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Evaluation of the Traffic Control System of Open Bus Rapid Transit Corridors: An Application to the City of Guangzhou

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Dissertation for Master Degree

Complex Transport Infrastructure Systems

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Acknowledgements

To be frank, this is the biggest step I've made in my life. I attended in CTIS in 2009. It was two years already from now. At the same time of last year, I was thinking to quit and go back to China. But now I am able to finish my dissertation. I would never thought of this one year before. This progress I've made is all because of the following people who have helped and supported me. First of all, I would like to thank my supervisor, Professor José Manuel Viegas, who has accepted me as one of the members of CTIS, teaching me the knowledge and giving me chance to stay here during my studying year. I would like to thank him for the good advices and support he offered during my dissertation time.

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Abstract

Public transport systems play a crucial role on cities, especially in large and dense urban areas. Bus Rapid Transit (BRT) is one of public transport services that are under a rapid development, due to its reduced investment cost compared with Light Rail Transport (LRT) and high transport capacity and performance. As this system can operate on dedicated infrastructure, or in shared corridors with dedicated lanes, traffic control system play a very relevant role on the resultant performance of the system.

This dissertation aims to evaluate the traffic control system of an open BRT system, measuring the influence of general traffic on the performance of the system, but also the modeling of some disturbance processes to the overall system operation, as punctual reductions of the system capacity. This analysis was based on the very successful case study of Guangzhou Bus Rapid Transit (GBRT). The part of GBRT network selected for this study has approximately 5km of length and 7km of width, including BRT stations inside the dedicated corridor, but also in areas where the BRT lanes share their operation with other traffic.

The modeling of the current problem was developed through the creation of plausible synthetic data of the case study, based on a calibrated road network, using data available from traffic speed and flow during the afternoon peak period.

The problem was then modeled using traffic simulation software, inputting information about the general traffic of the study area, as well as the BRT services with the respective expected headways. With this model, four different scenarios were computed: the system without disturbances, with disturbances, with disturbances controlled and preemption BRT buses introduced.

The assessment of the performance of the system considered all the perspectives of the different agents of the system: the BRT corridor manager, the BRT line operator, the BRT user and the overall traffic. For that purpose, several different indicators were developed to assess the performance of the system in the different scenarios of disturbance of the system and control.

The results obtained show the significant added value of the performance of the system, especially for the BRT line operator, of introducing advance control systems to avoid disturbances to the system, and the pre-emption on traffic lights, not only inside the BRT corridor, but also in all the areas with no dedicated lanes for the bus operation. The developed model may allow also identifying in which traffic conditions an open BRT system may perform efficiently, producing high levels of service for the operators and the clients.

Keywords: BRT, Open system modeling, Evaluation, Different agents, Disturbances, Preemption, Guangzhou.

Resumo

Os sistemas de transporte público desempenham hoje em dia um papel crucial nas cidades, especialmente em grandes e densas áreas urbanas. Os Sistemas de Autocarro Rápido (BRT) são um dos serviços de transporte público em rápido desenvolvimento, devido ao seu custo de investimento reduzido em comparação com os sistemas de metro ligeiro (LRT), ligado a uma elevada capacidade de transporte e desempenho. Como este sistema pode operar em infra-estrutura dedicada, ou em corredores partilhados com faixas exclusivas, os sistemas de controlo de tráfego desempenham um papel muito relevante na qualidade de serviço do sistema.

Esta dissertação tem como objectivo avaliar os sistemas de controlo de tráfego associados a um sistema BRT de operação aberta, medindo a influência do tráfego geral sobre o desempenho do sistema, mas também a modelação de alguns processos de perturbação para o funcionamento geral do sistema que provocam reduções pontuais da capacidade do sistema. Esta análise foi baseada no para um caso de sucesso: o Guangzhou Bus Rapid Transit (GBRT). A parte da rede GBRT seleccionada para este estudo tem aproximadamente 5 km de comprimento e 7 km de largura, incluindo estações dentro do corredor BRT dedicado, mas também em áreas onde o BRT circula em vias de tráfego misto.

A modelação do problema actual foi desenvolvida através da criação de dados sintéticos plausíveis da área de estudo, com base em uma rede de estradas calibrada, usando dados disponíveis de velocidade de tráfego e fluxo durante o período de ponta da tarde.

O modelo foi desenvolvido usando um software de simulação de tráfego, baseado em informações de tráfego da área de estudo, bem como as frequências de serviços dos respectivos serviços de BRT. Com este modelo, criaram-se quatro cenários diferentes: o sistema sem perturbações, com perturbações, com perturbações controladas e sistemas de prioridade nos cruzamentos semaforizados para os autocarros.

Foi então desenvolvida uma avaliação do desempenho do sistema considerando todas as perspectivas dos diferentes agentes do sistema: o gerente do corredor BRT, o operador de linha de BRT, o usuário BRT e o tráfego em geral. Para o efeito, vários indicadores diferentes foram desenvolvidos para avaliar o desempenho do sistema nos vários cenários de perturbações.

Os resultados obtidos mostram o significativo valor acrescentado dos sistemas de controlo no desempenho segundo as perspectivas dos vários agentes, especialmente para o operador de linha de BRT. A introdução de sistemas de controlo das perturbações e de preferência nos semáforos, não só dentro do corredor BRT, mas também nas restantes áreas de tráfego misto, aumentam significativamente o desempenho do sistema. O modelo desenvolvido pode permitir também identificar em que condições de tráfego de um sistema BRT de operação aberta pode desempenhar de forma eficiente, produzindo elevados níveis de serviço para os operadores e os clientes.

Palavras-chave: Avaliação de sistemas BRT, simulação de tráfego, perturbações de tráfego, semaforização com detecção de prioridade.

List of Abbreviations

Acronym	**Definition**
BHLS	Bus with High Quality of Service
bphpd	Buses per Hour per Direction
BRT	Bus Rapid Transit
GBRT	Guangzhou Bus Rapid Transit
GDP	Gross Domestic Product
GIS	Geographic Information System
ITPD	Institute for Transportation and Development Policy
LRT	Light Rail Transit
LSS	Lane Support System
pphpd	Passengers per Hour per Direction
PPP	Public Private Partnership
TAZ	Traffic Analysis Zones

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I. Introduction

I.1 Motivation

Nowadays BRT has become a relevant worldwide mass public transportation mode, especially in the developing countries. Those countries which cannot afford the funds to build Light Railway Transit (LRT) tend to turn to Bus Rapid Transit (BRT) systems as a viable alternative. Compared to the conventional bus service, BRT has advantages such as regulated schedule, high capacity and speed.

Furthermore, some BRT systems deployed around the world have already showed its capacity to surpass the transit volume of LRT, such as the Bogota's TransMilenio in Colombia and Guangzhou Bus Rapid Transit (GBRT) in Guangzhou, China. Having GBRT as reference, its peak hour ridership is 27,400 passengers per hour per direction (pphpd) and its peak hour number of buses is 350 buses per hour per direction (bphpd). The success and high level of service of the system derives from a very complex operation management and traffic regulation. The high frequency of services, with values around 350 buses per hour per direction, results on buses passing at some stations every 10 seconds. This high frequency leaves to bus drivers and operators very little maneuver time to work outside the set schedule.

This dissertation intends to take GBRT as research object, which operates in almost unique operational model: an open system formed mainly by direct services. Two different operation stages of each bus line should be analyzed: the operation of the buses inside the BRT corridor, where the system presents dedicated lanes, and the operation outside the corridor mixed with the general traffic, where traffic disturbances may play a decisive role on bus headway stability and the quality of the service provided.

This dissertation intends to analyze in detail the effects of traffic disturbance phenomena in the operation of the BRT system under and open system operational framework. This analysis may provide relevant guidelines to be aware during the planning stage of BRT systems to avoid problems while operation, which may prevent implementations in some cities to be fully successful.

I.2 Research Questions

This dissertation tries to answer to four main research questions:

1. What kind of disturbance that exists in the network that have impacts on the system performance?

2. What measures can be adopted to improve the present condition of GBRT's network?

3. How are the performances of the controlling measures, according to each perspective point of view of the agents of the system?

All this questions will be addressed on the following Chapters of the dissertation, always having in mind that the BRT corridor is not an isolate system, and that interventions in the system may impact also other agents on the urban mobility system.

I.3 Methodology

The methodology of this dissertation is based on four different steps:

- A thorough review of the main BRT systems operating around the world and the discussion of some of the main control mechanism available in the literature to improve BRT operation;
- Collection and processing of the data required for the creation of a traffic simulation model of the GBRT system, and the characterization of different traffic disturbance processes that might occur in urban environments;
- The development of a traffic microsimulation model of the study area that may allow testing different configurations of the system and assess the expected outcomes;
- The assessment of some performance indicators from diverse perspectives of actors that interplay in the study area for different scenarios of control of disturbances of the system, allowing withdrawing conclusions about their impact on the overall system.

The proposed analysis will raise some measures to control disturbances at urban contexts , such as building dedicated corridor for the children and controlling the traffic lights in order to adjust the flow of BRT buses, etc.

I.4 Structure of the Dissertation

In this dissertation we first will review the BRT development all over the world in the past decades and try to identify under what circumstance BRT might be a good mass transport mode for a certain city. The literature review will also include an analysis of the different methodologies that have been used in the three procedures: planning, operating and evaluating.

In case study, Guangzhou BRT system will be presented. In this chapter we first discuss some operational results of the system under evaluation, and then proceed to a process of data collection and processing of the information of the GBRT required for the its simulation.

The following Chapter devotes to the presentation of all the different components of the traffic microsimualtion model developed, and all the mechanisms available in the used software to model public transport operation and traffic control.

Then, the traffic disturbances that could appear along the BRT routes are discussed, presenting its formulation and the modeling approach, using the available tools in the microsimulation model. Considering the characteristics of the BRT in the following part of the chapter we try to model the control plans to the disturbances and also give priority to the buses in the BRT corridor, which is achieved by traffic light preemption.

In the final chapter, the model will be simulated in three types of scenarios: scenario 1, which simulates the network without any control plans; scenario 2, which includes disturbance processes; and scenario 3, which introduces disturbance control and bus preemption in traffic light intersections. The outputs of the three scenarios will be used to compare on different performance indicators that are related to the four agents that are involved in this system: BRT line operator, BRT corridor manager, BRT system client and private car user. Through the comparisons we will be able to withdraw conclusions about the level of controls that is suitable for the system, as well as how the controls will impact the system.

Finally, we will present some conclusions of the developed research and identify the main lines of future research streams linked with the current study.

II. State of the Practice and State of the Art

II.1 State of Practice

II.1.1 BRT Time Lines

The concept of BRT emerged in 1937 in Chicago and some decades later in other US cities as, Washington D.C. in 1956-1959, St. Louis in 1959, and Milwaukee in 1971 (Vincent 2010).

Yet, its real worldwide spreading was after 1970, when the city of Curitiba (Brazil). The concept BRT came into the mayor's mind, aiming to develop a quality public transport system using limited financial resources. This implementation was followed by several Latin American cities. Bogota's TransMilenio, which was developed at 1999, became a world famous system due to its high volume and high-quality mass transit system, providing the backbone of services in one of the region's mega-cities (Hidalgo & Carrigan 2010).

European BRT concept has been more aligned towards priority bus corridors, which does not presents the same service standards in terms of capacity and quality(Heddebaut et al. 2010).

BRT emerged also in 1980 The Brisbane system has matured into a world leader in the past decades (Currie & Delbosc 2010).

In Asia, although BRT has only been developed mainly in Indonesia, India and China in the last decade, it had a rapid growth rate, especially in China. There are 16, 15 and 8 BRT systems being planned or under construction, respectively in India, China and Indonesia. The BRT in Guangzhou was opened in February 2010, having already received the 2nd largest traffic flow per hour per direction (27,000 passengers). This data has surpassed virtually all Chinese subway systems (Fjellstrom 2010).

More recently, BRT has arrived at Africa, where a lack of human and financial resources has historically limited the extent of formal public transport. The conflicts between BRT and former public transit, or BRT and private taxis are much greater than any other region of the world. Fortunately, in 2008, Lagos launched a 'BRT Lite' corridor which, although basic in nature, proved that a form of BRT was possible in Africa. And backed up by 2010 FIFA World Cup, South Africa was able to initiate the BRT service in Johannesburg, Cape Town, and Port Elizabeth (Kaenzig et al. 2010).

II.1.2 Policy Statement

II.1.2.1 North America

Demand for public transportation services is relatively low in the North America, especially when compared with developing country cities. In most metropolitan areas, the public transportation mode share is under 10 per cent.

So in this area, the principle has been rather adopted rapid bus than BRT, which is more expensive, long-construction-period program and has more impacts on private cars.

The Obama Administration has sent mixed signals regarding its support for BRT. On the one hand, the administration has indicated a preference for rail transit, especially streetcars (Vincent 2010). This means BRT will face more competition for federal funding from rail systems, especially streetcars. On the other hand, the Obama Administration has expressed concern about the high cost of rail transit and the deteriorating financial and physical condition of many of the nation's rail transit systems. The maintenance of transit system in America is $78 billion and increasing, of which, 75% is for rail transit.

It still need time to wait for the new policy to come. But it becomes already widely common sense that Congress and the Administration will have to find ways to encourage communities to focus on lower cost alternatives, such as BRT in order to neither slow down the economic recovery nor deteriorate financial and physical condition of the transit system.

The most significant full BRT corridor implemented in the United States as showed in Figure 1 is the Healthline, located in Cleveland, Ohio. The corridor includes 5.7 miles (9.2 km) of exclusive, two lane median busway, with the remainder of the route incorporating kerbside bus lanes or mixed-traffic kerbside lanes.

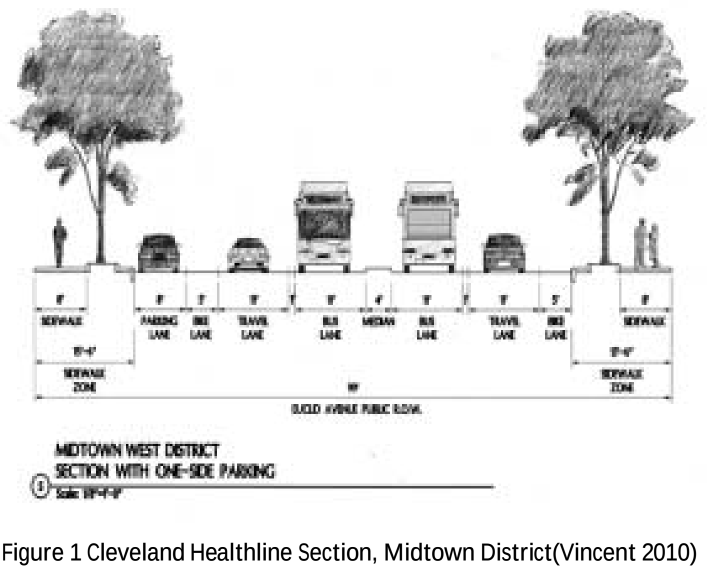


Figure 1 Cleveland Healthline Section, Midtown District(Vincent 2010)

Another relevant BRT project is the Los Angeles Orange Line. The Orange Line is a two-lane, 14-mile (22.5 km), dedicated busway. It was built in an abandoned rail right-of-way and includes thirty-four street intersections, with traffic signal priority, and five mid-block pedestrian crosswalks.

Moreover, as mentioned above, there are dozens of rapid bus lines rather than full BRT system being operated in Washington, DC, New York, Los Angeles, Salt Lake City, Kansas City, Seattle, and Las Vegas.

To support the above rapid bus lines, beginning in 2007, the US federal government began funding a new grant program for public transportation, known as 'Small Starts'. The purpose of the program was to implement a simplified grant-making procedure for projects that require relatively low amounts of capital funding, thus lowering the transaction costs and reducing the approval requirements for such projects.

II.1.2.2 Europe

As discussed above, Bus with a High Level of Service (BHLS), are more popular in Europe than BRT, inspired by the rapid bus lines in North America, although presenting specific features. In Europe, increase in stop-spacing is blocked by the resistance of users – in particular, disabled persons – while it is used by 89 per cent of future American projects planned for 2017 or earlier, (Kantor & Judd 2008). Off board payment, which is rare in Europe, should develop with public awareness of this measure's effectiveness (54 per cent of the projects in USA). Moreover, while long commute times encourage Americans to retain a high number of seats in their vehicles, capacity needs and attempts to reduce costs lead to fewer seats in European vehicles. This design results in a higher proportion of standing passengers whose comfort could only be ensured by special modifications of the bus platform, generating additional costs.

In most European cities, metros, tramways and suburban trains already fulfill the needs of high capacity transit.

BHLS has the same methodology and the same flexible approach as BRT. But another way in sharing the space, as Europe has less highways and narrow urban space. And BHLS in Europe does not in competition with tramway or metro market. Its capacity is between a standard bus and a tramway, as 2000pphpd.

The BHLS concept in Europe can be explained by the necessity to fill the gap between the regular bus and the tramway in terms of performance, cost and capacity.

It can be easily found in the political document that the European authorities encourage this new kind of technology:

"Public passenger transport must provide people attractive alternatives to the private car. [...] The promotion of a Citizens' Network for the development of high quality collective transport of all kinds [...] should make an important contribution in this regard" (European Commission 1996).

"Europe has a capacity for reflection proposal-making and mobilization for the formulation of policies that are decided and implemented locally" (European Commission 2007).

The problems of Europe transportation system today are: a) Decreasing use of public transport. b) Increasing use of car

So the administration and legislation should make public transport as an alternative for car (modal shift). Therefore they have to improve public transport to high quality standards, which came as BHLS.

Nowadays, BHLS can be found in Ireland, France, Spain, Sweden, Finland, Germany, Switzerland, CZ Republic, United Kingdom and Netherlands. And the average ridership change after the BHLS is 72%, which varies from 20% to 134% (Heddebaut et al. 2010).

II.1.2.3 Latin America

Latin America is considered to have the most successful BRT systems in the world.

The infrastructure to support system operations was built through local agencies with local and external (state or national government) funds. Supervision and planning agencies are typically funded with the general budget of the municipality and not transit user fares.

Most of the systems in Latin America have improved the travel conditions and the quality and performance of public transport, particularly with faster, more efficient travel. As efficiency has improved, systems have reduced energy consumption and emissions, showing that this type of system can also present good environmental performance.

Yet, it has been significantly difficult to upgrade the quality of the service with infrastructure improvement and the expansion of the system by raising its fares. Most systems do not have automatic mechanisms to update user fares and there is a lack of integration between traditional services and the newly organized systems.

Nowadays, several Latin American cities have envisaged the introduction of BRT systems, showing the importance and strength of BRT in the region.

II.1.2.4 Australasia

The BRT system in this region has been developing rapidly in the last decades. In a very short period, from 2006 to 2010, the extension of the system has increased 200%, while the ridership has raised 134% (Currie & Delbosc 2010).

Australasia also does not follow the traditional configuration of the routes. SmartBus was developed to lower the levels of fixed right of way infrastructure and emphasize branding and vehicle livery, low cost on-street bus lanes and real time passenger information.

In the next 2 to 3 years, there are already commitments for the expansion of BRT systems in Australasia between 100 km and 200 km of additional routes for the system (around the size of all BRT networks in 2006). Most of this expansion is derived from the Melbourne SmartBus network.

There is already evidence that BRT systems have been more attractive than rail in the past few years. However, it seems unlikely to retain this status in forward plans. A debate is underway within Australian cities regarding the relative merits of Light Rail Transit (LRT) and BRT. It remains open the question if the relative cost-effectiveness and ridership performance will influence system development outcomes into the future.

II.1.2.5 Asia

BRT adoption in Asian developing countries has been very strong in recent years. Currently, 12 systems are under operation in China in 2011, 51 systems are being constructed or planned (30% in India), and there significant support from national policies and funding for BRT development.

Public transportation had not played in the last decades a main concern for the government of Indonesia, leading to a severe declining of these systems. BRT was able to invert this situation more recently, bring public transportation into the center of the political agenda. Yet, as Indonesia is a less developed country, the system requires large subsidies to fund operational and investment costs, which limits the expansion of the system. One of the key problems of the operation of existent systems is the passengers' safety. Furthermore, there is no clear priority for the buses, which is the key feature of BRT. There is still a long way to go until the consolidation of BRT system in Indonesia (Ernst & Sutomo 2010).

As in Indonesia, India, does also present a low performance of public transport systems. As stated above, India government has showed a strong interest in BRT systems, where it is expected to have 18 BRT systems operating in the following years (2 under operating and 16 under planning or constructing up to 2008). Yet, there are evidences that the government has misevaluated some projects. In some cities, where the demands of the system are less than 2,000 passengers per hour per direction (pphpd), the main focus should be on the improvement of the operation of the existing bus systems, rather than invest approximately Rs 1–1.5 billion per km for development of new BRT corridors (Tiwari & Jain 2010).

In China, because the government policy has a very strict regulation on the subway system construction, many cities have moved into the adoption of BRT solutions. Only in 6 years, 12 BRT systems were built in 12 cities. Moreover, the government is investing on the optimization of the public transport system. The example with greater success in China is the Guangzhou BRT. There are 7 bus companies who run the BRT system, coordinated by a management company, which is responsible for the operation.

II.1.2.6 Africa

The BRT systems deployed in Africa have some specific features. Africa is often depicted as a poor but with fastest urbanizing continent, where private car ownership is rather low and there is a significant latent demand for public transport. However, most of the transit services are provided by the private sector, with extremely poor level of service. This fact generates additional problems to the authorities when they want to improve the public transit service. Due to the huge gap existent in the operation of conventional buses to BRT systems, there is a significant political resistance to promote these high efficiency systems. The government of Lagos in Nigeria and Johannesburg in South Africa adopted were the first cities in Africa to dare this huge change on the organization of the public transport system, facing huge opposition of the incumbent private transit sector. In the case of the city of Johannesburg, the city made a political commitment to incorporate the minibus taxi industry into the new system, leading to a successful implementation of the system that was able to coexist with the previous supply. Encouraged by these two successful systems, BRT projects have been emerging across the continent. As more successful case studies pop-up, there will be greater political support to endorse these projects make their projects a reality. (Gautier & Weinstock 2010).

II.1.3 Adopting Conditions

In terms of system design and operation, two types of BRT system have been deployed around the world: closed system and open system. In a closed system, buses run on a dedicated corridor without being affected by other traffic, presenting normally in intersections priority controlled by traffic lights. The system requires a planned feeder service from density of demand, hence where it is not financially feasible to provide trunk services. In an open system, existing bus services are upgraded by providing dedicated lanes for the movement of buses in congested areas. Open systems are thus flexible and easily adapt to existing bus routes and movement patterns. Buses can leave and enter the corridor at intersections, thereby reducing the number of interchanges required in the case of a closed system.

Here are some examples of the successful BRT systems worldwide.

II.1.3.1 Closed Systems

II.1.3.1.1 <u>Bogotá</u>

Bogotá is the capital city of Colombia, presenting currently the best perform BRT project in the world: the TransMilenio. The city has 6,441,801 inhabitants, presenting a very high population density of 9,629 persons per square mile (3,718 persons per square kilometers). Most of the urban area is flat, with some development in hilly areas in the southern and eastern parts of the city (Federal Transit Administration 2006).

Bogotá has an average household size of 4.7 members, while the average household income is much lower than in developed world cities. Table 1 show that 44 percent of city households have an average income of US$5.9 per day or less, and 43 percent has an income of US$11.4 per day. 80 % of the population does not have access to a car. Public transit and walking are the main two travel modes.

Table 1 Average Household Income(Hidalgo & Carrigan 2010)

Stratum (Av. Income)	% of Population
1 (US$4.2/day)	7%
2 (US$5.9/day)	37%
3 (US$11.4/day)	43%
4 (US$24.1/day)	7%
5 (US$39.2/day)	3%
6 (US$62.3/day)	2%

There are around 21,000 registered urban public transit vehicles and around 9,000 illegal vehicles. Urban routes are provided by 64 different private entities. The traditional system is very inefficient, with bus occupancy between 60 percent and 75 percent in peak periods, and 25 percent and 40 percent in off-peak periods. Traditional system productivity is also very low, with an average of only 2.4 passengers per kilometer. Furthermore, the national government did not have the necessary funds to build a subway system.

Bogotá adopted a traditional BRT closed system. The routes are showed in Figure 2. The TransMilenio has been developed in two phases. The first three trunk busways corridors are on Caracas Avenue, Autopista Norte and Calle 80. The other three busways are on the Suba, NQS, and Americas corridors.

Figure 2 The TransMilenio Network (Federal Transit Administration 2006)

Table 2 presents some data from the infrastructure costs of Phase I and II of the project, where an increase of the cost from Phase I to Phase II can be observed. The average cost of Phase I is $5.9M per km ($9.4M per mile). The average costs of Phase II range from $9.0M to $15.9M ($14.4M to $25.5M per mile).

On the first day of operation (December 18, 2000), the system carried 19,000 people. Ridership steadily grew throughout 2001 and 2002, and by October 2002 the system was carrying around 770,000 passengers per day. In May 2003, weekday ridership on the Phase I system was estimated at 792,000. When the first part of the Phase II busway opened in late 2003, ridership rose to over 900,000 passengers per day. Ridership surpassed 1,050,000 passengers per day (January 2006) and is expected to rise to 1.4 million passengers per day once Phase II is fully operational. Figure 3 tracks mode share from 1998 to 2005 (Federal Transit Administration 2006).

Table 2 Construction Phases of The TransMilenio (Federal Transit Administration 2006)

	Phase I	Phase II		
		Americas	NQS*	Suba*
Length (dedicated busway)	41 km (25.6 miles)	13 km (8.1 miles)	18 km (11.2 miles)	10 km (6.2 miles)
Busway lanes per direction	1 / 2	2	1	1
Feeder network coverage	7 zones (309 km / 192 miles)	7 zones (509 km / 316 miles)		
Terminal stations	4	1	1	1
Intermediate stations	4	1	1	0
Standard stations	53	16	21	13
Pedestrian overpasses	30	10	25	4
Buses	470 articulated (trunk) 235 conventional (feeder)	+335 articulated (trunk) +200 conventional (feeder)		
Expected date of commissioning	Different sections opened between 2000 and 2002	Opened 2003/2004	North: 2005 South: 2006	Expected 2006
Cost ($US)**	$240M	$117M	$286M	$142M
Funding sources	Local Fuel Surcharge (46%) Local General funds (28%) World Bank Loan (6%) National Government (20%)	Local Fuel Surcharge (34%) National Government (66%)		

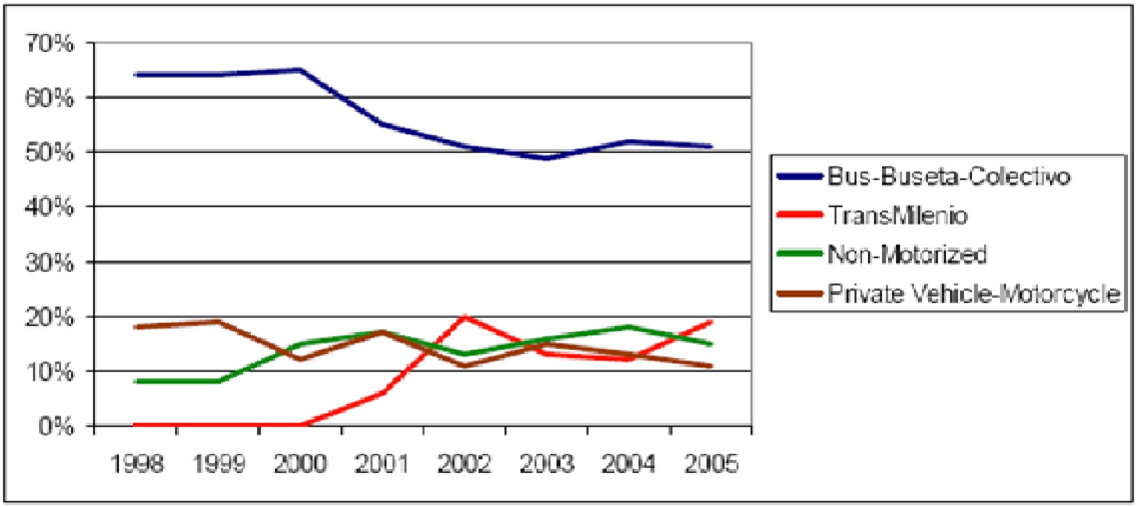


Figure 3 Mode Split from 1998 to 2005 in Bogotá (Federal Transit Administration 2006)

II.1.3.1.2 Curitiba

Curitiba has the first full BRT project in the world. Although Curitiba has a relatively small population of 1.8 million, the population density is bigger than Bogotá, about 4,200 inhabitants per square kilometer. According to the city's official website, the metropolitan region includes 25 municipalities having a total population of 2.42 million. Therefore, 38 percent of the metropolitan-area population is housed outside of Curitiba.

However, unlike Bogotá, the private car ownership rate is the highest in Brazil with almost 400 cars registered per 1,000 inhabitants.

The GDP of the city is R$ 32,153,307,000 (2006) ($20,443,073,085), while the per capita income for the city was R$ 17,977 (2006) ($11,430). From the above data, we can see that the life standard in Curitiba is higher than in Bogotá. But As typical in Brazil, lower-income workers live primarily in outlying areas and account for a large share of transit passengers. Employment was concentrated in two centers: retailing in the historic downtown, and industrial development in the Cidade Industrial de Curitiba, about 3 km away (Wikipedia 2011a). Curitiba is the only city in Brazil that has directed its growth by integrating urban transportation, land-use development and environmental preservation.

The city did also abort the plans for implementing LRT, mainly due to LRT's high capital costs and a successful implementation of a closed BRT system. But unlike Bogotá, with many years development, Curitiba managed to combine its closed BRT system with some direct lines where no transfer is required.

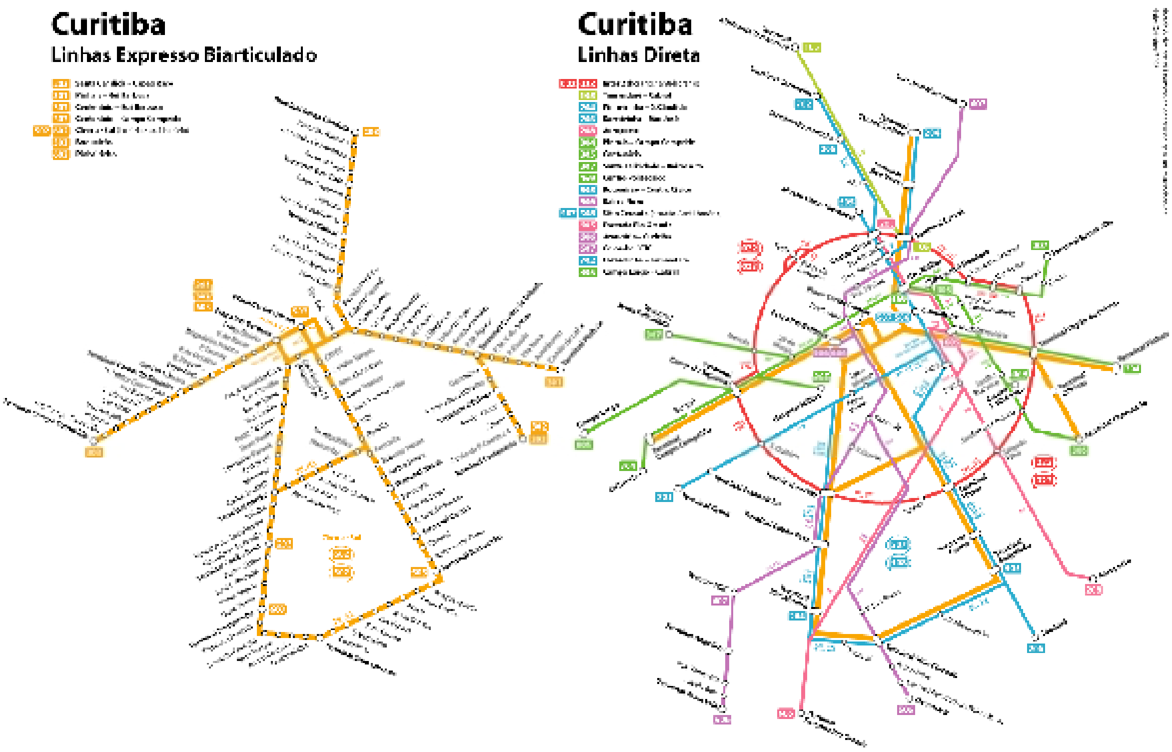


Figure 4 Curitiba BRT Network(Lindau, Luis António et al. 2010)

II.1.3.2 Open Systems

II.1.3.2.1 Guangzhou

Guangzhou is the capital city of Guangdong Province in southeast China. The population of Guangzhou is above 10 million (2008). The population density is about 1,351 inhabitants per square kilometer, which is much less than in Bogotá and Curitiba. Yet, the city presents a great variance in density from district to district. The highest population density in Yingxiu District, where most of the BRT lines are implemented, presenting values of 30,364 inhabitants per square kilometer(Wikipedia 2011b).

The public traffic flow in Guangzhou is about 6.6 million per day, being70% of the flow performed using the public bus service. It is worth mentioning that Guangzhou is the first city of China that can be considered as a developed city. The GDP of that city was ¥1,060,448,000,000 ($721,132 million) and the per capita income for the city was ¥103,278 ($15,257).

ITPD China took part in the design of the BRT system in Guangzhou, where the decision over the system operation configuration played the key decision in the planning process. At last, after comparing each plan they choose the open system.

Table 3 Indicators Used to Compared the Two Services (Source: Guangzhou Daily Newspaper)

	Indicator	Trunk and Feeder	Closed Corridor + Flexible circuits
1	Capacity	About 45,000 per hour per direction	About 3,5000 per hour per direction
2	Infrastructure	Needs large transit platform station of 250,000 m2 and many other small feeder stations	Doesn't need large transit platform station and other new feeder station
3	Vehicle	Needs 140 18m-buses in the Trunk part and 450 conventional buses in the feeder part	Needs 266 18-m buses
4	Reliability	Good: Buses will only running in the dedicated lane and have no negative influence by the traffic condition outside of the corridor	Bad: When the buses are running out of the corridor they will be influenced by the other vehicles
5	Transfer Efficiency	Small: It will save 2.8 minutes per person per time	Big: It will save 7.8 minutes per person per time
6	Impacts on the outside	None: The whole corridor is closed to the outside traffic	Relatively big: When the buses are running outside of the corridor, its big body(18m) will have some influences on the traffic
7	Impacts within the corridor itself	Because it needs lots of feeder buses, the Interference between each other will be big	No feeder buses need and small number of buses makes it more convenient inside the corridor
8	Impacts on the conventional bus service	Big: On one hand, because the BRT needs dedicated lanes, the bus companies must largely reduce the number of conventional buses in order to keep the traffic not getting worse; on the other hand, because it needs lots of feeder buses for transferring the bus companies have to changes their previous routes to the feeder routes	Small: Most of the conventional buses only need to change its vehicles and keep the rest such as routes and number as the same as they used to be
9	Impacts on the passengers	80% need to transfer	No need to transfer
10	Impacts on the bus company	At least to adjust 23 bus lines, which will impact the revenue of bus companies	Although need large investment at the beginning but the operation right of routes are not replaced
11	Revenue stream	Revenue stream is simple and no need to split	Because lots of the lines are operated together in the same corridor it's very complicated to split the revenue to different companies

As showed below, GBRT is relatively more concentrated in the same region, around Zhongshan Road. Zhongshan Road is the most important and busiest street connected east-west Guangzhou, like Changan Street in Beijing. Moreover, along with Zhongshan Road, also located the biggest residential districts and CBDs, they are the stations where the largest number has been recorded. Before BRT was set up, the road always suffered extremely heavy traffic jams. The high travel demand of the area, along with the lack of a subway system, allowed the GBRT becoming very competitive.

Figure 5 Guangzhou BRT Network (Source from Google Search Maps)

II.1.4 Summary of the BRT experience around the world

In this section, a brief summary of the BRT systems under operation, construction or planning around the world is presented. The data of the figures is generated from Wikipedia and articles about the BRT Built Environment Special Issue.

Table 4 Existing Fully BRT Systems

EXISTING FULLY BRT SYSTEMS	COUNTRY	NUMBER	TYPE	PERFORMANCE*
Africa	South Africa	3	Closed	Good
Australasia	Australia	8	7 Closed and 1 open	Good
	New Zealand	1	Closed	Good
Asia	China	12	10 closed and 2 open	Medium (Guangzhou has very good performance)
	India	3	1 closed and 2 open	Poor
	Indonesia	9	Closed	Poor
North America	United States	2	Closed	Good
South America	Ecuador	2	Closed	Good

EXISTING FULLY BRT SYSTEMS	COUNTRY	NUMBER	TYPE	PERFORMANCE*
	Colombia	1	Closed	Good
	México	3	Closed	Good
	Brazil	2	1 Closed and 1 open	Good
	Chile	1	Closed	Good

Table 5 Existing Un-fully BRT Systems

COUNTRY	NUMBER	PERFORMANCE*
Nigeria	1	Good
United States	7	Good
Ireland	1	Good (significant ridership change after construction)
France		
Spain		
Sweden		
Finland		
Germany		
Switzerland		
CZ Republic		
United Kingdom		
Netherlands		

Table 6 Planning or Under Construction BRT Systems

PLANING OR UNDER CONSTRUCTION BRT SYSTEMS	COUTRY	NUMBER
Africa	Tanzania	1
	Ghana	1
	Kenya	1
	Uganda	1
	South Africa	7
Australasia	NONE	
Asia	China	8
	India	15
	Indonesia	5

* The evaluations of the performances are listed based on the contents of the references as following: (Hidalgo & Carrigan 2010)(Vincent 2010) (Heddebaut et al. 2010) (Fjellstrom 2010) (Kaenzig et al. 2010) (Currie & Delbosc 2010) (Ernst & Sutomo 2010) (Tiwari & Jain 2010) (Gautier & Weinstock 2010)

Table 7 presents a summary of some of the characteristics of the cities where BRT systems were implemented. From this data, concluded that when a city's population reaches at half a million or the population density reaches 2,000 per square kilometers, it is very possible to adopt BRT system, even if the city is low income areas, such as Delhi, Jakarta and Bogotá. Furthermore, this type of transit system showed to be even more suitable for those cities, which may not consider LRT as a solution due to its high investment costs to present similar performance levels. This might not be the only one selection criteria, because there are some BRT projects operated in some region of certain cities where population density in that region is very high but the average population density is low in the city (such as Lagos in Nigeria)., where those projects proved to be also very successful. Further development is required in the extension of this dissertation.

Table 7 Summary of BRT Related Condition of Some Cities (Sources from Wikipedia and Internet)

Case studies	Cleveland, USA	Los Angeles, USA	Curitiba, Brazil	Bogotá, Colombia
Population	0.40 million	3.8 million	1.8 million	6.4 million
Population Density	2,381/km²	3,041/km²	4,200/km²	3,718/km²
GDP per Capital	$14,291	$16,535	$11,430 (Lack of data in 1970)	$3,300 (in 1999 before TransMilenio was operated)
Case studies	Jakarta, Indonesia	Delhi, India	Brisbane, Australia	Sydney, Australia
Population	9.58 million	16.75 million	2 million	4.58 million
Population Density	14,464/km²	9,294/km²	918/km²	2,058/km²
GDP per Capital	$3,400	$2400	$39,900	$58,300
Case studies	Quito, Ecuador	Guangzhou, China	Johannesburg, South Africa	Cape Town, South Africa
Population	1.84 million	12 million	3.89 million	3.50 million
Population Density	437/km²	1,351/km²	2,364/km²	1,424/km²
GDP per Capital	$8,022	$15,257	$13,000	$14,370

Table 8 summarizes the quantitative parameters of some BRT systems from ITPD-China (http://www.chinabrt.org/defaulten.aspx).

Table 8 Summary of quantitative parameters of some BRT systems (Sources from ITDP-China)

City	peak pphpd	peak hour speed(km/h)	peak bphpd	average bus occupancy(%)	length of dedicated busway(km)	operation mode	infrastructure cost($ million)
Amsterdam	960	34	18	53	44.5	trunk-feeder	2.4
Bangkok	1000	15	14	71	6.6	trunk-feeder	-
Beijing	3800	21	50	76	34.5	trunk-feeder	4.8
Bogota	30500	23	310	98	84	trunk-feeder	18.6
Brisbane	6500	29	175	37	19.3	open	30
Changzhou	7400	18	77	96	41	direct-service	4
Chongqing	600	31	16	38	6	trunk-feeder	-
Dalian	5800	24	75	77	9	direct-service	2.6
Guangzhou	27400	18	350	78	22.5	direct-service	4.4
Guayaquil	6700	2	-		29.1	hybrid	2.2
Hangzhou	6800	14	67	101	18.8	direct-service	-
Hefei	2900	16	60	48	12.7	direct-service	-

City	peak pphpd	peak hour speed(km/h)	peak bphpd	average bus occupancy(%)	length of dedicated busway(km)	operation mode	infrastructure cost($ million)
Jakarta	3000	20	40	75	119	trunk-feeder	1
Jinan	3300	14	40	83	34.4	trunk-feeder	-
Kunming	3500	14	120	29	46.7	open	1
Lima	13950	25	101	138	27.1	trunk-feeder	262
Mexico City	9000	18	60	150	66	trunk-feeder	-
Nagoya	750	21	13	58	6.7	direct-service	-
Nantes	2100	21	17	124	6.2	trunk-feeder	50
Quito	6000	-	60	100	37	trunk-feeder	-
Seoul	8400	16	210	40	43	open	1.2
Xiamen	7900	27	90	88	48.9	direct-service	-
Zaozhuang	700	30	27	26	33	trunk-feeder	-
Zhengzhou	5600	17	52	108	26.6	direct-service	-

II.2 State of Art

There are no official documents or policies about the standard of building BRT systems. But according to all of the successful BRT cases around the world, when the public transit service of a city needs to be improved and conventional bus service cannot solve the problem, besides, the funding cannot support the plan of LRT, BRT may be the best choice.

The routes should be chose based on the former conventional bus routes. The districts which suffer the worst traffic condition should be the priority consideration.

At the very beginning, the decision should be made very wise. A successful BRT system cannot be separated from those factors as accountability, commitment, strong political will, structured institutions, and fundamentally, a decisive leadership.

II.2.1 Planning

II.2.1.1 Funding

Nowadays the authorities of many cities tend to turn their attention to BRT rather than LRT. One of the main reasons is lack of funding. Therefore, BRT is very appropriate for PPP.

Public–private partnership (PPP) describes a government service or private business venture which is funded and operated through a partnership of government and one or more private sector companies.

BRT systems offer important gains in terms of sustainability over more conventional bus systems. There is evidence indicating they also contribute for increasing the performance of transit systems under an investment context that is compatible to the budgetary and financial constraints of cities in the developing world (Lindau, L. A. et al. 2008).

PPP and other forms of Public–Private Partnerships represent an opportunity for advance as they introduce economical and financial sustainability elements to BRT projects. The share of risk can guarantee the consistency of the funding. They offer the possibility of reducing the dependency of scarce public budgets to implement projects of public interest.

II.2.1.2 Dedicated lanes

It is very common to find the dedicated lanes of BRT systems are set up in the central lanes of the road as showed below.

Figure 6 Dedicated Lanes of BRT (Source from Google Search Map)

However, there are some cases that the former transit systems of some cities do not have the space required for additional infrastructure. Ward et al. (2006) mentioned that using dedicated bus shoulders is a key method to solve the problem. Yet, it may cause another problem: narrow width of the bus shoulder and the need to anticipate traffic hazards in the adjacent lane can both be significant stress factors for bus drivers. Driver stress in response to these conditions should be a significant concern for transit operators, not only because the potential impairment of driving performance might jeopardize BRT objectives, but also because the long-term effects of this occupational stress may become a health-risk factor for the bus drivers who staff the BRT services.

Figure 7 Dedicated Bus Shoulders (Source from Google Search Map)

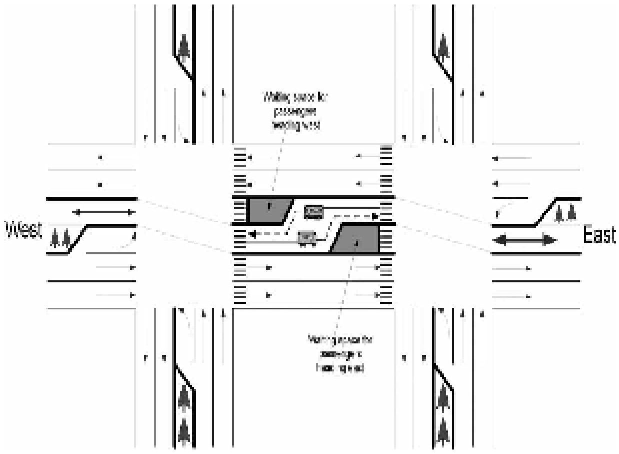


Figure 8 One-Dedicated-Lane BRT (Source: (Tsao et al. 2009))

The potential role of a prototype lane support system (LSS) such as 'lateral warning' and 'lane assist' systems to support vehicle control within the narrow shoulder boundaries with the information needs and context of the bus driving environment (Alexander et al. 2004).

Another solution was proposed by (Tsao et al. 2009). They proposed a concept of a one-dedicated-lane BRT. They proposed several designs according to different situation. One of them is showed in Figure 8. Based on a times pace diagram, they studied the deterministic relationships among the bus travel speed, headway of bus operations, distance between two neighboring crossing stations, and the number of crossing stations needed for the entire system. Furthermore, it turned out that the proposed concept is feasible and can achieve good operational performance. This model is especially suitable for the busy commute corridors in many developed counties that have sufficient right-of-way but do not have sufficient demand to warrant dedication of two mixed-use lanes to public transportation.

II.2.1.3 Operating Mode

As discussed above, there are two modes of BRT systems: Close systems and Open systems (see Figure 9).

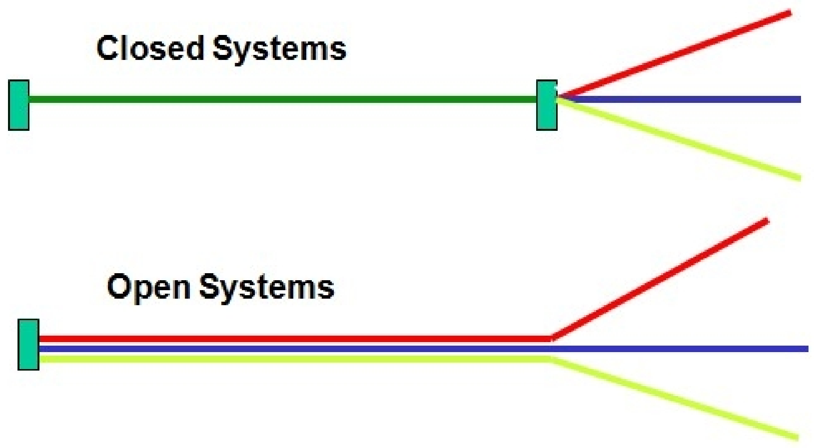


Figure 9 Examples of Closed Systems and Open Systems (Sources from Google Search Map)

Closed systems mainly provide one route of end-to-end service. And all other routes require transferring. Open systems lets other routes inside the system, promoting the need of less transfers for passengers. Regardless type of operating system, BRT operation can be formulated into two different types of services:

- *Trunk-Feeder*: This kind of service uses conventional buses in the feeder lines and uses larger buses in the trunk lines. Passengers must transfer between the trunk and feeder lines. This service is the backbone of closed systems.
- *Direct Service*: Services that reduce the need of transfers, having direct connections to areas outside the main BRT corridor, reducing the need of feeder services. It is very common to find Direct Service in an open BRT system.

The following table summarizes the main differences of both types of services.

Table 9 Difference between Closed System and Open System

Indicator	Trunk-Feeder	Direct Service
Travel Time	Time is wasted during the transfer period, but the trunk lines offer the buses higher speed than the latter service.	No time is wasted during the transfer period, but lower speed is found during the travel.
Operation Efficiency	Supply and demand can be easily adjusted to the optimal condition, even the population density differs largely between the trunk area and feeder area.	When population density differs largely from region to region it may bring the inefficient performances.
Infrastructure	Needs large stations for transferring	No transfer station is needed
Vehicle Type	Dedicated buses in the trunk lines and conventional buses in the feeder lines.	No special standard requested.
Capacity	Larger capacity than Direct Service	Less capacity
Public Acceptance	Easier for the passengers to understand the network, although providing low number of direct services	It may cause misunderstand to the passengers due to its complicated network, but enlarges significantly the number of direct connections for users

The *Trunk-Feeder* may be more effective under the following conditions:

- Higher transit demand around the trunk area.
- Population density differs largely from region to region in the city.
- The distance between the city center and feeder lines is more than 10 kilometers.

There is not absolutely optimal scheme. Each city has its own best-performance system according to different contexts. Sometimes the engineers may combine the two services together and develop a suitable system for a certain city.

II.2.2 Operation

This section devotes to the operation schemes available in the literature that allow optimized feeder routes and the coordination of the system.

In most previous studies, routes and schedules are developed independently so as to avoid complex mathematical formulations and computational burden. Most of the researchers have developed routes from a given initial skeleton using a heuristic approach, such as by insertion of nodes in the base network. Shrivastava & O'Mahony successfully attempted schedule coordination problem using genetic algorithms (Gas [1]). Shrivastava & O'Mahony (2006)) managed to develop a model using GAs for the Dun Laoghaire Dublin area rapid transit (DART).

The main procedure of development is showed below.

[1] A genetic algorithm (GA) is a search heuristic that mimics the process of natural evolution. This heuristic is routinely used to generate useful solutions to optimization and search problems. Genetic algorithms belong to the larger class of evolutionary algorithms (EA), which generate solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover.

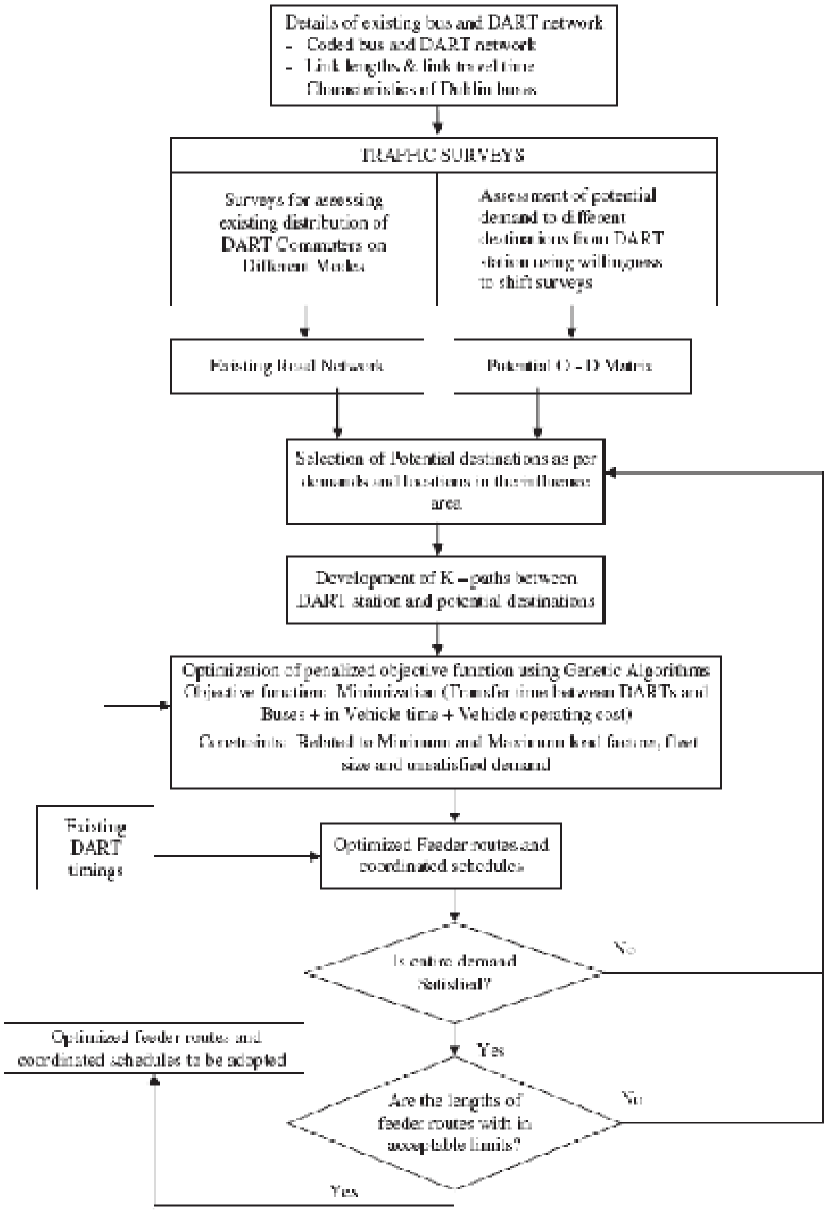


Figure 10 Procedure of the Model by Shrivastava & O'Mahony (2006)

Abdelghany et al. (2007) developed a model to support the evaluation and planning of Bus Rapid Transit (BRT) services in urban transportation networks.

The model framework is a generalization of the approach underlying the dynamic traffic assignment-simulation modeling framework (DYNASMART-P) simulation-assignment model for operational planning applications (Jayakrishnan 1994). The implementation is a major re-engineered extension of the capabilities of the methodology to include transit and intermodal simulation-assignment capabilities (Abdelghany, AF 2001; Abdelghany, KFM 2001; Mahmassani 2003) The model captures explicitly the dynamic interactions between travelers' mode and route decisions, and the resulting evolution of the network conditions. It determines the time-dependent assignment of travelers to the different mode-routes in the network, including the corresponding arc flows and transit vehicle loadings.

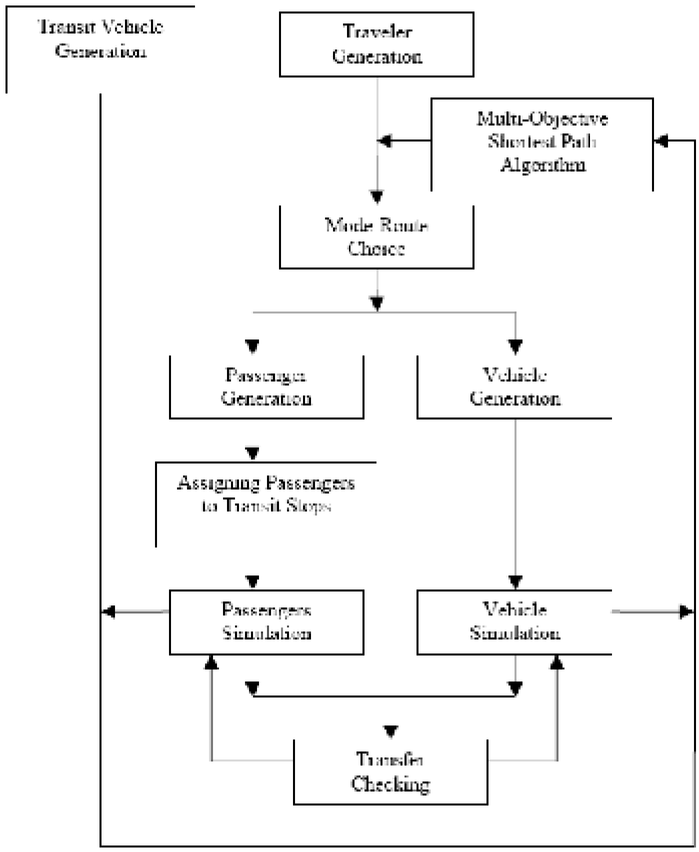


Figure 11 Procedure of Dynamic Intermodal Assignment-Simulation Methodology (Abdelghany et al. 2007)

The model have a demand input a file listing the population of travelers, their attributes and travel plans including origins, destinations, and time of departure and mode choice if known. Yet, the problem could be also inputted as an OD matrix of the travelers. Each generated traveler is then assigned a set of attributes, which include their trip starting time, generation link, final destination and a distinct identification number. Each traveler is also assigned a list of attributes to describe their preferences in choosing their best travel option. These attributes are randomly generated from distributions representing the travelers' population preferences for the traveler's origin zone.

The model allows representation of complete transit networks, with both exclusive and shared infrastructure. A set of bus lines is defined in terms of the constituent routes, for which the average headway, stop locations, and vehicle capacities are specified. Different bus capacities may be specified for the different routes. Given a timetable, buses are generated from their origin terminals and moved in the network along their pre-specified routes following prevailing traffic conditions. The model tracks all buses along their routes and records their respective arrival times at each stop. The model is also capable of simulating special bus services such as express service with limited stops and bus services with different deadheading strategies in which some stops could be skipped under certain conditions. Prevailing travel times on each link are estimated using a vehicle simulation component, which moves vehicles capturing the interaction between autos and transit vehicles. If separate transit lanes exist, transit vehicles move on these exclusive lanes according to their prevailing speeds with no interaction with the automobile traffic.

These operational characteristics of this model include lane separation, limited stops and passenger walking distances, and bus preemption.

Furthermore, the model can have different types of lanes. A dedicated BRT lane is only for the BRT vehicles to drive on. Otherwise, BRT vehicles, as well as the other vehicles are assigned to the lanes considering the next turning maneuver, which is extracted from their respective paths. And for each direction of the turns, the vehicles are assigned to the respective lane. Every time step, the number of vehicles on each lane is calculated using conservation principles; numbers in each class of vehicles in the traffic mix are kept separately.

Moreover, the inflow and outflow constraints bound the total number of vehicles from all approaches that can be accepted by the receiving lane, which reflects both physical storage consideration and inflow throughput capacity.

The model is designed to allow buses to stop only at stops specified in their routes. If a stop is to be skipped along any transit line, this stop is removed from the list of stops for this line. During simulation, if a bus reaches a stop, a check is made to see if there are any passengers waiting at this stop. Based on the number of passengers and the average passenger dwell time at this stop, the expected stopping interval at the bus stop is determined (10 seconds + (number of waiting passengers + average passenger dwell time)). The 10 seconds represent the time required for bus deceleration, acceleration and doors opening and closing. The bus is explicitly held at this stop for the calculated interval. The expected stopping time at each stop is also passed to the shortest path algorithm to determine the expected travel time for each transit line.

If a passenger is generated on one of the links of the starting transit line, the closest bus stop to the traveler generation location is determined and the passenger walking distance is calculated as the difference between the traveler generation location and the stop location (both are measured as distance from downstream intersection). If a traveler is generated on one of the inbound links to a link that is served by a transit line, the walking distance is calculated as the sum of the traveler distance to the downstream node of the generation location plus the distance between the upstream node of the next link and first non-skipped stop on the next link.

Yield signs, stop signs and signal controls can be provided in this model. The logic of the model is that the green time for a given phase is first determined based on the number of vehicles that would have reached the intersection at the end of the current simulation interval (in the absence of a queue).If a bus is detected on any of the approaches served during the current phase, the green time required to release this bus from the approach is also calculated. If the extension required for the bus is greater than the extension required to accommodate all vehicles that would have reached the stop line, the green time for this phase is extended unless the maximum green value is reached. In other words, the extension is still within the allowable maximum green time for that phase, and no exception is made for the bus.

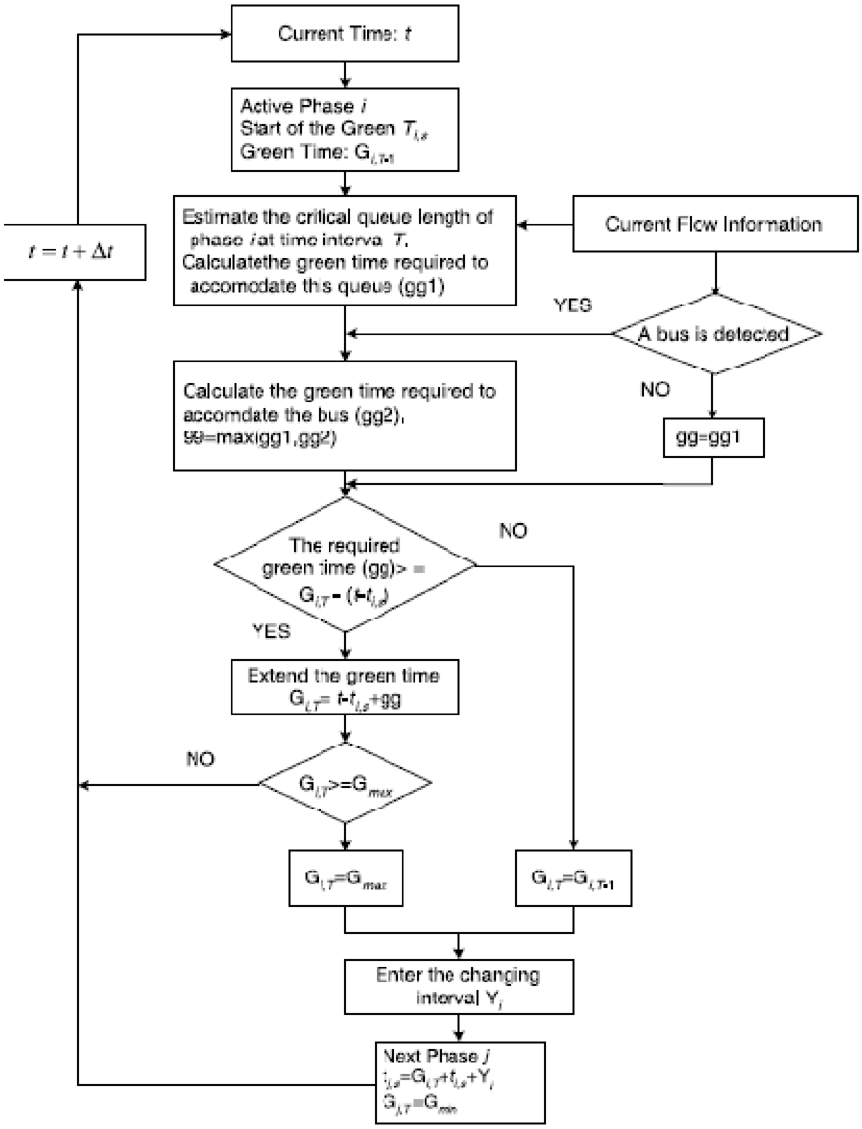


Figure 12 Procedure of Bus Preemption (Abdelghany et al. 2007)

II.2.3 Evaluation

In the recent years most of the BRT projects are mainly evaluated based on the following aspects: travel time, ridership, capital costs, operating cost efficiency, commercial speed, urban development and environmental quality.

The following sections present a brief review of these concepts and how they are evaluated in BRT systems.

II.2.3.1 Travel Time

Great travel time savings are expected with the implementation of a good BRT system. Several studies that travel time savings tend to be greater for people in the lower income groups. In the case of Bogota for instance, studies found savings of 18 minutes for the lowest income stratum, compared to 10 minutes for the people in the highest income stratum (Federal Transit Administration 2006). This fact is due to the location of the lowest income areas, which are congregated on the city periphery, typically enduring the longest distances to access the city's centrally located trip attractors. Travel time reductions were greatest for these longer trips. Travel time savings appear to be central to public acceptance of the service – 83 percent stated that time savings were the main reason for using TransMilenio, and 37 percent stated that they spend more time with their families as a result of the faster commute.

II.2.3.2 Ridership

BRT projects can serve a capacity of 20,000 to 25,000 pphpd, depending on the geometry.

Normally, the system performance is closely linked with the system ridership, which should present an increasing annual trend, and if possible, induce a significant shift from private modes to public transit.

II.2.3.3 Capital Cost Effectiveness

Usually the capital costs are divided by the total length of the system and that is cost per km. And the passengers per day per capital cost are obtained from the capital cost divided by the passengers per day. The evaluation is usually made based on these two parameters.

Table 10 presents some data collections of ridership and capital cost of the cities around the world.

Among those cities some have very high ridership but very low construction cost. Some cities have low ridership but very high construction cost. The last column of

Table 10 is the Cost-Ridership ratio of those systems. From this column it can be concluded that the systems in Seoul and Guangzhou have the best efficiency while Brisbane, Ottawa and Beijing have the worst ones.

Table 10 Collected Information of Some BRT Cases around the world (Sources from Wikipedia)

City	Ridership (pphpd)	Cost per km ($ million/km)	Cost-Ridership ratio ($/(km.pphpd))
Bogotá	43,000	11.25	262
Johannesburg	16,000	5.5	344
Sydney L-P Transit way	14,000	11.3	807
Delhi	13,500	3.2	237
Guangzhou	26,900	4.57	170
Brisbane South East	16,800	27.6	1.643
Ottawa	10,000	15.4	1.540
São Paulo	18,000	7.48	416
Curitiba	18,000	6.25	347
Seoul	8,400	1	119
Jakarta	4,000	1	250
Beijing	3,800	4.8	1.263

II.2.3.4 Operating Cost Efficiency

The revenues of the system are obtained mainly from the high fare collection (much more ridership than conventional buses). The system's profitability can be explained by higher productivity levels. This high productivity is achieved through high bus frequency on dedicated busways unaffected by traffic congestion; efficient boarding/alighting due to well designed stations; vehicles with multiple doors and off-board fare payment; and the high capacity of the articulated buses Hidalgo states that two additional factors are also responsible for this high productivity: the ability for local and express services to share the same infrastructure and, centralized control, which reduces bunching and improves reliability (Hidalgo, 2008).

Take Bogota for instance, the ridership of system in 2006 is measured at 1,050,000 passengers per day, with up to 41,000 passengers per hour per direction on the busy sections. And the daily revenue is estimated at US$572,727. Of this, US$113.4M (66%) was paid to the trunk line operators, US$34.4M (20%) was paid to feeder bus operators, US$17.2M (10%) to fare collectors, and US$6.9M (4%) to TransMilenio, to cover system management and administration. No subsidize need at all.

II.2.3.5 Transit-Supportive Land Development

BRT projects in the developing countries have facilitated urban renewal and economic growth within the city, following the same trend as LRT systems. The upgrade of road infrastructure has enhanced in several cities land use integration and the promotion of more sustainable transport modes, as the construction of bikeways, public areas construction (walkways, green space, road dividers, sidewalks), improved maintenance of public areas, busway construction, new roads and secondary network construction, and real estate maintenance and rehabilitation. Moreover, BRT may also have impacts on the land use around the corridors and the stations.

BRT projects, as other heavy public transport infrastructure, have proved to have impacts on real estate prices inside the influence area. Rodriguez et al. (2009) used a panel hedonic price model in 2009 to determine the property value impacts on properties already served by the transit system caused by extensions to Bogotá's bus rapid transit system.

The results of their study support BRTs ability to attract dense development that will in turn enhance the BRT system in the future. The capitalization of accessibility benefits stimulates development by enhancing the attractiveness of parcels for development or redevelopment. Parcels that were not previously considered prime candidates for real estate investment appear more attractive after the transportation investment is announced or implemented. Alternatively, a parcel already developed or in the planning stages may be developed more intensely as a result of the increase in values.

In addition to the transit-oriented development potential instigated by the BRT network investments, land value increases are also relevant to municipal finances and project-specific financing. The success of local instruments such as tax increment financing and value capture hinges on the land value and related development changes associated with the project. By determining the capitalization of positive network expansion effects, the localized evidence from this study provides tools for exploring the usefulness of innovative land-based tax instruments that apply to areas benefiting from network extensions. The results are expected to inform local transportation planners and policy-makers about the potential of public funding tools for transit infrastructure, such as value capture (Rodriguez & Mojica 2009).

"Value capture represents an alternative approach of capital cost recovery that has not been fully explored and examined for funding mass transit investments. With BRT extensions and rail investments planned over the next decade for Bogotá, the network benefits quantified provide a basis for a broader and more nuanced conceptualization of the land value impacts of mass transit investments."(Rodriguez & Mojica 2009)

II.2.3.6 Environmental Quality

BRT is expected also to have a localized positive impact on air pollution, but it is not clear whether its impact is significant at a city scale.

McDonnell et al. (2008)investigated the role of BRT as a tool for mitigation of transport-related carbon dioxide (CO_2) emissions in Dublin, Ireland. The results showed that the implementation of the BHLS has had a positive effect on abatement of CO_2 emissions. They found that in the absence of the QBC, CO2 emissions would have been approximately 50% higher. Furthermore, if assuming that modal shifts in the region of approximately 15% and 29% can be achieved through increased service levels of the bus, and further significant reductions can be achieved.

II.2.3.7 Deployment

BRT systems differ from more traditional transit services by its features that combine elements associated with other forms of mass transit such as light and heavy rail transit with highly flexible service and advanced technologies to improve customer convenience and system reliability. BRT systems can thus be seen as a bus based "rapid" transit system that combines vehicles stations, running way, and intelligent transportation systems technologies into a fully integrated system with a unique identity.

The success and popularity of initial BRT demonstration programs has made some transit agencies consider expanding their BRT programs and deploying more BRT lines.

In Asia, over 50 cities are considering planning or already constructing the BRT systems. For the existed BRT systems in Austrasia and Latin American the authorities are planning to extend the system to a wider range.

Although it is a new transit service, compared to the conventional service, it has been extremely developed during the last decades. And it will definitely continue to shine in the future.

II.3 Summary and Conclusions

BRT is not a new concept but has only been rapid developed in the recent decades. Compared to LRT, BRT has its own advantages, such as less construction cost and feasible lines. Some cases such as Bogotá and Guangzhou around the world have already proved that BRT can replace LRT with less cost and consuming less urban space but obtaining the same ridership.

Meanwhile, BRT is becoming popular in developing countries, where several projects are in planning or construction phase, in developed countries, there has been a significant resistance to switch from LRT to BRT. In developed countries, the available implementations of BRT systems do not follow completely the same patterns than in developing countries. The authorities tend to provide high quality services, which have some BRT characteristics. The cities of developing countries which cannot afford the cost of LRT but have very high demand of public transport service showed, until the moment, the be most successful examples of BRT systems.

BRT systems mainly can be categorized in terms of their operation framework in two main categories: closed and open. Closed systems have stable schedule but long transfer time. Open systems have unstable schedule but less transfer time. Nowadays most of the BRT systems in the world are operated as closed system because of its easy and simple manage procedure. It cannot be concluded that which system is better. The best two BRT systems in the world belong to the two types separately. The operating modes should be chose based on the specific conditions of the cities.

There is not a specific rules and regulation about the whole procedure of BRT systems. The professionals are still under discovering which way or model can be the best for planning, operating and evaluating procedure, respectively.

BRT is expected to have its own booming period all over the world in the next decades, which will convert it in one of the main public transit services.

III. Case study presentation

III.1 Introduction

Guangzhou is the capital and largest city of the Guangdong province in the People's Republic of China. Meanwhile it is the third biggest city in China. Guangzhou is also a key national transportation hub and trading port. As one of the five National Central Cities, it holds sub-provincial administrative status (Wikipedia 2011b).

In the 2000 census, the city had a population of 6 million, and an urban area population of roughly 11.85 million, making it the third most populous metropolitan area in China. Some estimates place the population of the entire urban agglomeration as high as 24.2 million, making it the 2nd biggest urban area in the world after Tokyo. The Guangzhou government's official estimate of the city's population at the end of 2009 was 10,334,500, an addition of 152,500 people from the previous year. When the migrant population is included, defined as being present in the city 6 months or more the city's population is over 14 million (Wikipedia 2011b).

Currently the underground network of Guangzhou is made up of eight lines, covering a total length of 236 km. A long term plan is to make the city's underground system expand over 500 km (310 mi) by 2020 with 15 lines in operation. In 2010 Guangzhou introduced the second largest Bus Rapid Transit system in use, after Bogota's TransMilenio, the GBRT. The operating and servicing buffers of those two kinds of public transit are not overlapped.

The BRT lines are mainly located in Zhongshan Road, which is the most important and busiest street connected east-west Guangzhou, like Changan Street in Beijing. Furthermore, along with Zhongshan Road, also located the biggest residential districts and CBDs, especially around the station where the largest number of passengers has been recorded. Prior to the BRT implementation, the road traffic of this area suffered from severe congestion. All these factors play an important role on explaining the very large demand of the system in this area.

III.2 BRT Network Description

The first line of the Guangzhou BRT system was put into operation on 10 February 2010. It handles approximately 1,000,000 passenger trips daily with a peak passenger flow of 26,900 pphpd (second only to the TransMilenio BRT system in Bogota). In fact, this rapid transit system contains the world's longest BRT stations - around 260m including bridges - with bus volumes of 1 bus every 10 seconds or 350 per hour in a single direction. The BRT system has two new lines and two extensions planned.

Guangzhou BRT (GBRT) corridor located in Zhongshan Dadao and consists of 26 dedicated stations with the total length of 22.5 km as showed below.

Figure 13 Road Network of GBRT (Source from Google Search Map)

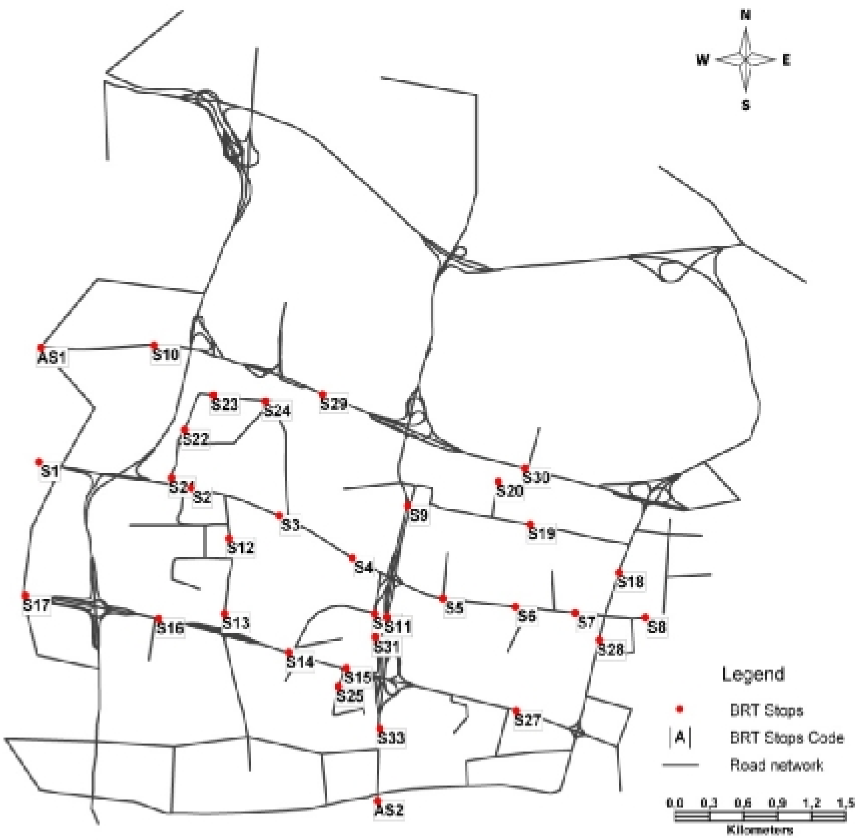
III.3 Data Acquisition

This section presents the process undertaken for data acquisition. All the data generated for the case study was generated through indirect data acquisition processes or by plausible synthetic data to reproduce the system behavior.

III.3.1 Choosing the Network

As data from the BRT was not available, this dissertation focused in a specific section of the BRT corridor and its surrounding area. The study area is presented in Figure 14, presenting a total length of approximately 5km and a width of approximately 4km.

This selected study area contains 8 BRT, overlapping the corridor section where the largest number of buses and passengers flow is registered. The 8 stations are Shida Jida, Huajin Xincheng, Shangshe, Xueyuan, Tangxiacun, Tangdong, Tianlangmingju, Chebei which are assigned S1, S2, S3, S4, S5, S6, S7 and S8 in Figure 14. The other stations in Figure 14 are located outside of the corridor and are shared by the conventional buses.



Stop	Name
S1	Shida Jida
S2	Huajin Xincheng
S3	Shangshe
S4	Xueyuan
S5	Tangxiacun
S6	Tangdong
S7	Tianlangmingju
S8	Chebei
S9	Tanganlu
S10	Shengnonggankeganyuan
S11	Keyunlu
S12	Tianhegongyuan
S13	Tianfulu
S14	Chengjiecun
S15	Yuancunsihenglukou
S16	Yuancunshanding
S17	Huaqiaoyiyuan
S18	Jiajialeyiyuan
S19	Xiaoqudonglu
S20	Tangxiaxiaoqu
S21	Huajinglukou
S22	Huajingxincun
S23	Hanjinglu
S24	Huajingxinchengzongzhan
S25	Yuancunsihenglu
S26	Huagongchang
S27	Zhujiangzhichang
S28	Chebeilu
S29	Kexueyuandihuasuo
S30	Tangdexiaoqubei
S31	Keyunlugongjiaochang
S32	Keyunluzongzhan
AS1	
AS2	

Figure 14 Location of the BRT stops in the study area

III.3.2 Geographic Data

Due to the lack of GIS data available from the case study, the geographic network description was obtained using Google Earth as base for Geocoding, for later post-processing in the GIS software Geomedia Professional.

III.3.3 Traffic Speed and Traffic Time

Traffic data used in this study was gathered from the website http://traffic.96900.com.cn/ , which presents real time traffic speed of each road and street in Guangzhou at any time of the day.

This information allowed the computation of arcs traveltimes, using the length estimated with the geographic data and the speed estimates.

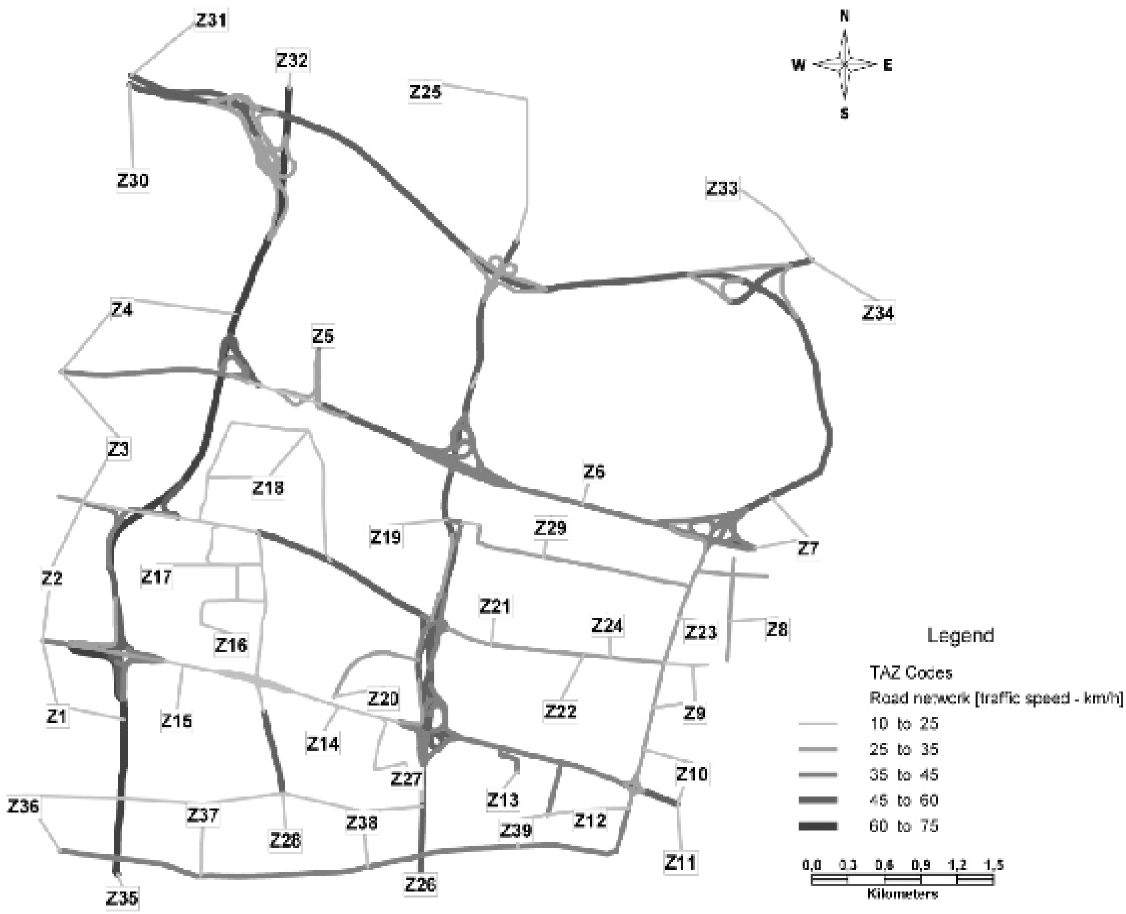


Figure 15 Traffic Speed of Each Arc in GBRT

III.3.4 Traffic Flow

As there was no source available for real data about in this area, this data was gathered through informal data published in articles and newspaper.

Figure 16 presents a rough traffic flow of the main roads of Guangzhou in 2008.

Figure 16 Traffic Flow of Guangzhou Network (Sources from: http://www.gztpri.com/index06.html)

The estimates of each arc obtained from this map were then translated to the GIS model to calibrate the traffic condition of the study area.

III.3.5 Bus routes

The data about the bus routes was obtained from available information on official websites of the service. The attributes of Bust routes are ID, Name, Headway minimum, Headway maximum, Paths and Stops.

The headways were obtained on http://bus.mapbar.com/guangzhou/, while the geographic specification of the routes was collected from http://www.gzbrt.org/cn/routes/routes.aspx .

III.4 Data Processing

As stated above, the data processing of all the data gathered was performed in the GIS software Geomedia Professional.

The spatial configuration of the road network was then fined turned, breaking arcs into edges, and defining the direction and the number of lanes of each edge.

The study area was also discreticized into 39 Traffic Analysis Zones (TAZ), which represent the sources and destination of traffic. Some of TAZ represent internal traffic generators of the study area, while others represent the connection of the selected area to the rest of the city network. The spatial specification of the

TAZ is presented in Figure 17, where the definition of the zone's centroid and connectors to the network is also showed.

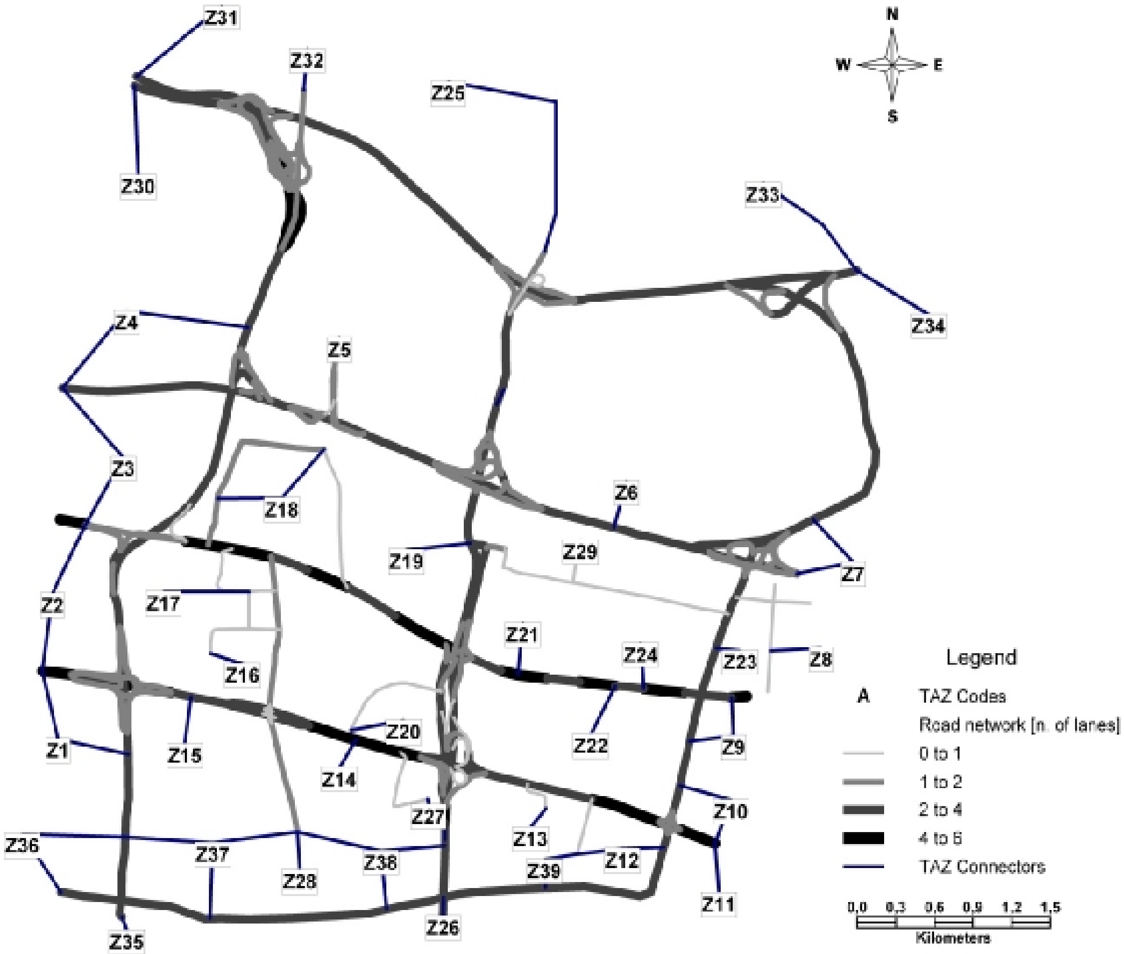


Figure 17 Zone centroids and their connectors

III.5 Data Description

III.5.1 The Road Network

This section present a description of the main data collected and processed for the characterization of the road network of the study area.

This performed analysis was undertaken for a specific period of the day. After a detailed analysis of the travel speed data collected, we decided to use the period from 18:30 to 19:30, which corresponds to the most congested period of the day.

Table 11, presents some of attributes that characterize the road network, as the speed, length link type and the capacity.

Table 11 Attributes of Road Network

ID	Name	Length (m)	Speed (km/h)	Travel Time (min)	Number of BRT lanes	Number of other lanes	Number of mixed lanes	Link type	Capacity
1	A1	188.435	28.49	0.396	4	6	0		5400
2	A10	119.914	45.17	0.159	4	6	0		5400
3	A100	137.84	32.9	0.251	0	0	8		7200
4	A101	166.797	32.9	0.304	0	0	8		7200
5	A102	178.902	39.66	0.270	0	0	8		7200
6	A103	292.956	39.66	0.443	0	0	6		5400
7	A104	1137.79	26	2.626	0	0	2		1800
8	A105	318.402	19.85	0.962	0	0	2		1800
9	A106	654.121	26	1.510	0	0	2		1800
10	A107	348.118	24.22	0.862	0	0	8		7200
11	A108	269.683	32.9	0.492	0	0	2		1800
12	A109	124.602	32.9	0.227	0	0	2		1800
13	A11	128.754	45.17	0.171	2	8	0		7200
14	A110	263.261	32.9	0.480	0	0	2		1800
15	A112	1056.91	14.69	4.317	0	0	2		1800
16	A113	171.777	71.61	0.144	0	0	8		7200
17	A114	87.9638	45	0.117	0	0	4		3600
18	A115	208.457	53.77	0.233	0	0	6		5400
19	A116	211.223	46.41	0.273	0	0	8		7200
20	A117	211.83	40.27	0.316	0	0	12		10800

III.5.2 Calibration of Traffic Flow

The process of traffic flow calibration relies in two basic inputs:

- First one: We introduce the centroids for the different zones and connect to the calibrated network. Then we estimate the shortest paths between zones, based on speed readings from the internet website during the afternoon traffic peak.
- The other one is the estimated interval of flow in the different arcs of the network based on the perception of picture.

With that information it is able to develop a procedure based on a single constrained gravitational O/D matrix estimation model, where the impedances between the different zones are obtained by the travel times of the shortest paths, and a beta coefficient that should be calibrated. Furthermore, it is able to estimate the mass of each zone as traffic generator/attractor, based on the knowledge of the study area, lacking more refined information. The estimates for each zone are presented in

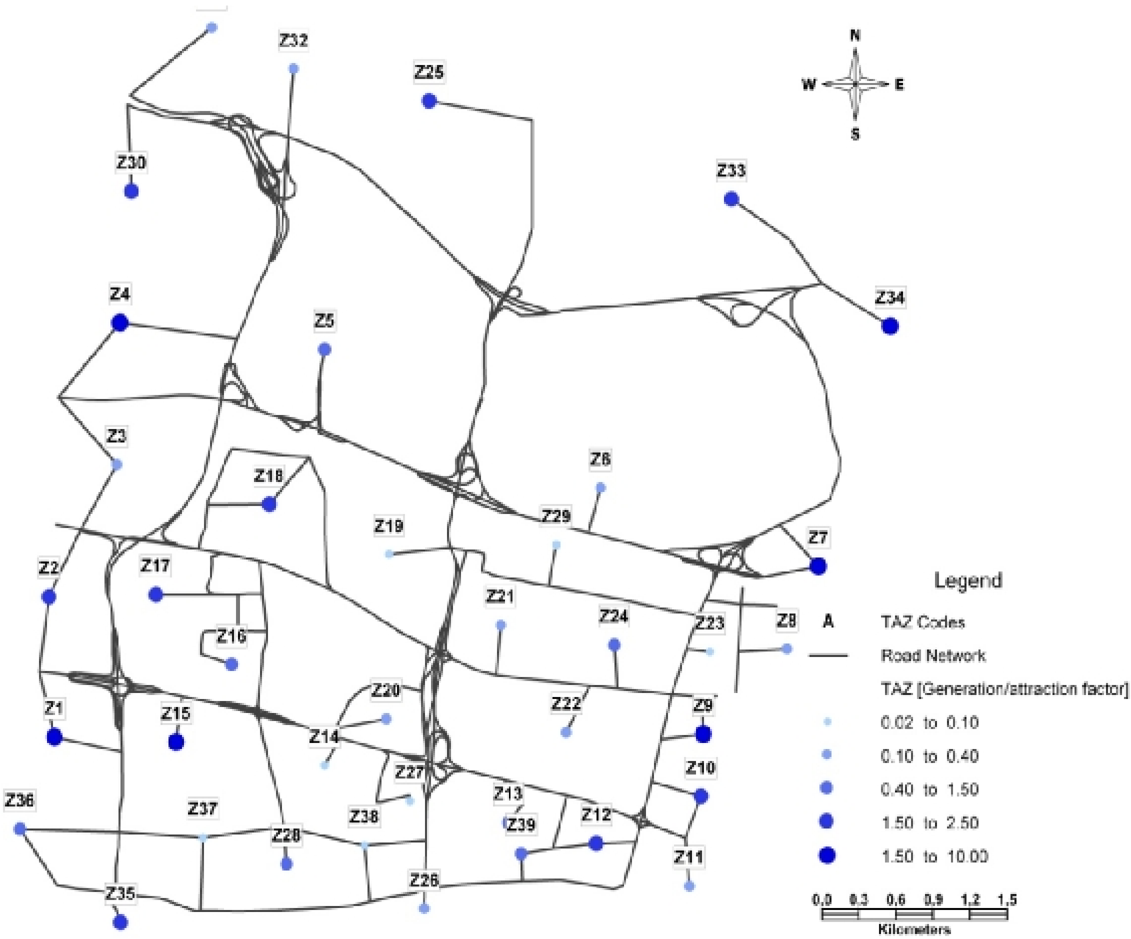


Figure 18 Generation/Attraction Factor of Each Centroid

The model is able to estimate then the flow between O/D pairs based on the beta parameter and the mass attributed to each zone, presenting as additional parameter an alpha value that represents the disequilibrium of a zone between the attraction and the generation mass.

With the O/D matrix estimates for each value of the parameters, the procedure generates a traffic assignment model to the arcs of the network as estimates its deviation from the original estimates.

For those zones which have more than one connector to the network, we will leave only one connector for the demand estimation. Then block this one and open another one and do the calculation again. In the end the OD matrix of one zone to another may be multiple choices. Each of the choices is assigned with a possibility that depends on the time spent on the trip.

This procedure was then encompassed in an optimization model that presents as objective function the minimization of the average estimation error on the links of the network described above, and the decision variables the parameters of the gravitational model.

This model was then run using a genetic algorithm program embedded in Excel, Evolver from the Palisade Decision tools, using as the pre-defined tuning parameters of crossover and mutation of the program.

The resulting O/D matrix will be then used as input of the model to simulate the influence of other traffic on the BRT operation in a complex open system.

Another thing should be brought up that the traffic flow in this dissertation refers to the traffic flows of the private cars. The public vehicles are driving in the fixed schedule.

IV. Building the Traffic Simulation Model

I

IV.1 Introduction

This Chapter presents the several steps undertaken to build the traffic microsimulation model that will be used to compute the analyses of the system. This model was built in a commercial software package: Aimsun 6.1.3.

This process includes several steps that go from the network modeling, the setting of the general traffic OD matrix, the specification of the BRT routes and stops, to the definition of traffic control plans at the traffic light intersection.

IV.2 Aimsun

Aimsun is an integrated transport modeling software, developed and marketed by TSS - Transport Simulation Systems based in Barcelona, Spain. Aimsun integrates three types of transport models (macroscopic, mesoscopic and microscopic) into one software application.

In this dissertation Aimsun is adopted to build Microscopic models, of which Capabilities include assigning traffic onto a network at a microscopic level, adjusting Origin-Destination (OD) matrices to reflect real-world data (at macroscopic level), and the evaluation and recommendation of detector layout and locations for the GBRT.

IV.3 Building the Network

The creation of the road network in Aimsun was performed by importing a GIS file previously created on the data processing step. The attributes of the GIS file included number of the lanes and the direction of the roads.

By default, Aimsun will break the network into sections with the defined attributes and build all the possible turns at each interaction, which had to be manually corrected after importing the network.

As the objective of the network is its use in a microsimulation model, the spatial configuration of the different directions and approaches to intersection play an important role on the output. This fine tuning of the network, originally imported from the GIS file, was performed in Aimsun, which was verified with small simulations of the individual cars behavior at each intersection approach.

IV.4 Introducing Zones

The developed general traffic model was calibrated using as travel demand an OD matrix of 39 zones, that can provide and receive the traffic flows located in the network. The location of the zones can be either imported from the GIS file or marked in the network manually.

After introducing the centroids of the zones into the network, the connectors of zones to network were built, trying to reproduce the source and destination of demand and connecting to sections or intersections that may allow easy routing within the network.

IV.5 Setting OD Matrix

As depicted before, the OD matrix was estimated from synthetic flow data based on a map of traffic flow in Guangzhou in 2008 and the traffic speeds measured from a website for the period of analysis. The calibration procedure resulted in an average estimated relative error of 16%. This procedure was recomputed in Aimsun, using the original OD matrix as source, using the OD matrix calibration procedure available in the software, improving the spatial output of the results and reducing the average relative error to approximately 9%.

This second calibration procedure was developed using the outputs of a macrosimulation estimation of the traffic flows in the study area and adjusting them to the traffic data of some arc some traffic data available from the Transport Department of Guangzhou.

After this double calibration procedure the traffic flow condition is a good proxy of reality during the analysis period (18:30-19:30). The obtained OD matrix is presented in the Appendix.

The estimated traffic flow spatial distribution is presented in Figure 19.

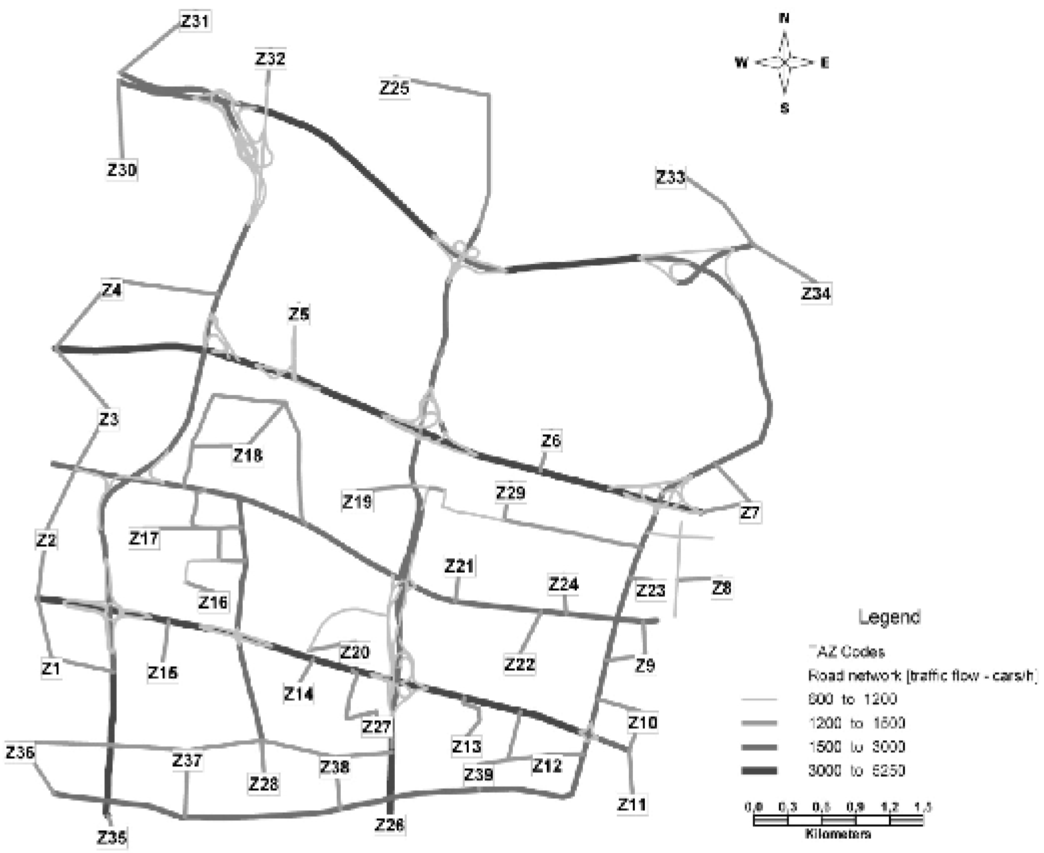


Figure 19 Simulated Traffic Flow of the Network

IV.6 Adding Traffic Control Plans

As several intersections of the study area present traffic light control, they have to be modeled in the microsimulation model. This feature is available in Aimsun under the name of traffic control plans.. The traffic control plans manage the movement of the vehicles when approaching and crossing an intersection.

The development of the control plan requires an a priori definition of the phases of the traffic light cycle, using the conflict assessment introduced by Webster and implemented in the Highway Capacity Manual 2000 (National Research Council (U.S.) Transportation Research Board 2000).

The traffic lights in the study area were modeled as actuated; being the time on the cycle assigned to each phase dependent on the traffic counts of sensors at each intersection entrance.

The network presents a reduced number of traffic light controlled intersections. Apart from the definition of the different phases of the cycle, which aggregate non conflicting movements, the yellow time and the all red time at each phase transition was also set. For the traffic lights of the study area, we used a yellow time of 5 seconds and 2 seconds of all red time.

IV.7 Bus Stations Configuration

As part of the network specification, the model also requires the definition of the location of all the bus stops in the study area-There are three types of bus stations in Aimsun: Normal, Bus bay and Bus terminal. In this simulation model it was used bus bay stations. Each bus station presents specific length and docking capacity, where each vehicle when arriving move forward.

Bus stations' locations were obtained from an inspection of the study area by Google Earth.

IV.8 Bus Routes and Timetable

The BRT routes are modeled in Aimsun by the function of adding public transport lines. The function contains the order of the sections, stops and the timetable that each route is using. The BRT routes were obtained from http://www.chinabrt.org/defaulten.aspx. The headways of the routes are available on http://bus.mapbar.com/guangzhou/

IV.9 Modeling of Pedestrians

The used software does also present the ability to integrate traffic and pedestrian flow modeling in a microsimulation platform. Yes, because we could not have access to a license of the Legion add-on, pedestrian crossings were not modeled using this feature.

An adapted modeling approach was pursued to resemble the effect of a pedestrian crossing in the traffic flow. When a traffic light is located in an intersection, the pedestrian moves would be able to walk through on the complementary phases of the conflicting movements. So, there is no additional refinement of the impact of pedestrians on the traffic flow in signalized intersections, only if the intersection was also actuated by pedestrian activation.

Unsignalized pedestrian intersections on zebra crossings were modeled by creating virtual intersections in the area where a pedestrian crossing is located. The intersection is modeled by a virtual traffic light, where the time of the cycle and time of each phase of confliction movements is fixed. The cycle of the traffic light was set to 50 seconds, where 40 seconds is the free time for the vehicles on the roads of both direction and 10 seconds is for the pedestrian to cross the road. This simplification of the pedestrian behavior in traffic may be insufficient to fully perceive the pedestrian effect on the traffic flow, due to its natural random nature. Yet, it is reasonable to set a very small duration in a short period to simulate the pedestrian crossing effect on the traffic flow.

IV.10 Detect Vehicles in the Simulation

One of the key features that traffic microsimulation enables when compared with macrosimulation procedures is the ability to output individual data from vehicles circulating in the network. This data acquisition procedure it will be used in this study to compute the performance indicators that will be presented in network evaluation Chapter, allowing the estimate of the distributions for the main variables of the traffic flow.

Since the core of this dissertation is the evaluation of the GBRT performance and its relative influence factors, the information about the performance of the individual BRT routes in the simulation, is a key components of this analysis. By default, the outputs that characterize the aggregate behavior of the public transport lines are the following:

Table 12 Attributes of the Outputs of Section Information

Attribute Name	Type	Description
did	integer	Replication or Average identifier
oid	integer	Public transport line identifier
eid	char	Public transport line External id
sid	integer	Vehicle type (from 0 for all vehicles, to number of vehicles)
ent	integer	Time interval, from 1 to N, where N is the number of time intervals, and 0 with the aggregation of all the intervals
nbveh	integer	Number of Vehicles that have arrived to the end of the public transport line
speed	double	Mean speed (km/h or mph)
spdh	double	Harmonic mean speed (km/h or mph)
ttime	double	Mean Travel Time (seconds)
dtime	double	Mean Delay Time (seconds)
stime	double	Mean Stop Time (seconds)
nstops	double	Number of stops per vehicle
travel	double	Total number of km or miles travelled
traveltime	double	Total travel time experienced (seconds)
fuelc	double	Total litres of fuel consumed*

Those attributes are not enough for the evaluation of the performance of GBRT. As discussed above, BRT system is a highly regulated public transport service. To maintain its advantages such as high ridership and fast driving speed all the BRT buses should be holding up tightly to the schedule. The headway of the buses at each station should be steady and present a small deviation, otherwise in some stations the buses are waiting in a long queue to entering the stations but the other stations are empty. This incident would cause significant disturbances to the BRT system operation, much greater than to the conventional one because of its high capacity which makes the service must carry the corresponding passengers to avoid the big mass in the stations. Furthermore, the buses from the line, should maintain the headway as stable as possible in order to ensure an efficient operation.

Thus to record the headway of the buses of each line in each station, the BRT buses are defined the as Equipped Vehicle in Aimsun. In Aimsun, when an Equipped Vehicle crosses a detector, the detector will record the following information:

Table 13 Attributes of the Detection Information

Attribute Name	Type	Description
did	integer	Replication or Average identifier
oid	integer	Detector Identifier
timedet	double	Detection time of the Equipped Vehicle
idveh	integer	Vehicle identifier
vehtype	integer	for all (from 0 vehicles, to number of vehicles)
idptline	integer	Public Transport Line Identifier, for public transport vehicles, -1 otherwise
speed	double	Detected vehicle speed (km/h)
headway	double	Headway of this equipped vehicle (seconds)

To record the information of the BRT buses' routes, such as the simulated headway of each line, it is necessary to add a detector at the entrance of each bus stop on each direction. Then the output of the database of the detector will store the dataset of each vehicle.

One more thing should be noticed is that, if a bus station located on the entrance of the network, there is no need to set a detector at the bus stop. Because the buses are created from that station and their schedule through that station won't be affected no matter how bad the traffic condition in the network is. The headway of each line at that station will be definitely matched with the headway defined in the timetable for each BRT lines.

Vehicle detection was also used to estimate the behavior of individual drivers in the network. The detections of this type are set at the essential intersections, entrances and exits of the zones to detect the traffic flows that are passing by and record the information in the outputs.

In the Chapter devoted to the evaluation of the system's performance with different scenarios of traffic control, the individual data will be gathered for public transport and private vehicles to compute the performance indicators.

IV.11 Summary and Conclusions

This section presents a brief summary of the characteristics of the road traffic model developed to emulate the environment of the network of GBRT. The geographic data and traffic information are gathered in two ways: assistance from China and rational estimation. The gathered data was first imported into GIS software. Then, the GIS files were imported into Aimsun for simulation.

The model in Aimsun presents the following general attributes:

Table 14 Simulation Information

Type	Number
Road Sections	451
Bus Stops	60
Detectors	102
Bus lines	62
Zones	39
Cars	47,294
Intersections	10

In the model there are 60 bus stops located in the network, 16 of which are in the BRT corridor. 32 bus lines are moving inside of the corridor while the rest are entering or leaving the corridor using main intersections located in the corridor. There are three signalized intersections where the signals are adapted to model BRT preemption, being the intersections split for general traffic and the dedicated lanes for the BRT buses.

The lane change and car following algorithms used in the microsimulation model were the default algorithms proposed by Aimsun without any calibration due to the lack of accurate traffic flow data to calibrate the parameters of the models.

The route choice model used for cars was C-logit, which is based on the Cascetta research (Cascetta 2009).

All the other parameters in Aimsun are set as default.

V. Modeling of Processes of Traffic Disturbances in the Road Network

V.1 Introduction

One of the key factors to BRT system success is the regulation of its schedule. Once it is broken, the system inside the corridor may rapidly unbalance and become inefficient, especially in an open system. And outside of the BRT corridor, there are some disturbances that can easily delay the regulation timetable of a single BRT line.

The BRT buses can be mainly affected by three types of traffic disturbances:

- The traffic flow of the network increased and causes traffic jam in the network. This condition occurs when the traffic flow of most of the lanes are reaching their capacity. When a traffic jam occurs, BRT buses which are driving out of the BRT corridor will be delayed. But it is very hard to measure whether a traffic jam is caused by the additional flows. The traffic jam can be resulted from multiple factors' co-effect.
- Sudden and large concentration of pedestrians, such as students, which may cross in locations where no traffic light is settled, or even in intersections with traffic lights, unbalancing the intersection phase distribution, producing significant delays, Student at the end of classes leave school, which may change the intersection conditions during a period of high concentration of pedestrian crossing. The time which is provided from the vehicles to the pedestrians can easily cause delay to the BRT buses. This kind of situation is happening very common in the areas both inside the corridor and outside the corridor and are around all types of schools.
- Temporary occupation of some of the lanes of the road, reducing instantly the arc capacity.

By searching from the Internet and assistance from Guangzhou, we were able to figure out 9 places of disturbance that are located along the BRT lines which are partly outside of the BRT corridor. Those places have different disturbance behavior, influencing differently the network performance. We will depict the main types of disturbances into three main categories, which will present are clustered considering the type of impact that they may present to the traffic flow:

- Car storage companies/Construction material markets, which create temporary occupation of the right lanes of the adjacent roads, creating temporary reductions of capacity of the section. This disturbances are characterized by small to intermediate durations (normally 2 minutes), but averagely frequent (approximately once every 10 minutes) (*Type II*);
- Factories/Industrial locations, which create long disturbances to the nearby roads when materials are being loaded or unloaded. This type can by characterized by long duration

disturbances (averagely 5 minutes) but with reduced frequencies (normally once per hour) (*Type II*);

- Schools, which concentrate intense pedestrian crossing during the arrival and departure times of students, which may limit significantly the capacity of traffic flow. This type of disturbance presents very low durations (approximately 5 second per lane crossed) but very high frequencies (once every 5 minutes) (*Type III*).

Analyzing the study area, we were able to identify several of the previously described disturbances. In the following sections we will present this disturbances and their statistical modeling approach, as well as their representation of the case study.

V.2 Specification of the disturbances for the case study

In this section, a detailed assessment of all the possible disturbances to traffic flow in the study area are presented and discussed. We will start to describe the disturbances of Type I found in the study area.

These disturbances are presented in Figure 20, and designated as:

- Disturbance 1 (D1) & Type: Car Storage Company
- Disturbance 3 (D3) & Type: Construction Material Market
- Disturbance 4 (D4) & Type: Construction Material Market
- Disturbance 5 (D5) & Type: Construction Material Market
- Disturbance 6 (D6) & Type: Construction Material Market

Those two types of activities share the same characteristics of effect over traffic. Because of their non-normal size and continuity, the road will be blocked for a while. The thinner the roads are the worse condition the network can get.

This type of disturbance can be treated as the similar condition of the third type of the above classification. For type 1, the companies and market won't have the ability to create any flow that is about to impact the whole network even to a small part one. For type 2 those places won't stop the traffic on all of the lanes at the same time either. So type 3 is more suitable for those places. When the trucks are entering or leaving the places they may stop on the right lane of the roads and make the road temporarily narrow.

In Aimsun there is a strategy called Lane Closure that can be used on modeling the disturbance. This strategy' function that based on the fixed time schedule, the lane that we choose will be closed for the duration we've set up. This strategy can well model the reality condition that when the trucks are driving on the lanes to entrance or exit the companies or markets those lanes are like closed temporally for the other vehicles. The timetable of this strategy is set as duration of 2 minutes in every 10 minutes.

Disturbance 2 (D2) & Type: Coal-Fuel Electricity Factory

Disturbance 7 (D7) & Type: Stone Quarry Factory

Those factories will affect the network in the same way that the previous one does. The difference in the modeling is that they don't have that much frequency of transiting cargos as the market does. In Aimsun I intend to stop the traffic flows that are passing by only for one time but last longer about 5 minutes during the whole simulation.

Disturbance 8 (D8) & Type: School (neither directly connected with the intersections that have traffic lights nor any intersections with traffic lights nearby)

Disturbance 9 (D9) & Type: School (the school gate is directly connected with an intersection without traffic light, and there is also a pedestrian bridge located 100 meters away from the school gate).

Figure 20 Location of traffic disturbances in the study area

As depicted above, this type of disturbance must have a scheduled green light time for the children's safety. The model will have 20 seconds and 40 seconds minutes green light for each 5 minutes, respectively to the number of the lanes on the roads.

There are two ways to improve the condition:

- The first one as depicted before, to control the movements of the children. When a BRT bus is passing by, the flow of children should be stopped. The model procedure is similar to the previous one. And in reality, this movement can be controlled by the teachers of the schools. This method can be adapted to the Disturbance 8.
- The second one is to build the corridor to prevent the children from the intersections without traffic light and guide them to the intersections with traffic lights or the bridges nearby. To model this procedure is also very easy; I just need to delete the intersection in front of the school gate. The disturbance can also be avoided by building the bridges over the road. But this method will cost a lot of money.

Here are the BRT lines that may be influenced by the disturbance:

- With D1, B8 (45), B15 (53) and B22 (61) can be affected.
- With D2, B7 (61), B7k (43) and B25 (66) can be affected.
- With D3, B15 (54) can be affected.
- With D4, B15 (53) can be affected.
- With D5, B15 (53) can be affected.
- With D6, B15 (54) can be affected.
- With D7, B8 (45), B8 (46), B21 (59) and B21 (60) can be affected.
- With D8, B1 (1), B1 (2), B1k (3), B1k (4), B2 (5), B2 (6), B2A (7), B2A (8), B3 (9), B3 (10), B3C (11), B4 (13), B4 (14), B4A (15), B4A (16), B4B (17), B4B (18), B5 (19), B5 (20), B5k (21), B5k (22), B6 (23), B6 (24), B12 (25), B12 (26), B16 (27), B16 (28), B17 (29), B17 (30), B20 (31), B20 (32), B27 (33), B27 (34) B3A (35) B6k (39), B6k (40), B7k (41), B7k (42), B7 (43), B7 (44), B8 (45), B8 (46), B21 (59), B21 (60), B22 (61) and B22 (62)can be affected.
- With D9, B9 (47), B9 (48), B13 (51) and B13 (52) can be affected.

The numbers in the brackets are for identification of the directions of the same BRT lines.

From the above, it can be concluded that B15 suffers the most, with 5 places of disturbance affected. What's more, D8 has the most serious affection. 46 BRT lines can be affected by D8. Those two factors will be paid more attention in the section of processing disturbance.

Besides of the BRT lines above, actually all of the BRT lines will be influenced by the disturbance. Because BRT system has a very tight schedule, even only one of the lines is delayed, when the bus enters into the corridor, it will disorganize the other lines' buses. In this dissertation the BRT lines will be evaluated separately initially then as a whole.

VI. Analysis of the BRT System and Road Traffic Performance under Different Traffic Control Scenarios

VI.1 Introduction

This Chapter presents the analysis of the outputs from the 3 types of scenarios described above: GBRT without disturbances, GBRT with disturbances and GBRT with disturbances controlled & preemption introduced.

The analysis is based on the different performance indicators according to the different agents involved in this system, which will be detailed in the following section.

In the first scenario, the affection that disturbances may have towards the network will not be considered. The interactions will only occur between general cars, BRT buses, traffic lights and pedestrian crossings. The controlling level in this scenario is the lowest.

In the second scenario, we add 9 places of disturbance into the network. Those disturbances are divided into three groups which have their own ways to influence the network as described in the previous Chapter. Thus, this scenario integrates the interactions of the different agents with the disturbances. The controlling level in this scenario is medium.

In the last scenario, all of the 9 disturbances are controlled under appropriate measures. Besides of this, to ensure the schedule is stable along the corridor, we introduced intersection preemption to the network. The preemption will give the buses priority to across the intersections. The controlling level in this scenario is the highest.

VI.2 Performance Indicators

There are basically four types of agents which are involved in the simulation:

- BRT line operator;
- BRT Corridor manager;
- BRT system client;
- Private Car user.

For the BRT line operator, there are two key indicators that will be more relevant: average headway time and its deviation. Both of them should be controlled within a certain range so that the operation of the line may be successful, maintaining a high and steady load factor for all the service vehicles.

For the BRT corridor manager, the main focus will be the efficiency and the frequency of the usage of the BRT corridor. During the whole simulation, for the manager, the best indicator is that the corridor has a very high frequency of services and with stable headways, meanwhile, the number of buses per minute would maintain at a constant level. Having more than 10 buses driving into the station during the same minute can raise problems of the overall system operation. This problem may be avoided by coordinating the BRT manager with the general traffic manager, which may hold up some buses at traffic lights to reduce the entropy at bus stations.

For the BRT system client, the passengers mostly would consider that the shorter headways of the buses are the better performance the BRT system has, because shorter headways do also lead to smaller waiting times. Moreover, they also want the buses have a stable schedule to ensure a reliable service.

For private car users, this analysis will focus on the 30% of the vehicles that are worse off in terms of delay in the three scenarios. The performance indicator for this agent will be the changes of travelling time for each OD pair.

VI.3 Simulating Disturbance

The procedure of modeling the disturbance in Aimsun was described in Chapter VII.

In this section we separate the project into two different modeling approaches. One, where the network does not consider the influences of disturbance processes, and another, where disturbance processes are added to the model. These two approaches will be run separately for the different outputs. The two sets of outputs are used for comparison and further development.

VI.4 Control the Disturbance

The modeling of the effects of control procedures over disturbances is straightforward: ignore the existence of the phenomena in the network.

For the disturbance which takes up one of the lanes on the road, in reality, those locations will be controlled as non-stop areas so that the lanes wouldn't be occupied and block traffic. To model those controls in Aimsun, those disturbances were deleted from the model. This is very similar to create a non-stop area at those locations.

Setting the non-stop areas can be realized by multiple ways. The main policy, for instance in Spain, is to add cameras in the areas where it is very common to have private cars stopping on the lanes for a certain period. Those cars that are detected by the cameras once occupy the lane for more than 1 minute will be fined. Thus the lanes won't be occupied all the time.

In the case of schools, two types of improvements can be introduced. One is made by the teachers of the school. The teachers should regulate the crossing time of the students and try to reduce the pedestrian influence to the least. The first method can be adapted to the area where D9 is located. For the area where D8 is located, since a crossing bridge is building within 100 meters, it is better to build a corridor by the two sides of the former crossing and lead the students passing the road by the bridge. Once again, the best way to simulate the effects of control is deleting the disturbances from the model.

VI.5 Intersection Preemption

Besides the controls that are made by the deleting disturbances in Aimsun, we intended also to introduce preemption to the intersections that are located along the BRT corridor. By this mean, the time lost for buses that are crossing will be controlled to the least range.

The reason why we don't make preemption to the other intersections that BRT lines are crossing is that, in those intersections, the approach lanes are not dedicated only for BRT buses, and the preemption will only bring priority to the buses rather than conventional cars. If there is a car in front of a bus, the bus would still not be able to have the priority to move. And the above situation occurs frequently on the mixed lanes.

As stated above, there would be two sets of outputs for network with and without disturbances. In this section we intend to increase the number of sets to three. The third one will be the outputs of the network with disturbances controlled and preemptions introduced. Those three outputs will be used together for further comparison and development.

VI.6 Running the simulations

The different scenarios were computed with 5 replications in each simulation to get the average traffic condition.

The intervals of recording detections and statistics are set as 1 minute and 10 minutes, respectively. And the duration of the simulations is 1 hour.

The outputs of the database contain the information about the whole system, sections, public transport, OD matrices, streams and detections.

VI.7 Analyze for the BRT line operator

The analysis of the performance of the system for the BRT line operator is summarized in Figure 21 and Figure 22, presenting the results of the headways at each bus stop. Figure 21 presents the average headways of each bus line, while Figure 22 presents the standard deviation of the headways of each bus line.

Figure 21 shows that the disturbances do not impact significantly the network, yet, the introduction of traffic light preemption does. For some lines, the disturbances can even make some positive effects for the average headway, such as B4A (16), B4B (18), B5k (22), B7k (41), B8 (45), B13 (52), B15 (53), B15 (54), B18

(55), B18 (56), B18k (58), B21 (60), B22 (61). Those lines with the influences of disturbances have over 30 seconds less headway than others in the model without disturbances, like line B21 (60) that presents a difference of 194 seconds. With the preemption introduced, the average headways are much shorter than the previous ones. And they get more similar to the scheduled average headways. However, it seems very strange that the scheduled headways of B1 (1), B1 (2), B3C (11), B4A (15) B4A (16), B3A (35), B3B (37), B7k (42), B13 (51), B13 (52), B18k (57), B18k (58), B22 (61) and B25 (65) are much longer than any others in the three scenarios. This fact derives from the procedure used to define the timetable of each BRT line, which only sets a range of headway and not a fixed value (from the website mentioned above we can only obtain a distribution of the headways of each line so we have to make the timetable of each line in the model with average value and deviation). For example, B2 (5)'s headway is between 2 minutes and 4 minutes, being inputted into the Aimsun model the average value and a deviation, which does not necessarily reproduce the available information. For those lines that have significant differences, they also have wide ranges. The bigger the deviation the greater difference it will be observed in the output. This misspecification won't influence the results of the evaluation. Because as depicted before, as lack of actual data the main goal of this dissertation is about to evaluate the model learned from GBRT, not based on GBRT. In this dissertation we are not comparing the model with the real network. We only use the actual data for reference, rather than comparison with the 3 scenarios in the first section of evaluation. In the next sections we are evaluating the performance only between the 3 scenarios. Compared to scenario 1, disturbances delay the headway as an average of -0.84%. Yet, preemption shortens the headway as an average of 8.6%.

However, in Figure 22 the situation is totally different. Nearly all the bus lines with the influences of disturbances have larger standard deviation than the ones without the disturbances. Meanwhile the differences are almost over 50 seconds. After disturbances controlled and preemption added, the performance improves, and most of the lines have smaller standard deviation than before. Nonetheless, some performances should paid attention like lines B7k (41), B7 (43), B11 (50), B15 (53) B18 (55), B23 (63), B25 (66) in the preemption scenario, in which they have very large standard deviation, especially B25 (66) which has over 500 seconds more than the previous scenarios. The reason will be discussed below. In average, disturbances increase the deviation in 19.77%, while preemption, in average, reduces the deviation in 0.43%.

Table 15 shows the average headway of all BRT lines and its deviation in the three scenarios. We can see that from the macro scene, the preemptions and disturbances controls improve the condition of BRT lines as a whole group.

Table 15 Aggregate headway and its standard deviation of 3 scenarios

	Average Headway (s)	Average Standard Deviation (s)
Scenario 1	468.622	327.688
Scenario 2	459.820	373.215
Scenario 3	422.938	311.350
Actual Schedule	485.323	138.912

Although there aren't many differences in the average headway time, the headway of each line is changing at very large amplitude when disturbances are included. This fact could jeopardize the quality and reliability of the public transit services, especially for the BRT services. As depicted in the previous section, regulated schedule is one of the key elements of BRT. Once it is disturbed, the system's performance could be severely affected. When the disturbances are controlled and the preemption is activated, the positive effect is not as obvious as they have towards the value of average headways. They even have negative effect towards some lines. To explain this, it should be mentioned again, that we only make preemptions in the intersections along the BRT corridor, and the preemptions would only give priority to the buses on the corridor. When a bus comes from the outside of the corridor to inside and the turning direction is left, they would be probably stopped by the priority buses since they never stop. It can only move when no bus on the corridor is moving forward. But this may only happen occasionally and for short durations, because the BRT corridor is a very busy tunnel and over 200 buses are moving on it during one hour. Those lines mentioned above present this type of behavior.

We can conclude then, that disturbances must be controlled when considering operating the BRT lines; otherwise the system would be unstable and very hard to operate. But, for the perspective of the BRT line operator, preemption is not that necessary. The preemptions can do bring positive effect to the lines in the corridor, but they may also bring new unstable schedule to other lines. This situation will be more polarized with the number of bus lines partly outside of the corridor increasing. To better utilize preemption from the perspective view of BRT line operators, close coordination between BRT operators and traffic authorities should be ensured to switch traffic lights to improve the BRT system efficient. In this dissertation we recommend that the operators could regulate 100 meters long dedicated lanes for the buses which have to turn left to enter in the corridor. By this way the preemptions will be available on those lanes to give the priority to the buses. Thus the delay of those buses can be avoided.

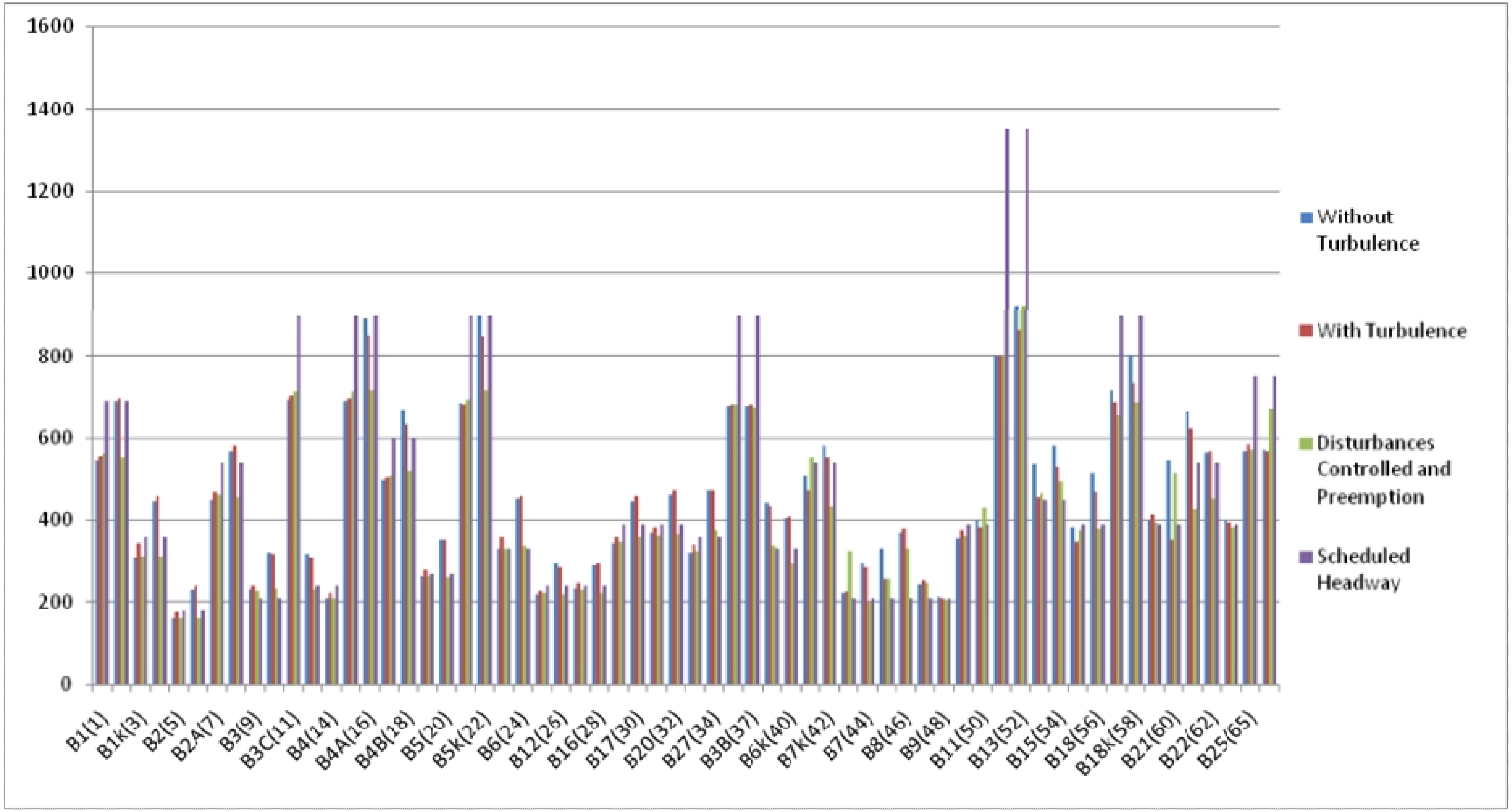


Figure 21 Average head way of each bus line (s)

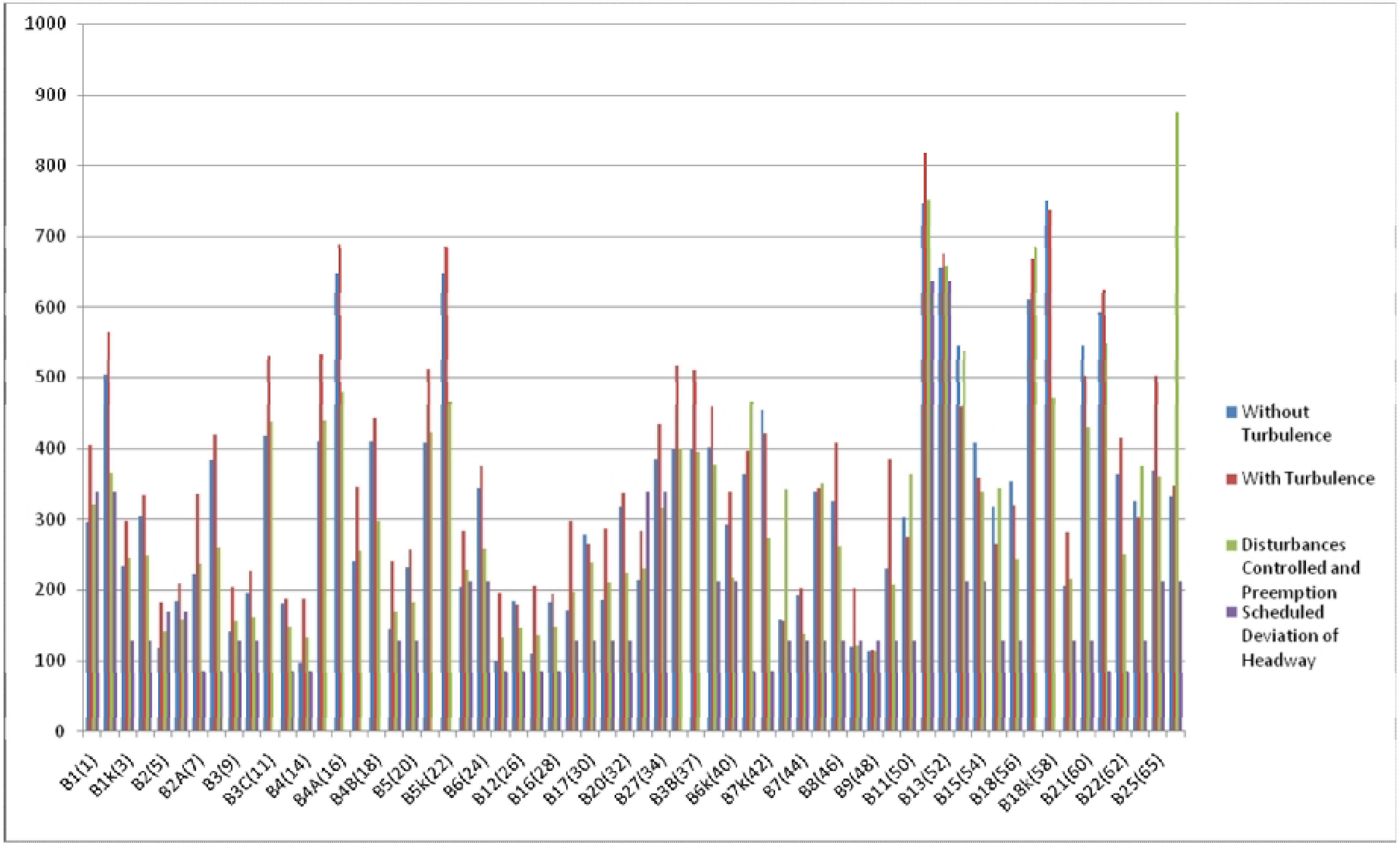


Figure 22 Average deviation of headway of each bus line (s)

VI.8 Analysis for the corridor manager

Figure 23 and Figure 24 show the average headways and their standard deviation of the BRT buses at each stop, which are the indicators that BRT corridor manager cares about. The reason why S1 (1) and S15 (16) are not included is because they are located at the entrance of this network we modeled. Their headways mainly depend on the previous BRT stations that were not modeled. So, the headway calculated from the outputs of our model must be very imprecise, being better not to consider them into the analysis. In average, disturbances delay the headway in 4.3% and increase the deviation in 35.76%. In average, preemption reduces the headway in 12.16% and the deviation in 0.59%.

From Figure 23 we can conclude that disturbances do not have significant impacts to the average headways in the corridor. Yet, the preemption has reduced considerably the headway of the buses at each bus station, especially for the stations that run in the east-west on the corridor. A first evaluation would indicate that the introduced measures enhance the efficiency of the corridor's usage, because in average the travel speed of the BRT buses is faster and the buses are moving more frequently on the corridor. And the reason why only one side of the stops have obvious benefit is that, most of the 31 lines that enter into the corridor from the downside of the network, the delay caused by the preemption to those lines are counteracted with the time saving caused by the preemption to the lines inside the corridor.

We can see in Figure 24 that, although disturbances do not influence the average time, they disturb the headway at the micro level as they do towards the BRT lines, which will definitely make the corridor manager very difficult to adjust the flows. In S3 (6), S4 (8), S5 (10), S6 (12) and S7 (14), the preemption improved the headway consistency considerably. However, in S7 (13) and S8 (15) the preemptions has a negative impact. This fact was thoroughly explained in the previous section.

However, we find that no matter whether the disturbances and preemption are inside of the network, the manager should still pay attention to very small headways that frequently happen inside the corridor. Taking S1 (2) for instance, in the scenario 1, from the simulation time 1377.07(s) to 1526.96(s) there are four buses that are detected at 1377.07(s), 1518.71(s), 1524.23(s) and 1526.96(s). This means the headway of the four buses at S1 (2) are 141.64(s), 5.52(s) and 2.73(s). In reality this is impossible unless the last two buses don't stop at those stations, which is not acceptable to the BRT line operators because they want to have the bus operating as much ridership as possible. The similar incidents can also be found in the outputs of scenario 2 and 3. The only difference is that scenario 3 have less number of the incidents than the others. In the outputs of scenario 3, the percentage that headway is less than 10s of all the headways is 56%. In scenario 1 and 2, the percentages are 62.8% and 63%, respectively. This kind of incidents can be avoided, as written before, by the cooperation between the corridor operators and traffic manager. The buses should be stopped by the traffic lights or announced by the corridor operator to drive at a lower speed if a lot of buses ahead are accumulating.

For conclusion, for the corridor manager, disturbances must be controlled even if the disturbances are far away from the corridor. They can still disturb the traffic inside of the corridor. Meanwhile, preemption is positive from the perspective view of the BRT corridor, since they do have positive effect either enhance the efficiency of corridor usage or maintain the consistency of the stops' schedule.

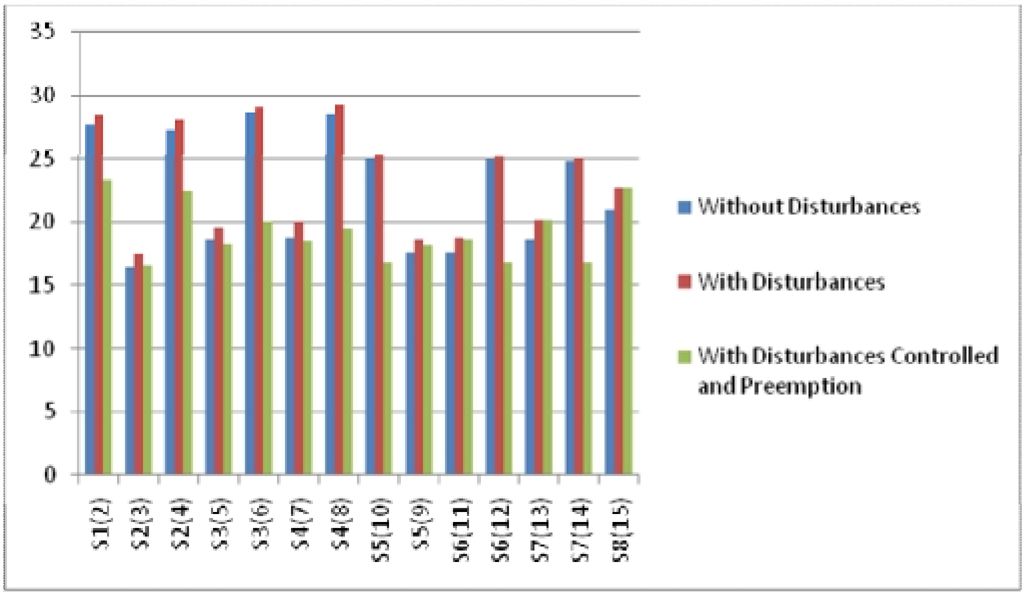


Figure 23 Average Headway Comparisons at Each Bus Station (s)

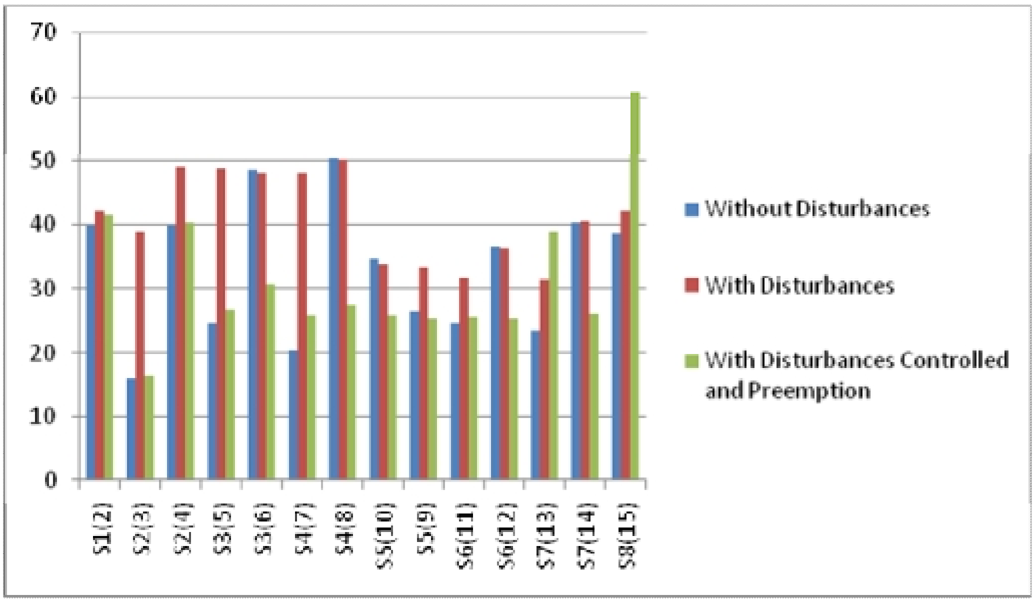


Figure 24 Comparisons of Standard Deviation of Headway at Each Station (s)

From newspaper and internet sources, we are able to identify that S8 (15) is the busiest station of all. Figure 25 shows the average bus number that arrive at S8 (15) in the three scenarios. We can observe that during the 52 minutes, in scenario 1 the number of buses that pass S8 (15) presents a wide range of variation; in scenario 2 the dispersion of the value reduces as well as the total number of bphpd; while in scenario 3 the number of buses per minute is more steady and homogeneous. This result indicates that preemption and disturbances' control may improve the efficiency of the corridor's usage.

However, as discussed already, the corridor manager should also pay attention to the specific indicators along with the average value. Because traffic light preemption gives priority to buses, this could also lead to the bunching of buses at specific stations. In scenario 1 and 2, the maximum numbers of buses during one minute is 8, while in scenario 3 the number becomes 12. Although this value is dependent on the time limits established for the assessment, the manager should pay more attention to the stations that are near the intersections with preemption control to avoid the bunching effect. This can be also avoided by a close coordination again with the traffic control entity, which may aid the bus corridor manager to have a steady operation by changing traffic lights in all the intersections of the network, avoiding bus bunching on a specific station.

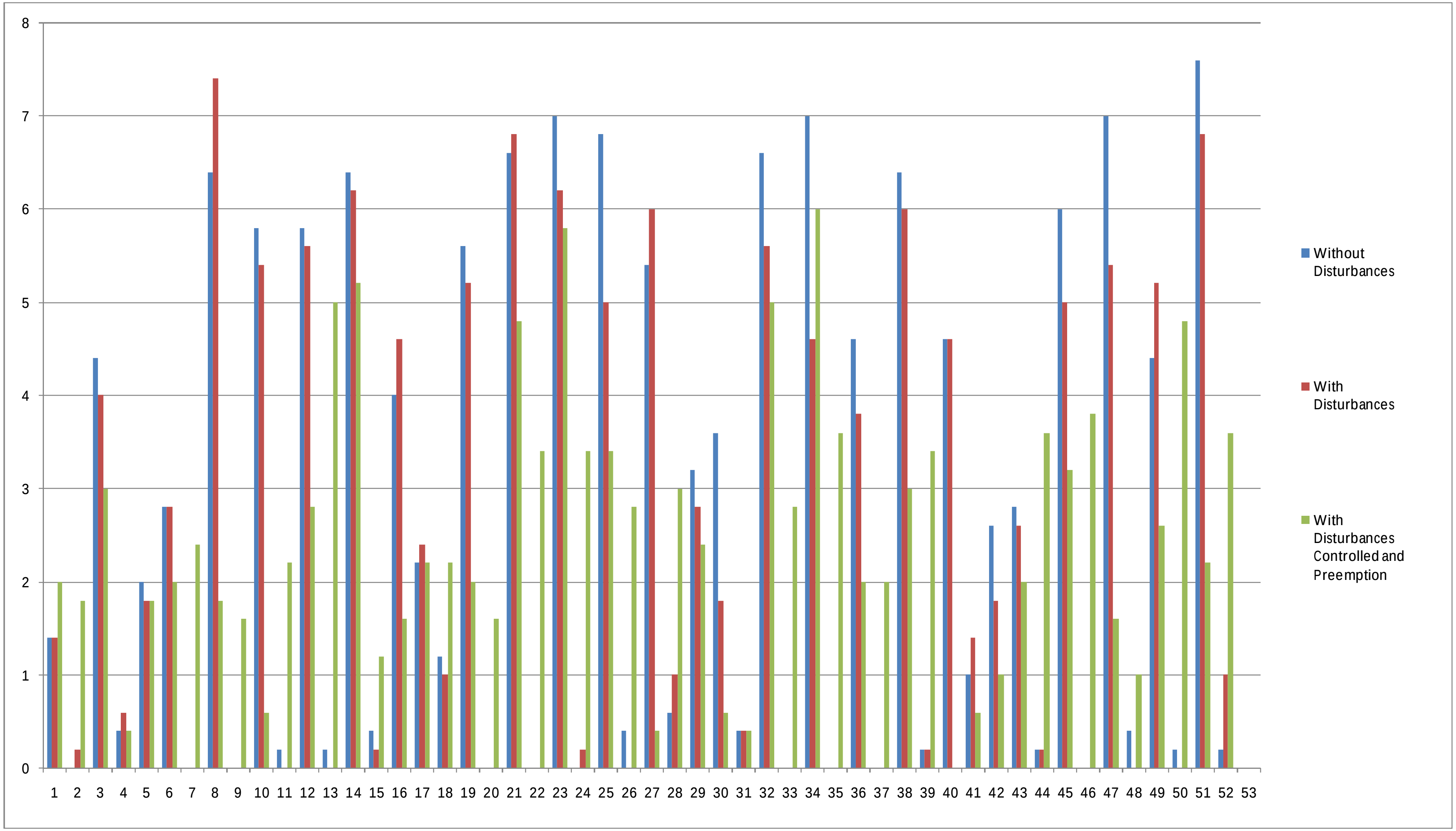


Figure 25 Average Bus Number that Arrive at S8 (15) of the Three Scenarios

VI.9 Analysis for the BRT System Client

For this kind of agent, Figure 21 and Figure 22 can also be used for evaluation, although using a different interpretation of the obtained results.

Figure 21 shows that disturbances will not increase significantly the average headways of BRT lines and that the preemption will reduce the average headways of BRT lines. So, from the perspective view of the passengers, they would like to have preemption along the BRT corridor but don't care about the disturbances.

However, after analyzing Figure 22, the BRT client may also be concerned, since the disturbances will make the schedule of the BRT lines unpredictable, which is not acceptable at all for the clients who have their own schedule and that need BRT lines arrive on time. The preemption control does not make the stability of most BRT lines worsen; showing that it may be a possible instrument from the clients' perspective.

One more indicator that the passenger would like to pay attention to is the average travel time of each line.

Figure 26 shows the average travel time of each line in the three scenarios. We can see that for the first half of the BRT lines which are moving wholly inside the corridor, disturbances don't have much impact on the travel time, while preemptions can reduce the travel time for the passengers, which is preferable to the passengers. For the rest BRT lines which are partly using the corridor, the disturbances have negative impacts towards B8 (45) and B8 (46), while preemptions have negative impacts towards B6k (39) and B7 (43). This is because for the long travelling period when dividing the time lost by the disturbances to the whole journey it won't actually have those obvious differences as the headways do. The result will be obvious only if the bus line is passing by a lot of disturbances. The preemptions are located along the corridor and will benefit the bus lines that are passing through the corridor together. The more stations in the corridor that the bus lines stop, the more benefit they can get from the preemptions. For those lines who suffer longer travel time the reason is explained already in the previous section, when the buses have to turn left to enter in the corridor, they will be blocked outside of the corridor because the buses which have straight direction routes in the corridor have priority to pass first. In this figure one more thing should be noticed that line B15 (53) don't have travel time in any of the three scenarios. It may be because that B15 (53) has the longest routes of all the bus lines and its route located along the most congested area of the network. It is very possible during the peak hour one hour is not enough for a single bus to start from the origin station to the destination station.

Table 16 Average Travel Time of the Total System

	Scenario 1 (s)	Scenario 2 (s)	Scenario 3 (s)
Average Travel Time	1090.598	1149.738	1044.250

Table 16 generates the average travel time of the total 62 bus lines in the three scenarios. From this we can see that on average, disturbances are increasing the travel time of buses but preemptions are decreasing the travel time.

We can conclude then, both disturbances control and preemption are positive to the BRT system client. To minimize the unstable schedule of BRT lines, it is necessary to have the adjusted schedule of each line time by time announced to the client by Internet or electronic boards.

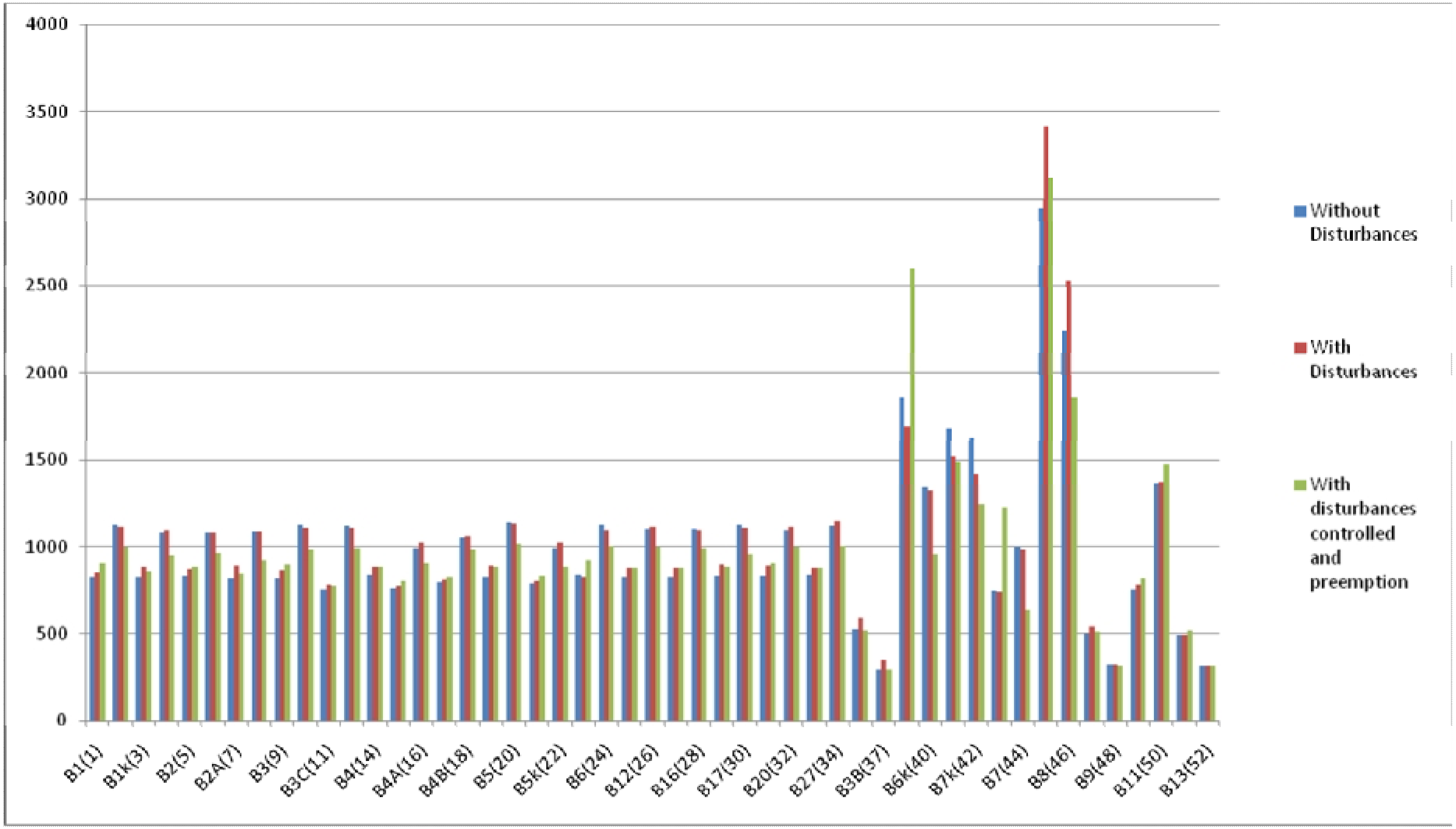


Figure 26 Average Travel Time (s)

VI.10 Analysis for Private Car User

As stated above, most of the private car users will not be impacted significantly by the proposed traffic controls. In this section we aim to focus on a sub-sample of the general car users, which may be affected the most from the controls.

From the perspective of disturbances, the private car users present similar concerns than public line operators, as they are impacted in the same way by disturbances. So, in this section we mainly focus on the impact of preemption in the performance to the private car users. Table 17 and Table 18 present a list of sections where preemption will has some influence.

Table 17 Section Information without Disturbances

Section ID	Average Speed (km/h)	Standard Deviation (km/h)
356	24.538	28.146
420	66.600	66.392
422	53.590	56.017
502	8.690	3.574
510	22.420	24.916
516	4.588	2.153
519	49.035	51.207
649	24.733	23.867
676	2.911	4.054
677	3.698	6.531
4108	17.402	24.778
5731	10.993	20.690
6217	10.623	0.595
6232	36.391	36.737
6241	34.990	35.302
6265	34.921	35.421
6268	31.786	33.941
6269	35.128	35.432
6270	4.153	7.626
6271	14.513	16.176
6285	34.378	34.461
6338	1.550	1.489

Table 18 Section Information with Preemption

Section ID	Average Speed (km/h)	Standard Deviation (km/h)
356	13.180	13.271
420	9.589	8.947
422	7.815	7.833
502	5.650	3.595
510	5.934	5.350
516	1.220	1.185
519	3.832	4.083
649	9.303	9.825
676	2.284	3.269
677	3.231	5.128
4108	13.450	13.379
5731	11.111	14.035
6217	10.021	0.100
6232	2.315	2.070
6241	2.289	2.296
6265	2.649	2.651
6268	4.702	3.839
6269	2.465	2.413
6270	2.212	4.053
6271	11.036	12.034
6285	2.466	2.340
6338	0.711	0.832

From Figure 27 and Figure 28 we can see that only two sections' speed have reduced their speed, presenting all the others the same level or even slightly improved. Normally it is considered that the preemption will bring delay for the non BRT vehicles, but in this case, the speed hasn't change a lot. It may be because in order to let the BRT buses keep a regulated schedule, we set the minimum green time for the bus lines at least 60 seconds. It makes the waiting time at other lanes very long. After the preemption is introduced, the buses will have no more consistent green light. Thus there are chances that the waiting time on the other lanes may have decreased.

One thing that should be noticed is the considerable degradation of section 6217 after the preemption is settled. Its average speed is only 0.60 km/h and its deviation is 0.1 km/h. It means the traffic is nearly stopped by the preemption. We can also conclude that most of the vehicles on section 6217 are turning left at the intersection. To solve this problem, the traffic lights operator of that intersection should reduce the priority of the BRT buses which are heading straight or right directions at that intersection to let the private cars turn left. Meanwhile, this control measure will also help the BRT corridor operator control the number of buses that are coming at the same time at S7 (14).

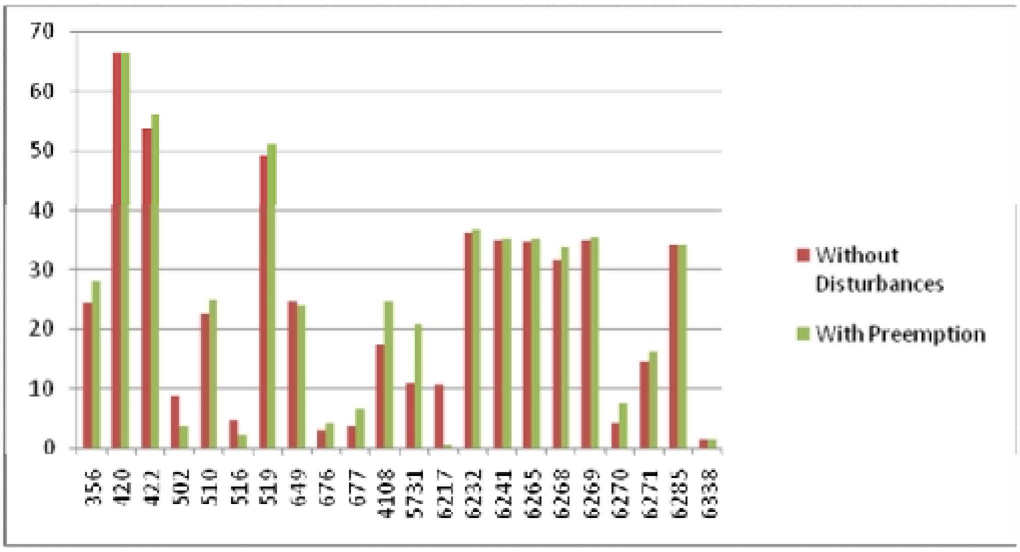


Figure 27 Speed comparisons between Scenario 1 and 3 (km/h)

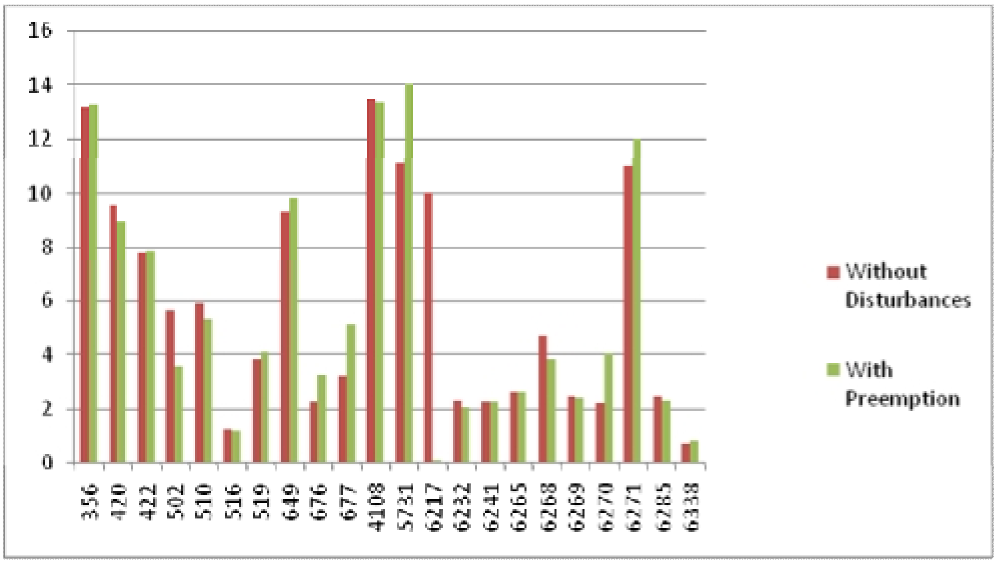


Figure 28 Speed Deviation comparisons between Scenario 1 and 3 (km/h)

For conclusion, most of the time private car users will not be influenced by the public transport control measures. But, in very specific situations, the private car users would like to have disturbances controlled and preemptions adjusted when the balance is unsettled.

VII. Conclusions

GBRT is the second best performance BRT system in the world, with very specific characteristics that convert it in very interesting case study. The simulation and evaluation of this system may produce relevant insights and lessons for the implementation in other cities and in further develop the used procedures for BRT operation around the world.

This dissertation, although developed mainly from synthetic data, had the concern to obtain plausible inputs that were validated with formal and informal data available in the internet, and also with some assistance from students in the city of Guangzhou, which helped obtaining and validating data.

The model developed for this dissertation tries to be the most realistic as possible by integrating the main characteristics of the network of the case study. The lack of real data and the need of detailed network definition, led to long data preparation process. With the network model calibrated, several scenarios of traffic behavior and control were tested: the GBRT network as without disturbances, with disturbances and with disturbances controlled and preemption added. The outputs of the three models are used for evaluating the performance of GBRT according to different level of control from different perspective views of the agents involved in.

The results of the evaluation show that for different agents the controlling policies have different answers. For BRT line operators, disturbances must be controlled but preemption should be considered carefully. For BRT corridor managers, disturbances as well must be controlled and preemptions are also welcomed. For public system users, both disturbances controls and preemptions can bring better performances. For private car users, normally neither of those two controls would have much impact towards them but when necessary disturbances must still be controlled, but while preemption is implemented in the network, the authorities must adjust the priority time by time otherwise the preemption will bring obstacles to other lanes.

The case study of GBRT shows that open BRT systems are a very complicated system, requiring more complex operation and control systems than closed ones. Every small improvement or change suggested by one group of the agents must have unexpected or disproportional impacts in other agents. Meanwhile, to maintain the system at a positive operating environment, all agents should cooperate establishing a common evaluation framework of efficient transport. If the cooperation is achieved, the open BRT systems will perform much better than the closed, due to its ability to reduce the numbers of transfers required to travel between different city areas.

Some of the mechanisms to model traffic perturbations and its control mechanisms discussed and modeled in this dissertation could be easily further refined in next steps of this research, which may improve the accuracy of some of the conclusion drawn in this study. Nevertheless, the results obtained can be used as guidelines prior to implementation of new BRT system, allowing a more sensible selection of the operation scheme during the design phase of new BRT systems.

	Disturbances	Preemption
BRT line operator	Control	Carefully treated
BRT corridor manager	Control	Welcome
BRT system client	Control	Welcome
Private car user	Control	Carefully treated

From this dissertation, when considering operating the same system in closed BRT systems, there are some details that should be considered differently. The good side is that there is no need to consider the negative impacts of preemptions and disturbances and the qualitative services can also be guaranteed. But the closed one needs bigger transfer stations at the entrance and exit of the corridor for the huge amount of transferring passengers, meanwhile the first and the last station of the corridor must be operated carefully because both transfer buses and BRT buses are connected there. Here we will make some qualitative evaluation also based on the four agents. Four BRT line operator and corridor manager the closed system can simplify the operation complexity and they will have higher revenue stream because closed system normally have higher passenger volume than open system. For BRT client, it is not good because it will take longer transferring time. For private car user, to satisfy the high passenger volume inside the corridor the bus company must provide more conventional buses because of their relative small size, this makes the road network related to the corridor more crowded.

For further development, we will consider the multiple different control plans' impact towards the network. And we'd like to put more effort on obtaining the actual data of the case of GBRT. Thus we'll be able to make this model more realize and contribute more to the other cases. Meanwhile we are also considering applying the same model to the closed system and compare the different performance of the different systems.

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Appendix: OD Matrix

id	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1,388	340	32	204	18	38	127	61	55	90	466	124	160	89	1,165	48	113	23
2	91	292	5	29	4	13	49	20	21	17	35	16	72	47	393	44	128	53
3	36	18	79	8	6	7	181	2	14	9	11	6	4	2	7	2	6	3
4	298	148	20	1,616	18	2	17	1	0	0	0	0	0	0	2	0	0	0
5	17	8	17	21	57	37	821	31	179	78	86	80	63	16	45	6	22	14
6	15	7	16	16	13	2	57	3	10	3	3	3	0	0	3	0	1	4
7	186	69	566	229	721	86	945	22	10	3	3	5	9	19	59	2	5	3
8	8	3	27	12	31	4	11	5	2	0	0	1	2	0	5	0	1	1
9	528	125	63	40	49	27	73	17	261	58	70	105	115	74	234	12	27	19
10	253	65	32	44	52	13	35	8	103	144	45	49	74	31	101	8	14	11
11	43	11	6	11	12	1	5	1	14	19	24	2	13	5	17	1	3	2
12	252	63	60	109	106	19	30	6	66	130	131	111	29	28	89	11	26	20
13	140	34	33	60	59	14	64	12	91	182	184	25	16	14	45	6	14	12
14	7	1	0	0	0	0	4	0	7	9	9	3	0	1	2	0	1	0
15	952	223	13	73	6	10	64	11	56	197	542	91	53	22	375	11	27	5
16	121	28	18	9	2	7	98	5	9	17	90	22	16	7	36	21	30	5
17	166	40	34	16	4	13	191	10	16	15	43	18	24	11	54	19	81	9
18	193	94	156	85	7	19	57	15	14	11	42	16	12	7	27	8	24	141
19	9	2	8	10	8	2	55	1	13	4	5	5	0	1	2	0	1	0
20	16	4	1	1	0	0	5	0	1	2	9	3	2	2	5	1	1	0
21	14	4	7	4	12	2	8	2	4	1	2	2	2	1	5	1	3	2
22	10	4	5	3	10	3	10	2	5	2	2	3	2	1	4	1	2	2
23	4	0	1	2	2	0	4	1	1	0	1	1	0	0	2	0	0	0
24	39	13	18	12	34	14	41	10	20	6	7	10	12	4	13	3	9	7

25	96	30	107	128	94	11	167	7	10	5	7	5	8	6	19	3	8	3
26	32	8	9	16	16	4	67	8	162	212	218	44	22	3	11	2	4	4
27	10	2	2	4	2	0	7	1	15	28	30	3	3	1	3	0	1	0
28	135	31	5	10	1	3	56	5	95	198	216	35	19	9	40	2	5	2
29	2	2	4	4	2	0	3	1	1	0	0	1	0	0	1	0	0	0
30	108	53	224	174	196	20	164	29	7	3	4	4	5	14	45	6	17	6
31	12	6	1	20	1	0	1	0	0	0	0	0	0	0	0	0	0	0
32	14	7	1	22	1	0	1	0	0	0	0	0	0	0	0	0	0	0
33	30	15	100	50	102	15	92	20	3	1	1	2	3	5	16	2	4	2
34	43	21	142	70	145	21	131	27	5	1	2	3	4	7	23	3	5	2
35	137	61	5	37	3	6	22	5	6	11	33	9	9	4	51	2	4	1
36	88	39	4	24	4	5	7	2	20	23	23	13	20	6	39	2	4	1
37	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
38	2	0	0	0	0	0	0	0	1	1	1	0	0	0	1	0	0	0
39	40	9	10	18	18	4	7	2	17	22	22	12	6	5	14	2	4	4

id	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
1	39	13	91	62	13	46	51	276	173	92	12	39	22	88	5	6	1,005	214	44	31	86
2	17	8	49	32	5	20	20	88	107	49	6	6	4	14	2	2	62	13	6	15	18
3	11	2	11	9	5	8	14	13	3	2	1	3	2	4	10	14	40	9	2	1	3
4	2	0	2	1	0	0	2	2	1	0	0	64	67	224	5	6	331	71	14	0	0
5	61	16	82	64	83	61	58	63	25	8	15	14	4	10	43	51	17	4	1	4	29
6	3	0	5	14	5	14	3	6	1	0	6	3	1	3	17	17	13	2	0	0	0
7	14	16	20	23	7	26	82	471	7	12	6	138	40	67	200	225	189	68	14	1	2
8	2	0	3	3	1	4	11	24	1	0	1	1	1	2	3	3	10	5	0	0	1
9	12	13	52	64	10	71	11	803	52	48	6	14	4	7	19	21	58	99	25	11	41
10	19	7	24	30	5	33	17	492	29	21	3	7	2	4	9	10	34	61	14	6	17

11	4	1	4	4	1	5	4	20	6	2	0	1	0	1	1	1	7	3	3	0	3
12	40	13	76	31	3	29	34	212	42	18	4	26	9	16	9	10	68	26	7	8	22
13	23	7	47	58	7	58	20	94	25	9	8	16	5	10	19	21	38	11	4	9	11
14	0	0	0	1	0	1	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0
15	13	3	21	18	7	17	12	76	42	23	4	15	8	32	4	4	19	11	10	8	41
16	10	4	23	19	2	18	9	25	14	7	3	7	2	4	7	9	25	6	3	2	11
17	21	9	46	38	5	36	18	36	21	11	7	12	3	7	15	18	46	11	5	4	15
18	25	7	39	29	4	27	25	27	15	6	5	18	12	42	2	3	199	43	9	2	7
19	4	1	4	3	8	3	3	3	1	0	1	2	1	1	2	2	8	1	0	0	0
20	0	3	1	1	0	1	0	4	3	1	0	0	0	1	0	0	1	1	0	0	2
21	4	2	16	10	1	9	4	7	2	1	1	3	1	1	3	4	7	2	0	0	1
22	3	1	10	17	1	12	3	10	2	1	1	2	1	1	3	3	6	1	0	0	1
23	1	0	1	2	1	2	1	9	0	0	0	1	0	1	1	1	1	0	0	0	0
24	12	4	36	46	6	63	10	41	8	3	3	9	3	5	11	12	22	5	1	1	4
25	25	6	34	27	3	25	326	20	10	4	5	18	13	53	12	14	95	8	2	1	2
26	6	2	12	11	6	11	5	56	5	2	2	4	1	3	4	5	11	4	2	2	21
27	1	0	1	1	0	1	1	4	6	1	0	0	0	0	0	0	2	1	0	0	3
28	5	2	10	9	5	9	4	28	16	21	2	3	1	4	4	4	5	3	2	4	16
29	1	0	1	1	0	2	1	2	0	0	1	1	0	0	1	1	2	0	0	0	0
30	60	15	76	36	4	20	35	54	24	9	4	231	81	117	171	191	120	25	5	3	1
31	0	0	0	0	0	0	0	0	0	0	0	9	28	0	1	1	14	3	1	0	0
32	0	0	0	0	0	0	0	0	0	0	0	10	0	18	1	1	15	3	1	0	0
33	22	5	14	8	2	8	17	41	7	3	2	82	22	32	339	17	34	8	1	1	1
34	31	7	20	11	3	12	24	58	10	5	3	116	32	45	21	440	48	11	2	1	1
35	6	1	9	6	2	4	7	18	7	4	1	7	4	16	1	1	247	45	9	1	4
36	6	4	7	6	1	6	6	309	6	3	1	6	3	10	2	3	137	47	6	4	7
37	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2	0	0	0	0

38	0	0	1	1	0	1	0	2	0	0	0	0	0	0	0	0	1	0	0	0	0
39	6	2	14	5	1	6	6	28	7	2	1	4	1	3	2	2	12	3	1	1	7