MULTI-MODAL SYSTEM DESIGN FOR URBAN METRO SYSTEMS TO HANDLE EXCESSIVE DEMAND CAUSED BY MEGA-EVENTS

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by

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ABSTRACT

Due to the continuous expansion of the urban scale, the urban metro transportation system also needs to be constantly updated, especially those cities that need to carry mega-events. Larger carrying capacity, better collaboration mode and more optimized operation mode are required to handle the sudden increase in travel demand. The ever-growing micromobility system and the multimodal transport system of micromobility and other public transportation methods can well meet this trend.

This thesis aims to develop a multimodal transport optimization model that takes full advantage of the micromobility mode. This thesis, from the perspective of the traffic system administrator, explores the influence of micromobility on the cost of the entire traffic system under the premise of maintaining the normal operation of the metro system after micromobility joins the traffic system at the same level as the metro.

Firstly, through literature review, the research object is determined to be a representative shared bike in micromobility mode. The way to deal with the excessive travel demand brought by mega-events is to add shared bikes to the transportation system with the same status as the metro on the basis of maintaining the normal operation of the metro system, and cooperate with the metro system to meet the demand.

Secondly, the research methods are qualitative research and quantitative research. In the qualitative research, model design, adjustment and optimization are carried out in combination with actual experience to realize the design of the multimodal transport system of shared bike and urban metro system. In quantitative research, this thesis describes a case study area based on real condition and proposes six scenarios. And through demand forecasting and parameter changes, this thesis explores the situation that only metro participates in the transportation system, and micromobility mode participates in the transportation system with metro with different parameters, etc., under the premise of meeting the excessive travel demand brought by mega-events, impact on total travel costs.

Through model optimization and scenario verification, it is concluded that when the micromobility mode participates in the transportation system in a reasonable way, the multimodal transport system will be able to reduce the total cost, and the degree of reduction is related to the characteristics and parameters of the mode.

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1 INTRODUCTION

1.1 BACKGROUND

With the development of cities and the expansion of urban scale, the existing transportation facilities and transportation system also need to be constantly updated and optimized. Especially for those cities that need to host large-scale events (mega-events) such as the Olympics.

For such large-scale event, it will be replaced by a more specific word, and will be used in later chapters in the article: mage-events. Mega-events are events which will attract a large number of individuals (including but not limited to direct participants, spectators, and related staff), and will put enormous pressure on the environment and infrastructure (including the transportation system) in the area where the event occurs.[Stephen D. Parkes, 2016] In other words, the sudden increase in passenger and traffic demand will make the existing transportation system face greater challenges.

As for the urban transportation system, public transportation system has been promoted to replace private transportation with its many advantages in order to reduce energy consumption, reduce pollution and improve the utilization rate of transportation tools. Therefore, when faced with mega-events, public transportation systems will take on the major transportation work and will be the main challenger to excessive demand.

Compared with other public transport systems, urban metro system (underground railway system in cities in this paper) has been widely used in big cities due to its advantages such as small ground space occupation and less traffic disturbance.

At the same time, when the construction of sustainable cities has become the general trend, micromobility has been proposed again, paid attention to, studied and developed. This flexible, sustainable mode of transportation can effectively solve the last mile problem, thus becoming one of the possible ways to solve the excess demand.

Now the well known mode of micromobility includes shared bike, electric bike and electric scooter, etc. These low-speed, user-driven public transport vehicles offer great advantages in terms of accessibility and flexibility[wikipedia, 2018]. Micromobility's stations are mostly located outside other public transportation (metro, bus and taxi drop points, etc.) stations. Connected infrastructure and payment make "last mile" travel easier and provide a solution to the excessive demand of metro systems. For example, passengers can choose micromobility to avoid some crowded stations, or directly use micromobility to replace metro as the choice of short-distance trip. [ITDP, 2021]. Although some modes of micromobility (such as electric bikes and electric scooters) may cause potential safety problems, and there are restrictions or gaps in traffic safety laws and regulations, it is no doubt that this will not prevent it from becoming an important way to solve the problem of excessive demand.

Therefore, this paper takes urban metro as the research object, adding mode of micromobility to traffic system, aiming to maintain its normal and stable operation when excessive demand appears especially caused by mega-events.

For the evaluation of the entire transportation system, there are many ways to make judgments at different levels. The evaluation method chosen in this paper is from the point of view of the system manager, that is, focusing on the total cost at the macro level, while the cost and preference of each passenger at the micro level will not be considered as influencing factors.

Another important aspect is that this paper hopes that the participation of micromobility can ensure the regular operation of the metro system as much as possible, that is, there is no need to make special adjustments to the transportation capacity and frequency due to mega-events.

With the above situation as the background, this paper will explore treatment method and design a multimodal transport system (Micromobility was added as the main auxiliary measure) to deal with the excessive demand that may occur to urban metro system caused by mega-events.

For research objects and case study, this paper aims at the general situation, which means that the situation under the influence of COVID-19 will not be considered at this stage. On this basis, A designed scenario based on Beijing 2022 Winter Olympics will become the case study.

1.2 RESEARCH OBJECTIVES AND RESEARCH QUESTIONS

1.2.1 Research objectives

This TIL's master's thesis, has a main research objective which is to design a multimodal transport system (in which micromobility was added as the main auxiliary measure) to handle the excessive demand of urban metro system caused by mega-events, and verify whether and how the addition of micromobility reduces the total cost of the system.

Its sub-objectives include the following:

1. Analyze the current status of urban metro system in the study area to find advantages and disadvantages.
2. Design a multimodal system (in which micromobility was added as the main auxiliary measure) for urban metro systems to handle the excessive demand.
3. Identify the role of micromobility in the transportation system and how to take advantage of it.
4. Represent the system by model and solving algorithm.
5. Propose case studies, propose design cases based on the characteristics of the existing area, and collect the required data.
6. Run the model and algorithm with the relevant data in the case study, and analyze the result.
7. Verify and optimize the model according to the forecast data.
8. Compare the operation of the design scenario with the existing traffic system and the optimized system, and draw realistic conclusions and explore its application value in reality.

1.2.2 Research question

Main research question:
What is a multimodal transport system dominated by micromobility should be to handle the excessive demand of urban metro system caused by mega-event?

In order to study this issue, a research area needs to be proposed, and this project takes the metro lines (and the transport system) as research object.
Sub-questions:

1. How to design a multimodal system supported by micromobility modes for urban metro systems to handle the excessive demand?

   a) How to model an urban transport system supported by micromobility modes?
   b) What modes of micromobility should be used in this system?
   c) What roles will micromobility mode and metro play in the transportation system.
   d) How will this multimodal system work to handle excessive demand?
   e) What kind of study area should be proposed as a case study?
   f) How will the new model be used in case study?

2. What is the state of the current public transport system (metro lines) in the research area?
   a) What are the characteristics of the current public transport system (metro lines)?
   b) What are the problems the current public transport system (metro lines) facing?
   c) What are its weaknesses?
   d) What are its strengths?

3. What will be influence of the metro system in the study area during mega-event?
   a) What is the current daily demand and carrying capacity of the metro system in the study area?
   b) What is the potential and excessive demand of public transport (metro) system in the study area during mega-large event?

4. What a designed research scenario should be?
   a) Which existing scenario in reality should this research scenario be based on?
   b) In the actual scenario that is the basis of the design scenario, what should be kept and what needs to be adjusted? What is the basis and reason for the adjusted part?
   c) In the design scenario, how to reasonably distribute data as a research basis?
   d) Reasonableness and practicability analysis of design scenario.

1.2.3 Other research aspects

Other research aspects (such as which mode of micromobility will be used in this paper,what is the specific research area and metro line in case analysis, etc.) will be clearly defined later.

1.3 RESEARCH METHODOLOGY

1.3.1 Qualitative research

Qualitative research is mainly about the review of current urban metro system research. The research of this part is mainly review of following aspects:

1. Existing multimodal urban networks and example of case studies.
    a) The main characteristics, advantages and disadvantages of multimodal urban networks, (especially of urban metro system) in different places.
    b) Research on the characteristics of the urban metro system within the research area and of similar area.
    c) The cooperation and connection between multimodal transportation modes, especially with urban metro system.
2. Policy research in the study area and applicability of different micromobility modes.

1.3.2 Quantitative research

The quantitative research part mainly refers to the total cost, including the total cost before and after micromobility participates in the transportation system, and its difference. Use the difference to determine whether micromobility helps reduce the total cost of the transportation system. Mainly include the following methods:

1. Collection of relevant data.
2. Data forecast.

1.4 LIMITATIONS

1.4.1 To do

The To do part is mainly based on the research objectives and research questions, with the research objectives as the benchmark and the research question as the orientation, subdividing the relevant transportation system, and exploring the parts that are directly related and will have an impact on the research conclusions. This project focuses on the following two aspects:

1. The design of a multimodal transport (micromobility modes of transportation) system to deal with the potential risks (excessive demand) that may occur to urban metro system, and propose solutions. Including model design, algorithm optimization.

2. Analyze and study the existing multimodal transport network of the case study, and the impact of mega-events on the existing transportation system (especially the urban metro system). Including demand forecasting, model design, feasibility study, practical value and case study application.

3. The use of the designed scenario: will be based on but different from the actual scenario, for the convenience of research, and to get rid of some of the limitations in the actual scenario.

1.4.2 Not to do

Although this project is a design project, including demand forecasting and model design etc, many factors and parameters are not within the research scope, nor will they appear as parameters in the model.

1. In the network analysis and case study, the focus is mainly on metro lines within the research area. In other words, it mainly focuses on the surrounding of the stadium hosting the opening ceremony of the Winter Olympic Games (Bird's Nest Stadium) to identify the study area and do the demand forecasts. This scope may include sections of many lines, the focus is not on any entire line, but on the sections in this region. This is to determine the research focus, that is, the research area is a fixed distribution range centered on the destination, and other weakly correlated parts are selectively ignored.

2. In demand analysis and demand forecasting, only factors directly related to demand are considered, such as ticket price and other factors are not considered as parameters. Because the study area is based on the existing reality, and the fares etc. are almost certain. Passages will not change their decision only because of ticket price, so these will only be used as a reference and not a decisive factor.

3. The study of Metro lines does not consider factors such as geographical features and construction and operation costs. Because geographical features, such as topography, steep slopes and flats, etc., do not affect passenger choices, nor do they affect the operation of transportation modes. And the operating cost will be amortized to every year of the life cycle, even every use, which will not affect the overall conclusion (also mentioned in later chapters).

4. In addition, passenger behavior,other private modes of transport (for example:cars) and road conditions. It is assumed that passengers will not cancel their trips because the metro system is overloaded, but will choose to wait or use other modes of transportation to continue trips. Meanwhile, passengers' primary goal is to get to their destination, rather than considering or worrying a lot about the economic factor that switching to other forms of transportation will cost them slightly more (but no more than they expected). Another assumption is that road traffic will not exceed capacity due to the presence of micromobility and will not result in additional congestion. In addition, the interaction between the new micromobility modes and existing private vehicles is not considered.

2 LITERATURE REVIEW

2.1 LITERATURE REVIEW

The following aspects will be reviewed in this chapter:

1. Literature review of abnormal operation of the urban metro system.
2. Literature review of restoration of urban metro system operations.
3. Literature review of the characteristics and applicability of micromobility modes.
4. The current laws and regulations on micromobility norms and restrictions, and the most suitable mode obtained accordingly as the research object.
5. Literature review of the methodologies that will use in this research.

2.1.1 Abnormal operation of the urban metro system

The abnormal operation mentioned here is compared with the normal operation, that is, the actual operation is contrary to the planned schedule, safe operation, stable operation, etc., mainly from the following aspects:

1. It stems from the problems of the transportation system and the transportation means itself: abnormal operation caused by the damage of the transportation vehicle itself, the illegal behavior of passengers, the wrong operation of the staff, etc.[Jens Clausena, 2009]
2. Disruption caused by emergencies: The suspension, cancellation or delay of the transportation system due to emergencies (including but not limited to fire, power system failure, water seepage in tunnels).[Nikola Besinovic, 2021]
3. The sudden increase in demand causes the demand to be far greater than the carrying capacity. This surge in demand generally stems from planned mega-events, such as Olympics, Paralympics, football matches, etc.[Yukun, 2008]

The above three situations will be called situation A, situation B and situation C in order in the following analysis. In order to effectively solve the above problems, it is necessary to analyze the characteristics of their occurrence.

1. Situation A is contingent and unpredictable. Although contingency plans will be prepared in advance, the complexity of events cannot be predicted in advance. The diversity of possibilities and the high level of participation in technology complicates the discussion and is beyond the scope of this article.
2. The occurrence of situation B is also random, but the emergency plan for this situation is relatively standardized, and the processing difficulty is much lower than that of situation A.
3. The occurrence of situation C can be predicted in advance, and the handling of such situations can be prepared and demonstrated in advance to demonstrate the possibility and applicability. Therefore, to deal with such events, planned preparation is feasible and necessary.

2.1.2 Restoration of urban metro system operations

Restoration here refers to the use of some way to bring abnormal operations back to normal or at least to the point where they can be controlled and dealt with. The existing methods mainly include the following:

1. Traffic management, i.e. transport supply. This method mainly refers to dealing with abnormal demand by adjusting the timetable or frequency, such as increasing the number of trains and shortening the time interval between two trains to deal with excessive demand.[Michelle Dunbar, 2014]This method is actually using a controllable abnormal operation to solve the uncontrollable abnormal operation. In other words, the changed schedule is not actually a daily normal operation, but an adjustment strategy. Therefore, there are also unknown risks and possible failures in this approach.
2. Passenger assignment, i.e. transport demand. This method mainly refers to controlling the passengers entering the station, that is, controlling the amount of entry, entry speed, etc.[Jing Teng, 2016] Although this method can limit the excess demand to the urban metro station to a certain extent, in order to ensure or as much as possible to ensure its normal operation.[of Transportation, 2010] However, this method does not consider enough passengers who have not entered the station (including passengers who have to queue up due to the limited entry speed).
3. Combination of the above. This method is a combination of the above two methods. The combination of adjusting the operating timetable and controlling the passengers entering the station effectively ensures the normal operation of the urban metro system and reduces the degree of adjustment of the system. A simpler explanation is to realize the cooperation of metro service and metro gate.[Nikola Besinovic, 2021]

2.1.3 Characteristic of micromobility modes

The definition of micromobility has undergone a change from small modes of transportation driven by individuals with a speed of less than 25km/h to modes of transportation without an internal combustion engine and a speed of less than 45km/h, which is still changing over time, technological developments and regulatory revisions.[wikipedia, 2018]
However, the expansion of the scope of the definition does not mean an increase in the research objects. Under normal circumstances, the common micromobility refers to bicycles, electric bicycles, electric scooters, electric skateboards, etc.[wikipedia, 2018] These transportation modes have been included in the original definition of micromobility. Therefore, when micromobility is mentioned in any chapter, it means that the original definition (speeds lower than 25km/h, etc.) is still used.

At the same time, with the continuous development of the sharing economy, micromobility began to be closely integrated with sharing. Shared bicycles, shared electric skateboards, shared electric vehicles, etc. began to appear on the roads of many cities.[Taozige, 2020] And it is worth mentioning that shared micromobility has greater applicability than traditional micromobility. This means that the modes of micromobility are no longer exclusive to someone, but belong to everyone who needs them and has the right to use them. This enables efficient use of resources and sustainable development of energy. It is also useful for solving urban environmental problems and residents' health problems. At the same time, it also plays a positive role in the diversified development and optimization of the urban transportation system.[Konstantinos Pelechrinis, 2017] Pelechrinis et al. also pointed out that shared micromobility based on shared bicycles, shared electric scooters, etc. is gradually developing into the city's most important street section travel mode, and people will even develop a habit when they frequently travel between two points. From time to time, shared bicycles and shared electric scooters will become one of their first choices.[Konstantinos Pelechrinis, 2017]

Due to the development and improvement of the smart phone supply chain, the prices of batteries, display screens and GPS receivers are relatively cheap, providing conditions for rapid development of global dockless services.[Taozige, 2020] Dockless e-scooters and dockless e-bike have become the newest micromobility modes after the update. They allow cyclists to park and access them at any location or in a designated virtual area, greatly improving the convenience of travel. Due to the difference in driving experience, electric scooters are more used in the first and last mile of travel to complete a trip in coordination with other public transportation modes in the urban transportation system. Electric bicycles are more used for leisure riding and to complete a trip independently in comparison (that is, only electric bicycles are used between the departure place and the destination without any other mode of transportation).[Tomasz Bieliński ORCID, 2020]

According to the above review, a conclusion can be drawn that micromobility combined with the sharing economy will become a trend, among which bicycles, electric scooters and electric bicycles are the main components. Therefore, referring to micromobility again in later chapters means sharing micromobility, rather than personal micromobility in the traditional sense.

Next in this chapter, one or more main research objects will be selected from bicycles, electric scooters and electric bicycles as representatives of micromobility to participate in the problem of excessive demand in urban metro systems based on the existing literature.

2.1.4 Applicability of micromobility modes

Electric bicycle

With the continuous development and update of micromobility, discussions on the quality of its products and driving safety have gradually increased. For example, Yanyong Guo et al. pointed out in the study that through statistical analysis of more than 5,000 samples (including bicycles, electric bicycles and electric scooters), the consequences of illegal behaviors (mainly running red lights) on drivers from the perspective of safety Perform analysis. In the seemingly safe situation, the red light running rate of electric vehicles and electric scooters is about 7 percentage points higher than that of bicycles (18%). [Yanyong Guo, 2014]This means that the extra power and higher speed will bring additional psychological hints to the driver: the time to run the red light through the intersection is shortened, and the safety is improved. But this is obviously wrong.

Compared with electric scooters, the emergence and development of electric bicycles has taken a longer time, and relevant research and regulations have been more adequate. In addition to the false psychological suggestion that faster speed brings low risk of running a red light, electric bicycles are also widely discussed in other aspects. On the one hand, the lanes of electric bicycles are controversial. In other words, mixing with bicycles has a higher speed than bicycles. This means the inevitability of overtaking, and this also means a higher probability of accidents. And slower than the speed of the car will also make it seem impossible for an electric bicycle to drive in a motorway.[People's Government of Hunan Province, 2020]In addition, the charging and modification of electric bicycles are also issues worth considering. Electric bicycles using lead-acid batteries, which have a market share of more than 90% in China, have an explosion risk caused by the characteristics of the material themselves when they are overcharged, and there are also difficulties in the market supervision of the highest speed of electric bicycles.[Jurisprudence Daily, 2017]Although this problem does not seem to be a problem for the research object of this article (shared micromobility). Standardized company supervision and market supervision will make electric bicycles used to solve the problem of excessive demand in the urban metro system to have higher quality, better speed limits, and safer batteries and charging processes.

But in addition to the quality standards of electric bicycles, another issue that cannot be ignored is the real-name registration management of electric bicycles, which is more common in the field of private electric bicycles, while the real-name registration system of application seems to be able to achieve similar effects in the field of shared electric bicycles.[Beijing Traffic Management Bureau, 2018] However, there are still various problems in actual operation.The most important ones are the inconvenience caused by real-name registration and the doubts about information security, which have yet to be resolved.[People's Daily online, 2021]

Due to the above reasons, there is still a gap in the use of stakeless electric bicycles to deal with the excessive demand of urban metro systems, so this article will not use this as a micromobility mode for further analysis.

Electric scooter

Figure 2.1: Electric scooter(Xiaomi [2022])

The popularity of electric scooters in Europe exceeds that of any other region. Among them, the four companies with the highest market share are Voi, Tier, Wind and Dott. In addition, American companies Lime and Bird are also trying to occupy more European market shares. Electric scooters are easy to learn and do not require users to have many skills when using them. More importantly, they occupy a small space and can freely shuttle through the streets and blocks of the city, and are used to connect to public transportation (such as urban metro) to achieve the last mile. At the same time, stakeless design greatly improves the convenience of the electric scooter.

But at this stage, many countries' attitudes towards electric scooters and the formulation of relevant laws and regulations are still under discussion. For example, on July 4, 2020, the UK started the marketization process of electric scooters. The rented electric scooters will legally run on certain British roads, after which the government will decide whether to legalize the use of electric scooters within the UK.[Zhongguancun Online, 2021] In the Netherlands, despite the increasing market demand, electric scooters are still illegal in most cases, and the police will stop and supervise people trying to ride on the road. But the Dutch government is still discussing whether to legalize electric scooters in the foreseeable future.[ANP, 2021] It is worth mentioning that the acceptance and legalization of electric scooters will take more time in China. Traffic control departments in various places have repeatedly proposed that electric scooters do not have the right of way, and cannot be driven on non-motorized vehicle lanes and motorized vehicle lanes. The scope of their use is only in closed professional places and indoor venues. [E Zhichao, 2020]

In summary, in most areas, electric scooters cannot be used as a normal micromobility mode to deal with the excessive demand of urban metro systems in a short period of time. However, with the gradual improvement of relevant regulations, its application scenarios and applicability and convenience will be greatly improved. Therefore, in the analysis of this article, electric scooters will become possible research objects, but it needs to be assumed that they have been legalized.

Bicycle (Shared bikes)

Bicycle (Shared bikes), as one of the most traditional modes of transportation, has undergone a long period of development and has formed a complete set of supervision systems. Its characteristics, safety, universality and user acceptance do not require much discussion. As the fourth generation of dockless shared bicycles, taking ofo and Mobike as examples, there is no need for a fixed parking area. When the previous user ends the trip and locks the shared bicycle at the destination. The next user can use a mobile phone application with GPS support in the background to search for the bicycle closest to the place of departure, scan the code to unlock, and start a new journey. [Wikipedia, 2020] When the company finds that the distribution of shared bicycles is unbalanced or the bicycles are damaged and cannot meet the needs of use, it will assign staff to recycle or repair them, and then re-position them to the required location. Another way to manage shared bicycles is to use a transportation card or other methods to pick up the bicycle at a fixed access point, and then return it to its original location or other permitted locations after use. Examples of this are OV-fiets (Dutch personal OV-chipkaart can be used as proof of eligibility for access).[NS.NL, 2020]

2.1.5 Summary of micromobility modes

Table 2.1: Summary of micromobility modes

	Speed	Safety	Acceptance of road conditions	Driver's ability needs	Regulatory Integrity	Applicable distance
Bicycle	1	3	3	3	3	2
E-bike	3	1	2	2	2	3
E-scooter	2	1	1	1	1	2

What needs to be explained in this table 2.1:

1. The larger the number, the better the modes performs on that feature, such as faster, safer, etc.

2. In terms of safety performance, according to the samples analysis of the literature above,[Yanyong Guo, 2014] bicycle is undoubtedly the safest, and the remaining two cannot be clearly compared, so they are given the same value, which also occurs in the applicable distance.

3. The earlier it appears, the higher the popularity, and the more modes that have been studied have a more complete regulatory system, so the bicycle has the most complete regulatory system.

4. For the applicable distance, the bicycle is not suitable for long distance travel because it has only the single power of the driver. The main reason why e-scooter is not suitable for long-distance travel is that it cannot adapt to a variety of terrains. Therefore, for e-scooter, the advantage of convenience is far greater than the distance adaptability when traveling.

Regardless of the way mentioned above or other ways to manage shared bicycles, a conclusion can be easily obtained, which is that the development model of combining bicycles with the sharing economy has been relatively mature, and this method has also been used as a solution for the last mile which has been fully verified and improved and now become advanced. Therefore, there is no doubt that bicycles will be used as a key research object in the following to solve the problem of excessive demand in the urban metro system.

2.1.6 Research methodology

Traffic demand forecasting

It needs to be mentioned first is that since this study mainly focuses on the design of a multimodal transport system dominated by micromobility and mathematical optimization, the data forecasting is only a concise and general description. The forecasting results are used as data support for quantitative assessment when the case is analyzed. Therefore, this part will make a simple explanation, and choose a simple and feasible way in the process of writing paper and combine with past cases to make demand forecasting.

In general, there is a relatively mature method for traffic demand forecasting, namely the four-step traffic demand forecasting method, which contains four steps and has become a standardized research method after years of development:

1. Trip generation
2. Trip distribution
3. Mode split
4. Trip assignment

The four-step transport demand forecasting method has been proposed since the paper *Chicago Area Transportation Study* , which was published in Chicago, USA in 1962 [John F. Mcdonald, 1988]. This method only had three steps at the time. In other words, the mode split was later combined with the other three steps in different forms to produce various forecasting methods, which were all classified as the four-step method. This was also mentioned by Wirasinghe and Kumarage and other authors [S.C. Wirasinghe, A.S. Kumarage, 1998].

As for the demand forecasting caused by large events, more factors need to be considered, and the four-step traffic demand forecasting method is further optimized. As for the methods for the forecasting of traditional parametric techniques, autoregressive integrated moving average (ARIMA) is often mentioned[S. Lee, D.B. Fambro, 1999]. This method is often used for short-term demand forecasting, and has also been frequently applied to forecasting public transport related parameters (such as travel time, waiting time, travel speed, passenger flow, capacity utilization, etc.)[S. Lee, D.B. Fambro, 1999].

As the research focus of this paper is mainly on the impact of big events (taking Beijing Winter Olympic Games as an example) on the passenger flow of urban metro system, it is not a seasonal change, nor a difference between peak hour and off-peak hour, but a special short-term event. Therefore, another method can also be considered to make traffic demand forecasting, that is, historical average method which was studied by Smith and Demetsky in 1997[B.L. Smith, M.J. Demetsky, 1997]. This method can be used as a supplement and verification of other methods to make the forecasting more accurate.

The above research methods have their own advantages and disadvantages, but each method has undergone years of development and has its own fixed way of use. This paper will combine the flow changes of the study area in the past few years when big events occur, and take the four-step traffic demand forecasting method as the main method and the historical average method as the verification method.

Excessive demand management method

Regarding the processing methods for the excessive demand of the urban metro system, this chapter mainly reviews from two aspects.

1. Theoretical research on handling excessive demand of the urban metro system.
2. Practical experience in handling excessive demand of the urban metro system.

As for the theoretical research, the research object of this paper is the excessive demand caused by large-scale events, which means that the excessive demand does not come from the subway system itself, for example, the disruption caused by metro failures or accidents. But the results are similar, that is, the urban metro system cannot deliver all passengers in demand to their destinations in time. Therefore, in terms of theoretical research and models, this article mainly refers to the metaheuristic method proposed by Besinovic et al. [Nikola Besinovic, Yihui Wang, Songwei Zhu, Egidio Quaglietta, Tao Tang , Rob M.P. Goverde., 2021].This method takes the interaction between train services, passengers and station gates into account, with the purpose of focusing on passenger satisfaction and train service to achieve maximum passenger satisfaction (minimum total delays) and most stable train service (minimum adjustments and cancellations). This study will refer to the above model, adjust the purpose, parameters, etc., and focus on maintaining the normal operation of the metro system and lines (rather than adjusting or canceling), using micromobility to deal with excess demand,that is to design a multimodal system which contains possible micromobility modes of transportation as the supporters and alternatives of the metro system in order to handle the excessive demand based on case study in the study area. Except for the above studies of the aspects of modelling and algorithms, this paper also needs to consider where the new micromobility modes will be distributed and what role they will play in the urban traffic network, etc..

As for the practical experience, in 2017, Nanjing, China, conducted a research on the cooperation between micromobility (shared bicycles) and the urban metro system. The research pointed out that in the morning peak, metro passengers used more than 3,300 shared bicycles, of which the Longjiang Metro station reached 450. In order to better utilize the combined advantages of the two modes of transportation, the municipal government decided to cooperate with shared bicycle companies to establish a 30-minute rapid response mode, and increase the number of shared bicycles at the metro exit according to demand.[Liu Weijuan , Yu Jianxi, 2017] Another example that is more closely related to the case area is that, according to the Beijing Municipal Transportation Department, by 2022, all administrative districts in Beijing will allow and encourage shared bicycles to operate in a better way and integrate them with the existing transportation system. At the same time, the application of the electronic fence (virtual parking area based on the positioning system) system in the vicinity of 51 important metro stations in the city will be popularized to reduce the pressure on the metro system during peak hours and provide passengers with more convenience and multiple travel options.[Liu Yang, 2021]

2.1.7 Literature review summary

This chapter analyzes the characteristics and applicability of different micromobility modes (bicycles, electric bicycles and electric scooters), and draws conclusions from it. Bicycles have become a viable research object, and electric scooters have become a possible research object. Electric bicycles are currently difficult to popularize due to their driving risks and the restrictions of relevant laws and regulations. In terms of theoretical research, the metaheuristic method proposed by Besinovic et al. is used as the main reference, combined with practical experience to adjust, modify and optimize. A new model aimed at maintaining the normal operation of the urban metro system will be designed, with the shared bike as the representative of the micromobility mode, to achieve micromobility-led multimodal system design for urban metro systems to handle excessive demand.

2.1.8 Research gap

Through the above literature review, the existing research in the research gap is mainly reflected in the following two points:

1. For the research on restoration of urban metro system operations, the existing research mainly focuses on adjusting the metro system itself, and lacks the research on passengers outside the station. In other words, how to minimize the excessive pressure on the existing transportation system on the premise of meeting the travel demand of passengers to the greatest extent.
2. For the research on micromobility, the existing research mainly focuses on the choice of parking location and how to use micromobility to cooperate with the metro to complete the passenger's last mile travel demand, rather than using it as a means of transportation equivalent to the metro to play a similar role and provide passengers with another way of travel options.

3 PROBLEM DESCRIPTIONE

3.1 PROBLEM DESCRIPTION

This chapter will further refine the research questions and further define the research objects.

3.1.1 The ultimate goal

Under the condition of maintaining the normal operation of metro system as far as possible (i.e. when mega-events occur, the operation time and frequency of Metro system are at most the state of daily peak hours), add shared bikes into the system in the most efficient way and explore its impact on total travel costs.

3.1.2 Research object refinement

This study is based on the handling of excess demand during mega-events, which means that the excess demand which is mentioned needs to be compared to a normal demand. This normal demand has the following requirements:

1. ″Normal″ refers to the maximum capacity or average demand of the urban metro system, so ″excess″ refers to difference between forecast data and normal demand. In practical applications, the maximum capacity is taken as the upper limit. A more detailed explanation is:
    a) If a station has never reached its maximum capacity, the average demand is used as ″normal″ demand.
    b) If the demand at a station is greater than the maximum capacity, then the maximum capacity is used as the ″normal″ demand.
2. Although there is a lack of reference support, a reasonable assumption that the ″maximum capacity″ of a metro station is that the number of passengers queuing at the station equals to difference between the number of people in a metro and the planned full capacity of the metro has been given as a example. In other words, all passengers queuing in line can get on the upcoming metro. This assumption has been used in Besinovic's article to solve the problem more simply

and clearly[Nikola Besinovic, Yihui Wang, Songwei Zhu, Egidio Quaglietta, Tao Tang , Rob M.P. Goverde., 2021]. However, since the research object of this paper is not the interior of the metro station, but the entire transportation system, such an assumption will be far from the actual situation. Therefore, the assumption about the capacity of the subway station will be proposed in the following text based on the actual situation.

3. Demand forecasts refer to demand forecasts under normal circumstances, not exceptional circumstances (such as traffic restrictions under Covid-19).

3.1.3 Objective function description

The objective function will clearly reflect an important point, which is to supplement the gap of existing research, and use micromobility modes as a travel option at the same level as urban metro, rather than the bearer of the last mile. Therefore, the consideration of micromobility characteristics and related parameters will be very detailed.

Objective functionMinimize the cost of handling the excessive demand (caused by mega-events) of the urban metro system dominated by micromobility.

The general cost includes the following aspects: construction cost (infrastructure (charging piles, etc.) + procurement cost (shared bicycles, etc.)) + maintenance cost (bike relocating fee, etc.)+travel cost (cost of transportation + quantified time cost, etc.)

The subsections below are detailed explanations of several of the costs mentioned.

Construction cost

In general, construction costs include the possibility of selecting electric micromobility modes as an integral part of public transport in the future, Such as charging piles for e-bike and e-scooter, parking spaces with locks, parking spaces with protection, etc. For shared bicycles, the construction cost is almost negligible, because in most cities, shared bicycles are parked in parking areas marked on the ground.

Procurement cost

Procurement cost for the newly added micromobility modes, it mainly means purchasing the required modes of transportation (such as shared bicycles). But it is worth mentioning that this purchase is not for short-term use, but for long-term use. This means that procurement costs need to be averaged out for each year of use, or even each time a passenger uses it. So this averaged value can basically be ignored.

Another reason why the procurement cost can be ignored is that the construction and maintenance cost of the metro line is much higher than that of shared bicycles, but also due to its long service life, the cost per passenger is negligible when averaged. This procurement cost needs to be noted and will also play an important role in management decision-making. But for the purposes of this paper, it is reasonable to ignore both the construction and procurement costs of metro and micromobility modes.

Maintenance cost

The maintenance cost mentioned here refers to the cost of relocating the shared bicycle. Although the procurement cost and construction cost are proved to be negligible in the above description, it does not mean that enough shared bicycles can be purchased regardless of the cost to meet the demand.

In order to avoid excessive purchases, a potential constraint is maintenance costs, which means reducing the number of shared bikes that need to be relocated as much as possible. This means that the number of shared bicycles added to the transportation system should be as small as possible while keeping the total cost to a minimum.

3.1.4 Important Assumptions

In order to clarify the scope of the study and make the problem clearer and more explicit, some assumptions will be made. These assumptions are general and basic, and other assumptions directly related to case studies and mathematical models will continue to be made in later chapters.

1. Passenger behavior related assumption:
    a) The passengers will complete their trips, regardless of queue or using any transportation modes. It means if a passenger starts their trip, they will end the trip no matter what happens.
    b) Passengers can make choices without spending time. For example, LED screens will be used outside the subway station to disclose the queuing time, and passengers will instantly know which way to travel will minimize their total travel cost (including time cost and transportation cost). This assumption is also supported by the following assumptions:
        i. The location of parking spaces for shared bicycles is not a research problem. It is assumed that the planned parking lot for shared bicycles is set next to the metro station, that is, passengers can directly choose whether to enter the metro station or ride a shared bicycle, without requiring additional walking time to find the parking lot.
        ii. If the passenger chooses a shared bicycle to complete the trip, it is assumed that the time to scan the QR code and unlock the lock can be ignored. The reason is that this time is basically equal to the time it takes to open the metro station door with the ticket plus the time to walk into the metro station, which is inevitable for all passengers

(regardless of which mode of transportation they choose) and therefore has no effect on the result.

   c) There is no difference in ability of passengers, and there is no subjective and objective preference for choice. This assumption has the following specific aspects:

      i. Passengers’ personal circumstances, including but not limited to age, personal ability, etc., meet the requirements for the use of all optional modes of transportation.

      ii. Choices made by passengers are not influenced by any external factors (such as weather, road conditions, etc.)

      iii. Passengers will also not have a choice preference, and all choices will be based on the single principle of minimizing cost.

   d) Time cost may be given weight. To encourage the reduction of queuing time, to ensure the normal operation of the urban metro system and to encourage the use of shared bicycles, time cost will be weight reasonable higher.

   e) Since only the part that participates in the public transportation system is considered, the trip from the original point of departure to the metro station can be ignored, because no matter what mode of transportation the passenger chooses at the end, this part of the journey must be passed and will not be affects subsequent trips.

   f) In order to simplify the problem, it is assumed that the number of passengers arriving at each origin station per minute is the same, which simplifies the solution process while ensuring dynamic arrival.

2. Other assumptions

   a) Since the transfer also needs to participate in the queue, waiting for the metro at the new line at the transfer station, it can be simplified as the transfer means the end of a trip and the beginning of a new trip. This means that they need to re-queue, and they can also make a new choice of travel mode for the next trip.

   b) The cost of transporting the bikes will be directly related to the quantity of required bikes, and only related to this. This means that the cost of transporting bikes back to their original parking space is only related to the number of bikes, not frequency, number of staff, etc.

   c) A metro entering the study area will carry a certain number of passengers. This means that the number of passengers is fixed and reasonably assumed, independent of other factors.

d) Since the same metro is not used for round trips at the same moment, this means that only one-way trips are considered, and return trips are considered separately.

4 MODEL DEVELOPMENT AND ALGORITHM

In order to better develop multimodal transport (led by micromobility and metro systems), two steps need to be proposed:

1. To understand how should the travel needs of passengers be met. Which will answer the sub-question: **"How will this multimodal system work to handle excessive demand?"**
2. To analyse what roles will micromobility mode and metro play in the transportation system. Which will answer the sub-question: **"What roles will micromobility mode and metro play in the transportation system."**

4.1 TRAVEL OPTIONS

This section will discuss how the passenger's travel needs are met, that is, what are the passenger's travel options. First of all, it needs to be clarified that:

1. The passenger here refers to the passenger who needs to travel by public transportation, excluding the passenger who travels by private car. But the possible walking to the destination due to public transport needs to be considered.
2. Passenger's travel demand: depart from different origins and arrive at the same destination. The departure point mentioned here refers to the departure point where public transportation may be taken, rather than the passenger's home, hotel, etc., because the journey from home and hotel to the departure point of public transportation will not affect the entire system.

According to the previous analysis, shared bikes will participate in the entire system as a representative of the micromobilty mode, so the travel options for passengers to choose are:

1. Take the metro all the way, leave the terminal, and walk to the destination.
2. Ride a shared bike the whole way and go straight to the destination.
3. A combination of shared bikes and metro, that is, passengers can choose to ride to a nearby metro station without queuing, take the metro, or to avoid transfer time and queue time, get out of the transfer station, ride to the destination, etc.

4.2 ROLES OF TRAVEL OPTIONS

Here, it should be noted that the system pursues the minimization of the overall cost, which may violate the preference of some individual passengers, but compared with the preference at the micro level, the overall cost at the macro level can better reflect the feasibility of the system and also It can better reflect the effect (or problem) of optimization.

Therefore, all travel options will be equal, that is, under the premise of the pursuit of minimum cost, the shared bike will no longer only be the implementer of the last mile, but will play the same role as the metro. In the conversion of metro and shared bikes, the roles of the two are also the same, and there is no difference in priority (that is, passengers are not encouraged to take the metro first).

4.3 MODEL DESCRIPTION

This model aims to add a micromobility mode (in the case of shared bikes) to the public transportation system with the same priority as the metro, to meet the excess travel demand caused by mega-events.

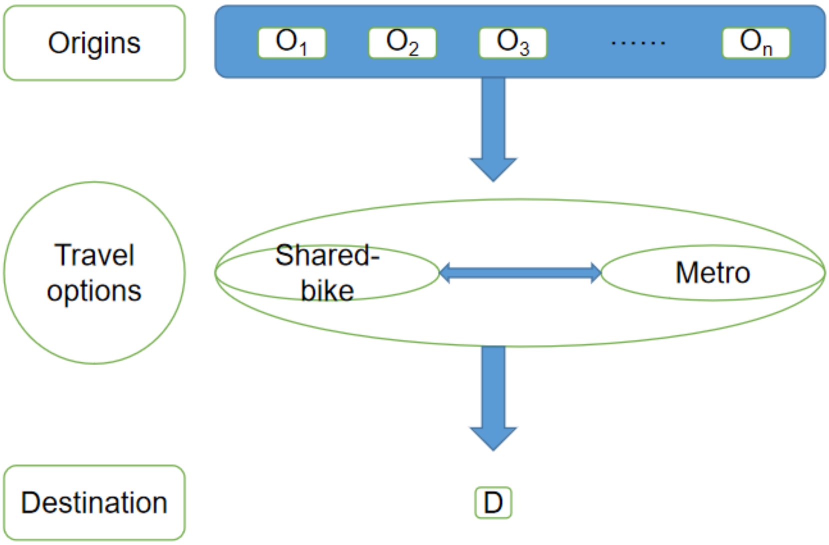

Figure 4.1: Multimodal system

Figure 4.1 shows the schematic diagram of what the multimodal system like and how does it work. And will answer the sub-question:" **How will this multimodal system work to handle excessive demand?"** in sub-section 1.2.2.

The downward arrow from origin in figure 4.1 means that passengers will start from origins and choose the travel mode through travel options, while the horizontal arrow means the possible cooperation between micromobility and metro, and finally arrive at the destination.

The location of origins will be set according to the actual situation, which will also be directly related to the distance and travel time from origins to the destination. After departing from origins, passengers will have a variety of travel options, which have been described in the section4.1. Since these travel demands are brought about by mege-events, the passengers will have the same destination.

One thing that needs special emphasis is that the origins mentioned in the mathematical model will be considered as the location of the nearest metro station to the real origins. Because the passenger trip from the real origin to the metro station will not have the participation of the metro. According to the assumptions about passenger behavior in the previous section 3.1.4, the shared bike station and the metro station are in the same location, so the trip from their real origins to the metro station will also not involve the participation of the shared bike. This means that this trip will not be taken into account, thereby affecting the transportation system.

According to the assumption in previous section 3.1.4, **it can be simplified as the transfer means the end of a trip and the beginning of a new trip**, figure 4.2 shows the schematic diagram of transfer station. The blue square means this is a transfer station ,so G and G′ are actually the same station, but in the model, they will be two different stations with the same location. Because when passengers need to transfer, they need to leave the metro from a platform, go through a certain transfer time to another platform, the difference of the platform can be simplified as the difference of the station.

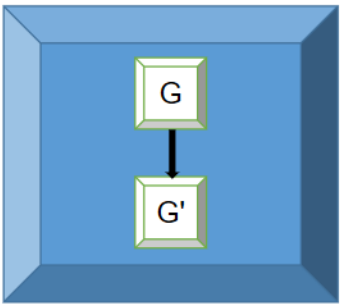

Figure 4.2: Transfer station G

Figure 4.3 shows the schematic diagram of time window for passengers getting on or off the metro in stations. A,B,C,D are time points:

1. Time point A is a certain time point before the metro arrives at the station.

2. Time point B is the time point when the metro arrives at the station.
3. Time point C is the time point when the metro leaves the station.
4. Time point D is a certain time point after the metro leaves the station.

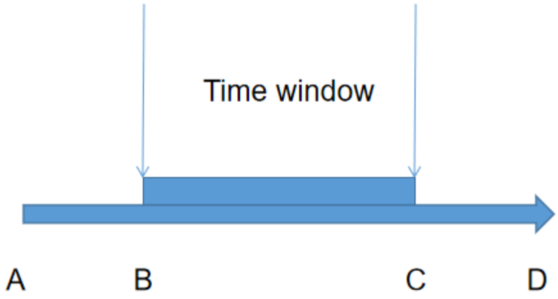

Figure 4.3: Time window for passengers getting on/off the metro in stations

For passengers, they can arrive at the metro station at any time, but there is a time window for when they board and leave the metro. This time window is the time period from time point A to time point B (And this period of time, to put it simply, means that the doors of the metro and platform are opened and closed), only when the doors are opened, passengers can get on or get off metro (boarding and alighting) during this time period. During this period, passengers' time on the metro is their ride time.

4.4 MATHEMATICAL MODEL

It is mentioned in section 4.1, When micromobility mode (take shared bikes as an example) is added to the transportation system, and when combined with metro, passengers will have a variety of travel options. And according to how the multimodal transport model mentioned in the section 4.3 works, this section will describe it in detail in terms of mathematical models.

$$Minimize\ F = F_1 + F_2 + F_3 + F_4 + F_5 + F_6 + F_7 \tag{4.1}$$

$$F_1 = \sum_{k \in K} \sum_{i \in N^b} (t_{iQ} * c_t + c_b + c_r) q^1_{ki} \tag{4.2}$$

$$F_2 = \sum_{k\in K}\sum_{i\in N^c}(c_t * ((t_{ki}^{'} - t_{ki} + t_{iC}^{m} + t_f) + c_m) * q_{ki}^{2} * M \tag{4.3}$$

$$F_3 = F_3^1 + F_3^2 \tag{4.4}$$

$$F_3^1 = \sum_{k\in K}\sum_{i\in N^g}(c_t * ((t_{ki}^{'} - t_{ki} + t_{iG}^{m}) + c_m) * q_{ki}^{3} * M \tag{4.5}$$

$$F_3^2 = \sum_{k\in K}\sum_{i\in N^g}(t_{GQ} * c_t + c_b + c_r)q_{ki}^{3} \tag{4.6}$$

$$F_4 = \sum_{k\in K}\sum_{i\in N^g}(c_t * ((t_{ki}^{'} - t_{ki}) + t_{iG}^{m} + t_t + (t_{ki}^{G'} - t_{ki}^{G}) + t_{GE}^{m} + t_f) + c_m) * q_{ki}^{4} * M \tag{4.7}$$

$$F_5 = \sum_{k\in K}\sum_{i\in N'}(c_t * ((t_{ki}^{G'} - t_{ki}^{G}) + t_{GE}^{m} + t_f) + c_m) * q_{ki}^{5} * M \tag{4.8}$$

$$F_6 = \sum_{k\in K}\sum_{i\in N^a}(c_t * ((t_{ki}^{'} - t_{ki}) + t_{IG}^{m} + t_{GE}^{m} + t_f) + c_m) * q_{ki}^{6} * M \tag{4.9}$$

These equations from equations 4.2 to equations 4.9 show different options for passengers to travel:

1. F_1: The cost of biking directly from the origin to the destination Q.
2. F_2: The cost of taking the metro to the station which is the nearest one of this line to the destination and walking to the destination.
3. F_3: The cost of taking metro to transfer station G and cycling to the destination.
4. F_4: The cost of taking metro to transfer station G, transferring to G′, taking metro to the station (Represented by E) which is the nearest one of this line to the destination, walking to the destination.
5. F_5: The cost of those whose origin is the transfer station G taking metro to the station which is the nearest one of this line to the destination, walking to the destination.
6. F_6: The cost of those whose origin (Represented by I) is on the same line of G′ taking metro to G′, taking metro to the station which is the nearest one (Represented by E) of this line to the destination, walking to the destination.

The above various travel costs show the various travel options for passengers from origins to destinations, among which micromobility also appears independently, taking on the role of directly helping passengers meet their travel demand.

4.4.1 Index

Q_s	Set of travel demands. $q_{ki}^{n} \in Q_s$, set of demands met by the number n_{th} travel option $Q^b \in Q_s$, set of demands met by shared bike.
K	Set of depature time.
N	Set of stations, $N^g \in N$, set of stations on the same line to transfer station G. $N^a \in N$, set of stations on the same line to $G^{'}$. $N^b \in N$, set of stations available for bike. $N^c \in N$, set of stations on the same line to the nearest station to the destination $N^{'} \in N$, set of station $G^{'}$.

The introduction of the index mainly reflects two points:

1. Micromobility mode (shared bike) is added to the transportation system.

2. Distinguish between the types of stations (Including the distinction between G and G′ of the aforementioned transfer station, reflected in the index) will make the problem study clearer.

4.4.2 Variables

q_{ki}^{n}	The number of people who departs at minute k chooses the n^{th} way to travel at station i, $i \in N^b$, $n \in 1, 2, 3, 4, 5, 6 \ldots\ldots$
t_{ki}	Passenger's departure time at station i, $i \in N$
$t_{ki}^{'}$	Passenger's time of getting on metro at station i, $i \in N$
$t_i^l = (t_{ki}^{'} - t_{ki})$	Passenger's real queue time at station i, $i \in N$
t_{ij}^{m}	Travel time of arc (i,j) by metro, $i, j \in N$
t_{ij}	Travel time of arc (i,j) by bike, $i, j \in N$
t_{iQ}	Travel time from station i to the destination by bike, $i \in N$

The time window mentioned above is explained here.

4.4.3 Parameters

c_t	Value of time
c_b	Cost of riding a bike, depends on riding time
c_r	Cost of relocating a bike
c_m	Cost of metro, depends on travel distance
t_f	Walking time from the end of metro to the destination, depends on walking distance
M	A large enough positive number.
t_t	Transfer time
$[a_i^n, b_i^n]$	Metro No.$n_t h$ arrival time and departure time at station i, $i \in N$.
Q_m	Available capacity of metro
Q_{im}^s	Capacity of station i, $i \in N$

The various costs mentioned above are described here and apply to the constraints that follow.

4.4.4 Constraints

$$\sum_{k \in K} \sum_{i \in N^b} (q_{ki}^1 + q_{ki}^2 + q_{ki}^3 + q_{ki}^4 + q_{ki}^5 + q_{ki}^6)) = Q_s \tag{4.10}$$

$$(q_{ki}^1 + q_{ki}^5) = Q_m \qquad \forall k \in K, i \in N^{'} \tag{4.11}$$

$$(q_{ki}^1 + q_{ki}^2) = Q_m, k \in K \qquad \forall i \in N^c \tag{4.12}$$

$$(q_{ki}^1 + q_{ki}^3 + q_{ki}^4) = Q_m \qquad \forall k \in K, i \in N^g \tag{4.13}$$

$$(q_{ki}^1 + q_{ki}^6) = Q_m, k \in K \qquad \forall i \in N^a \tag{4.14}$$

$$a_i^n \leq t_{ki}^{\prime G^{\prime}} \leq b_i^n \qquad \forall i \in N^{'} \tag{4.15}$$

$$a_i^n \leq t_{ki}^{\prime G^{\prime}} \leq b_i^n \qquad \forall i \in N^g \tag{4.16}$$

$$a_i^n \leq t'_{ki} \leq b_i^n \qquad \forall i \in N^c \tag{4.17}$$

$$a_i^n \leq t'_{ki} \leq b_i^n \qquad \forall i \in N^a \tag{4.18}$$

$$\sum_{k \in K}^{(k,k+h)} (q_{ki}^3 + q_{ki}^4) \leq Q_m + Q_i^s \qquad \forall i \in N^g \tag{4.19}$$

$$\sum_{k \in K}^{(k,k+h)} (q_{ki}^2) \leq Q_m + Q_i^s \qquad \forall i \in N^c \tag{4.20}$$

$$\sum_{k \in K}^{(k,k+h)} (q_{ki}^6) \leq Q_m + Q_i^s \qquad \forall i \in N^a \tag{4.21}$$

$$\sum_{k \in K}^{(k,k+h)} (q_{ki}^5) \leq Q_m + Q_i^s \qquad \forall i \in N^{'} \tag{4.22}$$

$$t_i^{G'l} = (t_{ki}'^{G'} - t_{ki}'^{G}) \geq 0 \qquad \forall i \in N^{'} \tag{4.23}$$

$$t_i^{G'l} = (t_{ki}'^{G'} - t_{ki}'^{G}) \geq 0 \qquad \forall i \in N^g \tag{4.24}$$

$$t_i^l = (t_{ki}^{'} - t_{ki}) \geq 0 \qquad \forall i \in N^c \tag{4.25}$$

$$t_i^l = (t_{ki}^{'} - t_{ki}) \geq 0 \qquad \forall i \in N^a \tag{4.26}$$

The above constraints mainly impose detailed constraints on the mathematical model from the following aspects, and the optimal solution will also be obtained based on these constraints.

Constraint classification:

1. Travel demand constraints: equation 4.10. All travel needs must be satisfied.
2. Number of travel demand constraints: equation 4.11, 4.12, 4.13, 4.14. By assumption in previous section 3.1.4, the number of departures per minute for each station is the same.
3. Time window constraints: equation 4.15, 4.16, 4.17, 4.18. The time requirement for passengers to enter the metro is within the time window of the metro's arrival and departure from the metro station.
4. Capacity constraints: equation 4.19, 4.20, 4.21, 4.22. h is the time difference between the arrival of two adjacent metros depends on the schedule and frequency of the metros. In any h time period, the number of departing passengers cannot be greater than the sum of the metro's available capacity plus the metro station's capacity.
5. Que time constraints: equation 4.24, 4.25, 4.26, 4.23. This constraint states that if a passenger chooses to take the metro, their entry into the metro needs to be after their departure.

5 CASE STUDY

This chapter mainly explain the analysis and evaluation framework, defines the study area in reality and important descriptions and explanations related to it, and propose a designed scenario then describe it in detail.

5.1 ANALYSIS AND EVALUATION FRAMEWORK

The analysis and evaluation of the overall transportation system will be based on the parts mentioned in the previous mathematical model and constraints. That is, taking the total cost as the main research object, the total cost is evaluated for the transportation system without micromobility (only the metro is the only public transportation) and the transportation system with micromobility (shared bike and metro are shared). Verify whether the addition of micromobility can reduce the total cost by exploring under which circumstances the total cost is lower, and how micromobility meets travel demand. By changing parameters, explore the impact of parameter changes on the results, analyze the reasons for the impact, and study its practical significance.

Through the formulation of mathematical models and constraints, a simple transportation system with multiple travel options has been constructed. As the connection between the mathematical model and the real situation, the construction of the scenario is particularly important. This chapter will construct two scenarios, including a real scenario, and a designed scenario based on the real scenario. These two scenarios will more intuitively show the structure and characteristics of the transportation system, as well as the points that researchers are most concerned about.

5.2 SCENARIO IN REALITY

The study area for this case study refers to the irregular area in the black rectangle, starting from the metro station closest to the boundary. The area includes nine metro stations, including two transfer stations (Olympic Green Station, Beitucheng Station) and six regular stations (Forest Park Station, Beishatan Station, Jiandemen Station, Anhuaqiao Station, Anlilu Station and Anzhenmen Station) belonging to three lines

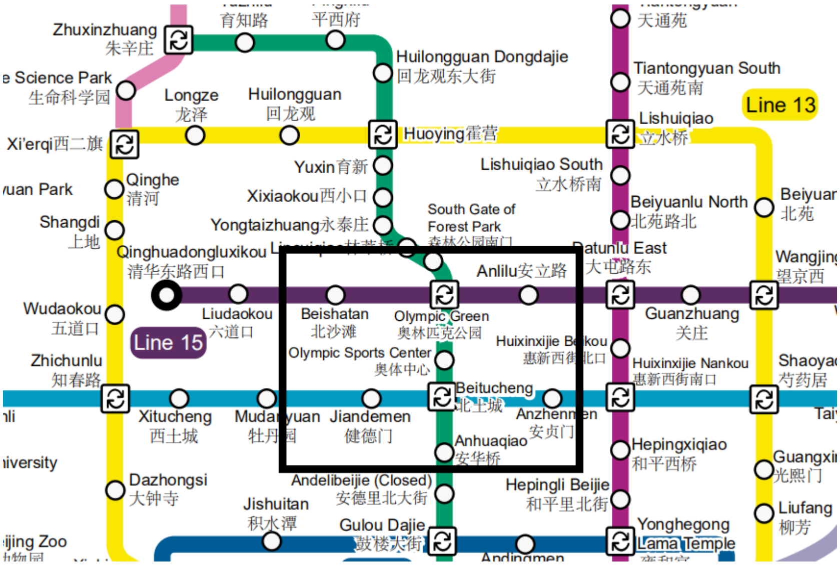

Figure 5.1: Map of Study area 2022 (guide maps online [2022])

(Line 15 in purple, Line 8 in green, and Line 10 in blue.), and the parts of the metro lines between the stations.

Due to the impact of Covid-19, the Beijing 2022 Winter Olympics adopts closed-loop management to ensure the health and safety of athletes, spectators and staff. In this context, the travel demand and the operation of the transportation system are far different from those of the past.

Therefore, in this case, it is meaningless to discuss the operation of the urban metro system, and the relevant data also lacks reference value for daily operations.

But despite this, aside from the data, the 2022 Beijing Winter Olympics can be used as a reference for the next designed scenario in the planning of the Olympic area and the update and construction of the metro stations.

The figure below shows the part of Beijing urban metro map of the 2008 Beijing Olympics. Compared with 2022, there are only 2 lines directly related to the Olympic area (the green metro Olympic line 8 and the purple metro line 10). Metro stations and routes around the Olympic Opening Ceremony stadium are boxed in the same way as before and shown in the figure below (the circled stations are not in the 2022 zone).

On August 8, 2008, on the day of the opening ceremony of the Olympic Games, at 4:38 Beijing time, the first train of the Olympic branch line was dispatched smoothly. Since then, Beijing urban metro has started a 45-hour uninterrupted operation, transporting spectators to and from the opening ceremony stadium and competition venues safely.[Yu-kun, 2008]

During the entire Olympic Games in 2008 (from August 8, 2008 to August 24, 2008), there were 7 to 9 million spectators, and 68.13 million passengers took the metro. As far as the opening ceremony is concerned, a total of 90,000 spectators with tickets

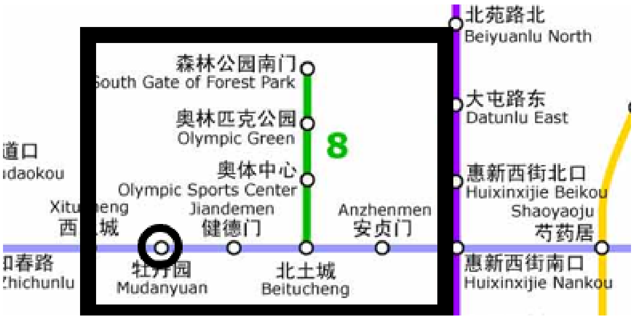

Figure 5.2: study area 2008 (China.org.cn [2008])

chose to travel by public transport (staff and athletes have a special car to pick up and drop off), and about one third of them (that is, about 30,000 spectators) chose to take the urban metro.[Yu-kun, 2008]

According to statistics, the passenger flow of Beijing's urban metro system is 142% of the usual holiday rate, and the growth rate of the three lines directly related to the Olympic area is over 60%.

It is worth mentioning that in 2008, the Beijing urban metro system had only 8 metro lines with a total length of about 200 kilometers. And at that time, the metro Olympic line was not fully connected to the metro system in both directions, but the end point was set in the center of the Olympic area, which meant that passengers on the other side could only choose other metro lines or other modes of transportation. meet travel demand.

On the other hand, in 2008, micromobility tools (such as shared bicycles) were not yet popular, and shared bicycles could not become a common mode of travel to choose to participate in the operation of the overall transportation system.

In 2022, Beijing urban metro will have a total of 27 lines with a total mileage of about 800 kilometers. Metro departure interval is also constantly shortening. At present, there are 10 lines in Beijing with a departure interval of 2 minutes or less, of which 4 lines, Line 1, Line 5, Line 9, and Line 10, even take 1 minute and 45 seconds. In contrast, the shortest time between the departures during the 2008 Beijing Olympics was between 2 and 3 minutes.

The increase in the number of stations also makes the connection of other modes of transportation and last-mile transportation less necessary if the travel demand can be met. For example, the Metro Station of the Olympic Sports Center is only a short walk from the "Bird's Nest" of the opening ceremony stadium. More than 600 meters, passengers no longer need to take the bus to complete the trip from the end of the metro to the travel destination.

But it is undeniable that due to Beijing's huge population, the accompanying travel demand is also huge. Even if it is not during the Winter Olympics, the Beijing metro system in 2022 is constantly under pressure and faces congestion. In order to provide passengers with a better travel experience, the Beijing metro management department launched the Ping An train product at the end of 2021. The application of this high-tech product can achieve several major functions:

1. Grasp the congestion situation of each metro in real time, and remind passengers through the mobile APP.
2. Accurately perceive abnormal behavior in the metro.
3. Grasp the full load situation of trains in real time and carry out precise passenger transportation organization.

The introduction and popularization of this product can better realize the assumption made before: Passengers can make choices without spending time. For example, LED screens will be used outside the subway station to disclose the queuing time, and passengers will instantly know which way to travel will minimize their total travel cost (including time cost and transportation cost). Passengers can more easily use the mobile app to make their own travel decisions in the shortest time, even without going to the metro station, the decision has already been made.

5.3 DESIGNED SCENARIO

In order to more intuitively show the difference between the optimized traffic system and the previous one, and to avoid some real emergencies and potential disturbances, this paper designs a new scenario based on reality for analysis and research.

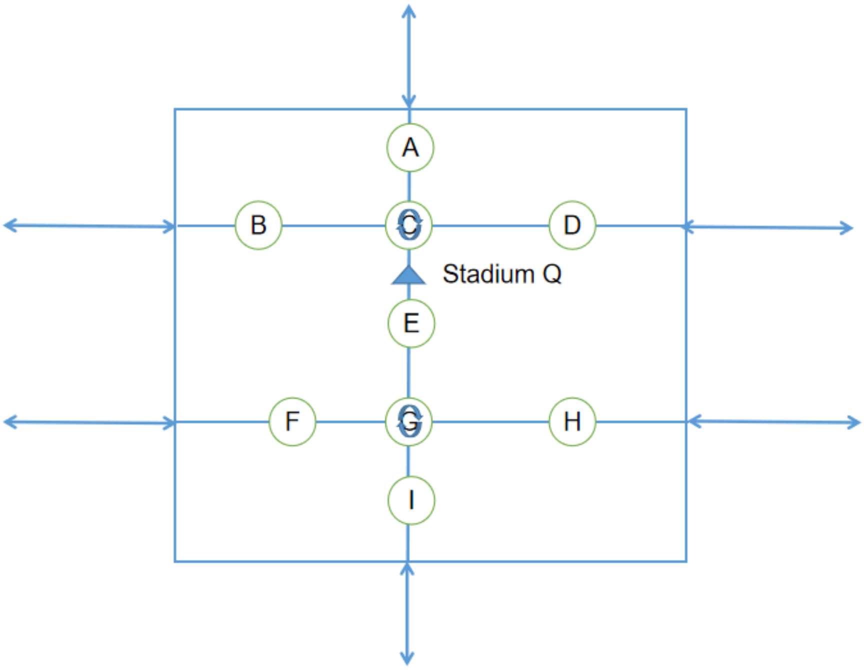

Figure 5.3: Designed Scenario

Connection between designed scenario and mathematical model

The designed scenario is a realistic reflection of the mathematical model, which can display the travel options and travel parameters in the mathematical model in an intuitive form.

The designed scenario starts from the metro station closest to the boundary. The area includes three metro line: Line 1(B,C,D), Line 2(A,C,E,G,I) and Line 3(F,G,H). Those three lines have nine metro stations, including two transfer stations (C, G) and six regular stations (A,B,D,F,H,I) belonging to three lines. The most noteworthy place is Stadium Q, the centerpiece of the entire mega-event, where the opening and closing ceremonies take place. The final destination of the audience is also Stadium Q.

Those equations from equations 4.2 to equations 4.9 show different options for passengers to travel, and these travel options have the following meanings in the designed scenarios.

1. F_1: The cost of biking directly from departure station to Q.
2. F_2: The cost of taking the metro to transfer station C and walking to Q.
3. F_3: The cost of taking metro to G and cycling to Q.
4. F_4: The cost of taking metro to transfer station G, transferring to G′, taking metro to the station E, walking to the destination.

5. F_5: The cost of taking metro to E who's origin is G, walking to Q.
6. F_6: The cost of taking metro to G′ from I, taking metro to E, walking to Q.

As a mathematical model of the general situation, there is another option of travel worth considering: when people find that there are too many people in line at the metro station in front of them, they can choose to ride a bicycle or walk to a nearby metro station and take the metro.

But in this designed scenario, since stations A, B, D, F, H, I play the same role in the system and will face the same travel demand based on assumptions, they will also face the same queuing situation. There is no point in changing the departure station. In addition, the next metro stations of stations A, B, and D are transfer station C, and the distance between station C and the final destination stadium Q is suitable for walking, and there is impossible to take the metro from station C.

5.3.1 Geographical situation

The scenario of this design is based on the basic situation of the Beijing metro line in 2022, which including but not limited to the station location and geographical distance. These cases will be described in the following data.

Travel distance

Table 5.1: Travel distance on bike between stations.(kilometer)[Wikipedia, 2022]

	A	B	C	D	E	F	G	H	I
A	-	2.8	1	2.3	3.7	5.1	4.7	5.3	5.4
B	2.8	-	2	3.3	3.6	3	4	5	4.8
C	1	2	-	1.4	2.6	4.1	3.6	4.4	4.3
D	2.3	3.3	1.4	-	3.8	5.5	4	3	5
E	3.7	3.6	2.6	3.8	-	1.9	0.99	1.9	1.7
F	5.1	3	4.1	5.5	1.9	-	0.91	2	1.7
G	4.7	4	3.6	4	0.99	0.91	-	0.88	0.87
H	5.3	5	4.4	3	1.9	2	0.88	-	1.8
I	5.4	4.8	4.3	5	1.7	1.7	0.87	1.8	-

This table5.1is based on the real situation and meets the following requirements:

1. The riding distance of bicycles between the two stations is calculated according to the AutoNavi map software[Wikipedia, 2022], which is reliable.
2. Due to the flexibility of the bicycle, and the estimated riding time already includes the traffic lights that may be encountered, the influence of other factors such as environment and road conditions on the riding time can be ignored.
3. According to the previous assumptions, ride time is independent of rider ability and bike condition.
4. All data in the table are in kilometers.

Table 5.2: Travel distance on foot between stations.(kilometer)[Wikipedia, 2022]

	A	B	C	D	E	F	G	H	I
A	-	2.8	1	2.3	3.7	5.1	4.7	5.3	5.4
B	2.8	-	2	3.3	3.6	3	4	5	4.8
C	1	2	-	1.4	2.6	4.1	3.6	4.4	4.3
D	2.3	3.3	1.4	-	3.8	5.5	4	3	5
E	3.7	3.6	2.6	3.8	-	1.9	0.99	1.9	1.7
F	5.1	3	4.1	5.5	1.9	-	0.91	2	1.7
G	4.7	4	3.6	4	0.99	0.91	-	0.88	0.87
H	5.3	5	4.4	3	1.9	2	0.88	-	1.8
I	5.4	4.8	4.3	5	1.7	1.7	0.87	1.8	-

This table5.2is based on the real situation and meets the following requirements:

1. The walking distance between the two stations is calculated according to the AutoNavi map software[Wikipedia, 2022], which is reliable.
2. Due to the flexibility of walking and road adaptability, the walking distance of pedestrians between two adjacent stations will be different from that of cyclists. For example, some major urban roads will provide pedestrians with overpasses and underground tunnels to cross the road, but this does not apply to bicycles.
3. All data in the table are in kilometers.

From this table5.2, it can be seen that the shortest walking distance between two adjacent stations is about 0.9 kilometers. There is ample discussion of acceptable walking distances, for example Ana V.Diez-Roux argues in his paper[Yong Yang, 2013] that people's acceptable walking distances are closely related to the purpose of their trips. For example, for recreational trips, the acceptable walking distance would be longer, about 0.5 miles (800 meters) or more, compared to a median of about 0.25 miles (400 meters) across all samples. This value means that the walking distance between two adjacent stations is greater than the generally accepted walking distance, so a new assumption is proposed:

If a passenger wants to complete the trip, and to avoid long queues to take a metro at an adjacent station, they will choose a shared bike instead of walking to the next station.

Table 5.3: Travel distance to the stadium Q from stations.(Bicycle) (kilometer)[Wikipedia, 2022]

	A	B	C	D	E	F	G	H	I
Q	2.2	3.2	1.1	2.7	2.8	3.6	3.6	2.7	4.5

This table5.3is based on the real situation and meets the following requirements:

1. The travel distance of bicycles between stations and stadium Q is calculated according to the AutoNavi map software[Wikipedia, 2022], which is reliable.
2. These data refer to the distance that people need to ride when they choose to ride a shared bike to complete their trips from different metro stations to Stadium Q.
3. All data in the table are in kilometers.

This table 5.3 shows another way to complete the trip, the distance required to ride a shared bike from the origin to the destination. This also explains the reason for choosing this designed scenario as the research area from another perspective. According to the literature [Juan Sokoloff, 2018], people's choice to ride a shared bike to complete a trip is often influenced by distance (ability is assumed to be the same and does not influence choice, based on the previous assumptions). Juan Sokoloff [Juan Sokoloff, 2018] analyzed and studied 10,000 random trips, combined with 17 million trips of Citibike, and came to a conclusion: the longest riding distance that cyclists can accept is about 4.5 kilometers (4.46 kilometers), and if the distance is greater than 4.5 kilometers, the number of trips will drop sharply.

In the designed scenario, the farthest metro station I from the final destination stadium Q is about 4.5 kilometers, which just reaches the longest riding distance acceptable to the cyclist. Therefore, within this range, shared bicycles will be considered as feasible mode of transportation.

Table 5.4: Travel distance to the stadium Q from stations.(Walk) (kilometer)[Wikipedia, 2022]

	A	B	C	D	E	F	G	H	I
Q	2.1	2.9	0.9	2.2	0.7	2.8	1.7	2.3	2.6

This table5.4is based on the real situation and meets the following requirements:

1. The walking distance between stations and stadium Q is calculated according to the AutoNavi map software[Wikipedia, 2022], which is reliable.

2. These data refer to the distance that people need to walk if they choose to do so from different metro stations to Stadium Q.

3. All data in the table are in kilometers.

Through the above research[Yong Yang, 2013], the longest acceptable walking distance for people to complete a trip is generally about 0.5 miles (800 meters). The above figureB.1, combined with the above table5.4, can show that the nearest metro station to the destination Stadium Q is Station E(0.7km), and the second nearest is Station C(0.9km), which are basically within the acceptable range.

For the above reasons, two new assumptions are proposed:

1. Assuming that people leaving metro from metro station C and metro station E and going to stadium Q will all walk there, and the distance required to walk is 800 meters (0.8km) (average of 700 meters and 900 meters).

2. Assuming that all people cycling to the stadium Q will arrive directly (no additional walking required), the required cycling distance is based on the table5.3.

Travel time

Table 5.5: Travel time on metro between adjacent stations.(minute)

	A	B	C	D	E	F	G	H	I
A	-	-	2	-	-	-	-	-	-
B	-	-	3	-	-	-	-	-	-
C	2	3	-	2	2	-	-	-	-
D	-	-	2	-	-	-	-	-	-
E	-	-	2	-	-	-	2	-	-
F	-	-	-	-	-	-	2	-	-
G	-	-	-	-	2	2	-	2	2
H	-	-	-	-	-	-	2	-	-
I	-	-	-	-	-	-	2	-	-

This table5.5 is based on the real situation and meets the following requirements:

1. Operation between two adjacent metro stations is possible in both directions.

2. The time for the metro to run in both directions is the same between adjacent stations.

3. The transfer station is an important node. The metros of the two intersecting lines travel on different tracks and arrive at different platforms, which does not affect the use of the transfer station and does not cause conflicts.

4. All data in the table are in minutes.

The transfer station has its particularity. In addition to the possible queuing time, passengers who need to transfer to other metro lines need additional transfer time (specifically, from one platform to the new platform through the elevator or stairway to the new platform to take another metro on other lines).

Taking Beijing Metro as an example, the metro management department is constantly optimizing the timetable and transfer process of transfer stations to shorten the transfer time, hoping to shorten the transfer time of transfer stations around the Olympic venues to less than 5 minutes.[Mu Tou, 2020]

A new assumption is proposed:

For passengers who need to transfer to other lines at Transfer Station C and Transfer Station G, an additional five-minute transfer time is required.

Table 5.6: Travel time on bike between stations.(minute)

	A	B	C	D	E	F	G	H	I
A	-	11.2	4	9.2	14.8	20.4	18.8	21.2	21.6
B	11.2	-	8	13.2	14.4	12	16	20	19.2
C	4	8	-	5.6	10.4	16.4	14.4	17.6	17.2
D	9.2	13.2	5.6	-	15.2	22	16	12	20
E	14.8	14.4	10.4	15.2	-	7.6	4	7.6	6.8
F	20.4	12	16.4	22	7.6	-	3.64	8	6.8
G	18.8	16	14.4	16	4	3.64	-	3.52	2.48
H	21.2	20	17.6	12	7.6	8	3.52	-	7.2
I	21.6	19.2	17.2	20	6.8	6.8	2.48	7.2	-

This table 5.6is calculated by the bike speed and travel distance. The bike speed is based on the report by BikeLockWiki[BikeLockWiki, 2022] and pick a reasonable value: 20km/h. But it cannot be ignored that cyclists will encounter traffic lights, turning, crossing roads and other inevitable situations on the real road, which will slow down the riding speed. Therefore, the riding speed calculated by the AutoNavi map software[Wikipedia, 2022] is about 15km/h (0.25km/min).

Table 5.7: Bike Speed.[BikeLockWiki, 2022]

Type of Cyclist	Speed(mph)	Speed(km/h)
Beginner	8-12	13-19
Intermediate	12-16	19-26
Advanced	16-24	26-39
Professional	>24	>39

This table5.6 is based on the real situation and meets the following requirements:

1. Common situations that can be encountered in riding have been considered, and other special situations such as car accidents, traffic control, etc. will not be discussed.
2. All data in the table are in minutes.

Table 5.8: Travel time to the stadium Q from stations.(Bicycle) (kilometer)[Wikipedia, 2022]

	A	B	C	D	E	F	G	H	I
Q	8.8	12.8	4.4	10.8	11.2	14.4	14.4	10.8	18

This table 5.6 is calculated by the bike speed(15km/h from table 5.7) and travel distance from table 5.3. And all data in the table are in minutes.

5.4 DISCUSSION ABOUT VALUES AND COSTS

5.4.1 Value of time

The value of time has been discussed for a long time, and the common opinion defines the value of time as:

> The opportunity cost of time spent by people traveling. That is, the value they will pay to save time, or the value they are willing to be compensated for, at the cost of wasting more of their time.[Ariel Goldszmidt, 2020]

Because the value of time (here refers to the value of travel time) is closely related to the national economic situation, the development of the transportation system, the income of the people and many other factors. The measure of the value of time and even the unit will greatly affect the judgment and conclusion of the entire study. And the value of time will also change with the development of the economy (such as changes in GDP). Therefore, in this article, because the designed scenario is based on the Beijing area, in order to unify the standard, the discussion of all values (including time value) will be based on the CNY(¥, Chinese yuan) (the currency unit of China) as the standard, and combined with the actual situation and obtained by calculation.

The existing literature mainly expresses the value of time in two ways[CHEN Xumei, 2015]:

1. The value of travel time. The value of such time has many sub-items, different purposes, different means of transport, the value of time is different, and varies greatly from each other.[for Transport, 2015]

2. The value of time in a broad sense. The value of such time does not distinguish the purpose and the mode of transportation, and is a single data finally obtained by combining various factors and parameters.[Ministerie van Infrastructuur en Milieu., 2017]

In this study, characteristics such as jobs of passengers did not affect that they had a common travel purpose: traveling to the final destination to participate in mega-events. No matter what mode of transportation they choose, as long as they can arrive at the scheduled time, the value of time does not matter to them. Therefore, in this study, the same time value will be selected for analysis.

Through the research and summary of the above literature, a reasonable value of time for the study will be proposed as a new parameter and assumption:

$$¥24/h\ (¥0.4/min)$$

5.4.2 Cost of metro

The research area is based on Beijing, so the cost of the metro will also refer to the charging standard of the Beijing metro system:

Metro fares have been changed from ¥2 across the board to ¥3 as the lowest fare (for a journey of 6 kilometers or less), and increase according to the travel distance.[Lie er, 2014]

5.4.3 Cost of shared bike

The research area is based on Beijing, so the cost of shared bike will also refer to the charging standard of Beijing:

The charging rule is ¥1.5 for the first 15 minutes, and ¥1 for every 15 minutes after that (less than 15 minutes will be calculated as 15 minutes).[Guo Mengyi, 2021]

5.4.4 Cost of relocating

The research area is based on Beijing, so the cost of relocating shared bikes will also refer to the real situation in Beijing:

Due to the uncertainty of the customer's riding destination, on average, the relocating cost of each shared bicycle is about ¥0.3 per time (in other words, the shared bicycle is transported from the destination to the departure point for the next use).[Wu Qiannan, 2019]

5.5 DISCUSSION ABOUT DEMAND AND CAPACITY

Travel demand

For the designed scenario, the most valuable reference is the 2022 Beijing Winter Olympics that took place in the reality of its original setting (Beijing Olympic area). Because its real passenger flow and travel demand are real and well-founded.

But the reality is that due to the existence of Covid-19, the 2022 Beijing Winter Olympics Committee chose the "closed-loop Olympics" in order to protect the health of relevant personnel. Therefore, the travel demand is very different from the conventional situation and cannot be used as a reference.

In the designed scenario, the prototype of stadium Q in reality is the Bird's Nest, the opening ceremony venue of the Beijing Olympic Games, with a design capacity of more than 90,000 people. It was also mentioned above that about one third of spectators who chose to take public transport chose to take the urban metrothat is, about 30,000 spectators .[Yu-kun, 2008]

With the continuous development of Beijing's metro system and the continuous increase of metro lines, the number of people who traveled by metro accounted for more than half of the number of people who traveled by public transportation in 2018[Beijing Business Daily, 2018], and now, this proportion is still increasing.[Beijing News, 2022]

Therefore, it can be reasonably predicted that under the premise that the total demand does not change much (because the maximum capacity of the stadium has not changed significantly), during the opening ceremony period, about 50,000 passengers will travel by metro. The travel time is also concentrated in within 1.5 hours (90 minutes) [Yu-kun, 2008] before the opening ceremony.

Metro capacity

The current common capacity of each metro is about 1410 (256 with seats),[wikipedia, 2021] and this value will gradually increase in the future, but it will be accompanied by the new construction and renovation of metro stations.

In the case of ensuring passenger comfort, this rated capacity will be reduced accordingly to ensure the distance between passengers. So this capacity will drop by more than 10 percent, ie 1200 passengers will be a suitable metro capacity to be adopted. [Beijing Daily, 2016] However, the capacity of the metro only represents the state of the metro when it is empty, which is inconsistent with the actual running state. Therefore, when the mathematical model is actually applied, the available capacity of the metro will be reasonably assumed.

Metro station capacity

In the actual situation, the capacity of the metro station needs special consideration. This is directly related to how many passengers will be allowed to queue in the subway station, and this value will also be a reasonable assumption when conducting mathematical model verification.

Demand distribution

Total demand was mentioned in the previous section: about 50,000 passengers will travel by metro to stadium Q. They will all complete part or all of their trips in the designed scenario. According to the Beijing Olympic Organizing Committee Ticketing Center's introduction at the press conference: Beijing citizens' ticket quota accounts for 30%, the public quota for regions outside Beijing accounts for 40%, and the remaining 30% will be randomly selected for the national public.[China Xinhua News Network Corperation, 2008] According to the population ratio (the resident population of Beijing accounts for about 1.5% of the national population), the tickets that can be obtained in Beijing are about 31.5% of the total, while that in other areas is about 68.5%.

Considering the total number of people, about 16,000 (15,750) people in Beijing took the metro to participate in the opening ceremony, while about 35,000 (34,250) people from other areas took the metro.

According to the arrangement, hotels near the stadium will be given priority to people from other areas so that they can reduce their commute time and attend the opening ceremony more conveniently.[China Xinhua News Network Corperation, 2008] So new assumptions will be proposed:

1. Passengers departing from Stations C and E are not included in the total travel demand because they do not participate in the public transport system.
2. 35,000 people from other areas will live within the designed scenario, and the distribution is random and uniform, which means they will be evenly distributed around metro stations A, B, D, F, G, H, I. In other words, every metro station will meets 5,000 passengers.
3. 16,000 people will enter the designed scenario from six directions, assuming they will travel evenly, ie 2667 people in each direction. They will take the metro directly to interchange stations C and G, and passengers arriving at C will no doubt choose to walk to stadium Q.

5.6 PRACTICAL VERIFICATION OF MATHEMATICAL MODELS

This section will discuss the practical application value of mathematical models and the conclusions that can be drawn from mathematical models.

When solving this mathematical model, **Python** is used as the programming language and **Gurobi** is used as the software for mathematical optimization.

5.6.1 Application of Mathematical Model in Design Scenario

Based on the designed scenario, some parameters in the mathematical model will be reassigned to verify the feasibility of the model and the fit of the model to the scenario.

In the following sections, the six types of scenarios with different kinds of characters and parameters will be given in tabular form.

In order to better demonstrate what changes the addition of micromobility will bring to the existing public transportation system, a scenario without micromobility participation will be presented separately as a reference scenario.

In addition to this, a test scenario will be presented to better explore how the model and the traffic system behave in extreme cases. This test scenario is to set all costs related to shared bikes to 0 without considering the cost at the manager level in the face of short-term travel demand increases.

Table 5.9: Six types of scenarios

Scenarios Type	Introduction
Scenario 1.0 (Only normal metro)	No shared bikes participate in the transportation system (only metro exists)
Scenario 1.1 (Only cheaper metro)	No shared bikes participate, reduce the cost of metro
Scenario 2.0 (Normal shared bike)	Shared bike participates with realistic parameters
Scenario 2.1 (Cheaper shared bike)	Reduce the cost of using Shared bikes
Scenario 2.2 (Expensive shared bike)	Increase the cost of using Shared bikes
Scenario 3 (Test Scenario)	Set all the cost of using Shared bikes to 0

Scenario 1.0 is a reference scenario. There is no micromobility involved in this scenario, and passengers' travel will be completely dependent on the metro (in fact, passengers will also use a shared bike to complete the "last mile" trip from the metro station to the destination, but this trip Independent of the transportation system, since

for passengers, the use of shared bikes is based on the fact that they have already taken the metro, so the necessary time and costs will only add up). As a reference scenario, other scenarios will adjust parameters around it to get a contrasting effect.

For the time window $[a_i^n, b_i^n]$, one example will be given in table A.1 to show the time difference between the arrival of two adjacent metros, while others will be shown in appendices.

Table 5.10: Time table of metro from station A to C

n	A	A	C	C
	Arrival	Departure	Arrival	Departure
1	0	1	3	4
2	6	7	9	10
3	12	13	15	16
4	18	19	21	22
5	24	25	27	28
6	30	31	33	34
7	36	37	39	40
8	42	43	45	46
9	48	49	51	52
10	54	55	57	58
11	60	61	63	64
12	66	67	69	70
13	72	73	75	76
14	78	79	81	82
15	84	85	87	88

As for station A, the time window $[a_i^n, b_i^n]$ for passengers to get in the metro is [0,1] if they arrive between minute 0 to minute 1, and if they arrive between minute 1 to minute 6, they could get on the third metro if there is no need to que in line.

The M is given as: if que time is less than 3*6 mins (18mins), M = 1; or, M = 999999999. Which is because the time difference between the arrival of two adjacent metros is 6 mins and a new assumption is that **when a passenger cannot be met by the next three metros, he will no longer choose this mode of travel**, which is also based on the value of time and the convenience of other travel options (micromobility: shared bike).

Scenario (Only normal metro)

In contrast, the transportation system without the participation of the micromobility mode will be re-implemented with mathematical models and programming.

Table 5.11: Scenario (Only normal metro) based on designed scenario

c_t	¥0.4/min
c_b	99999999
c_r	¥0.3/bike
c_m	¥3/time
t_f	8min
M	1
t_t	5 mins
$[a_i^n, b_i^n]$	will be shown in appendices
Q_m	253
Q_{im}^s	900

The difference between Scenario (Only normal metro) and Scenario (Normal shared bike)(will be mentioned below) is that when using micromobility mode (shared bike), the cost will become an infinite positive integer (take 99999999 as an example), which means that, in order to minimize the overall cost, all travels containing shared bikes options must not be the choice for passengers. For the queuing time, passengers have no choice, so the big M will always be assigned a value of 1, and will no longer be affected by the queuing time. In order to achieve the same effect, it is also possible to adjust the relocating fee to 99999999.

Result Based on Above Scenario (Only normal metro)

By solving the mathematical model, the optimal solution is given as:

¥262080

Scenario (Only cheaper metro)

As a comparison, without the participation of the micromobility mode, by reducing the cost of using the metro, here is an example of reducing the transfer time (reducing the fare can also have the same effect) to verify the application of the mathematical model in reality .

Table 5.12: Scenario (Only cheaper metro) based on designed scenario

c_t	¥0.4/min
c_b	99999999
c_r	¥0.3/bike
c_m	¥3/time
t_f	8min
M	1
t_t	2 mins
$[a_i^n, b_i^n]$	will be shown in appendices
Q_m	253
Q_{im}^s	900

Result Based on Above Scenario (Only cheaper metro)

By solving the mathematical model, the optimal solution is given as:

¥249984

Scenario (Normal shared bike)

Table 5.13: Scenario (Normal shared bike) based on designed scenario

c_t	¥0.4/min
c_b	if $t_{iQ} < 15$, 1.5; if 15< t_{iQ} <30, 2.5
c_r	¥0.3/bike
c_m	¥3/time
t_f	8min
M	if que time is less than 3*6 mins (18mins), M = 1; or, M = 999999999
t_t	5 mins
$[a_i^n, b_i^n]$	will be shown in appendices
Q_m	253
Q_{im}^s	900

Result Based on Above Scenario (Normal shared bike)

By solving the mathematical model, the optimal solution is given as:

¥222768

Scenario (Cheaper shared bike)

For comparison, the mathematical model was re-validated in reality by reducing the cost of using the micromobility mode (here, reducing the relocating fee, which would have a similar effect to reduce the using fee).

Table 5.14: Scenario (Cheaper shared bike) based on designed scenario

c_t	¥0.4/min
c_b	if $t_{iQ} < 15$, 1.5; if 15< t_{iQ} <30, 2.5
c_r	¥0.15/bike
c_m	¥3/time
t_f	8min
M	if que time is less than 3*6 mins (18mins), M = 1; or, M = 999999999
t_t	5 mins
$[a_i^n, b_i^n]$	will be shown in appendices
Q_m	253
Q_{im}^s	900

Result Based on Above Scenario (Cheaper shared bike)

By solving the mathematical model, the optimal solution is given as:

¥220500

Scenario (Expensive shared bike)

The proposal of this scenario is to better study the performance of the model from more aspects. One of the changes is that the cost of using shared bikes has been increasedchange the cost of using shared bike from if $t_{iQ} < 15$, 1.5; if 15< t_{iQ} <30, 2.5 to $t_{iQ} < 15$, 3.5; if 15< t_{iQ} <30, 4.5.

Table 5.15: Scenario (Expensive shared bike) based on designed scenario

c_t	¥0.4/min
c_b	if $t_{iQ} < 15$, 3.5; if 15< t_{iQ} <30, 4.5
c_r	¥0.15/bike
c_m	¥3/time
t_f	8min
M	if que time is less than 3*6 mins (18mins), M = 1; or, M = 999999999
t_t	5 mins
$[a_i^n, b_i^n]$	will be shown in appendices
Q_m	253
Q_{im}^s	900

Result Based on Above Scenario (Cheaper shared bike)

By solving the mathematical model, the optimal solution is given as:

¥244339

Scenario (Test Scenario)

In order to better explore the performance of the model and the transportation system in extreme cases, a scenario will be proposed that sets all costs related to shared bikes to 0, called a test scenario.

Table 5.16: Scenario (Test Scenario)

c_t	¥0.4/min
c_b	0
c_r	¥0/bike
c_m	¥3/time
t_f	8min
M	if que time is less than 3*6 mins (18mins), M = 1; or, M = 999999999
t_t	5 mins
$[a_i^n, b_i^n]$	will be shown in appendices
Q_m	253
Q_{im}^s	900

Scenario (Test Scenario)

By solving the mathematical model, the optimal solution is given as:

¥173578

5.6.2 Comparison of optimal solutions with different scenarios

In this section, the optimal solution in the above section 5.6.1 will be considered. The optimal solutions based on six types of scenarios is shown in following table. In addition to the optimal solution, there are two related conclusions worth noting that will be presented. One is the number of passengers who choose a shared bike to travel after the shared bike is added as a travel option, and the second is the comparison of the travel time before and after the shared bike was added.

Table 5.17: Optimal solutions of six types of scenarios

Scenario Type	Optimal solutions(¥)	Total travel time	Average Travel time
Only normal metro	262080	438480	12.4
Only cheaper metro	249984	438480	12.4
Normal shared bike	222768	388080	11
Cheaper shared bike	220500	388080	11
Expensive shared bike	244339	394128	11.2
Test Scenario	173578	510048	14.5

For the total travel time and average travel time, when the shared bike is added to the transportation system, the total travel time is reduced by 11.5% compared to before ((438480-388080)/438480). The reasons for the change in travel time are as follows:

1. The addition of shared bikes gives passengers the option of avoiding queues (although this choice is driven by overall cost savings rather than personal preference).
2. The addition of shared bikes helps passengers avoid transfer time when traveling for short distances.
3. The addition of shared bikes can directly achieve ”O to D” and ”door to door”, which means that passengers can selectively avoid the walking time to their destination after exiting the metro station(although this choice is also driven by overall cost savings rather than personal preference).
4. The reason the travel time doesn’t vary as much is because some metro stations are so far apart that despite the queues and waiting, the total cost is still lower than cycling from origin to destination.
5. Test scenario reduces the cost of using shared bikes to zero. It can be seen from the results that, except those who cannot directly use shared bikes due to the long travel distance, all other passengers will choose shared bikes to travel. This

is why the overall cost is reduced. The reason for the increase in the total time is that compared with metro when traveling for a longer distance, shared bike will bring longer travel time.

In addition, when micromobility (shared bike) participates in the transportation system, micromobility (shared bike) has become one of the important choices for passengers, and 15,120 passengers choose to use only shared bikes to complete their travel demands, which occupied 42.8% (15120/35280) of total passengers (35280).

But two points that still need to be explained are:

1. The reduction in the cost of riding a shared bike will not bring more passengers to travel in this way. The reason for this is that the total cost is considered in this study, so the personal preference of passengers is not considered, so passengers will choose the way that makes the total cost lower, rather than the lowest personal travel cost. More specifically, when the cost of using bikes is normal, the normal competitive balance has been broken, and the passengers who choose shared bikes have been determined. For example, all passengers departing from stations B and D choose shared bikes, while others passengers who need to take the metro (depart from station I) and passengers who need the combination of metro and shared bike (depart from station F and station H) will not change their choices because of the lower cost of shared bike (because travel If the distance is too long, it is not suitable to ride directly to the destination). This point can also be proved in another way. When the focus is scenario 2.2 (Expensive shared bike), longer travel time means that the price competition between shared bike and metro becomes more fair. Passengers departing from stations B and D also start to choose to take metro (although there may be a queue and the final walking time is longer, but the total cost is reduced), and passengers from other departure points will also start to weigh whether to choose to queue for a metro or share bike as a means of travel.

2. No passenger chooses the way the metro and shared bike work together. There are two reasons for this:
    a) Choosing a way of cooperating with shared bike and metro will increase the cost, that is, passengers need to pay for the two travel methods separately. This does not serve the purpose of minimizing the total cost.
    b) The assumption in this case is different from the actual situation. The difference is that the case cannot fully consider the personal preference of passengers, and the value of time has not been specially weighted.

Comparison of Result (Normal shared bike) and Result (Only normal metro)

The difference between scenario (Normal shared bike) and scenario (Only normal metro) is whether there is a micromobility mode involved in the traffic system, and the results show that:

When the micromobility mode participates in the transportation system with reasonable parameters, the overall cost of the system will be able to be reduced.

Although the cost reduction may vary as the scenario is changed, with scenario (Normal shared bike), the cost can be reduced by 17.7 % ((262080 - 222768)/ 262080).

Comparison of Result (Normal shared bike) and Result (Cheaper shared bike)

The difference between scenario (Normal shared bike) and scenario (Cheaper shared bike) is that the use cost of micromobility mode has been reduced, which also undertakes part of the problem in the previous comparison (The cost reduction may vary as the parameter is changed). The result shows that:

When the cost of micromobility mode reduces, the overall cost of the system will be able to be reduced.

When the relocating fee is reduced by half, the overall cost will be reduced by 1 % ((222768 - 220500)/222768).

Comparison of Result (Only normal metro) and Result (Only cheaper metro)

The difference between scenario (Only normal metro) and scenario (Only cheaper metro) is that the use cost of metro has been reduced(Here is to reduce the time cost of passengers by reducing the transfer time). The result shows that:

When the cost of metro reduces, the overall cost of the system will be able to be reduced.

When the transfer time changes from 5 minutes to 2 minutes, the overall cost will be reduced by 4.6% ((262080 - 249984)/ 262080).

But it must be pointed out that, based on the assumptions in the design scenario, when there is a micromobility mode participating in the entire transportation system, the parameters of the metro are changed in small increments (for example, reducing the fare from ¥3 to ¥2, or changing the transfer time from 5 minutes to 2 minutes, etc.) will not affect the final result.

The reason for this result is that the cost of micromobility is too low, so that a small reduction in the cost of metro use cannot change the choice of passengers for micromobility (here, shared bike), because in this way, the total cost is lower.

Since the parameters about the shared bike are all based on reality. Therefore, the emergence of this result is not a problem of mathematical models, but a problem of competition in the management and operation of shared bikes in reality. This competition causes every shared bike company to reduce the cost of using shared bikes, even if they lose profits or even waste investment, because occupying more markets is their first purpose. How to solve this problem will be the need for future research. The purpose of the research is how to balance the cost of micromobility and other modes of transportation, so that they can compete and cooperate in a reasonable role to participate in the transportation system.

Scenario (Expensive shared bike) result analysis

Scenario (Expensive shared bike) provides a relatively reasonable parameter for the mathematical model, in other words, the cost of using a shared bike is close to the fare of an urban metro system. Although this method does not meet the realistic pursuit of reducing travel costs, it can prove the complete performance of the model from another aspect.

Compared with Scenario (Nomal shared bike), Scenario (Expensive shared bike) has a 9.6% (244339-222768)/222768 increase in the total cost of travel. And its travel time increased by 1.6% (394128-388080)/388080.

This means that when passengers choose a shared bike and the cost is close to that of a metro, they will better weigh their travel options.

And this also proves an important question, why compared to Scenario (Nomal shared bike), Scenario (Cheaper shared bike) reduces the cost of using shared bikes, but cannot reduce the total travel time.

The reason is that the cost of the shared bike in Scenario (Nomal shared bike) is low enough that the metro can no longer reasonably compete with it. Passengers will ignore many other factors (such as longer travel time, etc.) in order to reduce the total travel cost. . In this case, the distribution of travel demand at each metro station has been fixed and cannot be further changed by reducing the cost of shared bikes. The main reason is that there is a fixed cost (fare + the time cost of the last 8 minutes of walking time) to take the metro, whether or not to transfer and queue. When the cost of using shared bikes is too low, metros with fixed and variable costs will be unable to compete with them, and passengers' travel options will change from dynamic changes to fixed choices.

Test scenario result analysis

The test scenario is an extreme case in which all costs associated with shared bikes are set to zero (except for the time cost incurred by travel time). Compared with the scenario (Normal shared bike), the total travel cost of the test scenario is reduced by 22.1% (222768-173578)/222768. At the same time, the total travel time increased by 31% (510048-388080)/388080.

Some details need to be mentioned: when the cost of the shared bike is set to zero, all passengers except the passengers departing from the transfer station G′ choose the shared bike as the travel option. This reflects an important issue. When the cost of shared bike is low enough, metro does not have the ability to compete with it, which is why scenario (Cheaper shared bike) does not save travel time than scenario (Nomal shared bike).

Regarding the total travel time of the test scenario, the reason for the increase is that the cost of the shared bike is low enough that longer travel time can no longer affect the total cost reduction brought by the low cost.

5.7 ANALYSIS OF MODEL VALIDATION

In the validation of the model, six parameters are proposed and applied in the designed scenario,

The results brought by these six parameters are shown in the table B.1 above. The differences of the parameters and the impact on the total cost have also been shown. This section will focus on analyzing the internal reasons.

The reason for changing the parameters in a way of reducing the usage fee is that, in reality, the government management department keeps reducing the public transportation fee within a reasonable range to encourage passengers to use public transportation to meet the travel demand.

The participation of shared-bikes makes more independent and combined travel options possible, and metro will not be the only choice for passengers to travel. But this requires that shared-bikes must join the transportation system with reasonable parameters. The reason is that the low cost of shared-bike may completely guide passengers to choose shared-bike in pursuit of the lowest total cost when the two travel options are: only bike or only metro, and metro will no longer be an option, which is obviously inconsistent with the purpose of the research and the pursuit of reality. The conclusion of the previous section can already reflect the irrationality of the shared-bike realistic parameters to a certain extent, mainly reflected in:

Reducing the cost of using shared-bike cannot increase the number of users of shared-bike. Since the maximum number of shared-bikes was not set in the early stage, the reason for this result is that the cost of using shared-bikes in reality is too low, resulting in no price advantage in the selection of metro.

Other reasons why metro's competitive advantage is weakened or even replaced are

1. Not weighting the cost of time will diminish the speed and time advantages of metro.

2. Metro cannot achieve ”door-to-door”, that is, passengers need to walk to the destination after leaving the metro, which undoubtedly increases the travel time, and shared-bike can effectively avoid this.

3. Restrictions on the extent of the study area. In other words, the study area of this thesis is small, and in this area, it is difficult for the metro to exert its speed advantage and time advantage. But one thing that has to be considered is that the travel mode has a suitable distance, and an excessively large research scope will make shared-bike unable to become one of the options.

Another analysis about model validation is about the research object :total cost. Research analysis of total cost will undoubtedly selectively ignore several important aspects: personal travel cost, total travel time and personal travel time.

Ignoring personal travel costs will help avoid the shift in research focus caused by personal travel preferences. Although this is different from the reality, the purpose of this study is to explore whether and what impact the addition of micromobility will have on the entire transportation system, so it is reasonable to ignore individual travel costs.

Regarding the total travel time, in the study, the travel time is used as one of the variables, which is reflected in the value of time and time, so from this aspect, the total travel time has not been ignored. While the previously assumed ”total travel time window” refers to the most reasonable and in line with the arrangements before mega events occur, the existence of micromobility will help ease travel pressure and reduce the ”travel time window” from the existing one to the assumed and reasonable one.

As for personal travel time, which, like personal travel cost, does not belong to the main research object, personal travel time is also reflected in the results in the form of variables.

5.8 SUMMARY OF MODEL VALIDATION

In this chapter, six scenarios(including a reference scenario) and related parameters are proposed, and the mathematical model is verified. At the same time, the scenarios are evaluated and analyzed using the verification conclusions. The conclusions reached are as follows:

1. When the micromobility mode adds in the transportation system with reasonable parameters, 42.8% of the passengers will use shared bikes to complete their travel demands.

2. When the micromobility mode participates in the transportation system with reasonable parameters, the overall cost of the system will be able to be reduced and the rate can reach 17.7%.
3. When the micromobility mode adds in the transportation system with reasonable parameters, travel time will be reduced by about 11.5%.
4. To reduce the cost of shared bike and metro respectively, the total cost will be reduced by about 1% to 4.7%, which means that the effect of this method is not very significant.
5. Increasing the cost of using micromobility will increase the total cost, and it can also prove that the satisfaction of travel needs is directly related to the cost of micromobility.
6. The performance of the model and transportation system in extreme situations (test scenarios) demonstrate that a reasonable competition between micromobility and metro should be based on reasonable costs.

5.9 THE SIGNIFICANCE OF MATHEMATICAL MODELS IN REALITY

This mathematical model and solution process and parameter settings are designed to solve the problem of excess demand brought about by mega-events. This problem can be extended based on this mathematical model:

1. Through the study of the above models and conclusions, it is found that under the condition of reasonable parameters, the participation of micromobility (shared bike) in the urban metro transportation system is helpful to reduce the total cost of travel. In the previous assumption, the shared bike parking area is assumed to be the same as the metro station to simplify the problem. However, in subsequent studies, combining this mathematical model with the ″shared bike location problem″, it can solve the problem of minimum cost to meet passengers' travel demand when the parking area of shared bikes is not in the same location as the metro station in real life.

2. The travel demand mentioned in this study is ″partially dynamic″, that is, passengers will come continuously, providing a dynamic demand for the transportation system. This is not entirely based on reality, but the travel needs are allocated according to a fixed number of people per minute, so combining this mathematical model with dynamic demands can solve real-life dynamic travel problems for passengers.

3. The introduction of travel options in the previous mathematical model section is universal, but it is relatively simple. In real situations, travel options may be more complicated. Therefore, changing the travel options in this mathematical model can adapt to the travel problem of a single destination in more scenarios.

4. The correlation of parameters and final results in this mathematical model also helps stakeholders to study the balance of different travel modes.

6 CONCLUSION AND RECOMMENDATION

The final chapter of this thesis consists of conclusions of this research and relevant recommendations. This chapter will contain two parts:

1. Answer the research questions proposed in section1.2.2 based on previous chapters.

2. Give relevant recommendations based on the conclusions

6.1 CONCLUSION

Due to the particularity of travel demand brought by mege-event: a single destination, a sudden increase in demand in a short period of time. Research questions and sub-questions are posed step by step and will also be answered step by step here.

What is a multimodal transport system dominated by micromobility should be to handle the excessive demand of urban metro system caused by mega-event?

1. How to design a multimodal system supported by micromobility modes for urban metro systems to handle the excessive demand?

First of all, it is necessary to model the real transportation system, focusing on the travel mode and the important parameters of the travel mode, and represent them in the form of mathematical modeling. Secondly, select modes of micromobility to participate in the transportation system. In this paper, through the comparison of the characters of various modes of micromobility, the final choice is shared bikes. Thirdly, clarify the role of the newly added micromobility mode in the transportation system. In this paper, the role of the micromobility mode is the same as that of the metro. The micromobility mode, like the metro, has the ability to independently meet the travel demands, and passengers can choose when there is no subjective priority. Fourthly, combined with the travel mode, select travel options and express them in the form of mathematical models.

2. What is the state of the current public transport system (metro lines) in the research area?

In this paper, the research on the research area includes: background research, geographic research and data research. Background research can better present the current status and existing problems of the transportation system. Geographical research can show how many lines there are in the metro system in the study area, how many stations each line has, how many transfer stations, how the relative positions of each station are, etc. Data research can reflect the current ability to meet travel demand in the study area, and find the gap between ability and demand.

3. What will be influence of the metro system in the study area during mega-event, and what a designed research scenario should be?

These two questions will be answered together. In this paper, the designed scenario is based on the realistic scenario. In the designed scenario, the metro network is simplified, the distance between stations is clarified, travel time and various related travel costs are calculated, and the meaning and characteristics of various costs are explained. All of the above will lay the foundation for the application of mathematical models in the design scenario.

4. How will the new model be used in case study?

This is the last step in the entire paper about the mathematical model, and it is also the most intuitive and important step. In the above steps, the mathematical model has been proposed, and the relevant parameters in the design scenario have also been proposed. The parameters in the mathematical model are assigned, and the results are obtained through programming and model solving software, and the results are analyzed to find the realistic meaning.

Conclusion Summary

Through the combination of mathematical model and designed scenario, this paper designs a multimodal transport system dominated by micromobility to handle the excessive demand of urban metro system caused by mega-event. And through the scenario verification, it is proved that when the mode of micromobility participates in the transportation system in a reasonable way, this multimodal transport system will be able to reduce the total cost of the system, and the amount of reduction is related to the characteristics of the modes.

The innovation and contribution of this research are briefly summarized as below:

- This paper proposes to use the micromobility mode to participate in the transportation system as the same role as the metro (public transportation mode).

The related literature is more about using the micromobility mode as the implementer of the last mile, cooperating with public transportation modes to meet the travel demands.

- This paper makes a detailed classification of the travel options with the participation of micromobility mode, which is similar to the travel options provided by the navigation software in mobile communication tools such as mobile phones for passengers, which helps to better connect the mathematical model with real life.
- This paper provides a new solution to the problem of excessive travel demands brought by mega-events, focusing on the cooperation of multimodal transport. The related literature focuses more on increasing the number, frequency and operating hours of public transport modes, or on the conditions in metro stations to maintain normal operation.
- The verification of the mathematical model by the designed scenario also proves the feasibility and practicability of the model and the way of solving such problems.

6.2 RECOMMENDATION

6.2.1 Scientific recommendations

The work of this thesis still has drawbacks and limitations. The next step in future work can focus on these aspects:

- In this thesis, when considering the travel demand, the average distribution is used, but in fact, the travel of passengers is random, and research on the distribution of passenger travel demand needs to be added in future research.
- When considering the design scenario of this thesis, the scope of the metro network is limited. In reality, the impact of the travel demand brought by mega-events will be wider, which will be considered in future research.
- In this thesis research on micromobility mode, the selected characters are limited. In reality, more characterse.g. relocating time, frequency, etc. that may affect the transportation system will be added.
- In this thesis, the shared bike parking lot is assumed to be located at the same location as the metro station. This is to simplify the research problem. In future research, the site selection problem can be combined with existing problems.

6.2.2 Practical recommendations

- When considering the cost, this thesis focuses on the overall cost in order to prove that the addition of micromobility will reduce the cost, and does not consider the actual needs and travel preferences of passengers. The personal preferences of passengers are also an important part in practical research.

- When considering the character of micromobility, this thesis is more based on the reality, but in reality, especially in the research area, the rationality of the price of micromobility due to its market competition and other reasons needs to be demonstrated in the future. Moreover, the case studies in this thesis demonstrate the existence of a balance point between micromobility and metro price (this balance point means that the competition is fair, not the case that the attractiveness of the mode to passengers is not sensitive to changes in the cost of use). However, due to reasons such as technology and time, the specific value of the balance point has not been further explored, which will be studied in the future.

- When this thesis is considering the metro, the pursuit is to maintain its daily operation, but in fact, when mage-events occur, the management department will consider appropriately increasing the frequency or number, which will be considered in future research.

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A TIME WINDOW BETWEEN STATIONS

Here the detailed time window between stations.

Table A.1: Time table of metro from station A to C

n	A	A	C	C
	Arrival	Departure	Arrival	Departure
1	0	1	3	4
2	6	7	9	10
3	12	13	15	16
4	18	19	21	22
5	24	25	27	28
6	30	31	33	34
7	36	37	39	40
8	42	43	45	46
9	48	49	51	52
10	54	55	57	58
11	60	61	63	64
12	66	67	69	70
13	72	73	75	76
14	78	79	81	82
15	84	85	87	88

Table A.2: Time table of metro from station B to C

n	B	B	C	C
	Arrival	Departure	Arrival	Departure
1	0	1	4	5
2	6	7	10	11
3	12	13	16	17
4	18	19	22	23
5	24	25	28	29
6	30	31	34	35
7	36	37	40	41
8	42	43	46	47
9	48	49	52	53
10	54	55	58	59
11	60	61	64	65
12	66	67	70	71
13	72	73	76	77
14	78	79	82	83
15	84	85	88	89

Table A.3: Time table of metro from station D to C

n	D	D	C	C
	Arrival	Departure	Arrival	Departure
1	0	1	3	4
2	6	7	9	10
3	12	13	15	16
4	18	19	21	22
5	24	25	27	28
6	30	31	33	34
7	36	37	39	40
8	42	43	45	46
9	48	49	51	52
10	54	55	57	58
11	60	61	63	64
12	66	67	69	70
13	72	73	75	76
14	78	79	81	82
15	84	85	87	88

Table A.4: Time table of metro from station F to G

n	F Arrival	F Departure	G Arrival	G Departure
1	0	1	3	4
2	6	7	9	10
3	12	13	15	16
4	18	19	21	22
5	24	25	27	28
6	30	31	33	34
7	36	37	39	40
8	42	43	45	46
9	48	49	51	52
10	54	55	57	58
11	60	61	63	64
12	66	67	69	70
13	72	73	75	76
14	78	79	81	82
15	84	85	87	88

Table A.5: Time table of metro from station H to G

n	H Arrival	H Departure	G Arrival	G Departure
1	0	1	3	4
2	6	7	9	10
3	12	13	15	16
4	18	19	21	22
5	24	25	27	28
6	30	31	33	34
7	36	37	39	40
8	42	43	45	46
9	48	49	51	52
10	54	55	57	58
11	60	61	63	64
12	66	67	69	70
13	72	73	75	76
14	78	79	81	82
15	84	85	87	88

Table A.6: Time table of metro between station I , station G′ and station E

n	I	I	G′	G′	E	E
	Arrival	Departure	Arrival	Departure	Arrival	Departure
1	5	6	8	9	11	12
2	11	12	14	15	17	18
3	17	18	20	21	23	24
4	23	24	26	27	29	30
5	29	30	32	33	35	36
6	35	36	38	39	41	42
7	41	42	44	45	47	48
8	47	48	50	51	53	54
9	53	54	56	57	59	60
10	59	60	62	63	65	66
11	65	66	68	69	71	72
12	71	72	74	75	77	78
13	77	78	80	81	83	84
14	83	84	86	87	89	90
15	89	90	92	93	95	96

B SCIENTIFIC PAPER

MULTI-MODAL SYSTEM DESIGN FOR URBAN METRO SYSTEMS TO HANDLE EXCESSIVE DEMAND CAUSED BY MEGA-EVENTS

by

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This scientific paper will elaborate and discuss from the following aspects:

1. Introduction: including research background, research objects, research methods, etc.
2. Research question: including the summary of literature review, research gap and final purpose, etc.
3. Model development: including the basic situation of the model, case studies, research scenarios, etc.
4. Conclusion and recommendation: including the response to the research question, the analysis of the conclusion, the difference between the conclusion and the expectation and the reasons for it, etc.

B.1 INTRODUCTION

This scientific paper has a background of in the development of cities and the expansion of urban scale, the existing transportation facilities and transportation systems(take urban metro system as an example and research object) also need to be constantly updated and optimized. Especially for those cities that need to host large-scale events (mega-events) such as the Olympics,the urban metro system cannot independently fulfill the sudden increase in excess travel demand brought about by mega-events. Therefore, this paper proposes to take (take shared bike as an example and research object)as another main research object, and cooperate with the urban metro system to handle excessive travel demand.

Qualitative research and quantitative research will be used as the main research methods in this paper. In the qualitative research, micromobility characteristicsmodel design, adjustment and optimization are carried out in combination with actual experience to realize the design of the multimodal transport system of micromobility and urban metro system. In quantitative research, this paper describes a case study area based on real condition and proposes six scenarios. Data collection and demand forecasting are used as methodology to underpin model development and algorithm to address two main issues: How will this multimodal system work to handle excessive demand, and what roles will micromobility mode and metro play in the transportation system. And through demand forecasting and parameter changes, this paper explores the situation that only metro participates in the transportation system, and micromobility mode participates in the transportation system with metro with different parameters, etc., under the premise of meeting the excessive travel demand brought by mega-events, impact on total travel costs.

B.2 RESEARCH QUESTION

The literature review of this paper mainly includes the following aspects:

1. Literature review of abnormal operation of the urban metro system.
2. Literature review of restoration of urban metro system operations.
3. Literature review of the characteristics and applicability of micromobility modes.
4. The current laws and regulations on micromobility norms and restrictions, and the most suitable mode obtained accordingly as the research object.

Through the collection, analysis and summary of some existing literature, this paper proposes the following research gap

1. Through the literature review on abnormal operation and restoration of urban metro system operations, the research gaps found are mainly: To deal with the excess demand, the existing research mainly focuses on adjusting the metro system itself, and lacks the research on passengers outside the station. In other words, how to minimize the excessive pressure on the existing transportation system on the premise of meeting the travel demand of passengers to the greatest extent.
2. Through the literature review on the characteristics, applicability of micromobility modes, and current laws and regulations on micromobility, shared bike is chosen as the research object,and the research gaps found are mainly: For the research on micromobility, the existing research mainly focuses on the choice of parking location and how to use micromobility to cooperate with the metro to complete the passenger's last mile travel demand, rather than using it as a means of transportation equivalent to the metro to play a similar role and provide passengers with another way of travel options.

In view of the above research gap, a more explicit research content is presented as the ultimate goal by this paper: under the condition of maintaining the normal operation of metro system as far as possible (i.e. when mega-events occur, the operation time and frequency of metro system are at most the state of daily peak hours), add shared bikes into the system in the most efficient way and explore its impact on total travel costs.

B.3 MODEL DEVELOPMENT

In order to better solve research questions, this paper proposes a general mathematical model, which provides different travel options for all travel demand, in other word, passengers who need to travel:

1. Take the metro all the way, leave the terminal, and walk to the destination.
2. Ride a shared bike the whole way and go straight to the destination.
3. A combination of shared bikes and metro, that is, passengers can choose to ride to a nearby metro station without queuing, take the metro, or to avoid transfer time and queue time, get out of the transfer station, ride to the destination, etc.

The equations show different options for passengers to travel:

1. The cost of biking directly from the origin to the destination Q.
2. The cost of taking the metro to the station which is the nearest one of this line to the destination and walking to the destination.
3. The cost of taking metro to transfer station G and cycling to the destination.
4. The cost of taking metro to transfer station G, transferring to G′, taking metro to the station which is the nearest one of this line to the destination, walking to the destination.
5. The cost of those whose origin is the transfer station G taking metro to the station which is the nearest one of this line to the destination, walking to the destination.
6. The cost of those whose origin is on the same line of G′ taking metro to G′, taking metro to the station which is the nearest one of this line to the destination, walking to the destination.

Besides, some important assumptions need to be pointed out to better explain the mathematical model:

1. Passenger behavior related assumption:
    a) The passengers will complete their trips.
    b) Passengers can make choices without spending time.
    c) There is no difference in ability of passengers, and there is no subjective and objective preference for choice.
    d) Time cost may be given weight.

   e) The trip from the original point of departure to the metro station can be ignored.
   f) It is assumed that the number of passengers arriving at each origin station per minute is the same.

2. Other assumptions
   a) Transfer means the end of a trip and the beginning of a new trip.
   b) The cost of transporting bikes back to their original parking space is only related to the number of bikes.
   c) A metro entering the study area will carry a certain number of passengers.
   d) Only one-way trips are considered, and return trips are considered separately.

Based on the above description and assumptions, the objective function is proposed: Minimize the cost of handling the excessive demand (caused by mega-events) of the urban metro system dominated by micromobility.

The general cost includes the following aspects: construction cost (infrastructure (charging piles, etc.) + procurement cost (shared bicycles, etc.)) + maintenance cost (bike relocating fee, etc.)+travel cost (cost of transportation + quantified time cost, etc.)

The objective function clearly reflects an important point, which is to supplement the gap of existing research, and use micromobility modes as a travel option at the same level as urban metro, rather than the bearer of the last mile. Therefore, the consideration of micromobility characteristics and related parameters will be very detailed.

Total travel costs are divided into six situations based on travel options, show the various travel options for passengers from origins to destinations, among which micromobility also appears independently, taking on the role of directly helping passengers meet their travel demand. Through dynamic departure scheduling, changes in total cost and total travel time are explored to determine the impact of the addition of micromobility on the performance of the transportation system, and to explore the impact of parameter changes on the results. After the mathematical model is proposed, this paper conducts model verification through case studies, so two scenarios are proposed: ”realistic scenario” and ”designed scenario”.

The realistic scenario truly shows the real situation of the research area, including but not limited to geographical conditions, distribution of metro stations, distribution of metro lines, etc.

The designed scenario is based on the realistic scenario, which simplifies the traffic system and traffic network in an intuitive way and displays them in the form of lines and nodes.

The above-mentioned mathematical model will be specified as follows according to the designed scenario, and the total travel cost is the sum of the following costs:

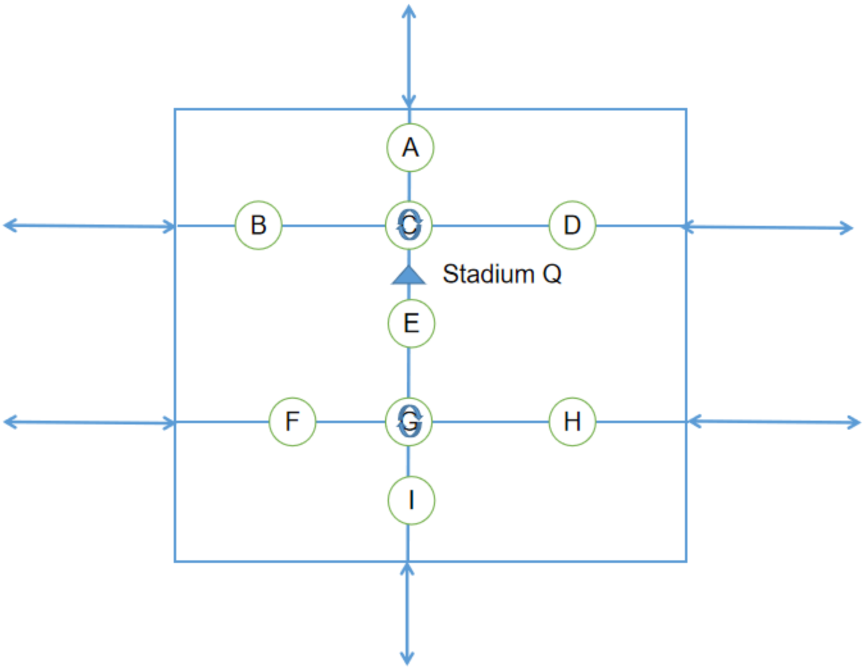

Figure B.1: Designed Scenario

1. The cost of biking directly from departure station to Q.
2. The cost of taking the metro to transfer station C and walking to Q.
3. The cost of taking metro to G and cycling to Q.
4. The cost of taking metro to transfer station G, transferring to G′, taking metro to the station E, walking to the destination.
5. The cost of taking metro to E who's origin is G, walking to Q.
6. The cost of taking metro to G′ from I, taking metro to E, walking to Q.

According to different travel options and related parameters, the "design scenarios" are divided into six different situations: "Normal shared bike" for reference, "Only metro", "Cheaper metro", "Cheaper shared bike" and "Expensive shared bike" for comparison , and a "Test scenario" with zero cost to use micromobility as an extreme case to explore.

Through the parameter changes under different scenarios, this paper solves the corresponding algorithm of the mathematical model, and obtains the following table:

Table B.1: Optimal solutions of six types of scenarios

Scenario Type	Optimal solutions(¥)	Total travel time	Average Travel time
Only normal metro	262080	438480	12.4
Only cheaper metro	249984	438480	12.4
Normal shared bike	222768	388080	11
Cheaper shared bike	220500	388080	11
Expensive shared bike	244339	394128	11.2
Test Scenario	173578	510048	14.5

In this chapter, six scenarios(including a reference scenario) and related parameters are proposed, and the mathematical model is verified. At the same time, the scenarios are evaluated and analyzed using the verification conclusions. The conclusions reached are as follows:

1. When the micromobility mode adds in the transportation system with reasonable parameters, 42.8% of the passengers will use shared bikes to complete their travel demands.
2. When the micromobility mode participates in the transportation system with reasonable parameters, the overall cost of the system will be able to be reduced and the rate can reach 17.7%.
3. When the micromobility mode adds in the transportation system with reasonable parameters, travel time will be reduced by about 11.5%.
4. To reduce the cost of shared bike and metro respectively, the total cost will be reduced by about 1% to 4.7%, which means that the effect of this method is not very significant.
5. Increasing the cost of using micromobility will increase the total cost, and it can also prove that the satisfaction of travel needs is directly related to the cost of micromobility.
6. The performance of the model and transportation system in extreme situations (test scenarios) demonstrate that a reasonable competition between micromobility and metro should be based on reasonable costs.

Combining the mathematical model and the scenario verification of the model, this paper draws the corresponding conclusion: it is found that under the condition of reasonable parameters, the participation of micromobility (shared bike) in the urban metro transportation system is helpful to reduce the total cost (and travel time)of travel. But when the cost of use of micromobility is very low (referring to the reality), continuing to reduce the cost of use will not continue to reduce the total travel time, because when the cost of use of micromobility is low, metro with fixed costs (including the cost of fare and last walking time) will not be able to compete reasonably with micromobility, and the travel options for passengers have been fixed. When reducing the cost of using micromobility to zero (test scenario), travel costs will decrease and travel time will increase, because micromobility will provide passengers with options that are sufficient to reduce the overall travel cost, although choosing micromobility will result in longer travel times. The case study proves that this mathematical model can well demonstrate the impact of micromobility on the transportation system in the delineated area when short-term mega-events (opening ceremonies, etc.) occur.

B.4 CONCLUSION AND RECOMMENDATION

This paper concludes: Through the combination of mathematical model and designed scenario, this paper designs a multimodal transport system dominated by micromobility to handle the excessive demand of urban metro system caused by mega-event. And through the scenario verification, it is proved that when the mode of micromobility participates in the transportation system in a reasonable way, this multimodal transport system will be able to reduce the total cost of the system, and the amount of reduction is related to the characteristics of the modes.

But it should be mentioned that, the scope of application of this research method is the traffic situation of different origins and a single destination. The limitation of the mathematical model is that it cannot solve the problem of completely random and dynamic departure of passengers, and it cannot analyze and study the complex transportation system. In addition, the important assumption of this model is that passengers will depart from the metro station. Future research can combine the starting point with the actual situation to study more complex situations.

This conclusion is broadly similar to the expected result, but there are slight differences that need to be pointed out:

- The expected situation should be that if the price competition is fair, then as the cost of micromobility decreases, more passengers will be attracted, but the reality is that the number of passengers who choose micromobility has not increased.
- The expected dynamic demand will bring more complex results, but the reality is that because the transportation network is simple, the conclusions drawn are also simple.

Therefore, some important recommendations need to be made:

B.4.1 Scientific recommendations

The work of this thesis still has drawbacks and limitations. The next step in future work can focus on these aspects:

- In this thesis, when considering the travel demand, the average distribution is used, but in fact, the travel of passengers is random, and research on the distribution of passenger travel demand needs to be added in future research.
- When considering the design scenario of this thesis, the scope of the metro network is limited. In reality, the impact of the travel demand brought by mega-events will be wider, which will be considered in future research.

- In this thesis research on micromobility mode, the selected characters are limited. In reality, more characterse.g. relocating time, frequency, etc. that may affect the transportation system will be added.
- In this thesis, the shared bike parking lot is assumed to be located at the same location as the metro station. This is to simplify the research problem. In future research, the site selection problem can be combined with existing problems.

B.4.2 Practical recommendations

- When considering the cost, this thesis focuses on the overall cost in order to prove that the addition of micromobility will reduce the cost, and does not consider the actual needs and travel preferences of passengers. The personal preferences of passengers are also an important part in practical research.
- When considering the character of micromobility, this thesis is more based on the reality, but in reality, especially in the research area, the rationality of the price of micromobility due to its market competition and other reasons needs to be demonstrated in the future. Moreover, the case studies in this thesis demonstrate the existence of a balance point between micromobility and metro price (this balance point means that the competition is fair, not the case that the attractiveness of the mode to passengers is not sensitive to changes in the cost of use). However, due to reasons such as technology and time, the specific value of the balance point has not been further explored, which will be studied in the future.
- When this thesis is considering the metro, the pursuit is to maintain its daily operation, but in fact, when mage-events occur, the management department will consider appropriately increasing the frequency or number, which will be considered in future research.

COLOPHON

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