible to aggregate the cells in the coverage area of each stop (Huang, et al., 2009; Huang, et al., 2010).

- **OD matrix calculation method**

OD matrix calculation is an essential method for the estimation of bus trip probability according to the bus trip distance between each pair of OD. The appropriate bus trip distance should be more than 3 km.

Therefore, the shorter the distance between each pair of OD, the lower the bus trip probability is. Meanwhile, it is also a basis for the calculation of non-transfer coefficient.

- **Dijkstra algorithm**

Dijkstra algorithm employed here aims to assist the candidate routes generation. For each pair of terminals predefined, a certain number of shortest paths are searched following the rule of Dijkstra algorithm.

- **Genetic algorithm**

Genetic algorithm is used in order to create the optimal route set from the candidate route set (or individual). Each individual combines selected routes into a solution, and in each generation, if the solution is improved, it is stored as the best solution. The fitness value is a decision which judges that whether a solution is improved or not. Principles of genetic algorithm will be thoroughly discussed in this chapter.

5.2.2. Candidate Routes Generation

For each pair of predefined bus terminals, multiple shortest routes are generated by using a k-shortest path algorithm. When a path between a terminal pair is created, the stops along the path can be identified, and meanwhile the production and attraction of the path can be derived. A path becomes candidate only if it meets several criteria that are defined in the following:

- Route length falls in the standard range.
- Minimum number of stops along the route, and a candidate route of which the number of stops cannot be less than a given threshold value.
- Accepted nonlinear coefficient.
- Minimum passenger flow per kilometer along the route.
- Minimum route efficiency. Route efficiency is defined for balancing production and attraction of a route.
- Minimum number of different stops with previous candidates.
- Minimum number of shared adjacent stops with considered rail route. A candidate route of which the number of shared adjacent stops cannot be more than the given value.

With the constraints of these criteria, some paths cannot be accepted as candidate routes, and the next shortest path is searched. If the path length exceeds the maximum predefined length, the search process is ended. It means that the number of routes between each pair of terminals would be equal or smaller than the given value k defined in the k-shortest path algorithm.

5.2.3. Bus Route Optimization based on Genetic Algorithm

5.2.3.1. Individual and Population

Using genetic algorithm, two concepts named individual and population need to be defined. An individual in GA is a group of candidate bus routes that serves as a candidate route set for optimization, and routes in the candidate set are sequentially arranged to form a chromosome. The potential number of individual that can be constructed is $m \times k$, of which m is the number of terminal pairs, and k the number of candidate routes between each pair.

A population is a candidate individual set that consists of a certain number of individuals, which is essential for the implementation of genetic algorithm. The size of population is fixed in the computing process, and individuals are added in and removed from the population in each optimizing generation.

5.2.3.2. Fitness Function

For different optimization purposes, fitness function can be different. In this research of bus route optimization, route efficiency and stop coverage are considered as two major factors in the built fitness function.

According to the report of "Space Allocation and Optimization Technology of Multi-modal Public Transport Network in Metropolis" (Huang, 2009), global service efficiency is the weighted sum of the average effectiveness of all routes and stop coverage. The fitness function is shown as follows:

$$E = a \times \overline{W} + b \times Cov \quad \textbf{Function 5-1}$$

where, E is the fitness value, constant a and b are the weights of the average effective value and stop coverage respectively to adjust the importance of each factor; the stop coverage Cov is defined as the ratio between the number of bus stops covered by the optimal bus route set and all the candidate bus stops which are optimized by random walking method and model of maximum covering location, and $\overline{W}$ represents the average value of effectiveness of all routes in each candidate route set (individual or chromosome mentioned above). As for the effectiveness W_i of each route, it is defined as the mismatch degree of production and attraction of all stops on this route, and the corresponding calculation function is:

$$W = \sum W_i = \sum (1 - \frac{|P_i - A_i|}{P_i + A_i}) \quad \textbf{Function 5-2}$$

where

- W is the total effective value of all routes in each candidate route sets.
- W_i is the effectiveness of route i.
- P_i is the total production of all stops on route i.
- A_i is the total attraction of all stops on route i.

5.2.3.3. General Process of Bus Route Optimization

The general process of bus route optimization in TransitNet is described in Figure 5-2.

In a GA process, reproduction, also named selection, is an operator that makes more copies of better individuals which are from the fittest individuals of the previous population in a new population (Pattnaik, et al., 1998). In every reproduced generation, each individual or chromosome is removed or copied depending on the fitness value. Meanwhile, new individuals are added in through crossover and mutation. Therefore, individuals that are copied from the previous population and recombined form a new population.

In the crossover operation, candidate routes in two different individuals of the previous generation are recombined to compose a better individual. Actually, the crossover operation is a recombination process that creates different individuals in the successive generation (Pattnaik, et al.). Crossover is usually performed with a probability called crossover probability to preserve some of the good candidate routes found previously.

Mutation is an operator that adds new information to the genetic search process randomly (Pattnaik, et al.). It is embodied in that new route would be added into the individual instead of the corresponding route between the same terminal pair. Mutation operates with a probability named mutation probability to create new routes.

All three operations on the current population described above are applied to create a new population. During the transforms, the size of the GA population is kept stable, and individual should not contain two candidate routes of the same terminal pair. In each generation, if an individual is improved, it is stored as a best individual. The new population creation is repeated until that the solution meets the criteria or loop is over.

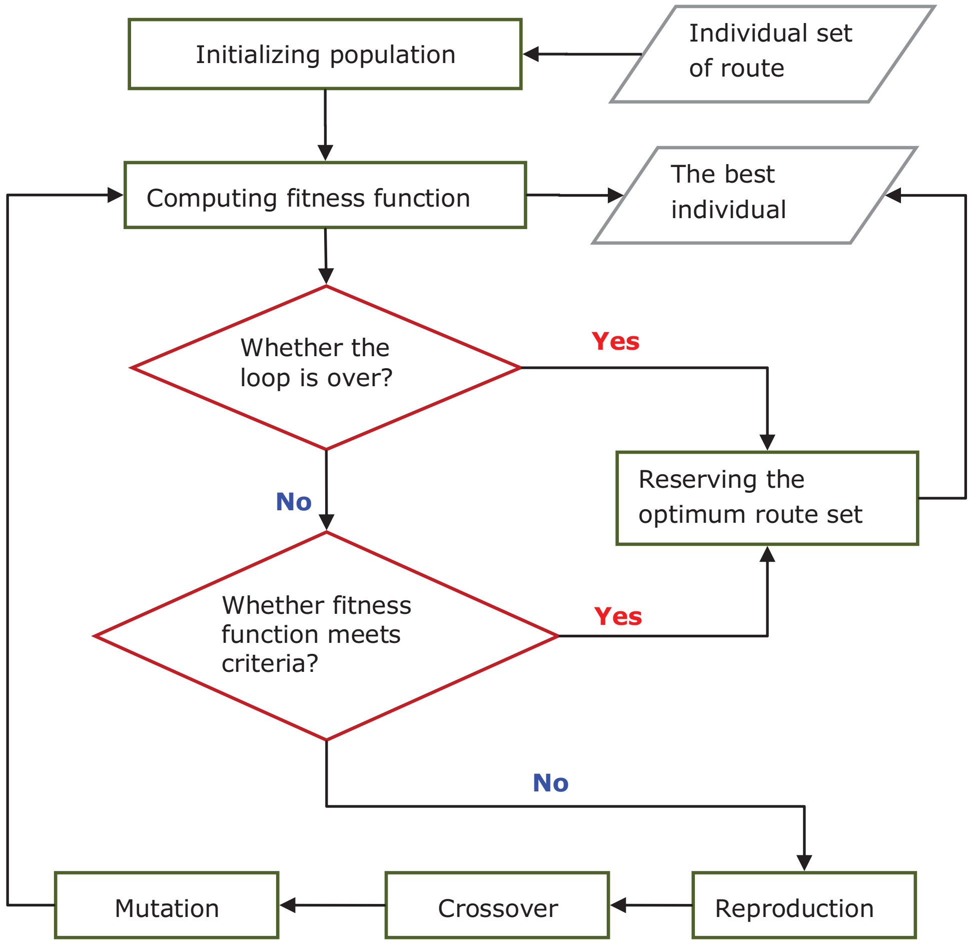


Figure 5-2 General process of bus route optimization

5.3. Evaluation and Discussion

The evaluation after optimization aims to check out that whether the gap between the standard and optimized route routes is narrowed, or whether the expected improvements are achieved. If not, what the possible causes and possible solutions are. It is supported by the comparison between the optimized routes and existing routes both at the network level and at the individual route level. ArcGIS can support sufficient spatial analysis and statistic tool to calculate the accessibility and compile statistic of passenger flow change of individual route which are main considered factors for bus route evaluation. The improvements and limitation will be discussed in detail respectively in Chapter 6 and 7.

Table 5-1 Indicator Selection and Definition at the Network Level

Indicator Selection and Definition at the Network Level		
Term	**Definition**	**Explanation**
Network density	$\mathrm{ND} = l / S$ - l is the total length of road passed by bus routes. - S is land use area in bus service coverage.	It reveals the degree of consistency between residents and public bus routes. According to the theoretical analysis, the most suitable public bus network density is 2.5 km/km^2, and the density should be increased gradually to 3-4 km/ km^2 in the urban central area and decreased contrarily to 2-2.5 km/km^2 in the suburban areas (W. Wang, et al., 2002).
Route overlapping coefficient	$\mathrm{ROC} = l / L$ - l is the total length of bus routes. - L is the total length of bus route network.	It describes a situation where two or more different routes that serve the same passenger markets and appear within close or overlapping proximity. This indicator is designed to control the repetition of bus routes to ensure that transit services within a service area have adequate and rational spatial distribution which can provide service to as more passengers as possible (A. L. Huang, et al., 2007; Q. Li, et al., 2006). The high value of the coefficient could result in the low operation efficiency of urban public transit system. Normally, the coefficient on the arterial road should be lower than 8 at the most and lower than 5 for the best (W. Wang, et al., 2002)
Average nonlinear coefficient	$\mathrm{ANC} = \frac{\sum_{i=1}^{n}(L_i / D_i)}{n}$ - i is the ID of a bus route. - L_i is the length of bus route i. - D_i is the spatial linear distance between the terminal pair of this route. - n is the total number of bus routes.	It reflects the average bending degree of public bus routes. It assesses the average degree of bus routes' deviation from the linear paths. The higher the value of this indicator, the more the unnecessary kilometers, as well as the lower the operation efficiency. Also, it can measure economic benefit, because it indirectly reflects the operation cost of a transit company and time that passengers spend on a route in the overall level.
Non-transfer coefficient	$\mathrm{NTC} = n / N$ - n is the number of passengers who need no transfer. - N is the total number of passengers.	Non-transfer coefficient reflects the convenience of network.
Transfer coefficient	$\mathrm{TC} = n' / N$ - n' is the number of transfer passengers. - N is the total number of passengers.	In theory, the sum of transfer coefficient and non-transfer coefficient should be 1.
Stop coverage[5]	$\mathrm{SC} = pop / P$ - pop is the population served in the certain buffer area of a stop. - P is the total population of a study area.	It is an important indicator which reflects the convenient degree of bus transit. According to the national standards (GB50220-95, 1995), stop coverage can be considered in the buffer area of both 300m and 500m.
Average stop distance	$\mathrm{AD} = l /(n - 1)$ - l is the length of a bus route - n is the total number of bus stops passed by this bus route.	The average stop distance can indirectly interpret that whether the bus stops are redundant or insufficient. Redundant bus stops would increase the total bus travel time while insufficient bus stops results in small bus service coverage and low walking accessibility (Wei, 2010).

[5] **Stop coverage:** This indicator has the different meaning and analysis content from that "stop coverage" in the fitness function, which refers to the percentage of served population in the certain buffer area of one bus stop to total urban population.

6. BUS ROUTE OPTIMIZATION IN CURRENT SITUATION

6.1. General Evaluation for Existing Bus Routes

The study area is the central area of Wuhan, including three road rings, with the built-up area of approximate 470 km^2 and the urban population of 4.5 million heads. In this study area there are 244 bus routes of which the total route length is approximate 4 km. The network density is 1.24 km/km^2 and route overlapping coefficient is 6.8, as Table 6-1 shows. The table also gives an overview of the general level of bus routes in study area from the point of view of the layout of bus route and the point of view of service quality. Here, the service quality specially indicates the non-transfer coefficient and transfer coefficient of the whole bus route network in study district. The values in the table are calculated with the assistance of TransitNet. The definition and computing method of each indicator are shown in Table 5-1.

Existing bus routes used in this research are the real ones existed in the current bus transit system of study area. In the real optimization process, there are three strategies to deal with the exsiting routes, which are route reserving, route removing and route adjusting. Due to the difficulty of route adjustment, only the first two strateties are considered in this research. Evaluation at the general level of existing bus routes aims to dig out and analysis the possible reasons that lead to the problems exposed in the current bus transit system. According to these reasons, more detailed evaluation at the single route level will be carried out, and the evaluation results will be the determinants of that whether an existing bus route should be removed or kept. The survived existing bus route as well as the planned rail route(s) will be taken as restrictions of the layout of new designed bus routes generated in TransitNet.

Table 6-1 Evaluation Result of Existing Bus Routes before Optimization

Individual indicator value in current situation		
	Without No.1 rail route	With No.1 rail route
Total number of routes	244	244
Total route length (km)	3999	3999
Average route length (km)	16.4	16.4
Average nonlinear coefficient	1.6	1.6
Network density (km/km^2)	1.24	1.24
Route overlapping coefficient	6.8	6.8
Stop coverage (300m)	66.2%	66.2%
Stop coverage (500m)	89%	89%
Non-transfer coefficient	31.1%	33.6%
Transfer coefficient for once	66.3%	64.2%
Transfer coefficient for twice	2.6%	2.2%
Transfer coefficient for three times	0%	0%
Total transfer coefficient	68.9%	66.4%
Maximal stop distance(m)	4665.27	4665.27
Minimal stop distance(m)	50.27	50.27
Average stop distance (m)	614.08	614.08

From the Table 6-1 above, it can tell that the appearance of No.1 rail route contributes to an increase of 2.5 % of non-transfer rate. It means that another 2.5% of total passengers can reach their destinations from the origins without transfer when the No.1 rail route is put into full operation. However, the results have still exposed the current problems of bus transit system in Wuhan:

I. Irrational layout of current bus routes: the average route length is 16.4 km, and it has exceeded the accepted route length range from 6 km to 15 km, which is set under the consideration of urban size of Wuhan. According to the length statistic of existing bus routes in the urban central area, as Figure 6-1 shows, length of most bus routes concentrates in the range from 6 km to 26km, and the longest route has its length up to 35.6 km. Long bus routes cause the speed instability of bus and make the arrival punctuality difficult.

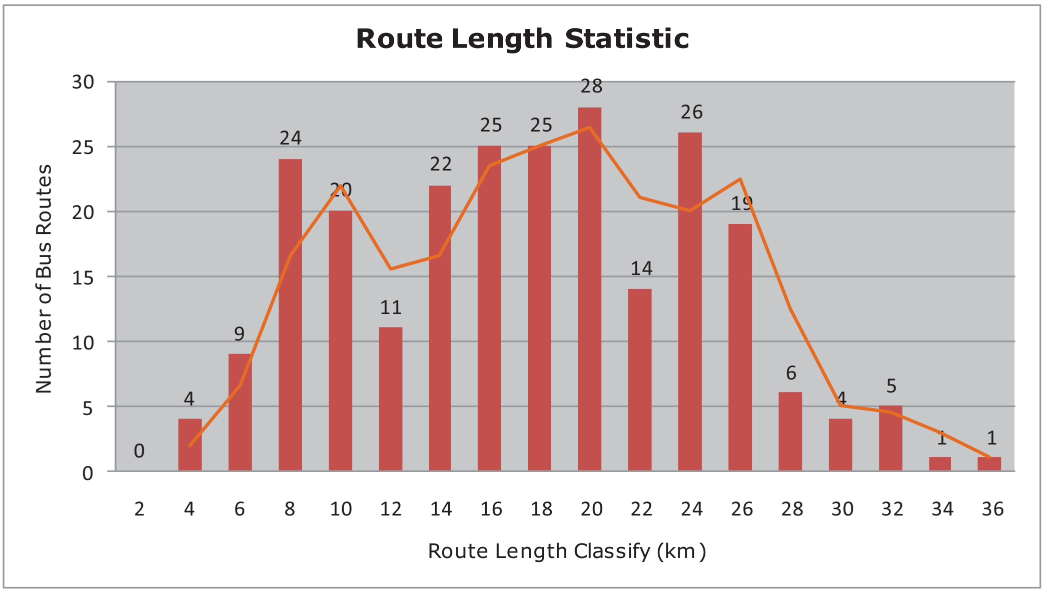


Figure 6-1 Length statistic of existing bus routes in study area

II. The presence of circuitous routes leads to the high average nonlinear coefficient of 1.6, exceeding the national standard (GB50220-95, 1995) of 1.4. It directly increases the running time of bus and travel time of passengers.

III. Low network density results in the small coverage of routes. According to "Code for Transport Planning on Urban Road" (GB50220-95, 1995), the network density of bus routes planned in urban central area should be a value in the range from 3 km/km^2 to 4km/km^2. However, the density of current bus route network is only 1.24 km/km^2, which is far below the standard.

IV. High overlapping coefficient reflects the low quality of route layout. Now, the overlapping coefficient of bus routes is up to 6.8 in urban central area. Of all the current bus routes, the accumulative number of routes which go through a same road arc is up to 41, as Figure 6-2 shows. The figure tells that bus routes across the two main bridges occupy the majority of all the routes in city center.

Therefore, as the problems exposed above, the corresponding actions, such as reducing the hign overlapping and increasing the network coverage, must be taken to solve or alleviate these drawbacks.

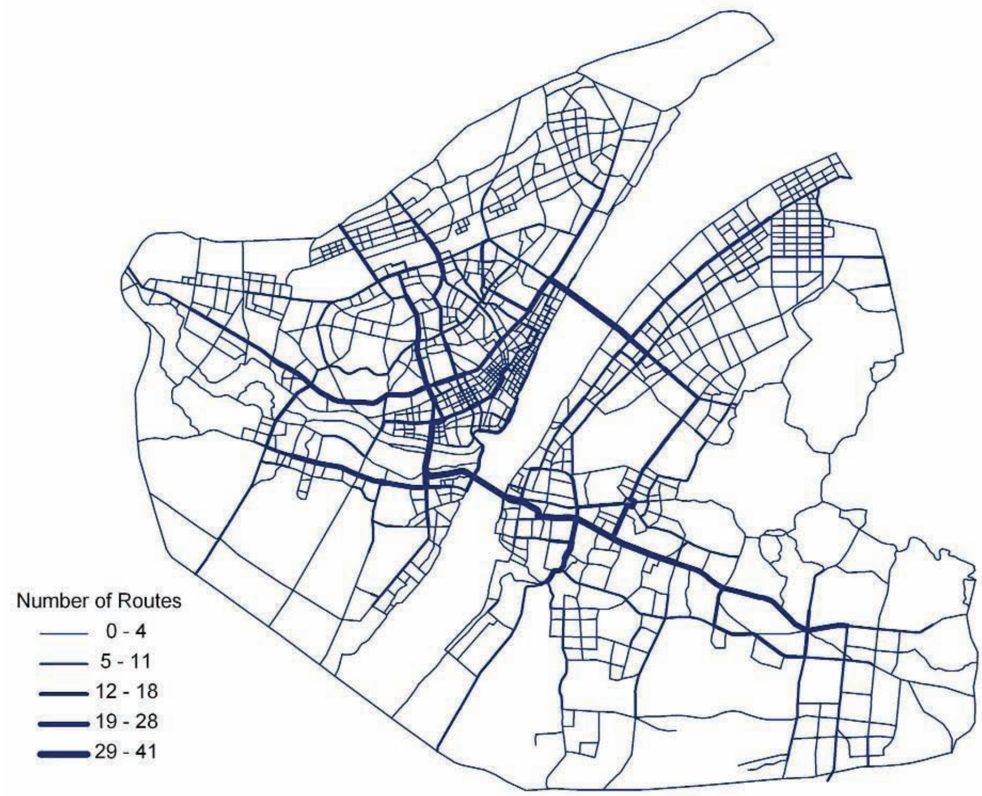


Figure 6-2 Distribution of existing bus routes in study area

6.1.1. Competing Degree with No.1 Rail Route

For multi-modal transportation, bus routes play a key role in the connection with the subway. However, while they develop their feeder function, these bus routes also compete with the subway based on the passenger flow at the shared stops or stations. In order to bring the subway into full play, plans have to be made and executed to reduce the competition between bus routes and rail routes.

The competing degree can be reflected from the perspective of the parallel length between a bus route and a rail route, and it can also be reflected from the perspective of the number of adjacent stops (or stations) that are used both by bus routes and rail routes. In the actual analysis, the latter approach is adopted. The statistic result is shown in Figure 6-3, which tells us that 13 bus routes share more than 5 adjacent stops with No.1 rail route.

No.1 rail route has its length of 24.5 km and owns 22 stations; therefore, the average station distance is approximately 1.1km. According to the standard (Qin, Yan, 2000) that the overlapping length between a bus route and a rail route should not be over 4 km, combining with the actual situation of Wuhan at the same time, here 5 adjacent stops used in common are taken as an acceptable limit. Under this condition, the approximate overlapping length between a route and the rail route is 4.4km. In the next stage of route filtration, routes that share more than 5 same stops with No.1 rail route will be removed.

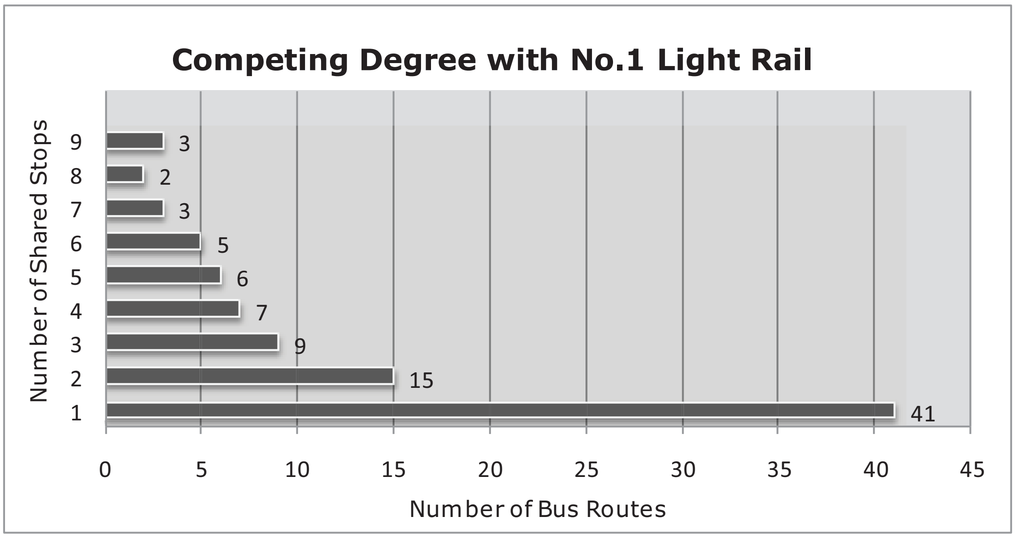


Figure 6-3 Competing degree between existing bus routes and No.1 rail route

6.1.2. Accessibility Analysis to Key Locations

Accessibility is defined as the degree of convenience from a given location to another location for work, shopping, recreation, seeing doctor or business(F. H. Wang, 2009). Accessibility is a key element to reflect the service quality of bus routes, and it has also become an issue of social equity. Therefore, accessibility analysis is important and indispensable.

- **Accessibility from key transit hubs**

Transit hubs face the coming and leaving of large passengers and cargo every day. Its existence makes it possible that passengers and cargo are exchanged across several modes of transport at the transport interchange. Train station of the national railway system is a typical representative out of all kinds of transit hubs. Therefore, its accessibility analysis has important implications. There are three train stations in the whole city, all locating in the urban central area (Hankou-, Wuchang- and Wuhan railway station).

This analysis has adopted the service-oriented method to evaluate the accessibility from the key transit hubs to their service areas. The whole analysis is carried out based on a fully-formed road network which includes walking system, bus route network and No.1 rail route. For different systems and road hierarchy, various speed assumptions are set accordingly. Combined the practice with experience, the specific speed values implemented for different transport routes are shown as Table 6-2. Take Wuhan station for example, the service area analysis shows the accessibility degree and the corresponding coverage within 120 minutes, as Figure 6-4 and Figure 6-5 describe. Here, the coverage refers the real land area covered within the given time, and it is different from the urban built-up area. Therefore, it is rational that coverage area is greater than the built-up area within 120 minutes. Due to the existence of the rail route and many secondary roads located in the other side of the Yangtze River, Hankou business district and its catchment area can be reached within 90 minutes. The corresponding coverage area reaches 313.56 km^2. A similar analysis is executed with the 3 stations together. Figure 6-6 and Figure 6-7 describe the accessibility and accumulative coverage from the three train stations to their service areas with a maximum of 120 minutes.

- **Accessibility to key central business districts**

This analysis has taken 4 key central business districts (CBDs) as representatives, one in Hankou, one in Hanyang and two in Wuchang, to evaluate the accessibility to key CBDs from the passenger-oriented perspective. Assume that each passenger would choose the closest CBD as destination (or proximity principle), and the result is shown in Figure 6-8. In this process, each road node is taken as a possible access to its closest CBD for passengers, and residential areas are not specifically considered. From the figure, we can see that it still costs more than one hour for passengers from some areas to their closest CBD.

Table 6-2 Speed Setting

System	Speed Setting	
Walking system	3 km/h	
Bus route network	Main road	36 km/h
	Secondary road	24 km/h
	Slip road	18 km/h
	Others	12 km/h
No.1 rail route	50 km/h	

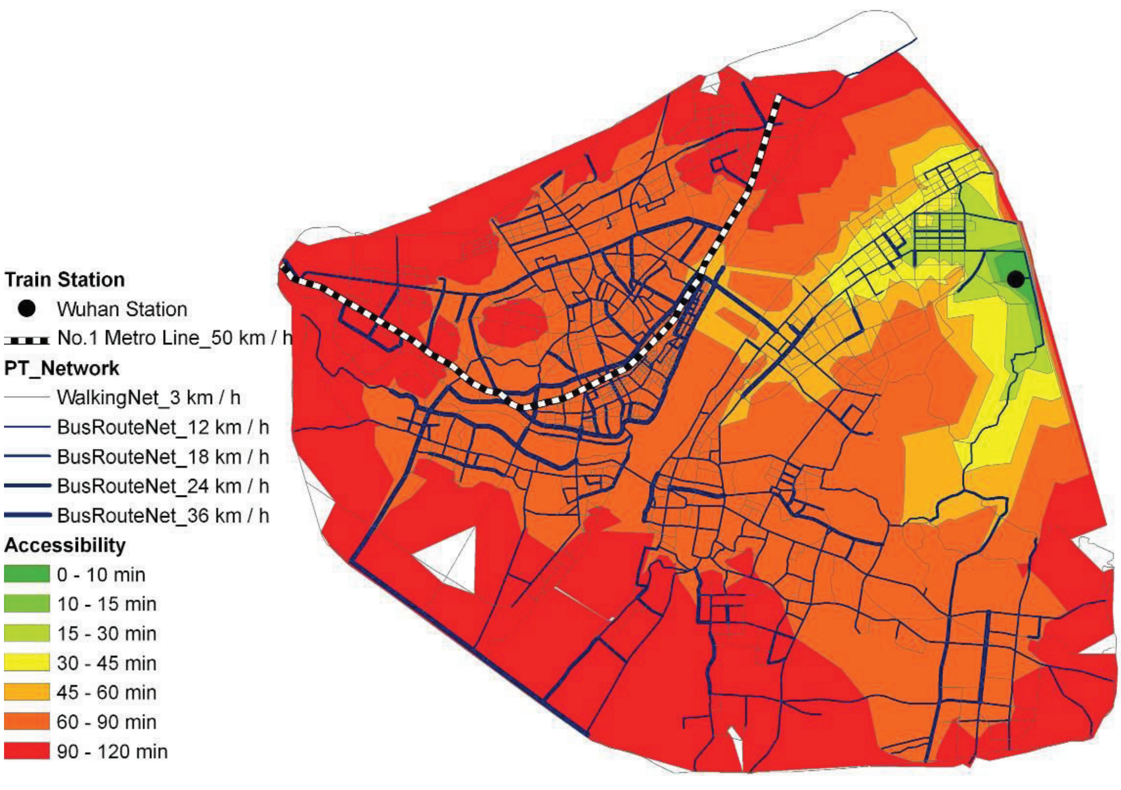


Figure 6-4 Accessibility to key transit hub – Wuhan Train Station

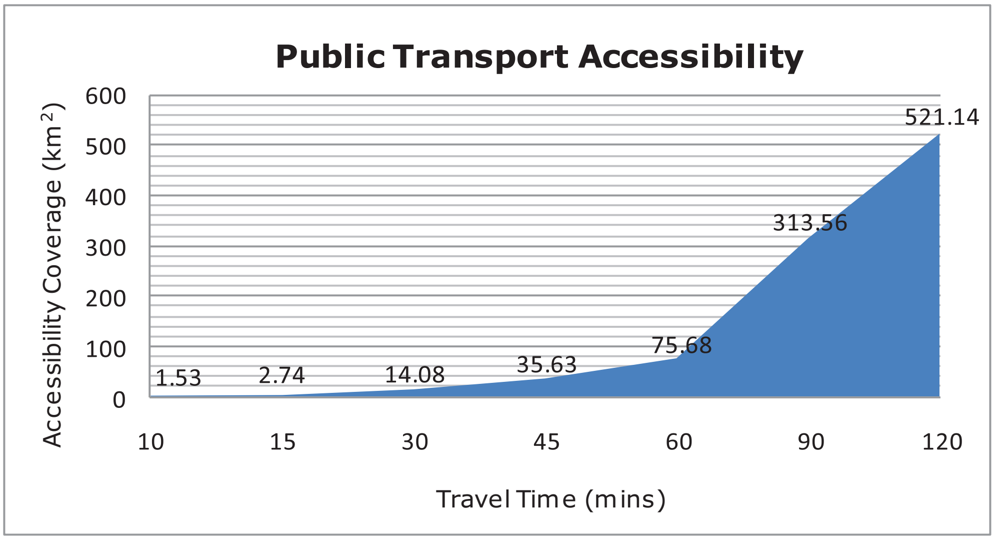


Figure 6-5 Coverage area within 120 minutes from Wuhan Train Station

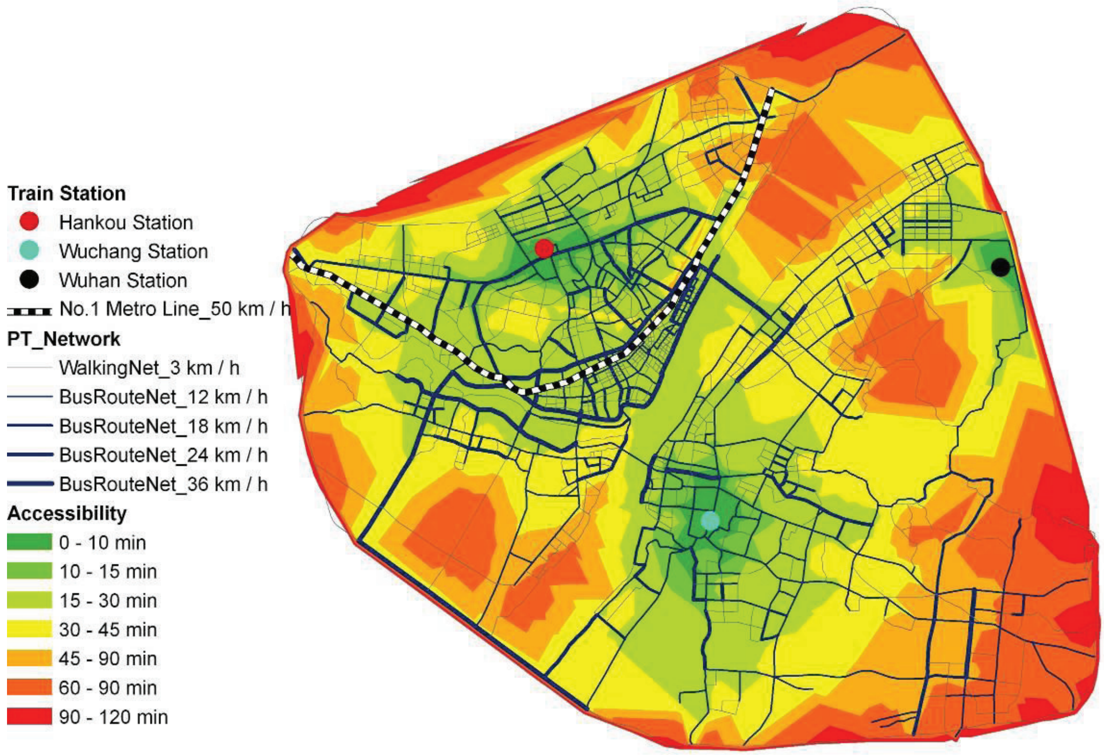


Figure 6-6 Accessibility to three key transit hubs

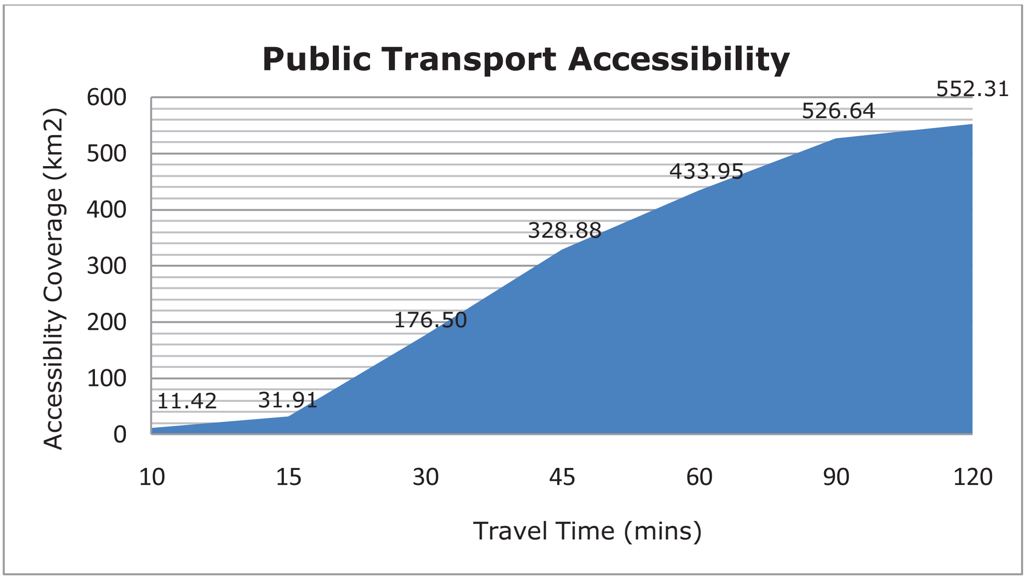


Figure 6-7 Accumulative coverage area within 120 minutes from the three train stations

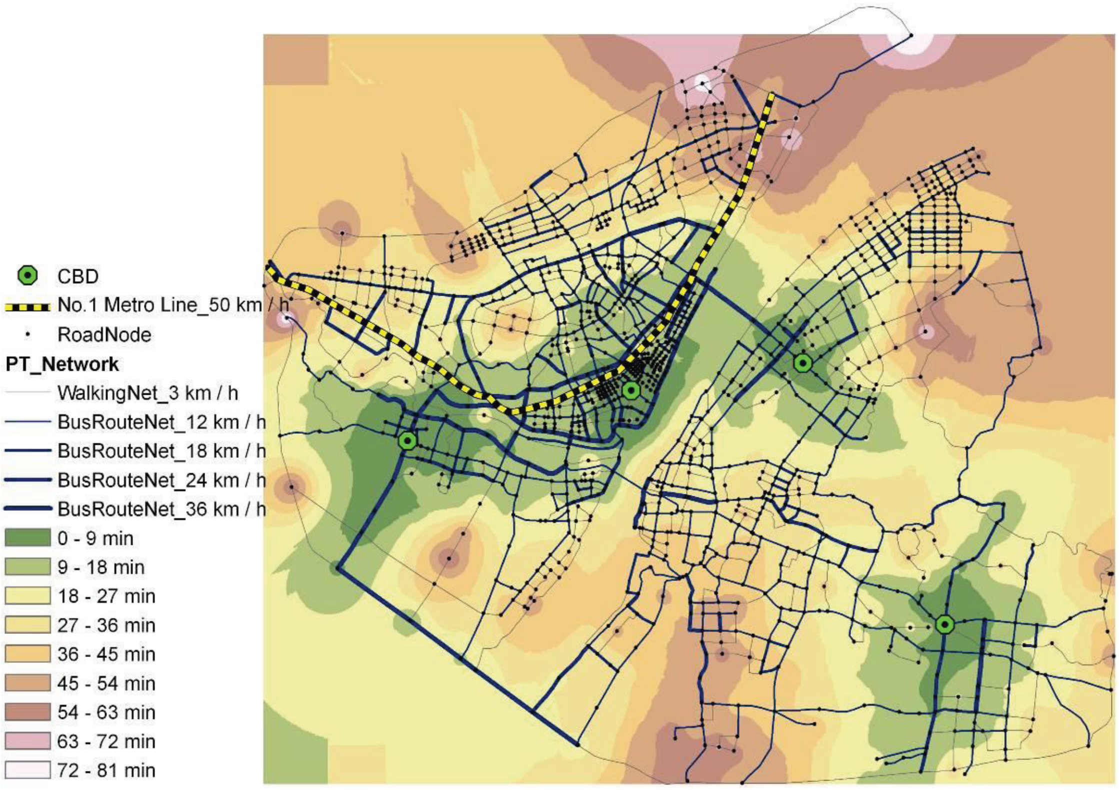


Figure 6-8 Accessibility to key locations – 4 CBDs

6.2. Existing Bus Route Filtration

This stage is still a performance evaluating process but more detailed. It is also a preparing process (or a "survival of the fittest" process) for bus route optimization. This preparing process is following the rules of route design perspective and service quality perspective as described in the very beginning of this chapter, to evaluate the individual bus route.

6.2.1. Indicator Selection, Definition and Standardization

In this stage, the conditaion that an indicator can be selected is whether this indicator is useful for bus route optimization. In new route generating process, elements to consider include the route basic design parameters as well as passenger flow volume, such as: route length, number of stop, nonlinear coefficient, passenger flow of individual route, route effectiveness and so on. The evaluating result is based on these indicators and will be taken as a basis for the route filtration in the optimization stage.

Indicators selected are divided into two groups, scoring indicators and filtering indicators. Scoring indicator is used to score the performance of individual bus route. Route of which the comprehensive score is lower than a given threshold value will be deleted. The filtering indicator will be employed as a standard. A route of which the performance does not meet this standard will be removed directly. All the chosen indicators are exhibited in Table 6-3.

Table 6-3 Scoring Indicators and Filtering Indicators

Classification	Indicator for Individual Bus Route
Scoring Indicator	Route length
	Number of bus stop
	Nonlinear coefficient
	Unit passenger flow of individual route
	Route effectiveness
Filtering Indicator	Difference between real passenger flow and assigned passenger flow in rush hour
	Number of shared bus stop between bus route and rail route

- **Indicator Definition and Standardization**

1) Route length

According to the national standard of route length(GB50220-95, 1995), the optimum range of route length is from 8km to 12km. However, this limitation is too strict for metropolitan cities. A wider range of route length is suggested. As for Wuhan, the rational range is from 6km to 15km based on the city scale. Therefore, the calculation function is defined as

$$x' = \begin{cases} 1 - \dfrac{a-x}{c} & 2 \leq x < 6 \\ 0.9 & 6 \leq x < 8 \\ 1 & 8 \leq x \leq 12 \\ 0.9 & 12 < x \leq 15 \\ 1 - \dfrac{x-b}{c} & 15 < x \leq 36 \end{cases}$$ **Function 6-1**

where

- x' is the standardized value of x.
- x is the real length of bus route.
- $[a, b]$ represents a stable variable interval of real route length x, and here a is set as 6(km), b is 15(km).
- c is defined as

$$c = \max\{a - m, M - b\},$$

where m and M are respectively the integers of minimum and maximum of existing route length in study area. According to the length statistic result, as Figure 6-1 shows, m is set as 2(km), M is 36(km). So:

$$c = \max\{6 - 2, 36 - 15\} = 21,$$

and Function 6-1 becomes the form as follows:

$$x' = \begin{cases} 1 - \dfrac{6-x}{21} & 2 \leq x < 6 & x < \text{rational range} \\ 0.9 & 6 \leq x < 8 & x;\ \text{suboptimal} \\ 1 & 8 \leq x \leq 12 & x;\ \text{optimal} \\ 0.9 & 12 < x \leq 15 & x;\ \text{suboptimal} \\ 1 - \dfrac{x-15}{21} & 15 < x \leq 36 & x > \text{rational range} \end{cases}$$

2) Number of bus stop

In accordance with the regulation (GB50220-95), the rational range of bus stop distance within urban area is from 500m to 800m. Therefore, each route has its own accepted range of number of stops based on its length. Therefore, the function is defined as

$$x_i' = \begin{cases} 1 - \dfrac{a-x}{c} & 0 \leq x_i < a_i \\ 1 & a_i \leq x_i \leq b_i \\ 1 - \dfrac{a_i - x_i}{c_i} & x_i > b_i \end{cases}$$ **Function 6-2**

where

- x_i' is the standardized value of x_i.
- x_i is the number of stop of ith route.
-[a_i, b_i] represents a stable variable interval of x_i, therefore,

$$[\, a_i, b_i \,] = [\frac{l_i}{800} + 1, \frac{l_i}{500} + 1]$$ **Function 6-3**

Where

- l_i presents the real length of bus route i.
- c_i is defined as

$$c_i = \max\{a_i - m, M - b_i\},$$

where m and M are respectively the minimum and maximum of number of stop in study area. And m is 3; M is 60 according to the number statistic of bus stop.

3) Nonlinear coefficient

The optimum value of nonlinear coefficient is 1.4. But considering the actual situation in study area, bus route of which the nonlinear coefficient is lower than 2 is accepted. Therefore, the function is set as

$$x' = \begin{cases} 1 & 1 \le x \le 1.4 \\ 1 - \frac{5}{9}(x - \frac{7}{5})^2 & 1.4 < x \le 2 \\ 0.8e^{2-x} & x > 2 \end{cases}$$ **Function 6-4**

where
- x' is the standardized value of x.
- x is the real nonlinear coefficient of bus route, which is defined as,

$$x = \frac{L_i}{D_i}$$ **Function 6-5**

where,
- i is the ID of a bus route.
- L_i is the length of bus route i.
- D_i is the spatial linear distance between the terminal pair of this route.

4) Unit passenger flow
Unit passenger flow refers to the number of passenger per kilometer of a bus route. This indicator reflects the operational capacity of individual routes. Route of which unit flow is lower than 1000 will be deleted. Here, 1000 is the minimum value that can be accepted. The quantification function is set as

$$x' = \frac{x - m}{M - m}$$ **Function 6-6**

where
- x' is the standardized value of x.
- x is the real unit flow of bus route.
- m and M are respectively the minimum and maximum of real unit flow.

5) Route effectiveness
Route effectiveness reflects a possible mismatch between traffic production and attraction of each bus route. Routes of which the effectiveness is lower than 0.2 are not considered. The function is defined as

$$x_i' = 1 - \frac{|P_i - A_i|}{P_i + A_i}$$ **Function 6-7**

where
- x_i is the route effectiveness, and it is a standardized value of x.
- P_i is the total production of all stops on route i.
- A_i is the total attraction of all stops on route i.

6) Flow difference in rush hour
Flow difference reflects the difference between the real passenger flow and assigned passenger flow in rush hour of each bus route. The latter is calculated based on the road edge flow which is acquired according to the travel demand at stop level. The calcualtion process is implemented in TransitNet and ArcGIS. Flow difference is a filtering indicator.

7) Number of shared bus stop

Number of shared bus stop reflects the competing degree between bus route and rail route. It is a filtering indicator. As introduced in section 6.1.1, routes that share more than 5 same stops with No.1 rail route will be removed.

6.2.2. Correlation Test of Indicators

Correlation test is only carried out in the group of scoring indicators. It will check out that whether there is high correlation between each pair of indicators.

According to the definition of correlation degree (Tan, 2005), it is divided into the following six categories, in which variable r is defined as the correlation coefficient of a pair of indicator data:

- $r = 0$, complete dissociation;
- $0 < |r| \leq 0.3$, almost no correlation;
- $0.3 < |r| \leq 0.5$, low correlation;
- $0.5 < |r| \leq 0.8$, significant correlation;
- $0.8 < |r| \leq 1$, high correlation;
- $|r| = 1$, completely correlation.

After the correlation analysis calculation in excel, the result tells that all pairs of indicator data almost have no correlation, that is to say, the absolute value of correlation coefficient of each pair of data is located in the interval (0, 0.3]. Therefore, the evaluation result is reliable in this stage.

6.2.3. Bus Route Filtration

In this stage, the filtering process is implemented with the help of ArcGIS. The whole process consists of two stages:

I. Filtering based on the weighted sum of scoring indicators.

Weighted sum of scoring indicators here is taken as a basis that whether a route is kept or removed. For each indicator, the weights are respectively set as follows: route length, 0.15; number of stop, 0.15; nonlinear coefficient 0.15; unit passenger flow, 0.25; route effectiveness, 0.3. For the sake of keeping a certain amount of existing routes, 0.7 is set as the threshold. Route of which the weighted sum is lower than 0.7 will be removed. As a result, 163 bus routes are kept.

II. Filtering based on the filtering indicators.

- Competing degree with No.1 rail route.

As discussed before, route of which the number of shared bus stop with the rail route is over 5 would cause significant competition with the metro. Therefore, this kind of routes needs to be deleted. As a result, 8 routes out of 163 routes kept in the previous step are removed, and 155 routes kept.

- Flow difference in rush hour.

As discussed before, this indicator reflects the difference between the real passenger flow and assigned passenger flow in rush hour of a bus route. When the flow difference of a complete route in rush hour is over 10000 heads, it can be considered that corresponding routes are overloaded or high vacant. According to the statistic, 26 routes out of 155 routes (survived in the last filtering step) are overloaded, and another 26 routes have higher vacancy rate. Consequently, 103 routes are kept finally, and these routes will involve into the process of route optimization.

6.3. Bus Route Optimization in TransitNet

6.3.1. Optimized Plan Design and Scenario Development

The bus routes generation process consists of two parts: candidate routes generation and optimal routes generation. Each part needs a set of initial parameters, which is filled in according to the assumptions in scenario development, as discussed in section 5.2.2. All the bus routes will be generated considering the existence of No.1 rail route. This optimization aims to get the route set that have the best global efficiency, as discussed in section 5.2.3.2.

To obtain the optimized bus routes under the restriction of No.1 rail route, it needs to set the initial assumptions for generating the candidate bus routes, shown as follows:

1) Bus route length, the minimum length is set as 6km, and maximum is 15km, according to the appropriate length range of Wuhan.
2) A bus route, which at least passes 5 bus stops, can be accepted as a candidate route.
3) The non-linear coefficient of a candidate bus route cannot be greater than 2;
4) The valid effectiveness of a candidate bus routes cannot be lower than 0.2, and the effectiveness is defined as Function 6-7.
5) The number of passengers per kilometer of a candidate route cannot be less than 1000.
6) Number of the adjacent stops which serve both a rail route and a candidate bus route cannot be over than 5; otherwise this candidate route is supposed to be invalid. In the meantime, the connection between bus routes and the rail route is encouraged and promoted in the process of candidate route generation.
7) Every two distinct candidate routes must have at least 5 different bus stops.

TransitNet employs the genetic algorithm to extract the optimal route set from candidate routes under the different parameter settings, which are reflected as different assumed values shown as follows:

1) Route scale, which is defined as the total route number. Here, route scale is set as 244 in order that bus route set is comparable with the route set before optimization.
2) Population size is 40, in other words, there are 40 competing candidate bus route sets (also named individuals or chromosomes) in each generation of the whole evolution process.
3) Crossover probability is 0.7. That is to say, for each couple of candidate route sets, routes between the same bus terminal pair have 70% of possibility to cross with each other.
4) Mutation probability is 0.8, which means that 80% of route sets (or 32 route sets) in the population would change.
5) The number of evolution generation is 400, that is to say, the whole optimization needs to go through 400 optimized cycles.

In order to get the route set of the best global efficiency, optimization process has employed "route efficiency" as the fitness function. This fitness function has been introduced in detail in section 5.2.3.2. In the function, weights of route effectiveness and stop coverage are respectively 0.4 and 0.6.

6.3.2. Evaluation and Discussion

Following the rules and assumptions introduced in the previous part, the optimization result is shown in Table 6-4. The differences between the existing route set and optimizaed route set can be seen from Figure 6-9 and Figure 6-10. From the table, we can see that some problems exposed before the optimization have been obviously solved or improved. On the premise of the same total number of bus route, the total route length has decreased dramatically after optimization, accompanied with the shortened average route length. Average nonlinear coefficient is very close to the national standard 1.4. Also, on the premise of shortened route length, the network density has increased, and route overlapping coefficient has decreased. The increased network density reflects that the length of bus route network has increased, that is to say, the coverage of route network has grown up. The stop coverage of 300m buffer and 500m buffer have both come up to the national standards (coverage of 300m buffer cannot be lower than 50%, and coverage of 500m cannot be lower than 90%).

However, there are still some drawbacks of the optimized route set:

I. There is still a gap of bus route network density between the optimized route set and the national standard. A possible reason can be that the road construction in study area is not enough. Assume that each road arc has at least a bus route passing by it, and the route network density would be 2.35 km/km^2. There is still a gap compared with the standard.

II. Due to the constraint of route length, length of most routes has been shortened, which leads directly to the lower non-transfer coefficient. This problem cannot be solved fundamentally, and it only can be improved through the further adjustment.

Table 6-4 Comparison before and after Optimization

Individual indicator value in current situation		
	Before Optimization with No.1 Rail Route	After Optimization with No.1 Rail Route
Total number of routes	244	244
Total route length (km)	3999	3038
Average route length (km)	16.4	12.5
Average nonlinear coefficient	1.6	1.41
Network density (km/km^2)	1.24	1.48
Route overlapping coefficient	6.8	4.3
Stop coverage (300m)	66.2%	68.6%
Stop coverage (500m)	89%	92.1%
Non-transfer coefficient	33.6%	18.6%
Transfer coefficient for once	64.2%	67.5%
Transfer coefficient for twice	2.2%	13.7%
Transfer coefficient for three times	0%	0.2%
Total transfer coefficient	66.4%	81.4%
Maximal stop distance(m)	4665.27	5307.03
Minimal stop distance(m)	50.27	50.27
Average stop distance (m)	614.08	639.47

Figure 6-9 Existing Bus Routes and Stops

Figure 6-10 Optimized Bus Routes and Stops

- **Accessibility to key transit hub**

After the optimization, accessibility to Wuhan Station has improved to some degree. Especially in the time range from 45 minutes to 90 minutes, the accessible coverage increases dramatically, as shown in Figure 6-11 and Figure 6-12. Within 90 minutes, the coverage has increased 37.7 km² compared with the coverage before optimization. However, the optimized route set has its drawbacks around the third road ring; therefore, some districts cannot be accessible within 120 minutes. For example, the area located in the blue ellipse lacks an important connection; as a result, the corresponding district has low accessibility. This kind of problem can be improved through the adjustment in the future.

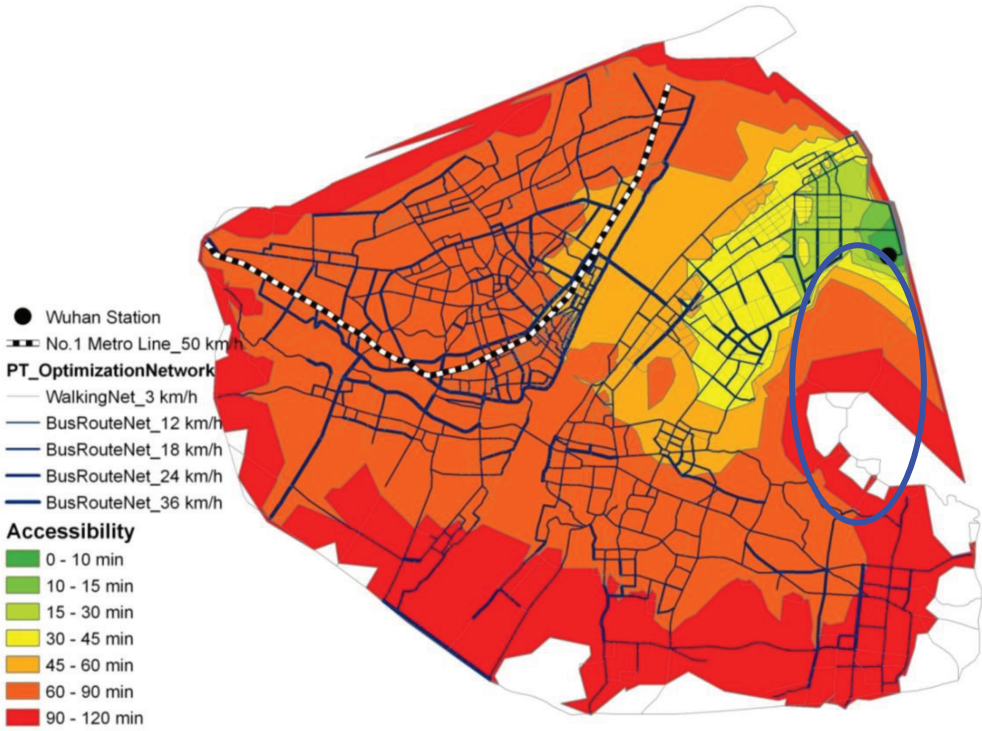


Figure 6-11 Accessibility to Wuhan Station after optimization

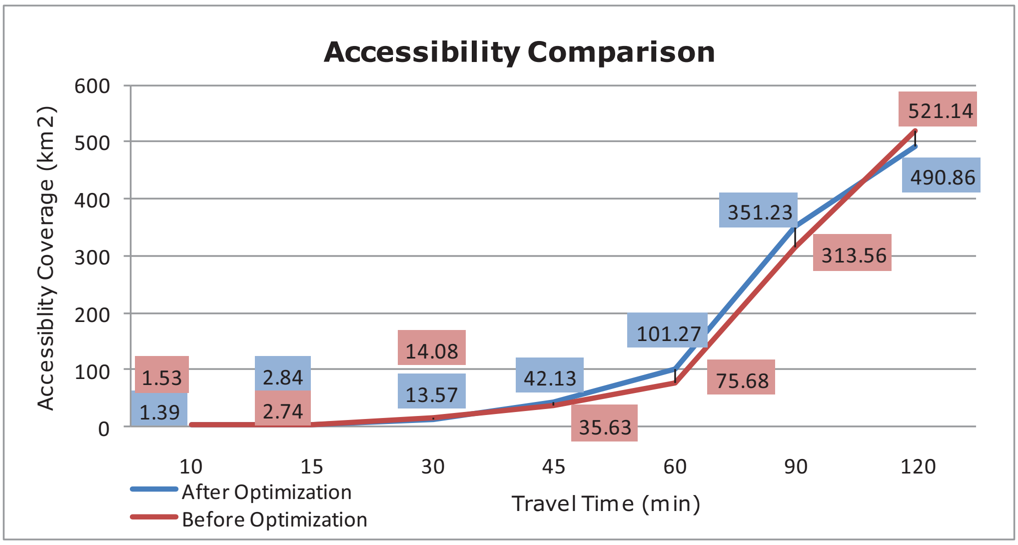


Figure 6-12 Accessibility coverage comparison before and after optimization

7. BUS ROUTE OPTIMIZATION IN SHORT-TERM SITUATION

In this chapter a scenario will be worked out envisaging the situation for 2013. Until the year of 2013, No.2 rail route and No.4 rail route will be completed and put into operation, as shown in Figure 7-1. Bus routes in 2013 should be adjusted or optimized to ensure an optimal coordination with the three then existing rail routes, No.1, 2 and 4. Bus route optimization in this stage still aims to generate the route set of the best global route efficiency.

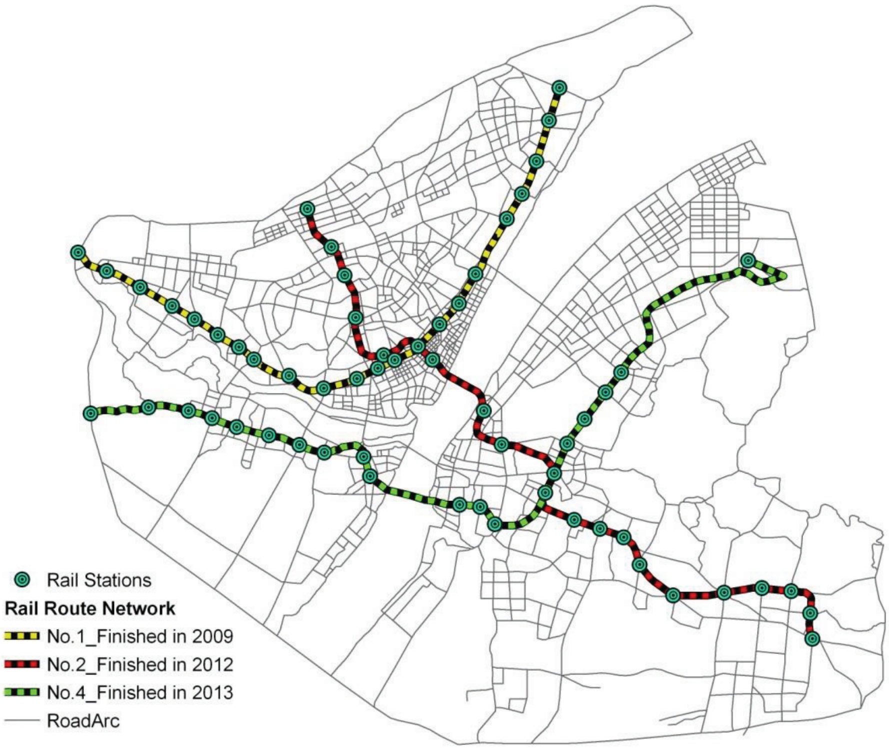


Figure 7-1 Layout of three rail routes in short-term situation

No.2 and No.4 rail route are two important passenger transport corridors that go through the north-south and east-west of the study area. The operation of these two rail routes will bring a great convenience for residents from the both sides of the Yangtze River. The most important contribution of the two rail routes is that they will effectively alleviate the existing traffic pressure of No.1 and No.2 bridges of the river, furthermore alleviate the traffic congestion. In particular, No.2 rail route passes through an army of commercial centers, new residential areas, large intercity transit hubs, high-tech development zones and urban central squares; therefore, it plays a key role in lightening the traffic pressure within the third ring road (Zhou, 2007). It can be said that the No.2 and No.4 rail routes take the responsibility of bus route optimization. The outset in this scenario is that for the coming years there will be no change in the distribution and growth/deline of the population and number of jobs. The starting point of this scenario is the set of candidate bus stops as discussed and derived in section 5.2.

7.1. General Evaluation for Existing Bus Routes

Evaluation generated in this step aims to dig out the drawbacks of existing bus routes when another two metro lines are considered (No.2 and No.4). Assume that there will be no change in the distribution of the existing bus routes for the coming years.

7.1.1. Competing Degree with the Three Rail Routes

As discussed in section 6.1.1, in the multi-modal transport environment, another function of bus routes is the feeder function for rail routes, and it is also an important push factor for route optimization and adjustment. With the appearance of the two new rail routes, competition between the existing bus routes and rail routes becomes stiffer, which is reflected in the longer parallel length of bus route with rail route and more shared adjacent stops between the two. Figure 7-2 and Figure 7-3 respectively shows the number of shared stops with No.2 and No.4 rail route. Competing degree with No.1 rail route can be found in Figure 6-3.

As defined, the competition between the two modes is not accepted when the number of shared adjacent stops is over 5. Therefore, route of which the number of shared adjacent stops with any metro line is more than 5 will not be accepted. According to the statistic of competition with No.2 rail route, there are 6 bus routes that each one shares more than 5 stops with the rail route. However, of these shared stops, the number of adjacent stops is lower than 5. Therefore, these 6 routes are accepted. An example is shown in Figure 7-4. This phenomenon only happens in the competition with No.2 rail route.

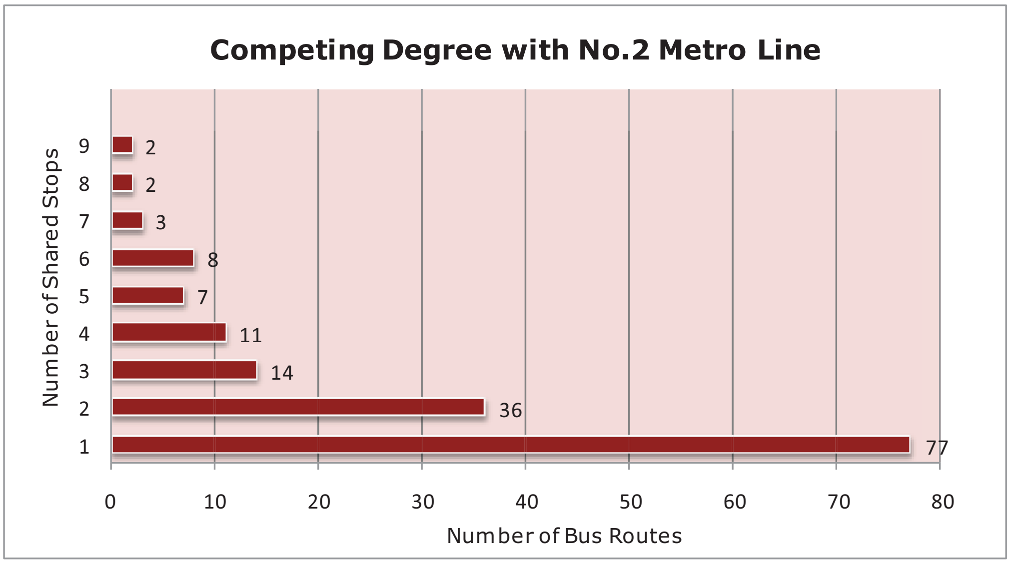


Figure 7-2 Competing degree between existing bus routes and No.2 rail route

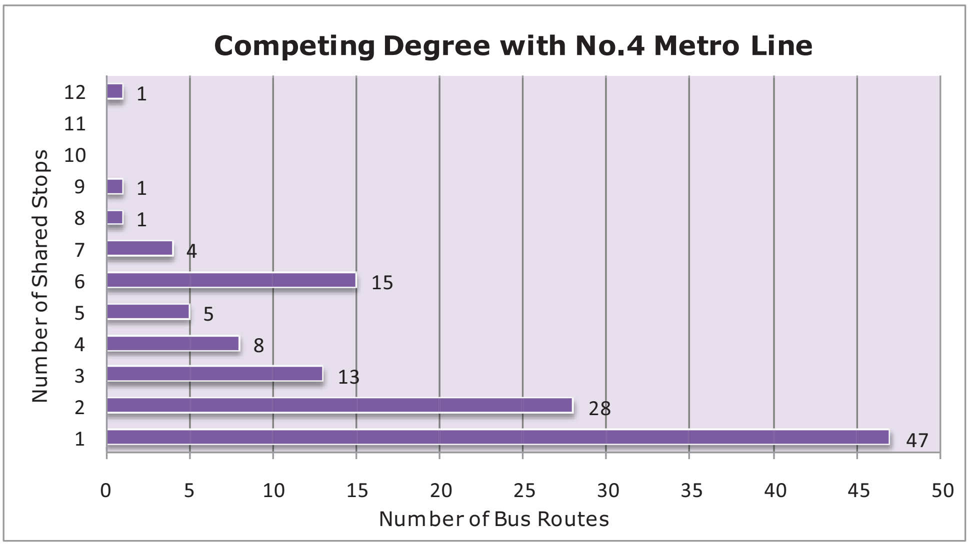


Figure 7-3 Competing degree between existing bus routes and No.4 rail route

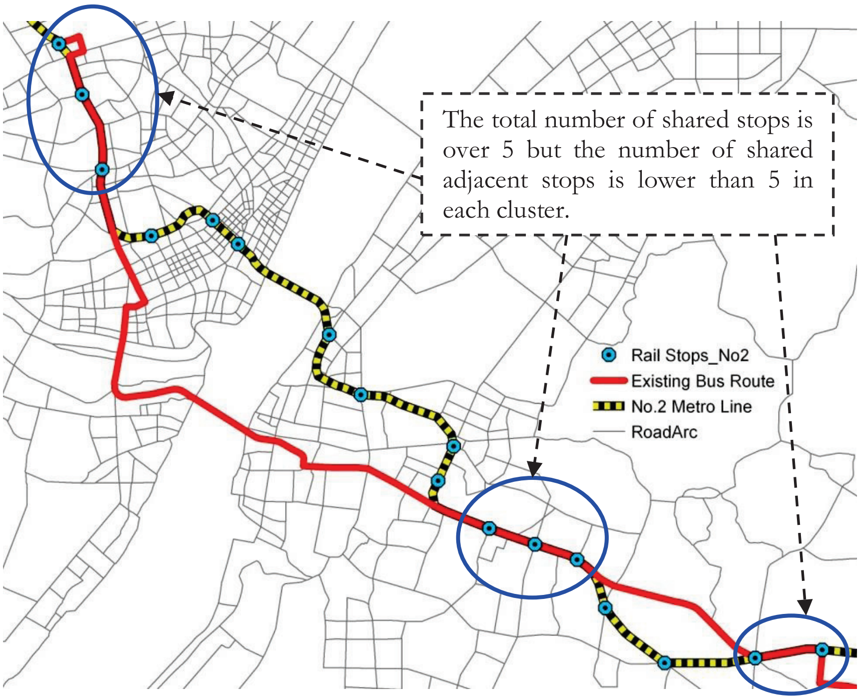


Figure 7-4 A special example in the competition with No.2 metro line

7.1.2. Passenger Flow Change of Individual Bus Route

The convenience and punctuality of metro will attracts large number of passenger in the near future, as a result, routes of which the passenger flow is shared (may be led by the parallel or overlapping length with the metro lines) in a large proportion should be optimized or adjusted. Of all the existing bus routes, 51 routes have their passengers reduced by more than 20%, 6 routes by over 30% and 1 route by almost 50%, when No.2 and No.4 metro lines are considered in the analysis. The result shows that passengers are effectively attracted by metro lines in the transfer stations or overlapping road segments between routes and metro lines, as Table 7-1 describes. All the results are generated with the assistant of TransitNet and ArcGIS.

Table 7-1 Relationship between Flow Change and Competing Degree

Reduction Rate	Number of bus routes			
	Total number of bus routes	Number of shared stops with No.1 metro line > 5	Number of shared stops with No.2 metro line >5	Number of shared stops with No.4 metro line >5
20% ~30%	45	1	7	16
30% ~ 40%	5	0	0	3
> 40%	1	0	0	0
	Total number of bus routes	Number of shared stops with No.1 metro line > 3	Number of shared stops with No.2 metro line >3	Number of shared stops with No.4 metro line >3
20% ~30%	45	2	15	25
30% ~ 40%	5	2	0	4
> 40%	1	0	0	0

7.1.3. Flow Analysis for Bus Routes across the Yangtze River

Traffic congestion at bridges across the Yangtze River has been a serious problem of Wuhan transportation. Passenger flow on the two bridges keeps remaining at a high level. Of all the existing bus routes, there are 69 bus routes crossing the Yangtze River with one of them passing through both two bridges, as shown in Figure 7-5. According to statistic, 52 out of 69 bus routes across the river have their length more than 20 km and 6 routes even over 30km. The total length of routes across the river is up to 1308km. Therefore, long and large number of routes carried only by two bridges leads to the serious congestion across the river and surrounding areas. This problem will be alleviated when No.2 and No.4 metro line are put into operation.

Assuming that no change would happen to existing bus routes when these two metro lines are finished, according to analysis, there are 19 routes crossing the river with their passenger flow reducing by over 20%. Of these routes, 11 routes shared more than 5 adjacent stops with No.4 metro lines and 4 routes with No.2 metro line. It interprets that the two metro lines will effectively play a part in sharing passenger flow with bus routes. For example, bus route of No.537 shared 12 stops with No.4 metro line, and the long overlapping length leads to the decrease of its passenger flow by 30.7%, as Figure 7-6 shows.

Figure 7-5 Distribution of existing bus routes crossing the river

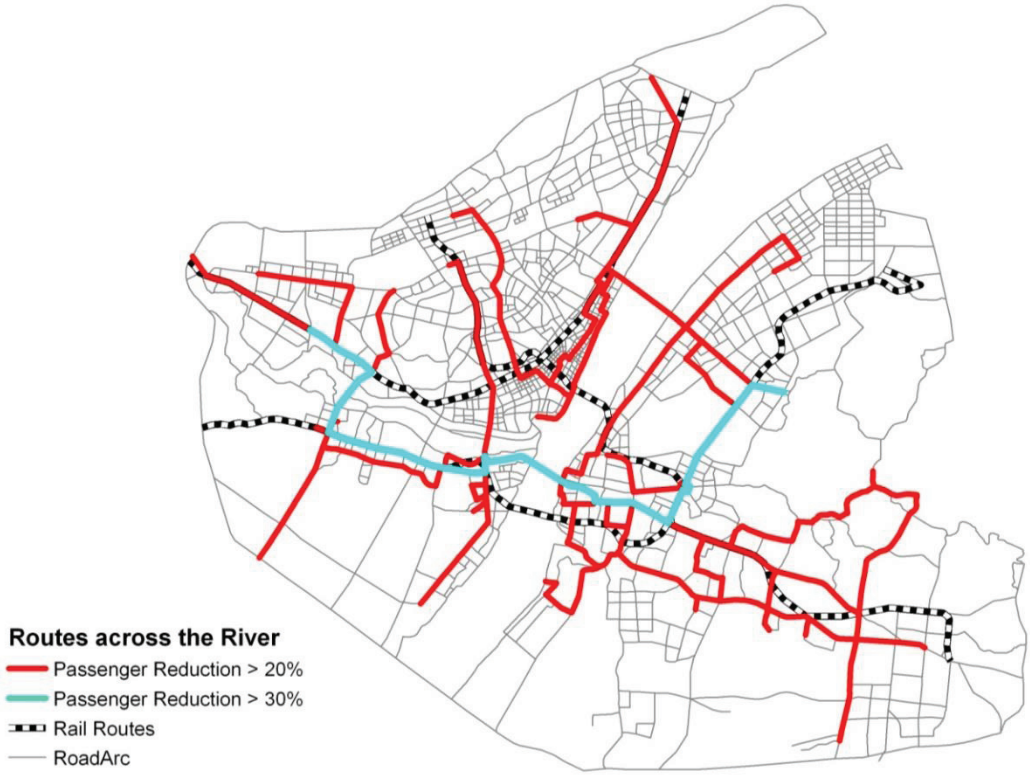


Figure 7-6 Passenger flow change of bus routes across the Yangtze River

7.2. Existing Bus Route Filtration

In this stage, the method of bus route filtration is almost the same with that in section 6.2.3. The only difference is the consideration of passenger flow reduction of existing routes when the two new metro lines are added. When the number of rail route increases, passenger flow of bus routes reduces accordingly. The specific filtering principle is revealed in Table 7-2.

7.3. Bus Route Optimization in TransitNet

7.3.1. Optimized Plan Design and Scenario Development

On the premise of no change in the distribution of population in the study area, same with the optimization process in section 6.3.1, the optimization consists of two steps; the initial parameters are set as shown in Table 7-3 and Table 7-4.

Table 7-2 Principle of Bus Route Filtration

Classification	Indicator		Filtering Principle
Scoring Indicator		Weight	When weighted sum of the indicator value < 0.7, removed.
	Route length	0.15	
	Number of bus stop	0.15	
	Nonlinear coefficient	0.15	
	Unit passenger flow	0.25	
	Route effectiveness	0.3	
Filtering Indicator	Competing degree with rail routes		When number of shared adjacent stops >5, removed.
	Flow difference in rush hour		When flow difference > 10000 heads, removed.
	Passenger flow reduction		When ratio of flow reduction > 20%, removed.

Table 7-3 Parameters of candidate route generation

Constraint	Parameter
Accepted length range of bus route	6km ~ 15km
The maximum of nonlinear coefficient	2
The minimum of route effectiveness	0.2
The maximum number of shared adjacent stops	5
The minimum number of stops of a candidate route	5
The minimum of unit passenger flow	1000
The minimum number of different stops of two distinct candidate routes	5

Table 7-4 Parameters of bus route optimization

Constraint	Parameter
Route scale	244
Population size	40
Crossover probability	0.7
Mutation probability	0.8
The number of evolution generation	800
Fitness function: Maximal global route efficiency	

7.3.2. Evaluation and Discussion

The result (Table 7-5) tells that the optimized bus routes have a more reasonable distribution on the road network. The differences between the existing route set and optimizaed route set can be seen from Figure 7-7 and Figure 7-8. Distribution of optimized routes laid on the road network is shown in Figure 7-9. The new route set has reduced the burden for the main roads greatly. The total length of main road arcs that has their number of bus routes laid on them reduced by more than 5 is up to 29km. These main roads are mainly located in the important areas (such as commercial zones and residential zones) in the study area, and the total length of these main roads that has their number of routes reduced by over 5 is up to 19km, as displayed in Figure 7-10. In this figure, it also can be seen that great increase of the number of bus routes happens on some road arcs. A possible reason is the high travel demand on this road arcs. Figure 7-11 shows the distribution differences of all roads located in the important areas after and before optimization.

With shorter total length of routes, optimized bus route network has its coverage larger than that before optimization. However, due to the constraint of route length, length of most routes has been shortened, which leads directly to the lower non-transfer coefficient. This problem can only be improved through the further adjustment.

Table 7-5 Comparison before and after Optimization

Individual indicator value in short-term situation		
	Before Optimization with No.1 Rail Route	After Optimization with No.1, 2&4 Rail Route
Total number of routes	244	244
Total route length (km)	3999	3021
Average route length (km)	16.4	12.4
Average nonlinear coefficient	1.6	1.37
Network density (km/km^2)	1.24	1.46
Route overlapping coefficient	6.8	4.4
Stop coverage (300m)	66.2%	68.3%
Stop coverage (500m)	89%	91.8%
Non-transfer coefficient	33.6%	22.3%
Transfer coefficient for once	64.2%	69.4%
Transfer coefficient for twice	2.2%	8.3%
Transfer coefficient for three times	0%	0%
Total transfer coefficient	66.4%	77.7%
Maximal stop distance(m)	4665.27	5307.03
Minimal stop distance(m)	50.27	50.27
Average stop distance (m)	614.08	639.99

Figure 7-7 Existing Bus Routes and Stops

Figure 7-8 Optimized Bus Routes and Stops

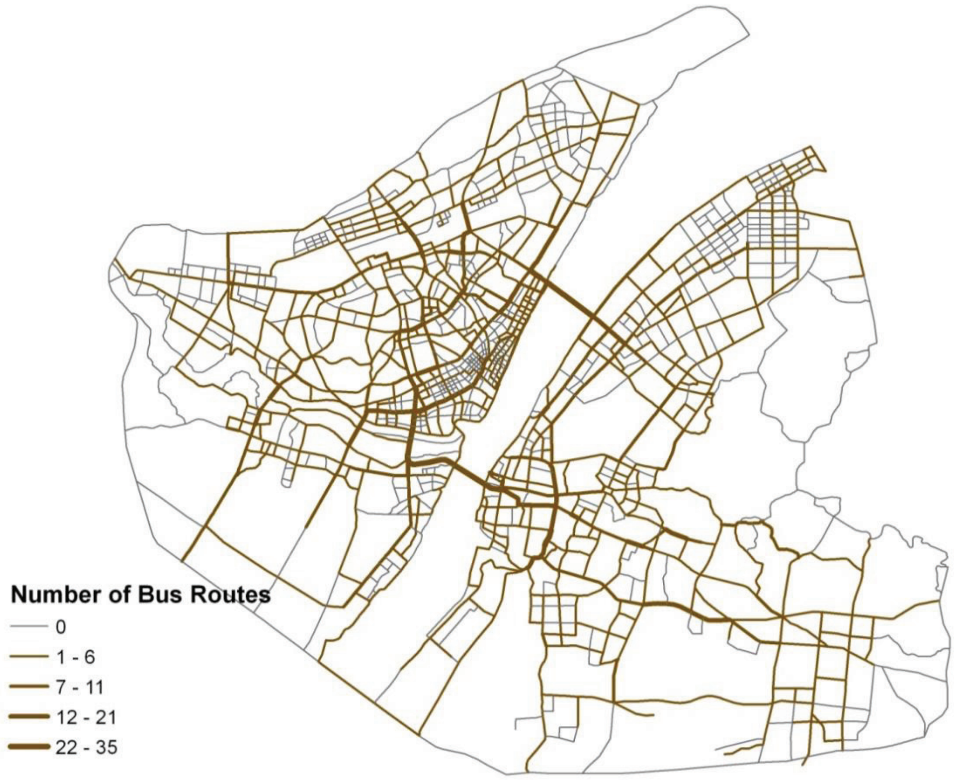


Figure 7-9 Distribution of optimized bus routes on the road network

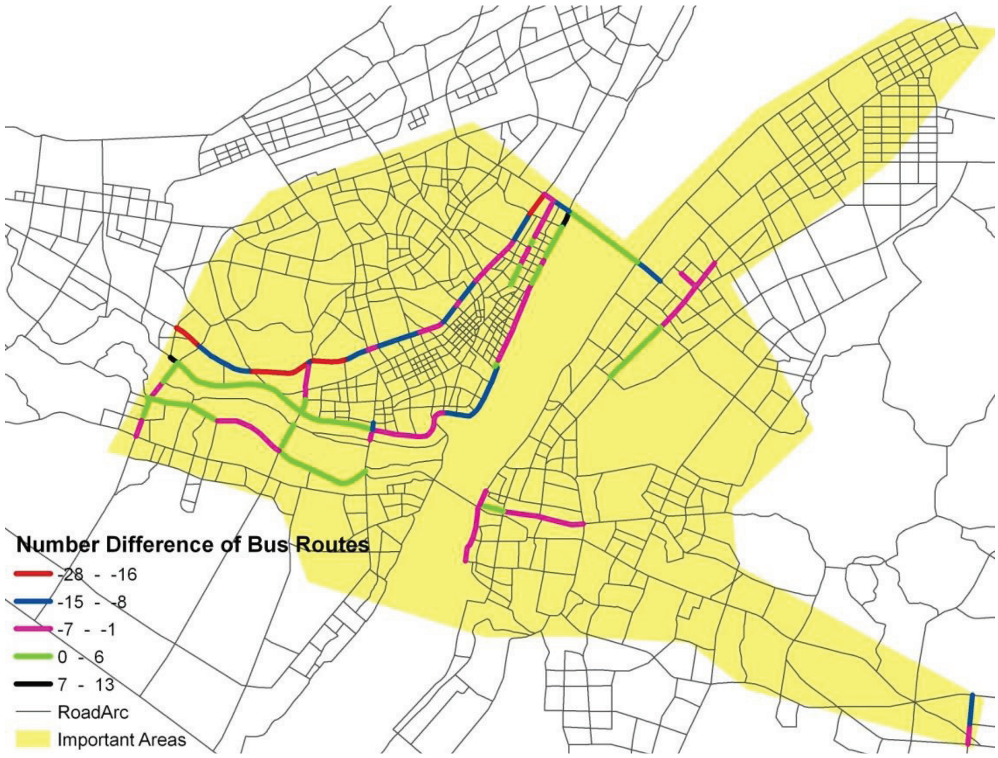


Figure 7-10 Distribution difference on main roads in the important areas after and before optimization

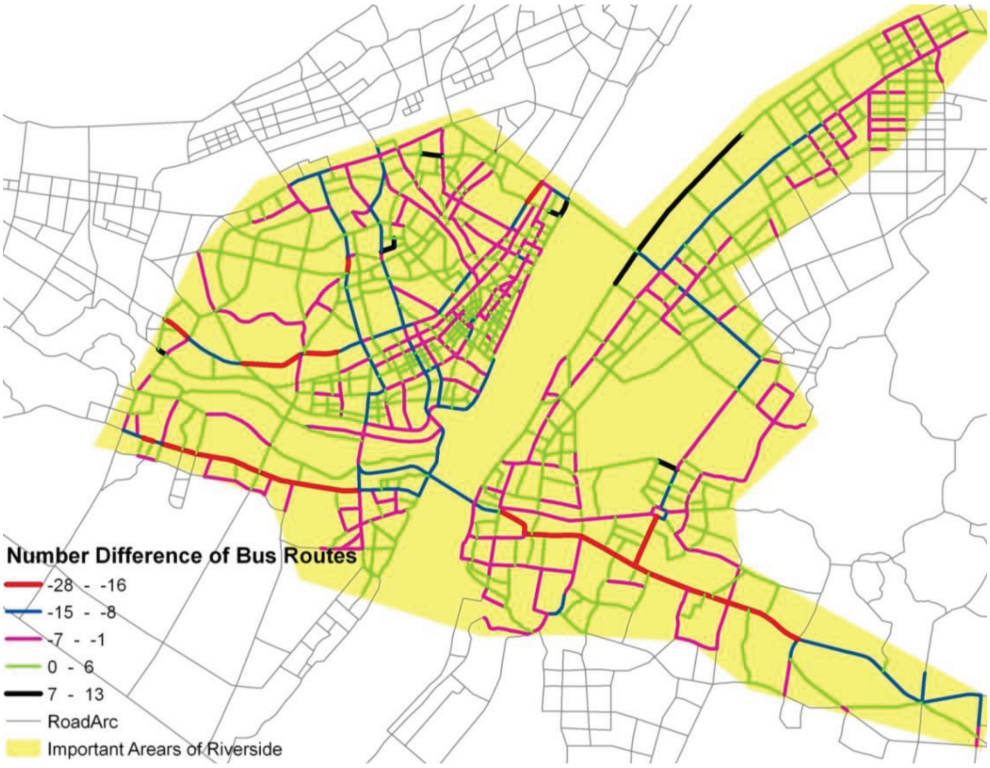


Figure 7-11 Distribution difference in the important areas after and before optimization

- **Passenger Flow Analysis**

I. Flow change at the stop level

After optimization, there are 764 bus stops optimized in total, out of which 652 stops are from the existing stop group and 112 stops are additional. Due to the restriction and attraction of No.2 and No.4 metro line, passenger flow at the stop level has changed a lot. More precisely, part of stops used in the bus system before optimization and now also used in the optimized situation has their passenger flow reduced greatly. As Figure 7-12 shows, 159 out of 652 existing bus stops have their passengers reduced by more than 1000 heads. The majority of these stops are located within the service area of the two new rail routes, and flow reduction of rest stops are caused by the decreased number of routes passing the corresponding stop. According to rough statistic based on the optimized result, there are over 290,000 passengers that would choose to take the metro instead of bus, which would alleviate burdens on the relative routes and road segments. The calculation of passenger flow is implemented in TransitNet, and the analysis is carried out in ArcGIS.

II. Flow change at the route level

To some degree, each optimized route has its passenger flow changed, especially the routes crossing the Yangtze River. Of all the river-crossed routes in the optimized set, there are 20 routes from the existing route group. 15 routes out of these 20 routes has their passenger flow reduced by more than 20,000 heads, and 9 routes reduced by more than 5000 heads in rush hour, as Table 7-6 describes in detail. According to statistic based on the optimized result, all the optimized routes would have their accumulated river-crossed passengers in rush hour reduced by 710,000 heads after No.2 and No.4 metro line put into operation, and the two metro lines would share over 50% river-crossed passengers all day. The calculation of passenger flow is implemented in TransitNet, and the analysis is carried out in ArcGIS.

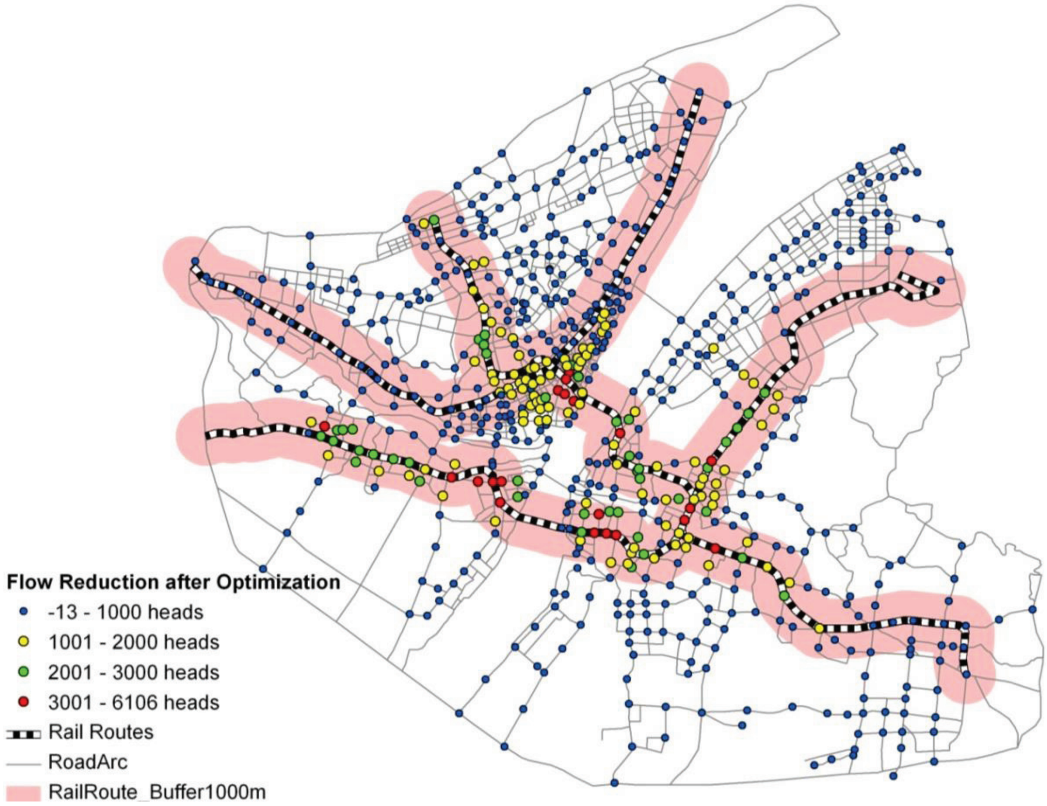


Figure 7-12 Flow reduction based on the stops used both before and after optimization

Table 7-6 Flow Reduction of Existing 20 River-crossed Routes

Reduction in All Day	Number of Routes	Reduction in Rush Hour	Number of Routes
< 20,000 heads	5	< 2,000 heads	2
20,000 ~ 30,000 heads	5	2,000 ~ 4,000 heads	7
30,000 ~ 40,000 heads	8	4,000 ~ 6,000 heads	9
> 40,000 heads	2	> 6,000 heads	2

- **Accessibility to key transit hub**

After the optimization, accessibility to Wuhan Station has improved greatly. Especially in the time range from 45 minutes to 90 minutes, the accessible coverage increases dramatically, as shown in Figure 7-13 and Figure 7-14. Within 60 minutes, the coverage has increased 149.82 km^2 compared with the coverage before optimization. However, the optimized route set has its drawbacks around the third road ring; therefore, some districts cannot be accessible within 120 minutes. For example, the area located in the blue ellipse lacks an important connection; as a result, the corresponding district has low accessibility. This kind of problem can be improved through the adjustment in the future.

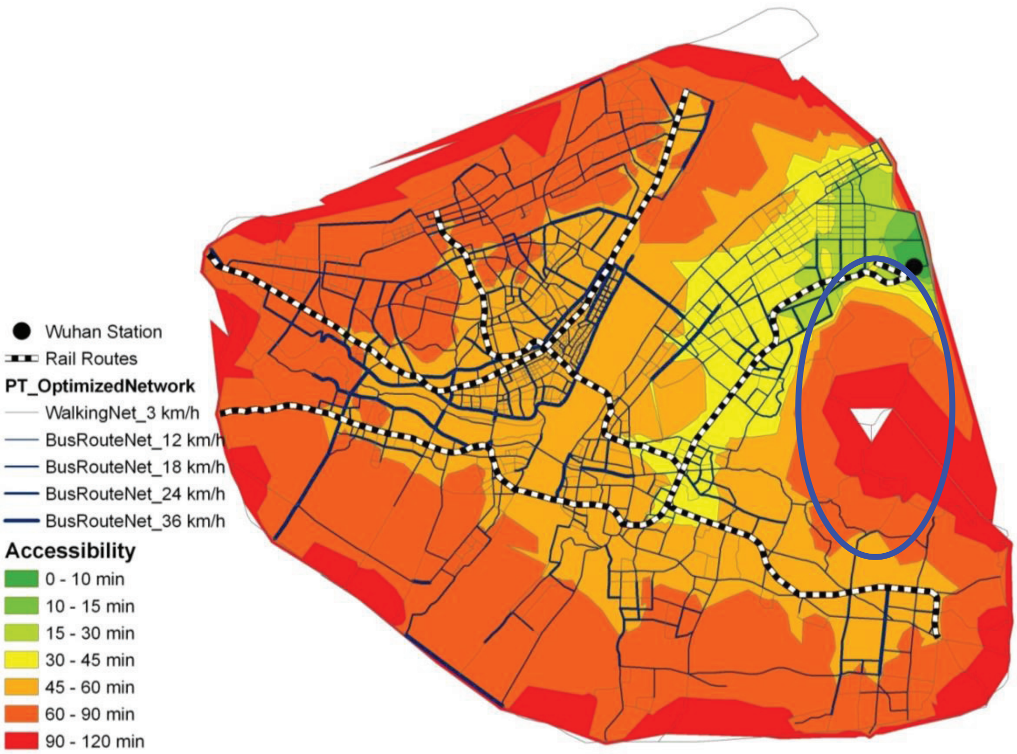


Figure 7-13 Accessibility to Wuhan Station after optimization

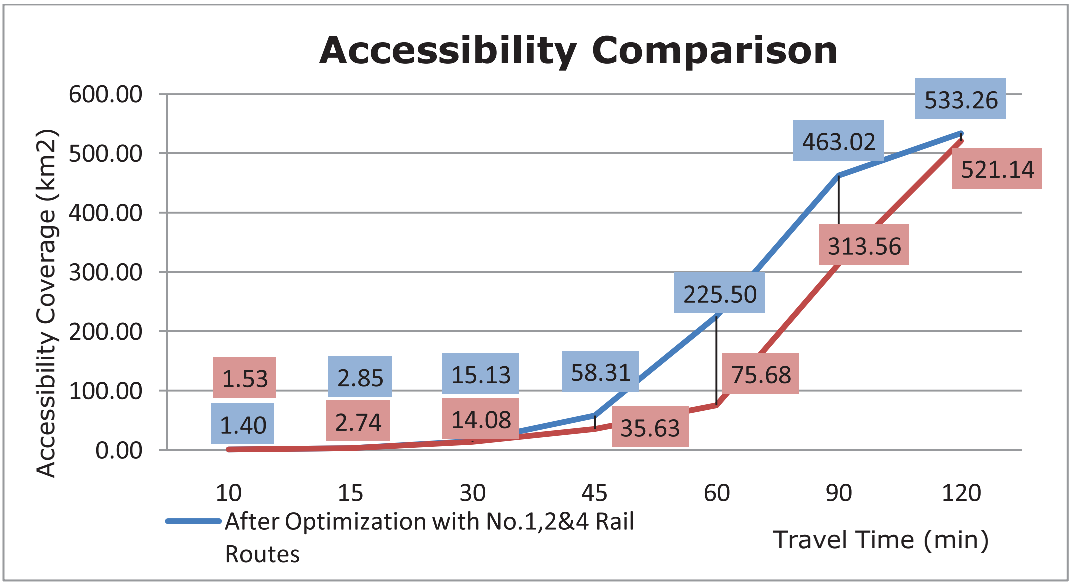


Figure 7-14 Accessibility coverage comparison before and after optimization

7.4. Conclusion

In this chapter, the whole process of scenario developemnt for 2013 from evaluating the existing bus to evaluating the optimized bus routes is discussed. With the consideration of the three rail routes, the optimized bus routes have a more rational distribution with the larger network coverage, lower overlapping rate and higher accessiblity. In addition, the burden of the two bridges across the river would be reduced greatly when the No.2 and No.4 rail routes are put into operation according to the analysis of the optimized bus routes.

8. CONCLUSION AND RECOMMENDATION

The objective of this chapter is to summarise the study with respect to achievements, limitations and recommendations for future work. This last chapter outlines a review of the research objectives; meanwhile gives some recommendations for future research.

8.1. Research Achievements

The objective of this research is to optimize bus routes in the central area of Wuhan. The operators (such as bus companies) will be the profit maker. Optimizing is implemented by the reduction of route overlaps, enlargement of the bus network coverage, the increase in the feeder bus routes for the existing No.1 light rail route and the planned No.2 & 4 metro lines, and the reduction of the burden of the two bridges across the Yangtze River.

The optimized bus routes are finally generated with assistance of the proposed research methodology. In line with the sub objectives and the corresponding research questions have been answered.

Question 1: What factors should be considered when designing a bus route network?

At the bus route network level, the basic characteristics of network should be considered, including network density, route overlapping coefficient, average nonlinear coefficient, non-transfer coefficient, stop coverage and average stop distance.

- Network density is an important indicator for public transport evaluation at the service level, which reflects that whether the routes are convenient for residents to access. The density should be increased gradually to 3-4 km/ km^2 in the urban central area and decreased contrarily to 2-2.5 km/km^2 in the suburban areas (W. Wang, et al., 2002)

- In the central area, much overlapping among routes would lead to traffic jam. Therefore, it is a key element which determines that whether the bus transit services within a service area have adequate and rational distribution.

- Average nonlinear coefficient is a reflection of the operation efficiency and operation cost from the operator perspective of network as well as travel time from a user perspective. Therefore, for both perspectives the lower the average nonlinear coefficient is, the better.

- Non-transfer coefficient reflects the convenience of network.

- Stop coverage presents the potential travel demand within certain service area of a bus stop. To some degree, average stop distance can indirectly indicate that whether the bus stops are redundant or insufficient. Redundant bus stops would increase the total bus travel time while insufficient bus stops results in small bus service coverage and low walking accessibility (Wei, 2010).

Question 2: What data is required for candidate bus routes generation?

According to the actual needs of bus route optimization, and considering the availability of data, urban basic information including population data, land use pattern data and homo-zone data, urban road network data, and bus route network data were collected, as shown in Table 4-1.

- Population data is key information for estimating the travel demand of bus mode, of which trip distribution determines the trend of traffic passenger corridors of the city.

- Land use patterns, especially the distribution of residential and commercial land, mainly affects the direction of traffic flows by determining the trip generation and production. In addition, it contributes to the estimation of job distribution which is also an important basis that attracts the passengers all over the city.

- The homogeneous weight zone is applied in cases where the land-use classification is not detailed enough to differentiate local variations in density.

- Basic road network provides the condition for candidate routes generation, and it is the skeleton of entire public transportation system of a city.

- The existing bus routes are used to: analyze the current defects of existing routes, filter the bad routes from the existing routes, and make a comparison possible with optimized routes to verify the improvements. Therefore, existing bus route network is a basis for route optimization.

Question 3: What factors are adequate to determine whether an existing bus route is rational and should be taken into account?

At the individual route level, evaluation of existing bus routes is implemented with the consideration of route length limitation, number of stops, nonlinear coefficient, unit passenger flow, and route efficiency. For different route length, the rational number range of stops is different. Unit passenger flow aims to reflect the carrying capacity per kilometer of individual route, while route efficiency reveals a possible mismatch between route production and attraction.

Question 4: How to perform the filtration with respect of determined factors?

The filtering process consists of two phases which are respectively based on the comprehensive evaluation result of individual route and additional filtering standards. The needed indicators are divided into two groups: scoring indicators (same with the factors introduced in Question 3) and filtering indicators.

- In the first phase, evaluation at the route level is carried out and associated indicator value is standardized based on the predefined function. Each route of which the weighted sum of scoring indicator value is lower than the give threshold is removed.

- In the second phase, routes that cannot meet the requirements of filtering indicators are removed directly. Finally, the survived existing routes will be put into the optimization process.

In the filtering process, the No.1 rail route is taken into consideration under the current situation. Two filtering indicators are incorporated, which are the number of shared adjacent stops and difference between the real passenger flow and assigned passenger flow in rush hour.

For the scenario where besides No.1 rail route also No.2 and No.4 rail routes are introduced, one more filtering indicator is taken into account which is the possible passenger flow reduction with the restriction of No. 1, 2 and 4 rail routes. This is reflecting the short-term situation in the year of 2013 when the 3 rail routes are planned to be in operation.

Question 5: What requirements should be satisfied in the optimization process?

In the real operation, requirements mainly act on the process of candidate routes generation, including route length limit, minimum number of stop, maximum nonlinear coefficient, minimum unit passenger flow, minimum route efficiency, minimum number of different stops with previous candidates and minimum number of shared adjacent stops with rail routes. In TransitNet, for different scenario developments, value of these parameters can be different, as discussed in section 6.3.1 and 7.3.1.

Question 6: How to evaluate the optimized bus routes both at the network level and individual route level?

A comparison between existing route set and optimized set (or between optimized set and standard) has been executed to be able to analyze if the process indeed did result in a better route distribution within the study area. It is a necessary step. The comparison executed at two levels:

- At the route network level

- Comparison of overlapping coefficients happens between existing route set and optimized set. The improvement is achieved when the coefficient decreases.

- As for network density, comparison happens between the optimized set and the national standard: the improvement is achieved when the mismatch between the two is alleviated.

- In the meantime, the increased accessibility coverage of the transit network also presents the increased network density. Spatially the accessiblity coverage is compared between the existing route set with No.1 rail route and optimized route set with No.1, 2 and 4 rail routes.

- At the individual route level

As the objective of reducing overlapping is to reduce the burden on the main roads, comparison is carried out based on the number of routes distributed on the main road arcs before and after optimization. The more the number of routes reduced, the better the effect of reducing the burden on the main roads. Passenger flow reduction of the survival existing routes across the river is taken as a basis to prove that the burden of the two bridges has been reduced.

In conclusion, the objective of bus route optimization is achieved basically, reflected in the reduced overlapping coefficient, enlarged network coverage, increased feeder routes and reduced burden on bridges, as shown in Table 8-1.

Table 8-1 Main Achievements

Main Achievements	Environment	Certification
Optimized bus routes	With No.1 rail route	Figure 6-10
	With No.1, 2 and 4 rail routes	Figure 7-8
Reduced overlapping coefficient	With No.1 rail route	Table 6-4 : Route overlapping coefficient
	With No.1, 2 and 4 rail routes	Table 7-5: Route overlapping coefficient
Enlarged network coverage	With No.1 rail route	Table 6-4: Network density
		Figure 6-11, Figure 6-12
	With No.1, 2 and 4 rail routes	Table 7-5: Network density
		Figure 7-13, Figure 7-14
Increased feeder routes	With No.1 rail route	Table 6-4 : Total transfer coefficient
	With No.1, 2 and 4 rail routes	Table 7-5: Total transfer coefficient
Reduced burden on bridges	With No.1, 2 and 4 rail routes	Table 7-6

8.2. Recommendations for Future Research

1. Methodology of additional terminals generation should be improved.

Methodology employed in this research has put the spatial distance constraint into the first place, then the job number constraint and population distribution constraint follows. In fact, more other factors should be considered, such as service capacity. For example, stop of which the service capacity in rush hour falls between standard can be taken as a potential terminal. In other words, a stop can be a potential terminal if its number of served passengers in rush hour falls between 800 and 2000 (Ding, 2010).

2. **Competition caused by the parallel bus routes with rail routes should be considered.**

Optimization methodology employed in this research only considers the number of shared stops (or overlapping length) between bus routes and rail routes. However, in the real situation, competition caused by the parallel bus routes is inevitable. Competition between the rail route and its parallel bus route should be taken into further consideration.

3. **More detailed passenger flow analysis should be carried out at the stop level.**

At the present, passenger flow analysis is mainly implemented at the route level. In this research, only aggregate passenger production and attraction of a route can be obtained. If the passenger production (or attraction) of this route can be disaggregated to each stop on the route, the river-crossed passenger flow statistic and analysis would be more accurate.

4. **All the optimized bus routes should be evaluated and compared.**

Due to the limitation of research time, evaluation after optimization is only carried out in some important areas (such as commercial zones and residential zones) at the individual route level. Characteristics of optimized routes distributed in other locations of study area are not considered. Also, analysis of passenger flow mainly focuses on the bus routes used in the bus system before optimization and now also used in the optimized situation. However, analysis of the new routes generated in the optimization process is not particularly considered.

LIST OF REFERENCES

APTA. (2009). Public Transportation Takes Us There: Job Analysis Survey. *Public Transportation Takes Us There* Retrieved December, 2009, from http://www.publictransportation.org/default.asp

APTA. (2010). Public Transportation Takes Us There: Facts at A Glance. *Public Transportation Takes Us There*, 2010, from http://publictransportation.org/takesusthere/docs/facts_at_a_glance.pdf

Austroads. (2007). National Performance Indicators. from http://algin.net/austroads/site/index.asp

Axhausen, K. W., Smith Jr, R. L. (1984). EVALUATION OF HEURISTIC TRANSIT NETWORK OPTIMIZATION ALGORITHMS. *Transportation Research Record* (976), 7-20.

Bertsekas, D. P. (1998). *Network Optimization: Continuous and Discrete Models*. Cambridge, Massachusetts: Athena Scientific, Belmont, Massachusetts.

Ceder, A., Wilson, N. H. M. (1986). Bus network design. *Transportation Research Part B: Methodological.*
, 20(4), 331-344.

Chakroborty, P. (2003). Genetic Algorithm for Optimal Urban Transit Network Design. *Computer-Aided Civil and Infrastructure Engineering, 18*(3), 184-200.

Chen, L. M. (2010). from http://news.163.com/10/0915/08/6GK0HMVI00014AEE.html

Chen, X., et al. (2009). Analyzing urban bus service reliability at the stop, route, and network levels. *Transportation Research Part A: Policy and Practice, 43*(Copyright 2010, The Institution of Engineering and Technology), 722-734.

de Hsu, J., Surti, V. H. (1975). FRAMEWORK OF ROUTE SELECTION IN BUS NETWORK DESIGN. *Transportation Research Record*, 44-57

Ding, Y. (2010). *Optimizing Bus Network in A Multi-modal Transit Framework of Large Cities.* Wuhan University, Wuhan.

Fan, W., Machemehl, R. B. (2004). *Optimal Transit Route Network Design Problem: Algorithms, Implementations, and Numerical Results*. Austin: Center for Transportation Research University of Texas.

Fielding, G. J., et al. (1985). Performance evaluation for bus transit. [doi: DOI: 10.1016/0191-2607(85)90009-3]. *Transportation Research Part A: General, 19*(1), 73-82.

GB50220-95. (1995). Code for Transport Planning on Urban Road. Beijing: Ministry of Construction of the People's Republic of China.

Goldberg, D. E. (1989). *Genetic Algorithms in Search, Optimization and Machine Learning*: Addison-Wesley.

Gomes, L. F. A. M. (1989). Multicriteria ranking of urban transportation system alternatives. *Journal of Advanced Transportation, 23*(Compendex), 43-52.

Holland, J. H. (1992). *Adaptation in natural and artificial systems* (2nd ed.). Cambridge, Mass: MIT Press.

Huang, A. L., et al. (2007). *Study on bus route evaluation system in Beijing based on AHP.* Paper presented at the 10th International IEEE Conference on Intelligent Transportation Systems, ITSC 2007, September 30, 2007 - October 3, 2007, Seattle, WA, United states.

Huang, Z. D. (2009). *Space Allocation and Optimization Technology of Multi-modal Public Transport Network in Metropolis* (Report No. 2007AA11Z207). Wuhan: Wuhan University.

Huang, Z. D., et al. (2009). *A GIS-based accessibility modeling process for estimating transit travel demand.* Paper presented at the 2009 International Conference on Management and Service Science (MASS), 20-22 Sept. 2009, Piscataway, NJ, USA.

Huang, Z. D., et al. (2010). A GIS-based framework for bus network optimization using genetic algorithm. *Annals of GIS, 16*(3), 1-10.

Huang, Z. D., et al. (2007). A Doubly Weighted Approach to Urban Data Disaggregation in GIS: A Case Study of Wuhan, China. *Transaction in GIS, 11*(2), 197-211.

Kakimoto, R., Mizokami, S. (2005). BUS INDUSTRY EVALUATION METHOD PER ROUTE. *Journal of the Eastern Asia Society for Transportation Studies, 6*, 519-528

Kuan, S. N., et al. (2005). Solving the feeder bus network design problem by genetic algorithms and ant colony optimization. *Advances in Engineering Software, 37*, 351-359.

Lampkin, M., Saalmans, P. D. (1967). The Design of Routes,Undertaking:A Case Study. *Transportation Research, 36*, 7.

Lao, Y., Liu, L. (2009). Performance evaluation of bus lines with data envelopment analysis and geographic information systems. [doi: DOI: 10.1016/j.compenvurbsys.2009.01.005]. *Computers, Environment and Urban Systems, 33*(4), 247-255.

Li, C. Q. (2008). Synthesis Evaluation Index System of Urban Public Tranport Service Level. *Communication Standardization, 181*(9), 5.

Li, L. M. (2005). *The Research of Traffic Jams and Congestion in Wuhan.* Wuhan University of Technology, Wuhan

Li, Q., et al. (2006). Readjustment Effect Analysis of Public Bus Network in Beijing. *Journal of Transportation System Engineering and Information Technology, v.8*(2), 27-33.

Liu, Y. F., et al. (2008). Complete Route Computing for Traveling by Public Transport. *Geomatics and Information Science of Wuhan University, 33*(4).

Mandl, C. E. (2003). Evaluation and optimization of urban public transportation networks. *European Journal of Operational Research, 5*(6), 396-404

Meng, W. Q., et al. (2009). *Comprehensive evaluation of the urban public transportation system based on grey entropy.* Paper presented at the 2009 IEEE International Conference on Grey Systems and Intelligent Services, GSIS 2009, November 10, 2009 - November 12, 2009, Nanjing, China.

Mo, Y. K., et al. (2008). *An Improvement Route Generation Algorithm for Bus Network Design*. Paper presented at the 2008 Workshop on Power Electronic and Intelligent Transportation System.

Pattnaik, S. B., et al. (1998). Urban Bus Transit Route Network Design Using Genetic Algorithm. *Jounal of Transportation Engineering, 124*(4), 368-375.

Peng, S., Gong, L. J. (2009). Development Policies of Wuhan Public Transportation in Two-oriented Society. *Fujian Forum, 8*, 69-70.

Pticina, I. (2008). URBAN TRANSPORT SYSTEM AUDIT: REVIEW OF METRIC SYSTEM, METHODS AND PROBLEMS. *Transport and Telecommunication, Vol.9*, 52–63.

Qin, Y., Yan, K. F. (2000). Systematic Analysis on the Join between Urban Rail Transportation and Conventional Public Transit. *Urban Transportation Research, 2*, 25-28.

Rea, J. C. (1972). *DESIGNING URBAN TRANSIT SYSTEMS: AN APPROACH TO THE ROUTE-TECHNOLOGY SELECTION PROBLEM*. Washington: Committee on Transportation Systems Design.

Rodrigue, J.-P., et al. (2009). *The Geography of transport systems* (Second ed.). New York: Routledge.

Schrank, D. L., Lomax, T. J. (2007). The 2007 Urban Mobility Report. *Transportation Research Board of the National Acadamies*, 138.

Sheth, C. H. (2003). *The Measurement and Evaluation of Performance of Urban Transit Sytem: The Case of Bus Routes* Unpublished Master of Science, Virginia Polytechnic Institute and State University, Virginia.

Shi, B. Z., et al. (2010). *Route Optimization for Bus Dispatching Based on Improved Ant Colony Algorithm.* Paper presented at the Computer and Automation Engineering (ICCAE), The 2nd International Conference

Skalak, D. B. (1994). *Prototype and Feature Selection by Sampling and Random Mutation Hill Climbing Algorithms.* Paper presented at the the Eleventh International Conference

Sun, H., et al. (2010). Research on Comprehensive Evaluation of Urban Public Transport Competitiveness in Hebei Province based on TOPSIS. *IEEE*, 250-254.

TAC. (2008). *URBAN TRANSPORTATION INDICATORS*. Ottawa: Transportation Association of Canada.

Tan, J. F. (2005). Correlation Analysis in Evaluation Index System. *Statistic and Decision, 11*, 146-147.

TRB, NRC. (1995). Bus Route Evaluation Standards: A Synthesis of Transit Practice Transportation Research, *Synthesis of Transit Practice 10* (pp. 63). Washington, D.C.: NATIONAL ACADEMY PRESS.

UrbanAudit. (2000). *THE URBAN AUDIT: Towards the Benchmarking of Quality of Life in 58 European Cities* (No. 92-828-9245-X). Luxembourg: Office for Official Publication of the European Communities.

Vaksman, S. A., Kochnes, N. G. (2007). *Systematisation of the indicators of urban transportation systems.* Paper presented at the the XIII international scientific and practical conference, Yekaterinburg, Russia.

Vuchic, V. R. (2002). Urban Public Transportation Systems. Unpublished Glossary of Terms List of Abbreviations University of Pennsylvania.

Wang, F. H. (2009). *Quantitative Methods and Applications in GIS* (S. G. Jiang & J. H. Teng, Trans. 1st ed.): The Commercial Press.

Wang, H. Y., et al. (2004). Application of Fuzzy Synthesis Evaluation Method in Urban Public Traffic Line Network. *Journal of Lanzhou Jiaotong University (Natural Science), 23*(3), 7.

Wang, W., et al. (2002). *Urban Public Traffic System Planning Methods and Management Technology*. Beijing: Science Press.

Wei, X. B. (2010). *Optimizing bus stop locations in Wuhan, China.* Unpublished MSc, Enschede.
WHSB. (2008). *National Economic and Social Development Statistical Bulletin in Wuhan, 2007*. Wuhan: Wuhan Statistic Bureau.
WMATA. (2006). *Findings of Bus Network Evaluation*. Washington: Washington Metropolitan Area Transportation Authority.
WTC. (2009). *Three-year Plan for Public Transportation Network Optimization* (Report). Wuhan,China.
WTPI. (2009). *Wuhan Transportation Annual Report*. Wuhan: Wuhan Transportation Planning Institute.
Yang, X. G., et al. (2010). Transit Capacity Equilibrium Evaluation for Transit Network Based on Matrixes' Matching Degree. *Journal of Highway and Transportation Research and Development, 27*(3).
Yang, Z. Z., et al. (2007). A Parallel Ant Colony Algorithm for Bus Network Optimization. *Computer-Aided Civil and Infrastructure Engineering, 22*, 44-55.
Yeh, C.-H., et al. (2000). Fuzzy multicriteria analysis for performance evaluation of bus companies. [doi: DOI: 10.1016/S0377-2217(99)00315-X]. *European Journal of Operational Research, 126*(3), 459-473.
Zhang, Q., et al. (2009). *DNA Algorithm on Optimal Path Selection for Bus Travel Network.* Paper presented at the 2009 4th International Conference on Bio-Inspired Computing: Theories and Applications, Beijing, China.
Zhao, F. (2004). Transit Network Optimization –Minimizing Transfers and Optimizing Route Directness. *Journal of Public Transportation, 7*(1), 63-82.
Zhao, F., Gan, A. (2003). *OPTIMIZATION OF TRANSIT NETWORK TO MINIMIZE TRANSFERS*. Florida: Lehman Center for Transportation Research
Florida Internaltional University.
Zhao, F., et al. (2006). Simulated Annealing–Genetic Algorithm for Transit Network Optimization. *JOURNAL OF COMPUTING IN CIVIL ENGINEERING*, 57-68.
Zhou, L. (2007). *Study on Adjustment for Public Bus System of Wuhan No.2 Subway.* Wuhan University of Technology, Wuhan.