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**MULTI-SCALE AND MULTI-MODAL GIS-T DATA MODEL
A CASE STUDY FOR THE CITY OF GUANGZHOU, CHINA**

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ABSTRACT

MULTI-SCALE AND MULTI-MODAL GIS-T DATA MODEL

RESUME: Les transports urbains connaissent des développements réguliers de plus en plus influencés par leurs impacts sociétaux, économiques et environnementaux. La prise en compte croissante des concepts de développement durable et de préservation de l'environnement impactent en effet la fonction et le rôle des transports publics. Les villes et mégalo-poles qui connaissent une forte croissance démographique, et une pression accrue en termes d'occupation de l'espace, abordent désormais leur développement et la restructuration de leurs transports urbains comme un élément significatif de leurs politiques urbaines. Cette tendance est accentuée par une forte demande de la population en termes de développement raisonné, de meilleure qualité de vie et de réduction de la facture énergétique. Les sciences et les technologies de l'information sont toujours à la recherche de meilleures solutions permettant la modélisation, l'analyse et la gestion des transports et des mobilités urbaines. La recherche en géomatique et en systèmes d'information géographiques développent en particulier des solutions de gestion et d'aide au développement de systèmes de transport prenant en considération la complexité et les contraintes du milieu urbain. Dans ce cadre, cette thèse aborde les méthodes et les principes de modélisation qui au sein d'un système d'information géographique permettent la conception et la gestion d'un système de transport urbain multimodal. La recherche présentée intègre les dimensions spatiales et temporelles d'un système de transport urbain, à différents niveaux de granularité, au sein d'un modèle de données spécifiant et permettant l'évaluation des systèmes et des services de transport urbains. Le modèle de données et de méta-données proposé émerge d'un ensemble d'objectifs, de besoins et de contraintes spécifiés par les services des transports de la ville de Guangzhou en Chine. Les concepts abordés sont mis en œuvre au sein d'un système d'information du district de Tianhe, district représentatif des phénomènes de transports multimodaux de la ville de Guangzhou. Le prototype développé illustre l'implémentation du modèle proposé, et permet la conception d'applications et de services tels que la planification de trajets. Cette approche de conception d'un système d'information géographique en transport a pour objectif d'assister à la fois les organismes publics dans leurs missions de gestion et de développement mais aussi les usagers en proposant des services de transports optimisés.

Mots-clés: *Système d'information géographique en transport, réseaux de transports multimodaux, modélisation de données orientée objet*

ABSTRACT: Urban transportation development is undergoing continuous change often prompted by the society, economy and environment, and policy-directed responses. The role of public transportation becomes increasingly important with the changes of demographic and economic patterns. The trend of better urban living for inhabitants has significantly increased the demand for efficient and sustainable public transportation in urban area. Although information sciences and technologies have provided many solutions to transportation sustainable development, the transportation network data modelling issue continues to be a challenge due to the complexity of urban systems. GIS appears as an appropriate technology for spatially and temporally referenced data. This thesis investigates how non-spatial, spatial and temporal data can be integrated within a data model of multi-scale and multi-modal GIS-T to formulate and evaluate transportation service and development. The model was developed based on a set and specific objectives, requirements and criteria. The set criteria are proposed taking into consideration the objectives to improve the development and accessibility of multiple transportation networks. A case study is undertaken within a selected transportation system in the city of Guangzhou, China. The prototype system implements appropriate multi-modal transportation applications and services in a GIS environment, which can be identified taking into account the needs of multiple transportation modes. The approach assists in the planning and development of a multi-modal transportation network, and thus optimizing usage of transportation GIS applications.

Keywords: *Geographical Information System for transportation (GIS-T), multi-modal transportation network, object-oriented data modelling*

摘要

多模式交通是未来城市交通的重要形式，它要求每个运输模式平衡发展并发挥其最好的服务性能以促进城市交通发展的可持续性。但是多模式城市交通网络的运输效率不是由运输模式的数据决定，而是在于管理和维持高效的网络可达性和模式间交互性和协调性，并且充分考虑到公共交通服务的质量。这就必须依靠对可靠交通数据和信息的获取。地理信息系统 (Geographical Information System, GIS) 在城市交通信息系统的应用，包括数据获取、表达、共享、服务、分析和融合，进一步发展和丰富城市交通 GIS 信息模型，最终为城市可持续发展服务。因此，多模式城市交通网络地理数据的集成和表达已经成为交通地理信息系统 (GIS for transportation, GIS-T) 研究领域中的一个重要课题。

论文提出了一种面向多尺度多模式的交通地理信息系统模型以支持不同交通网络地理数据的集成化、模型化和空间数据管理，分析和表现。多模式城市交通地理信息系统模型考虑到不同交通模式网络，包括城市道路，公共汽车线路，地铁线路和步行设施，如人行天桥、地下通道和斑马线等。交通线网的多尺度表达允许不同的交通地理信息系统应用和专门化信息服务的开发和实现。论文研究从单一模式交通地理信息系统发展到面向多模式交通地理信息系统，并实现交通网络信息的多尺度表达，即交通网络在多种抽象水平下表达以满足不同应用需求，增强交通数据模型的通用性和实用性。在概念和逻辑层面上，论文应用面向对象建模方法实现多模式城市交通网络数据建模，并基于 ESRI MapObjects 二次开发组件开发原型系统。统一建模语言(Unified Modelling Language,UML)集成

和扩展面向可视化语言插件(plug-in for visual languages, PVL)将不同交通线网集成于一个综合信息模型框架中,实现交通地理信息时空特征关系一致性描述和参照。原型系统应用在广州市多模式交通系统中进行可靠性和实用性验证。

关键词：交通地理信息系统、多模式交通网络、面向对象建模

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Chapter 1

INTRODUCTION

1.1 Context of the research

Nowadays, the concept of sustainable development becomes a key factor in the planning of modern cities. This trend is closely related to the improvement of the quality of life in a city, including the ecological, cultural, political, institutional, social and economic components without leaving a burden on the future generations (Rees and Roseland, 1991). Sustainability influences public policies, thereby favouring the development of better urban environments, and improving quality of life. This implies the availability of urban transportation modes and their effective accessibility, efficient coordination and high-quality information-based services. However, this is crucial as the continuous growth of world populations which has led to the emergence of modern megalopolis where urban transportation planners and decision-makers face extremely complex challenges. By 2007, more than 50 percent of the world's population lived in urban areas, and most of these dwellers are depending upon public transportation modes to meet their mobility needs (Stella *et al.*, 2006). Urban transportation is a fundamental mean to allow access to jobs, markets, education, health care and other primary services and leisure; it is a vital asset for the development of modern cities. Urban transportation has focused on the movement of individual commuters, as cities were viewed as locations of utmost human interactions with intricate traffic patterns linked to commuting, commercial transactions and leisure/cultural activities (Rodrigue, 2006). Nevertheless, conventional strategies of transportation development tend to suppose transportation development is linear, consisting of newer, faster modes (i.e., automobile) which replace older, slower modes (i.e., walk, bicycle and train/bus). This implies that the older modes are unimportant, thereby concluding that there is no harm if increasing automobile traffic causes congestion delay to public transit, or creates a barrier to pedestrian travel. Directed such strategies, it would be backward to give public transit or walking or cycling priority over automobile travel. Nevertheless, transportation sustainable development requires a coordinate concept that involves each useful mode, and strives to create a balanced transportation system which uses each mode for what it does best (VTPI, 2007). This presents a need of novel strategies to direct urban transportation sustainable development. The sustainable development of transportation reflects the efficient transport of passengers and goods, and effective freight and delivery systems.

The coordinate concept stresses the integration and parallel improvement of multiple transportation modes, which leads to transportation progress involving improvement of all useful modes (including walk, bicycle and train/bus), not just the newest modes, i.e., automobile. This implies that priority should not just give to faster, motorized modes over slower modes. This presents that increased travel speed is not the unique important qualitative factor in urban transportation development. Other qualitative factors need to be considered to improve high-quality accessibility to transportation services and connectivity of, and interaction, between transportation modes. This implies an adapted transportation information system which can be designed as a source of reliable data and thus information to facilitate all of activities that involve the use of information technologies for some aspect of transportation management, planning or information services.

The need for reliable data and information has motivated and favoured the application of Geographical Information Systems (GIS) to transportation systems (Thill, 2000). GIS can be defined as an information system to the integration, modelling, analysis and visualisation of geo-referenced information (Aronoff, 1989). Miller and Shaw (2001) defined GIS for transportation (GIS-T) as the principles and applications of applying geographic information technologies to transportation problems. GIS-T could help transportation planners and decision-makers to take better decisions, and provide high-quality spatial information-based services to the end-users. Moreover, one of the specific peculiarities when designing a GIS-T is that available networks can be represented at different granularities in order to reflect multiple abstraction levels used for either planning or managing tasks, or performing a decision-support system to the end-users (Mc Cormack and Nyerges, 1997). Nevertheless, the urban transportation modes are usually varied as these include street, bus, rail (metro), walking or cycling route networks and their interconnections. A crucial issue when delivering transportation information services to planners or end-users is the combination of these transportation networks. This implies that it needs to implement the integration of the traffic connections (derived from traffic-oriented rules or restrictions) and spatial connections between these transportation networks. This represents the static component of a multi-modal and multi-scale transportation GIS, to be completed by the dynamic properties of such a system (Goodchild, 1999). This implies the representation of the behaviour of discrete mobile objects, e.g., vehicle, people, buses, or metro, within the transportation system, such as a displacement over a given period of time between an origin area and a destination area (Fletcher, 1987). Moreover, this represents the integration of the static and dynamic components of a network system at different levels of abstractions (Etches *et al.*, 1999). In short, GIS-T models could be combined with origin-destination surveys and behavioural frameworks in order to study and understand the transportation patterns and trends that emerge from a given urban system (Lee-Gosselin and Doherty, 2005).

1.2 Research motivation

Multi-modal transportation is an important pattern of urban transportation systems. A multi-modal or inter-modal urban transportation system can be defined as the use of two or more modes (e.g., automobile, bus, tram and metro) involved in the movement of people or goods from an origin to a destination (Dewitt and Clinger, 2000). Large cities around the world, such as Hong Kong, Paris, London, Beijing and Guangzhou, have developed complex multi-modal transportation systems. Multi-modal transportation is increasingly recognised as an important transportation strategy by transportation

planners and decision-makers, which can support urban development (Krygsman, 2004). In these cities, the main objective of urban transportation units is not only to design, build, manage, and extend transportation networks, but also to emphasize the achievement of high-level accessibility to, and interaction between, these transportation systems, taking into account the value and quality of services provided to their inhabitants. This gives rise to efficient transportation systems in large urban areas to deal with the constant traffic pressure due to constant augmentation of urban mobility demand.

It appears that quality of multi-modal urban transportation system is determined not only by availability of main transportation modes, but also by accessibility to, and coordination/interaction between, these modes and services. This implies the re-consideration of the approaches which support the management and planning of the transportation network, and deliver information-based services to end users, in particular to commuters. However, multi-modal urban transportation system also leads to complex transportation networks where the integration of data becomes a large and not straight forward issue (Krygsman, 2004). This implies some crucial requirements that need to be addressed. These requirements involve topology structures and multiple data representations. As different transportation networks involve different spatial distributions and traffic-oriented rules/restrictions applied, it is important to implement an integrated topology structure of a multi-modal transportation network, taking into account the networks represented at different scales. Multi-level representation of transportation networks incorporates in different applications of multi-modal transportation modes which often require data representation at appropriate granularities.

In response to the issues and requirements outlined above a lot of attention in recent years has been given to potential GIS-T applications that can integrate GIS and multi-modal urban transportation systems (Claramunt *et al.*, 2006). Many research avenues have been discussed and studied in the GIS and transportation research communities, such as the representation of multiple transportation modes, multi-modal network topology, and trip planning. This brings forward the role of integrated GIS-T as a source to provide applications to meet the needs of different modes, either public or private.

In China, the city of Guangzhou has appeared as a dynamic city where a large amount of urban mobility demand needs to be dealt with. This makes a great impact on the development of urban transportation and the benefits for citizens. GIS applications to the urban transportation networks, particularly the public transit networks of bus and metro modes, have been developed in the city. However, these applications are not retained to meet the needs of multiple transportation modes. Each application only represents transportation data at a single level of abstraction for a specific application purpose. This presents the need of multi-modal transportation applications, involving multiple data representation management, network planning and information services. These applications incorporate with the sustainable transportation development which requires the parallel improvement of all the useful modes (including automobile, bus, metro and walk). This implies that the designing and implementation of an adapted transportation GIS, i.e., a multi-modal and multi-scale transportation GIS, are needed. The system encompasses the set of functions to apply GIS technologies to incorporate in the multi-modal GIS-T applications in a multi-user computer environment.

1.3 Research objective

Regarding the research context and motivation outlined above, the study presented in this thesis aims to introduce the principles to design, develop and implement a multi-modal and multi-scale transportation GIS data model. This involves an important topic pointing to the representation of multiple transportation modes and topology structures in a GIS environment. This implies special data structure to support multi-modal network analysis, particularly multi-modal routing process. A prototype system is validated for the experimentations of the functionality and practicability of the transportation GIS. The scenarios of multi-modal and multi-criteria routing applications are implemented at the end-user level, which are carried out by the prototype system. The routing applications are supported by added-value interfaces and services which promote multi-criteria selection of transportation modes and transfer information to the end-users. In addition, the routing models could facilitate the network analysis/evaluation based on any possible path identification between an origin and a destination. Other analysis related to networks, such as service coverage, are implemented in the prototype system which could be performed as a decision support system on network management and planning to urban planners and decision-makers. In short, the research objective presented is to provide multiple levels of services: (1) a decision-aided system for urban planners and decision-makers; (2) a flexible interface for multi-route planning at the end-user level. Moreover, the approaches to implement the objectives were also generally discussed.

In order to meet the research objectives presented above, research issues and needs of multiple transportation modes are discussed and identified in the modelling of multi-modal and multi-scale transportation GIS. Figure 1.1 illustrates the context of the research involving three parts: “research issues and needs”, “information technology” and “applications requirements”. The application requirements are identified by an extensive study of the transportation patterns, travel behaviours, and transportation applications particularly for the city of Guangzhou. The application requirements reflect the needs of multi-modal transportation networks. This also presents the issues and needs of the integration of GIS and multi-modal transportation systems. The needs and issues motivate the research objectives.

The information technology presents the investigation and exploration of the modelling approaches involving the transportation software and application development in a GIS framework. The modelling approaches applied to the multi-modal transportation networks are represented and verified by an experimental case study which is implemented in the urban transportation networks of the city of Guangzhou, and are supported by an object-oriented visual modelling language, i.e., the unified modelling language (UML). This involves the adaption, integration and extensions of spatial and temporal UML-based semantics to accommodate the description of transportation object and topology modes. In the modelling process, plug-in for visual languages (PVL) (Bédard, 1999) are applied to implement the extensions of the UML semantics. At the conceptual levels, a first cut of conceptual structural object architecture is built to represent the conceptual object model. At the logical levels, multi-modal transportation network is modelled and represented with special network topology structures by adapting UML-based notations and constructs. This implies the implementation of multiple representations of network components and topological structures. This presents an integrated network topology model which could provide set of principles to support transportation applications, as the connectivity of multiple transportation networks are identified, which involves spatial connections and traffic (semantic) connections derived from traffic-oriented restrictions and rules. This reflects the key research objective which aims to address the integration of different transportation networks, and the

representations of multi-scale transportation objects which are used to implement the different levels of interpretation of an urban network. This is important to take the transportation network from one data source in a multi-user context (commuters or planners).

The GIS software of the prototype is designed and implemented based on a collection of embeddable mapping and GIS components. ESRI MapObjects (ESRI, 2008) is applied to facilitate the designing and development of the prototype system. The software development project is experimented as a case study applied to the multi-modal urban transportation networks of the city of Guangzhou in China. The experiment is realised in close collaboration with the GIS centre of the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIGCAS), and Guangzhou CASample Information Technology Co., Ltd. These two institutions provide information-based data and services for the development and co-management of this project.

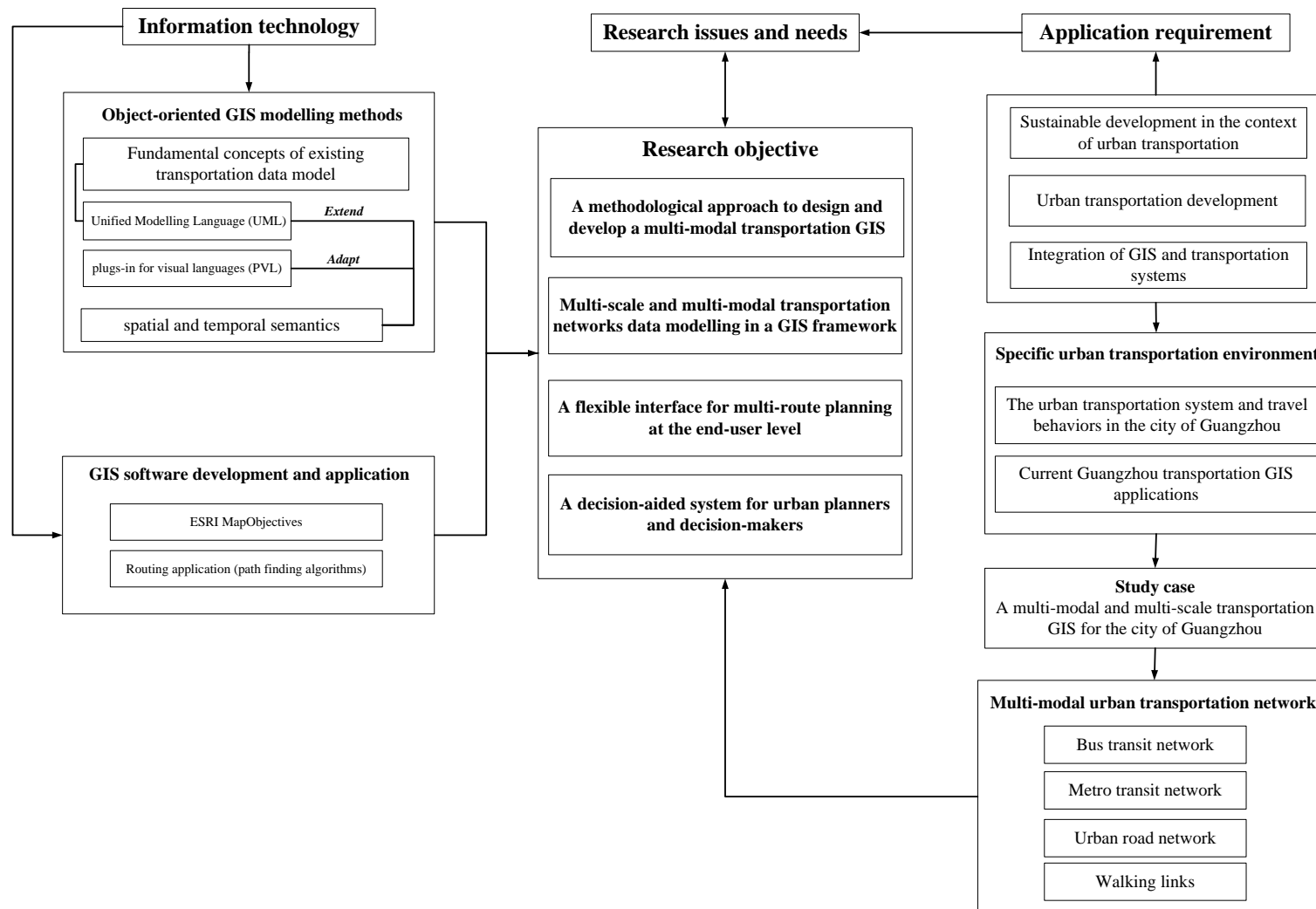


Figure 1.1 Research and development framework

1.4 Outline of the thesis

The thesis is organized by five chapters. This first chapter provides an introduction to the research context and presents research motivation. Research objective and approach are briefly introduced.

Chapter 2 provides a review of urban transportation systems of the city around the world, and particularly for the cities in China. A detailed and extensive study of a specific transportation environment, i.e., the urban transportation patterns and travel behaviours in the city of Guangzhou, is provided. Needs and issues in the context of transportation development are identified at both municipal and national levels, taking into account the experiences and practices of urban transportation development around the world. The chapter also provides a review on the integration of GIS and transportation systems, and applications of transportation GIS in the context of the city of Guangzhou. Regarding the users' needs to multi-modal transportation GIS, and issues towards to a multi-modal transportation GIS, the chapter investigates existing GIS-T data models and standards. This aims to explore the multiple data representation concepts, GIS data modelling, and object-oriented modelling method (i.e., UML), in order to clarify the needs and issues of the research. Transportation GIS development and routing application are finally studied.

Chapter 3 proposes a multi-scale and multi-modal urban transportation GIS model. A conceptual view of the object models is illustrated, followed by the design and implementation of a logical network topology model, with discussion of multi-scale transportation data modelling and representations. The descriptions of the components of the logical data models explain what each object class represents and how it functions. Topology and temporal referencing methods are also an important topic in this chapter. Connectivity for building interconnection between objects, i.e. spatial-based and traffic-based, are also highlighted. On top of the network topology model, multi-modal and multi-criteria route planning are finally discussed in detail.

Chapter 4 presents a multi-modal transportation GIS prototype applied to the urban system of the city of Guangzhou. This chapter introduces a solution for a multi-modal public transportation GIS. Supported by ESRI Mapobjects, the functionality of transportation GIS prototype coordinated with the users' needs is demonstrated by implementing and evaluating several application scenarios or experiments, including data management, representations and query, shortest-path finding, service coverage, multi-modal and multi-criteria route planning and network analysis.

The final chapter of the dissertation discusses the research purpose and the contribution, and draws some conclusions. Future research challenges are highlighted.

Chapter 2

GIS-BASED TRANSPORTATION DATA MODEL AND APPLICATION DEVELOPMENT

2.1 Review of urban transportation development

2.1.1 Urban transportation systems

Urban areas are locations of production, consumption and distribution, activities linked to movements of people and goods, where urban transportation is considered as a facility consisting of the means and equipments necessary for the movements (Xie and Zhang, 2006). This presents that the issues of the urban transportation system are of foremost importance to support mobility requirements of large urban agglomerations. Public transportation is an essential dimension of urban transportation system, notably in high density urban areas. A public transportation system, particularly for bus-based transit network, is usually regulated as a common carrier, and configured to provide scheduled service on fixed routes on a non-reservation basis for commuter. The current public transportation in the large urban areas is highly complex because of the diffident modes involved, multitude of origins and destinations and variety of traffic facilities. The term “multi-modal” in a public transportation system is taken to include bus and rail (metro) modes. In a multi-modal public transportation network, a transfer represents a special site where several modal-based service routes (such as bus or metro routes) meet, and passengers can change from one route to another.

2.1.2 Urban transportation development

The constant growth of urban mobility demand has led to a rapid increase of private car ownership and usage in the developed countries (Kenworthy and Laube, 2001). In the North American cities, for example, automobile ownership per 1,000 persons averaged 587, compared to 414 in Western European cities and 210 in high income Asian cities in 1995. By 1990s, however, the urban public transportation around the world was in a low-level compared to the private transportation development. Table 2.1 illustrates a comparison of the urban transportation modal split in North American, Western European, hi-income Asian cities and Chinese cities in 1995. The table shows that the popular urban transportation mode in most of these cities is obviously private motor vehicle except for the cities of China. Nevertheless, non-motorized modes (i.e., walking and cycling) in Chinese cities account for 65% of total trips while cars and motorcycles account for 16%, which is significantly lower even than the cities of North American and Western European in 1995. It is interesting to note that the level of bicycle ownership in most Chinese cities in the early 1990s is in excess of typical total motor vehicle ownership rates in US cities. In the 1990s, despite the unparalleled flexibility and freedom that a car might bring, the developed countries around the world have high levels of private automobile ownership and usage. Nevertheless, this has made negatively impacts (i.e., traffic congestion, safety and air pollution) on the urban development, and is still not enough to meet the increasing mobility demand in the large urban areas.

City	Walking/Cycling (%)	Public Transit (%)	Private Motor Vehicle (%)	Total (%)
North American cities	8.1	3.4	88.5	100
Western European cities	31.3	19.0	49.7	100
High income Asian cities	28.5	29.9	41.6	100
Chinese cities	65.0	19.0	16.0	100

Table 2.1 Comparison of modal split for all trips in global cities (Source: Kenworthy and Laube, 2001)

Nowadays, bus and rail (metro, light rail, etc.) have played an essential role in the urban passenger transportation. The transportation systems in the metropolitan cities all over the world generally depend upon a large set of various public transit networks, particularly bus and metro networks. In the cities of New York, Paris, Hong Kong and Tokyo, for example, a high priority and large investment have been given in developing the public transportation systems since 1990s. Effective measures (such as competitive alternatives and low-cost public transportation services) are established against unsustainable levels of private automobile use (Cherry, 2005). By these measures, the modes of private automobiles and motorcycles have played a secondary role in these cities. For example, since 1995 New York City has increased investment to its public transportation system to improve the service efficiency and quality (Pucher, 2002). New York City has built the most extensive multi-modal public transportation system made of bus and rail services routes in the United States, operated by the Metropolitan Transportation Authority (MTA). By 2004, 54% of households in New York City did not own a car, but depended on the public transportation modes (United States Census Bureau, 2004). Since the early seventies the public transportation system of the city of Paris has been modernized and extended. The public transportation system is based on a multi-modal public transit system made of three main modes of transportation: the bus, metro and Réseau Express Régional (RER). Importantly, the city has achieved an efficient

and economically priced transportation for all its citizens (SPG Media PLC, 2005). In Asia, the high-income cities, such as Hong Kong and Tokyo, have also developed extensive multi-modal transportation networks. For example, Hong Kong has a public transportation system based on multiple traffic modes and operated by different companies. Hundreds of service routes are served by different modes, including bus, metro, train, ferry and tram in Hong Kong. In Tokyo, the public transportation system is dominated by a complex and extensive urban rail network of clean and efficient surface trains and metro, with buses and mono-rails playing a secondary role. With the constant growth of the multi-modal public transportation systems, public transportation ridership has increased rapidly since 1990s in the countries presented above. In England, for example, the city of London has a high level of the bus use which has increased by 75%, and of metro journeys which have increased by 86% over the 1990s. In the United States, after a decline in the recession years of the early 1990s public transportation ridership has risen sharply by 32% from 1995 to 2002 (Pucher, 2002). Light-rail systems made the biggest jump by up 6.1% in 2007, compared with 2006, according to a report of American Public Transportation Association (APTA, 2007). In Hong Kong, by 2007 over 90% of total citizens depend on the public transportation system to travel (Transportation Department of Hong Kong SAR, 2007).

Emerging countries such as India, Brazil and China have been experiencing phenomenal economic and social growth, and have also desired more mobility and living space. In these countries, urban mobility demand has been increasing substantially due to the availability of motorized transportation and growth in household income, commercial and industrial activities. Moreover, the growing in population as a result of both natural increase and migration from rural areas and smaller towns has added to urban mobility demand. This demand will grow strongly for the foreseeable future with the booming social and economic development. The rocketing growth of urban mobility demand presents many opportunities and challenges for the development of multi-modal transportation system and public transportation ridership. For example, various transportation networks (such as roads and rail) have been built in some metropolitan cities, such as Delhi, Sao Paulo and Beijing. These efforts stimulate urban sprawl to provide larger living spaces than the traditional urban centres, and whose road infrastructure is developed to support high automobile use. However, some challenges are also raised, which involve spatially separated land uses, lower quality of accessibility to public transportation modes. The relative output has been further reduced as passengers have turned to personalized modes and intermediate public transportation, road demand overruns supply, and the urban road network becomes congested (Singh, 2005). In addition, economic cost and environmental pollution will continue to be deteriorated, as transportation mode shifts from transit and non-motorized modes to personal automobile. This entails the need to take more effective measures to improve the urban transportation development in these countries. These measures can be benefited from the practices of the developed countries which have been outlined above. Therefore, the efforts can include the priority to public transportation (e.g., low price and large investment), and the studies and improvements of transportation data management, network planning and information services.

2.2 Urban transportation development in China

Over the past decades, China, as a notable emerging country, has gone through a course of rocketing socio-economic development. This leads to the constant growth of urban transportation system. Nevertheless, before the eighties the urban transportation

development in China was directed to the goods transportation. As a result, the improvement of the levels of urban transportation management and planning did not incorporate with the urban transportation development. The reason behind this trend relied in the fact was that the goods transportation was important for industrial products, as before the eighties industrial development of the Chinese cities was considered crucially important to urban industrialization. Moreover, the development of urban public transportation was neglected due to a low mobility demand of people. After the eighties, with a growing trend to urbanization and modernization in China, opportunities for passenger transportation are raised. For example, in 1980 the city of Wuhan had about 35000 motor vehicles, of which 49 percent were goods vehicles, but in 1998 with a total number of nearly 284000 motor vehicles, the proportion of goods vehicles was only 20 percent (Statistics Bureau of Wuhan, 1999). Furthermore, the urban road networks of Chinese cities are rapidly sprawling, as the advances in motor vehicles and infrastructure construction materials incorporate with a great growth of the urban mobility demand since the middle of the 1980s. In the city of Shanghai, for instance, the length of highways increased threefold to over 10000 kilometres from 1990 to 2006 (Statistics Bureau of Shanghai, 2007).

2.2.1 Trip characteristics in the big cities of China

The urban transportation development makes a great impact on the change of the urban transportation modal split (i.e., urban trip characteristics) in the Chinese cities. Table 2.2 reveals an example of the transportation modal split estimates in some large cities between the mid-eighties and the early nineties. All selected cities have more than one million inhabitants. Although a direct comparison of the cities is less practical because of the different years of survey, it is realistic to extract some basic features in the period between the mid-eighties and the early nineties. In this period, one obvious feature was that the bicycle played an important role in all trips, i.e., over 30 percent of all trips, and even over 60 percent in some cities. Walking was a popular mode, especially with a trip rate of over 30 percent in the cities of Shanghai, Chengdu and Guangzhou. Also, the public transportation was quite important in the cities, particularly with trip rates of over 20 percent in Beijing, Shanghai, and Guangzhou. Another interesting characteristic was that, due to a low ownership, there were no indications of the use of private cars in this period.

City (Year)	Public transit (%)	Cycling (%)	Walking (%)	Taxi (%)	Motor cycle (%)	Other (%)
Beijing (1986)	28,7	54,0	13,8	0,3	-	3,2
Shanghai (1986)	26,2	34,2	38,2	0,2	0,2	1,0
Tianjin (1993)	7,2	60,5	28,0	-	2,0	2,3
Chengdu (1987)	5,8	54,6	36,0	-	-	3,6
Jinan (1988)	10,5	63,8	23,3	-	0,8	1,6
Guangzhou (1984)	21,7	33,8	30,6	6,1	6,4	1,4

Table 2.2 Transportation modal split in the cities of China between the mid-1980s and the early 1990s (Source: Li, 1997)

However, the transportation modal split in the cities of China has changed largely. Table 2.3 shows the transportation modal split estimates in two metropolitan cities (i.e., Guangzhou and Changsha) according to the travel behaviours surveys made in 2005 and 2007. One significant feature is the use of bicycles which is rapidly falling. In the city of Guangzhou, for example, bicycle use dropped from 34 percent of total trips to about 8

percent over the past three decades. Nevertheless, walking is still a popular mode with a trip rate of over 35 percent in these two cities. Also, the public transportation mode is important in these two cities, with trip rates of over 20 percent. However, private car rate increases more largely than public transportation rate. For example, in the city of Guangzhou, the rate of public transportation only increased 2 percent from 1984 to 2005. On the contrary, the rate of private car increased up to over 10 percent in the same period. Data from the Statistics Bureau of Beijing shows that private motor vehicle (car and motor cycle) in the city of Beijing increased from 0.17 million in 1996 to 1.8 million in 2006. In 2006, private motor vehicle ownership per 1,000 people has reached 200, 159, and 184 in Beijing, Shanghai, and Guangzhou (Statistics Bureau of Beijing; Statistics Bureau of Shanghai; Statistics Bureau of Guangzhou, 2007). The change of transportation modal split presents that the development of the public transportation did not keep pace with those of the private transportation in the cities of China over the past decades.

City (Year)	Public transit (%)	Cycling (%)	Walking (%)	Taxi (%)	Motor cycle (%)	Private car (%)	Other (%)
Changsha (2007)	24,3	3,5	45,2	2,3	11,5	9,7	3,0
Guangzhou (2005)	26,4	8,1	37,6	3,8	8,8	10,5	4,8

Table 2.3 Transportation patterns in the cities of China in 2005 and 2007 (Source: GITP, 2006; Changsha Urban Planning Administrator, 2007)

2.2.2 Issues of urban transportation development in China

The soaring growth of the number of private cars has led to many traffic problems including traffic congestion, traffic safety and air pollution in the large cities of China. For example, in the city of Beijing, average peak-hour vehicle speeds on the arterial roads between the Second and the Third Ring Roads have declined from 45 km per hour in 1994, to 33 in 1995, 20 in 1996, 12 in 2003, and less than 10 in 2005 (Beijing Research Centre for Transportation Development, 2006). Congestion is spreading severely beyond the Third and Fourth Ring Roads and along the major radial arterial roads. In the city of Shanghai, vehicle speeds are found to be less than 20 km per hour on most of the 29 major roads, and as low as 15 km per hour on night of them in 2004 (Shanghai Institute of Transportation Planning, 2004). Peak-hour vehicle speeds on the city centre roads were just between 9 and 18 km per hour. Moreover, traffic safety has become a serious traffic issue in China. In the city of Shenzhen, for instance, traffic accidents have been the top killer in 2001 (Shenzhen Daily, 2005). In China, the amount of carbon monoxide and hydrocarbons from auto emissions accounted for 79 percent of the total in urban areas nationwide in 2005 (World Bank, 2006). These traffic problems present a critical issue: Whether the urban transportation development will suffer severe decline if the cities were to increase its urban automobile ownership and usage to the Western level. This implies that it is necessary to build an effective public transportation system which can provide numerous enough capacity to meet the urban mobility demand. This usually involves high-level transportation data management and network planning, and high-quality information services, to attract travellers to use the public transportation mode instead of the private car mode.

Although the public transportation development is dropped behind the development of private car mode in China, the number of public transit vehicle per capital has had a rapid growth since the 1990s. For example, public transit vehicle numbers per million populations in Beijing, Shanghai, and Guangzhou in 2007 averaged 1581, as compared to 711 in 1995. In addition, these three cities have a significant higher capacity rail

component as a part of their public transit vehicle number. For example, in the city of Shanghai, there were 829 rail cars in 2006, according a report released the Statistics Bureau of Shanghai in 2007. However, the average occupancy per public transportation vehicle in the big cities of China is also high. In 1995, the figure has reached 53 persons per vehicle on average, as compared to 14 and 20 in the US and western European in the same period (Kenworthy and Laube, 2001). This is consistent with the crowded situation in buses in most larger cities of China. Average peak-hour speed of public transportation vehicle was just 10 km per hour in Chinese mega cities in 2005 (Chinese Construction Ministry, 2005). This speed is less than the technical speed (12 km per hour) of a bicycle. The poor public transit supply and service make a negative impact on public transportation use, which consists of "captive-riders", not "choice-riders". Choice-riders are transit users who could drive if they wished to. Captive-riders are transit users who use transit because they do not have access to an automobile for variety of reasons. Such captive riders will all too readily switch to cars as their growing incomes. This allows them to escape the crowded conditions and slow and unreliable services of public transport systems based mainly on buses. This is needed to promote the efficiency and quality of the public transportation system in the cities of China. This entails a necessary task to explore and study the information-based means applied to transportation data management, network planning and information services.

2.2.3 Guangzhou transportation systems

The continuous growth of urban mobility demand has led to a wider gap between public transportation supply and demand in the large cities of China, particularly in the city of Guangzhou. This massive imbalance has changed the patterns of the urban transportation modes and travel behaviours. As a result, a number of policies and factors are pushing its transportation system to greater reliance on public transportation modes and private car modes. The city of Guangzhou has developed a large multi-modal transportation network composed of streets, bus and metro transit networks. The network system generates many travel behaviours whose analysis could reflect the way the city and the dwellers interact with.

2.2.3.1 The city of Guangzhou

The city of Guangzhou is one of the main transportation hubs of South China (Figure 2.1). Figure 2.2 illustrates the large administrative area that comprises ten urban districts (i.e., Tianhe, Baiyun, Huanpu, Haizhu, Liwan, Yuexiu, Huadu, Luogang, Panyu and Nansha) and two suburban counties (i.e. Conghua and Zengcheng), with a total urban area of 7434,40 square kilometres (Statistics Bureau of Guangzhou, 2007). Amongst the districts, Liwan and Yuexiu are the historically downtown centres of the city, where the Guangzhou municipal and Guangdong provincial governments and many academic institutions locate. Tianhe is the new downtown centre, and is now attracting a lot of commercial activities. Other districts, such as Huanpu, Baiyun and Haizhou, surround these historical and current downtown centres to form the "core" of the city.

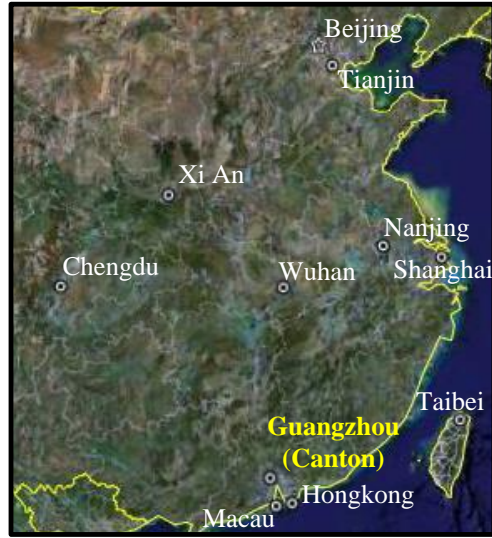


Figure 2.1 Location of the city of Guangzhou

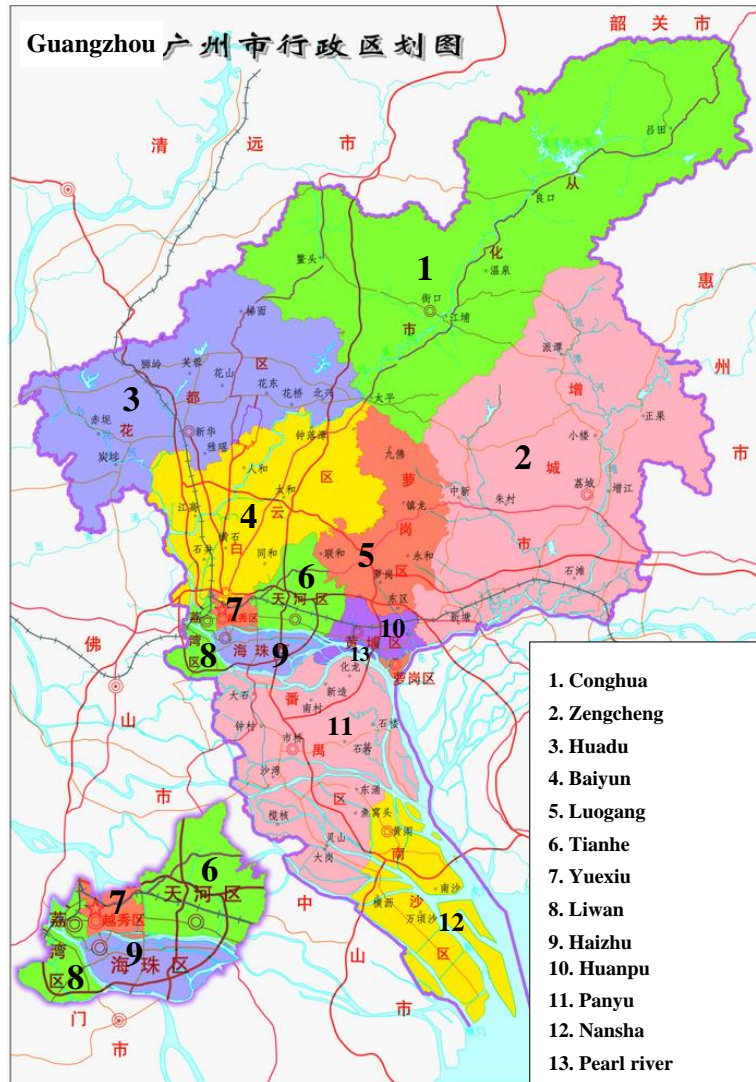


Figure 2.2 Area of Guangzhou in 2006

Population in the city of Guangzhou has been increasing steadily since 1980, as shown in Figure 2.3. In 2006, the population has risen to 7,6 million (nearly 2.3 million households). With a large number of floating populations (most of these populations cannot afford private cars, and then depend on public transportation modes to travel), the total population was more than 10 million in 2006 (Statistics Bureau of Guangzhou, 2007). Gross population density in now exceeds 10000 persons per square kilometre in the core area of the city (Table 2.4). The highest population density reached about 35000 persons per square kilometre in 2006 in the Yuexiu District.

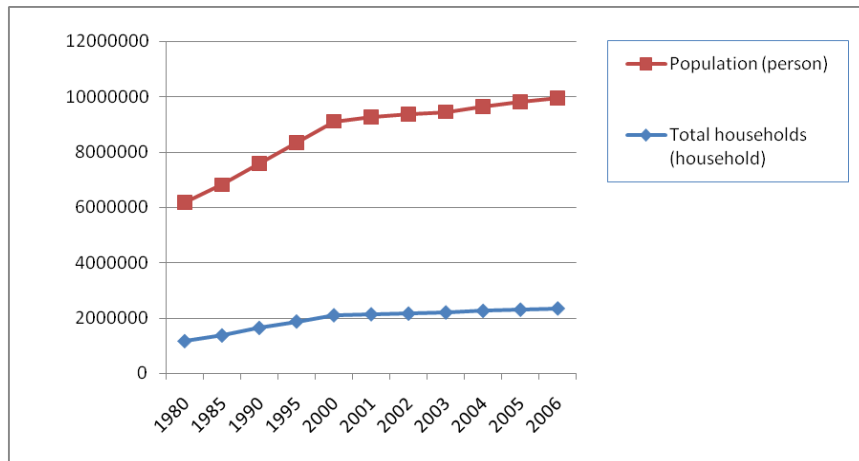


Figure 2.3 Population and households from 1980 to 2006 in Guangzhou (source: Statistics Bureau of Guangzhou, 2007)

District	Area (km ²)	Population density (person/km ²)
Liwan	59.1	11933
Yuexu	33.8	34067
Haizhu	90.4	9851
Tianhe	96.33	6700
Baiyun	795.79	965
Huanpu	90.95	2129
Total Area	1166.37	10940

Table 2.4 Area and population density of the core districts of Guangzhou (source: Statistics Bureau of Guangzhou, 2007)

2.2.3.2 Urban mobility demand

The city of Guangzhou maintains a rocketing economic development since the late 1970s, and is currently the industrial, financial and trade centre of South China. Annual growth of GDP (Gross Domestic Product) in Guangzhou reaches a double-digit rate since the 1980s. The constant economic growth gives a number of opportunities to the urban transportation development. A complex multi-modal transportation network including roads, public transit networks, railways and state highways make the city a prosperous place for passenger and goods transport and transfer over the past decades.

However, challenges on the urban transportation system are highlighted due to the booming augmentation of urban mobility demands. Over the past three decades, many efforts have been made to restructure and sprawl the urban street network to respond to the demands. Nowadays, the arterial road network is composed by 10 expressways, 18 throughways, 32 main highways and 244 cloverleaf junctions. In 2006, the total length and density of highways in the urban areas was nearly 4212 km (including 424 km of freeways) and 5.6 km/km², respectively. However, the pace of building new roads is still behind in contrast to the increase of the urban mobility demands. The demands lead to a continual growth of the number of motor vehicle, and stir up an intensive increase of the traffic flows since 1990s. For example, by the end of 2000, the number of motor vehicle in the city of Guangzhou has reached 1.2 million, over 28 percent more than at the end of 1999. In 2006, motor vehicles amounted to over 1.5 million. Moreover, this figure will be expected to nearly 2 million in 2010 according to a survey of the Guangzhou Auto Car Association.

Figure 2.4 illustrates a forecast of the urban mobility demands in the city of Guangzhou. In 2010, motor vehicle trips will be 0.5 million motor vehicles per peak-hour in the urban area of the city of Guangzhou. The average trip distance will be 12 kilometre, and traffic volumes reach 6.07 million motor vehicles per kilometre. The capacity of the road networks will increase to 8.58 million per kilometre, and traffic loading will be 0.71. In 2010, traffic volumes of expressways and throughways will be 38.5 percent of all motor vehicle trips; traffic loading will be 0.65. Nevertheless, traffic volumes of main roads will reach 41 percent, and traffic loading will rise to 0.89. In the downtown centres, motor vehicle trips will be 0.1 million motor vehicles per peak-hour, and traffic volumes will increase to 0.6 million motor vehicles per kilometre. Capacity of the road networks will reach to a high level of 0.8 million per kilometre and traffic loading will rise to 1. This implies that the capacity of the road networks in the downtown centres will be saturated in 2010.

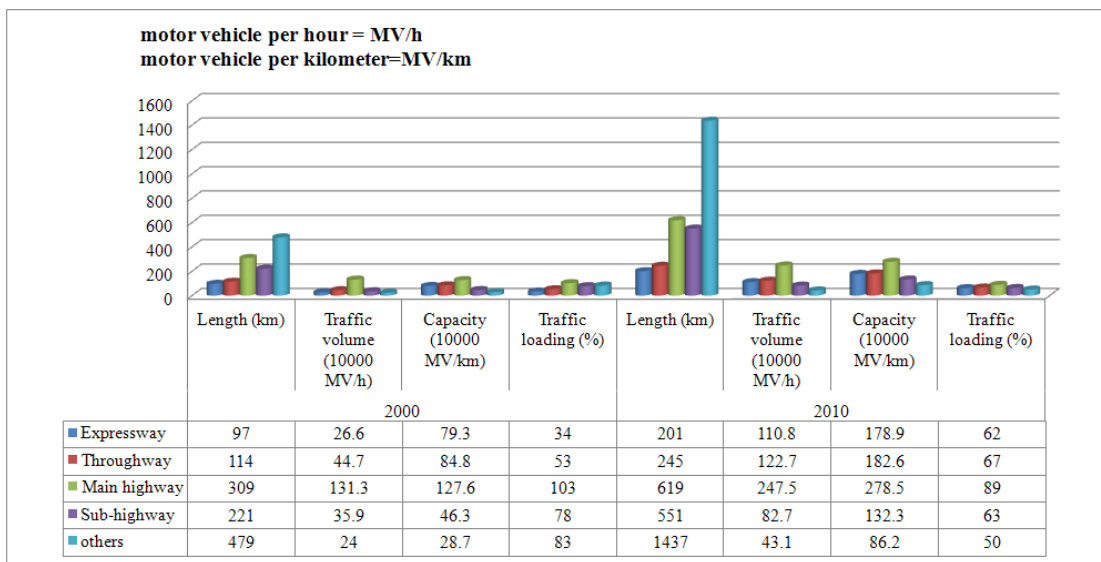


Figure 2.4 Forecast of traffic demands in the city of Guangzhou (Source: He and Deng, 2001)

2.2.3.3 Travel behaviours

The increasing mobility demand entails a need to implement traffic demand management and control, and give priority to the public transportation system, thereby optimizing the split of transportation modes (i.e., public transportation modes should assume most of trips) to meet the urban mobility demands. Nowadays, the multi-modal public transportation network in the city of Guangzhou is composed of bus and trolley lines (8748 km) and metro lines (108 km). In addition, there are about 17000 taxis in services according to the 2007 Guangzhou Statistical Yearbook. Table 2.5 presents the evolution of the public transportation modes from 1984 to 2006 in the city of Guangzhou. In 2006, there were about 8300 buses and 273 trolleys running on nearly 450 lines. These bus and trolley services routes transported over 5 million person-time passengers per day. A mass rapid transit network (i.e., metro) has been built as one of the components of the public transportation system from 1997. At the end of 2006, when two new metro lines (line 3 and line 4) were opened (a total of four lines are presently available), the metro daily person-time passengers increased to nearly 1 million. This is almost twofold that in the same period of 2005 according to a statistic conducted by the metro company. Currently, over 108 km of metro transit network has been completely built. By 2010, the metro network is expected to have 9 lines, generating 255 km of network in total.

Date	Public transportation mode
Before 1980's	Bus
1980's	Bus, Ferry
1990's	Bus, Metro (after 1997)
2006	Bus, Metro

Table 2.5 Guangzhou 1984-2006: evolution of popular public transportation modes

The development of the multi-modal urban public transportation system makes a large impact on the travel behaviours in the city of Guangzhou. For example, a commuter's trip to work may combine street, bus and rail service routes. The Guangzhou Municipality conducted a recent survey on the travel behaviours in the city from 2004 to 2005, called as "The 2005 Guangzhou Resident Travel Behaviours Survey (2005 TBS)". The survey covered 10 districts (excluding Panyu and Huadu), and applied a sampling rate of 3 percent, i.e., the sampling population reached 251 thousand persons. Figure 2.5 illustrates a comparison of the transportation modal splits of 1984 and 2005 in the city of Guangzhou. As shown in this figure, the rate of cycling use was dramatically dropped from 34 percent to 8.1 percent. However, the rate of private car use increased sharply from 1984 to 2005.

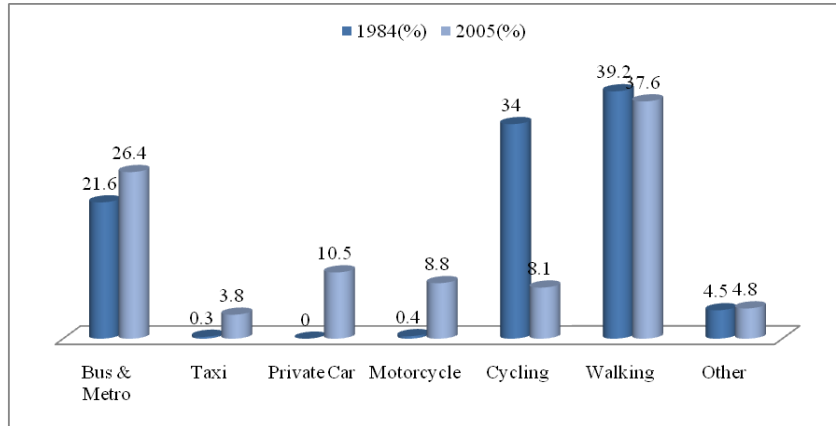


Figure 2.5 Transportation modes of 2005 compared with that of 1984 (Source: GITP, 2006)

Moreover, Figure 2.6 illustrates the proportions of different transportation modes for different trip motives in the city of Guangzhou in 2005. This shows that nearly 54 percent of the urban mobility depends on motor vehicles (about 22 percent in 1984). But 47.8 percent of the commuters who do not use private car mode choose walking mode to finish one trip. More than 60 percent of the urban mobility based on motor vehicles uses public transportation modes. A total of 34,3 percent of the all trips in the city depended upon the public transportation modes, either bus or metro modes in 2005, compared with 21,9 percent in 1984.

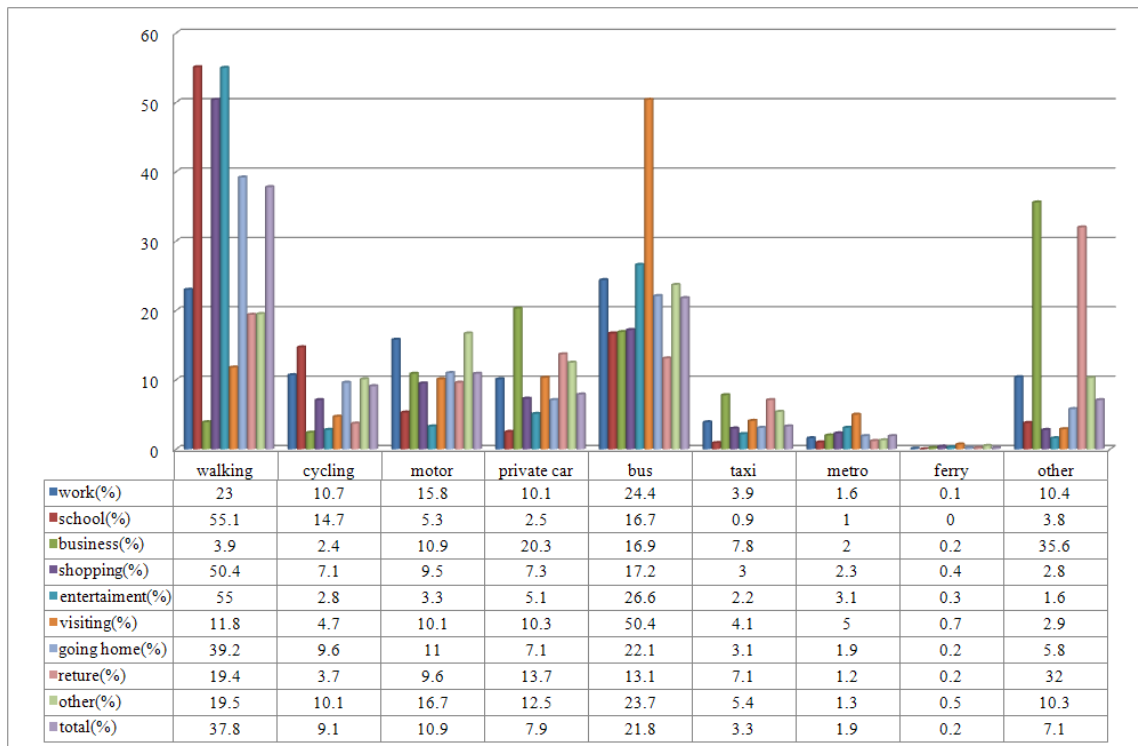


Figure 2.6 Transportation modes in different trip motives (Source: GITP, 2006)

The data of 2005 TBS also shows the rigid mobility demands, such as work and visiting usually depend on public transportation modes. This presents the important role of the

public transportation system in the city of Guangzhou. Figure 2.7 shows the spatial distribution of average OD (origin-destination) trips per day in the urban areas of the city of Guangzhou. All trips were finished based on the bus mode. The main bus passenger OD trips occurred within the old urban centre (involving the Dongshan, Yuexiu and Liwan districts), and between the old urban centre and the new urban centre (i.e., the Tianhe district). On the contrary, a small part of the passenger OD trips came from the urban periphery (Fangcun and Huangpu district) to the urban centres. This implies that a large amount of the bus passenger OD trips is overly concentrated, and the urban mobility demand is intensive, in the urban centres.

The traffic policies also can make changes of the travel behaviours. A motorcycle ban affecting all of the residents in the city of Guangzhou has been enforced since January 1st, 2007. As the high rate of motorcycle robbery brings a high pressure to public security organizations in the city of Guangzhou (Er, 2006), motor cycle modes have been eliminated from Guangzhou's traffic. As a result, motorcycle would not be an alternative transportation mode for the inhabitants in the city after 2006. However, this ban also implies that a large amount of motorcycle riders (nearly 0.5 million in 2005) has to choose other transportation modes. According to the 2005 TBS, the private car mode is an important choice for these motorcycle riders (17 percent), as the mode can provide more safe, swift and comfortable travels for citizens. Nevertheless, there are still over 50 percent of the motorcycle riders who choose the public transportation mode, as the mode is cheaper than the private car mode (Figure 2.8). This implies a larger increase of the public transportation demand in the city of Guangzhou.

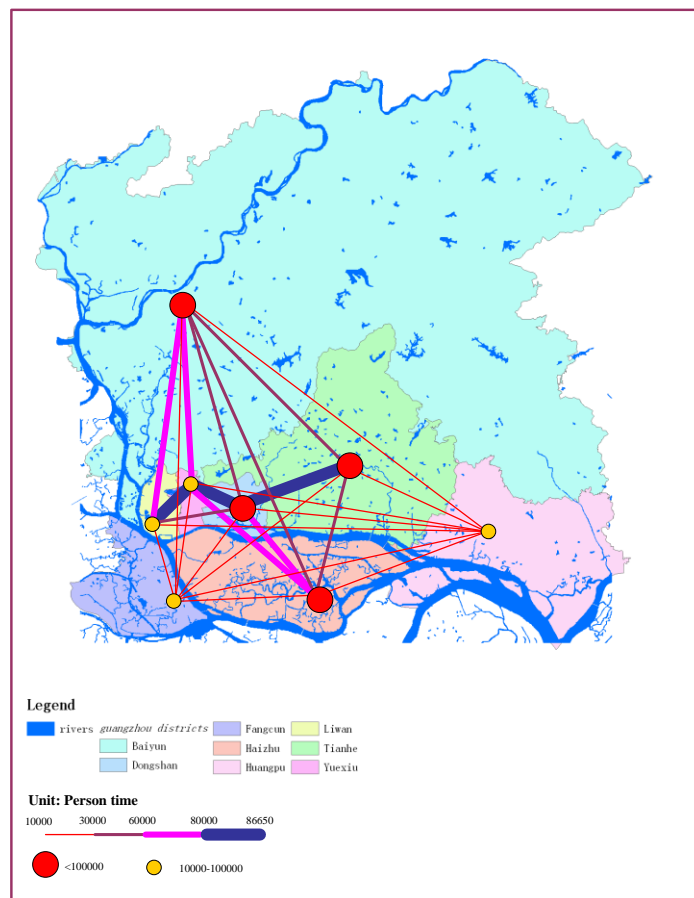


Figure 2.7 Spatial distribution of average bus passenger volumes, 2005 (Source: Source:

GITP, 2006)

(Note: In 2005, Guangzhou Municipality re-planned the districts. Dongshan district has been combined into Yuexiu district; Liwan district was combined into Fangcun district; Baiyun district was divided into two districts, i.e., Baiyun and Luogang districts; Panyu was also divided into two districts, i.e., Panyu and Nansha districts)

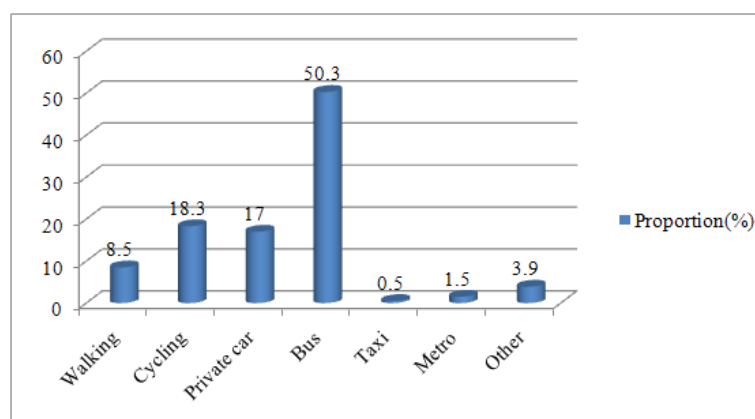


Figure 2.8 Transportation modes chose by motor cyclists

Data from the 2005 TBS also shows that 87.7% of the commuters need nearly 10 minutes to walk to the desired bus stops. In addition, 55.1% of the commuters need to go to their offices from home by using public transportation modes (bus/metro) for 30 minutes. Whereas, only 10% of the commuters accept to take more than 45 minutes to get to their offices by taking buses or metro. This implies that the accessibility to public transportation modes needs to be improved. This entails a need to evaluate the service coverage areas of, and walking opportunities to, the stops.

The transfer between different transportation modes is an important aspect to reflect the quality of the spatial structure of the multiple transportation networks. The 2005 TBS presents that 51.3% of the commuters use a public transportation mode (bus or metro) to finish their trips, but just nearly 1% percent choose two or more public transportation modes. A term "Transfer Frequency" (TF) is used to represent the transfer, i.e., the time of route change, between different public transportation modes, as shown in Table 2.6. In all transfer events, 28% emerges in the bus line network, and 14% between bus and metro transit networks (GITP, 2006). This indicates that the connectivity of different metro and bus service routes needs to be improved. The assessment of the transfer is also needed to evaluate the walking opportunity and service coverage area.

Transfer Frequency (TF)	Proportion (%)
Walking mode	47.8
Non-walking modes (TF=0)	51.3
Non-walking modes (TF=1)	0.84
Non-walking modes (TF>1)	0.06
Total	100

Table 2.6 Transfer frequency of walking and public transportation (non-walking) modes
(Source: GITP, 2006)

In short, the augmentation of the public transportation demand presents the requirement to promote the supply and the service quality of the public transportation modes, involving the improvements of the accessibility, spatiality, affordability and connectivity. This implies a need to evaluate the specific criteria which can reflect these aspects. According to the data of the 2005 TBS, the criteria can be concluded as follows:

- Time of route change (transfer)
- Travelling distance (involving walking distance)
- Travelling time (involving walking time)
- Fare

Although these criteria are not exhaust, they can reflect the service efficiency and the needs which the public transportation system has to meet. These criteria are also the important factors that impact on the trip planning to the end users, particularly the commuters. The time of route change (transfer) during a trip is an important criteria, as most of commuters just accept the value is one or two in a trip planning. Nevertheless, as different people have different expectations, the weightiness of the criteria may be different. Someone may consider fare as the most important criteria to finish a trip, but others consider the walking distance. This implies that a multi-criteria selection should be realized in the trip planning.

2.2.3.4 Needs to Guangzhou transportation development

The change of the travel behaviours in the city of Guangzhou implies that the attraction of public transportation modes is declining. More trips tend to shift from non-motorized modes to cars and motorcycles. As a result, the growth of public transportation ridership is dropped from 10 to 3 percent per year after 2002. This presents the needs to deal with the poor public transportation provisions. One need is to balance the investment in the transportation development. In the city of Guangzhou, compared to the investments for improving the service level of urban road systems, the investments of urban public transportation are low for highly improving the performance of the systems (Kenworthy and Hu, 2002). Therefore, the policy should be changed to balance investment in new high capacity road infrastructure with investment in improving the service level of the public transportation systems, or even to prioritize the public transportation systems above road investment. Besides the change of the investment policy, it is also needed to employ appropriate information-based means to evaluate the criteria to a multi-modal transportation network. In short, the implementation of information technology applications presents an important topic, which is to maintain the high-quality accessibility to, connectivity of, and spatiality of the multi-modal transportation network, taking into account the quality of public transportation services. This implies that a transportation information system needs to be developed to promote the data management, representation, planning, routing and pre-trip guidance of multi-modal transportation network.

2.3 Integration of GIS and transportation systems

2.3.1 GIS for transportation

Geographical Information Systems (GIS) is a special type of computerized information system which is designed to handle geospatial data, including data capture, storage, management, operation and display (Aronoff, 1989; Chrisman *et al.*, 1989). On the practical side, GIS allows geographical information to be integrated, managed, and analyzed to assist operators, dispatchers, and street supervisors to make on-the-spot decisions, and to assist planners in service assessment, restructuring and development. GIS is used in different research domains, particularly in the fields of transportation. In these fields, information-based applications have been conducted with the benefits of spatial-analysis and cartography functionalities of a GIS. For example, GIS is usually applied to provide spatial data analysis and management ability to promote application functionalities in Intelligent Transportation Systems (ITS) (Trinadha Rao *et al.*, 2003). This will reconcile the engineering and geographical views of an integrated transportation system.

Therefore, a specific branch of GIS concerning transportation issues is commonly labelled as Geographic Information Systems for Transportation (GIS-T). The evolution of GIS-T can be considered from three perspectives: the map view, the navigational view, and the behavioural view (Goodchild, 1999). The static nature of the map view implies an essential static perspective of a transportation system, thereby favouring applications related to inventory and description. The navigational view concerns connectivity and planarity, and the storage of time-dependent attributes. This assumes that information of a dynamic nature must be represented on the static geometry of the network. The behavioural view treats transportation events as dynamic, and occurring within a transportation space, and deals with the mobile characteristics of discrete objects on or off a linear network. Appropriate representations for the behavioural view have been one of the challenging transportation research issues (Shaw, 1999). According to these perspectives, Goodchild (1999) argued that true progress in GIS-T should be associated with an analysis of users' needs less dependent on prior technologies.

2.3.2 Users' needs and transportation GIS applications

The users of transportation GIS include commuters, transportation units of government, scientific institutes, enterprises or retailers. The commuters need to get more detailed transportation information, such as position services, path identification or pre-trip guidance, to make a swift and effective trip. For example, while we want to use the public transportation mode to travel, it usually needs to know where the nearest stops locate, which is the right path to a destination, and how to complete the trip with minimizing costs, e.g., travelling time, fare, transfer or walking distance. This reflects a multi-criteria selection in the trip planning, as different people may have quite different answers to the best path for travel. This implies that the optimality of a route can be decided by different criteria, involving transfer, travelling distance, travelling time, or fare. Transportation GIS is an integral part of the transportation units of the municipal or national governments who need to employ it to facilitate transportation data management and network planning. Reliable data and information provided by a transportation GIS is required by the transportation planners and decision-makers of the transportation agencies or scientific institutes. The data or information can involve service coverage areas of stops,

routes or stops density, spatial distributions of networks, travelling costs or transfer. In addition, the local, regional, and national transportation enterprises need to apply transportation GIS to implement transportation routing and scheduling. Furthermore, trucking and delivery companies need a transportation GIS to track their shipments. Newspaper publishers help to manage their fleets of delivery trucks with transportation GIS. Retailers can direct their customers to their locations with the support of transportation GIS. The users' needs outlined above present the necessary applications for an essential transportation GIS, which can be described in the following list (Waters, 1999; Yu, 2001):

- Path identification and routing analysis: Path finding is an essential precursor to GIS-T applications used to find the best route in terms of distance, time, fare, or other defined weights (Waters, 1999). This application can be used for en-route navigation or trip planning (Jiang and Tan, 1997; Keenan, 1998; Western *et al.*, 2000), or together with the help of GPS for car navigation (Chao and Ding, 1998). Routing analysis includes vehicle routing and arc routing. Vehicle routing application is to determine the routes for deliveries and/or pickups from one or more depots at one or more stops, e.g., delivering gasoline to several filling stations and further using in logistics planning (Ralston, 1997; 1999). Arc routing problems are a class of problems that involve finding efficient ways to travel over a set of links in a transportation network. Arc routing has a large number of public and private sector applications, including street sweeping, solid waste collection, snow plowing, mail delivery, and other door-to-door operations. In a typical arc routing problem, people or vehicles are dispatched from one or more depots to traverse a set of service links. The result of an arc routing problem is a set of one or more routes that cover all the service links with the minimal amount of deadheading.
- Network flow model and distribution analysis: The model is built to solve assignment problems within a transportation network. For example, transportation network flow models are essential for evaluating network reliability with bus routes distribution. Transportation network flow problems involve the transportation problem, the minimum cost flow problem and matching problem. The transportation problem involves identifying the most efficient way to service a set of destinations from a set of origins. For example, a company may be interested in finding the least-cost solution for shipping commodities from its warehouses to its vendor locations. The minimum cost flow problem is a more general version of the transportation problem that takes link capacities into account. For example, the procedure can be used to find multiple paths when capacity constraints make it impossible to utilize the shortest path for an entire shipment. Matching problems try to find the best one-to-one matching between two groups of objects where there is some quantitative measure to be minimized or maximized. For example, you can efficiently assign work to service centers. Therefore, transportation network flow model should have the characteristics of explicit link capacity constraints, decreasing demand owing to travel behaviours.
- Partitioning model: This is to create traffic zones with restrictions applied to a transportation network. Partitioning involves creating groups of features in a layer based on proximity or measures of similarity. The partitioning procedures could support applications in service territory alignment, sales and marketing, political redistricting, and many other disciplines. The partitioning model attempts to produce districts that are contiguous, compact, and balanced.

- Location-allocation model: The model is to determine optimal locations for facilities, e.g., bus stops or metro entrances. Indeed, location-allocation methods are one of the few modelling and spatial analysis tools offered in proprietary GIS today (Kim, Openshaw, 2002). Most of GIS software is capable to solve optimizing problems and run allocation models, such as ARC/INFO, ILWIS, ARCVIEW, IDRISI, and CARIS.
- Spatial interaction and gravity model: The gravity model is the most common formulation of the spatial interaction method. This method is an analytical technique which estimates the number of interactions occurring between an origin and destination locations. The number of interactions is based on the properties of the origin to produce a trip, destination's attractiveness and the impedance of the link between the two locations. The goal of spatial interaction modeling is to be able to model and predict the number of interactions occurring between populations for a particular type of activity such as retailing. Spatial interaction model is used in a classic model of transportation planning.
- Origin-Destination (OD) Matrix: OD Matrix is to store the information of defined weights, such as travelling time, distance or flows between each pair of origin and destination. These matrices are basic form of analysis on transportation research.

In short, different users have different needs toward which they work, and they have different constraints on the transportation activities they can conduct. This implies that each transportation applications may require data sets and information about travel, research or business practices and processes that are unique to their operations. This implies that the transportation organizations will have own rules about how their legacy databases can be used or modified. And they will have internally collected and maintained attributes that are not shared by any other transportation GIS practitioner. This requires a generic transportation GIS which has different levels of precision in data, to meet different users' needs and application purposes.

Although different needs show the varied nature of transportation GIS applications, there are many common elements among these applications as well. The most compelling common element among transportation GIS applications is the use of transportation networks. Although it is not every single application that employs the transportation network for analysis, the vast majority of applications are concerned with some activity that takes place on a transportation network, or even multiple transportation networks. In particular, path identification and routing applications are considered closely with transportation networks. Furthermore, transportation network flow model and distribution analysis should be built on network structures. Therefore, the transportation network is the foundation for an essential transportation GIS data model. For the users of transportation agencies and enterprises, the maintenance of urban transportation network has been a primary concern. This common item of interest presents a necessary task to study and implement of a model of multi-modal urban transportation network in a GIS framework. The GIS-T data model could support different applications, and organize or associate them in ways that encourage collaboration and cooperation among users with different levels of granularity in data.

2.3.3 Current GIS-T applications in the city of Guangzhou

The city of Guangzhou has moved away from the "build it and they will come" and infrastructure- and capital-intensive transportation strategies, but takes more effective and economic solutions to the urban transportation development. The solutions include

the improvements of the accessibility, management and planning of the transportation network by applying GIS applications, as most of transportation activities involve static and dynamic data with spatial and temporal dimensions. Table 2.7 gives the GIS-T applications which have been developed in some transportation agencies in the city of Guangzhou since 2002. These applications involve a wide range of transportation domains, ranging from traffic monitoring, control, safety, and public transportation management and planning.

Agency	Application (year)
Guangzhou Police Bureau of Transportation and Traffic Control Centre	Real-time Monitoring Geographic Information System for Road Network (2002)
	Intelligent Traffic Management and Control Geographic Information System (2005)
Guangzhou Bureau of Passenger Transportation	Public Transportation Geographic Information System (2002)
Guangzhou Police Bureau of Metro	Facility Management Geographic Information System for Metro Station (2004)
Guangzhou Metro Company	Metro Geographic Information System (2006)

Table 2.7 GIS-T applications in the city of Guangzhou

A traffic control and command system was developed and implemented by the Guangzhou Traffic Control Centre in 2001. The objective of this system is to manage the real-time traffic light/signalling control and surveillance of the conditions of most intersections on electronic maps in a GIS environment. In 2002, the Guangzhou Police Bureau of Traffic constructed a closed-circuit television (CCTV) monitoring system so as to constantly monitor traffic safety and flow. This system is composed of 87 CCTV monitors and 184 road sensors that cover most of intersections and traffic corridors including the highway from Guangzhou to Shenzhen. This real-time traffic information can be attained from Internet based on Web GIS. As for the public transportation management and planning, a public transportation GIS was designed and implemented by the Guangzhou Bureau of Passenger Transportation in 2002 (Chen and Tan, 2004). This system is the first GIS-based public transportation information system applied to the city of Guangzhou. The public transportation GIS was developed to the data management and support the planning of the bus line network. The core of the system is a GIS data model where the transportation network is modelled and represented as a node-link graphic network. In the data model, the connectivity between roadways is represented by a set of links and nodes, a node corresponds to an intersection while a link corresponds to a road centreline (Figure 2.9). A bus line is represented as two directional paths which are spreading on the road centrelines, and the bus stops are just represented as the points located on the bus lines (Figure 2.10). This model simplifies the representations of the transportation networks and the relationships among transportation facilities, and between networks. This leads to a high efficiency for network analysis and routing due to a simple topologic structure.

Nevertheless, Figure 2.10 also illustrates a case of the representation of a bus stop named as Sport Centre. In the real world, the bus stop location has several individual sites on the opposite sides of the road. Generally, the location of a bus stop has two sites on the opposite sides of a road, and these sites are not far away from each other along the road.

However, there are many cases in which a stop takes over two sites owing to the coexistence of many bus lines in the city of Guangzhou Guangzhou. In addition, a bus line usually has two different or partly different routes, when considering its directions (Figure 2.11). Reasons for such a special case may result from traffic rules (e.g. one-way streets and vehicle controls) or demand driven (e.g. omitting certain stops during peak hours).

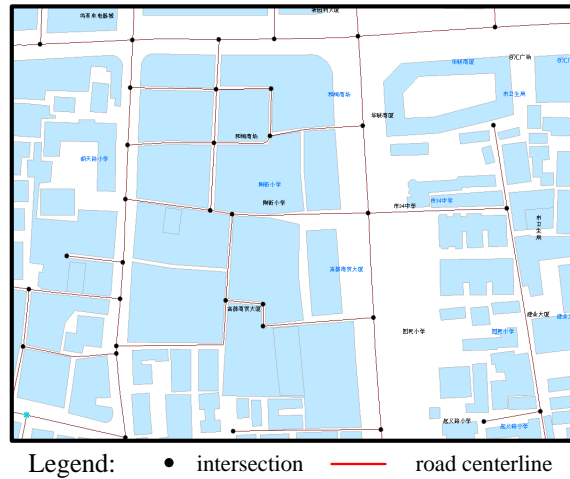


Figure 2.9 Example of a node-arc centreline road network representation



Figure 2.10 Case of bus line network representation

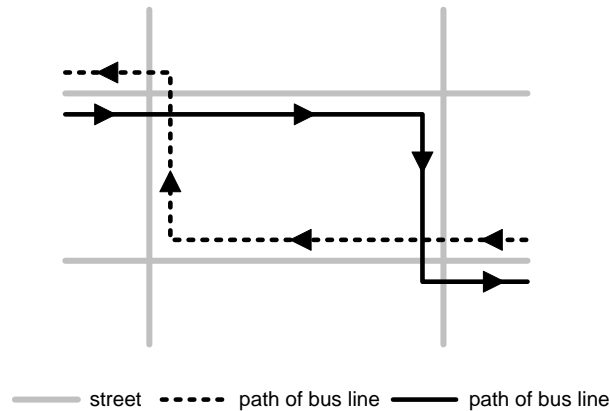


Figure 2.11 Example of bus line with different paths

Although the transportation network GIS data model applied in the city of Guangzhou involves the urban road network and the bus line network, carriageways/lanes, metro lines and walking links are lacked in the data model. This implies that transportation network analysis is less precise. In particular, as walk links are excluded in the data mode, the application requirements to an essential GIS-T, involving path identification, routing analysis and trip planning cannot be implemented. Except for above limitations, the modelling approach is still hampered by poor functionalities. For example, the transportation networks currently implemented do not support traffic-oriented connections (turning tables) and other public transportation modes (such as metro). This is limited to fully represent the complicated cases of the real transportation networks.

Nowadays, the growth of the multi-modal transportation network in the city of Guangzhou provides ample opportunities for the development of innovative GIS-T capabilities in the city of Guangzhou. However, complex urban transportation systems often leads to the development of specialized and separated transportation GIS data model. One approach to this issue by transportation organizations or enterprises involves the development of a multi-modal and multi-scale transportation GIS, where the various nature of GIS-T applications are concerned with some activities that take place in a multi-modal transportation network.

2.3.4 Towards a multi-modal and multi-scale transportation GIS

A multi-scale and multi-modal transportation GIS data model is required to deal with the multi-modal transportation activities by integrating different transportation networks as a federated system, and representing data at different levels of abstractions, i.e., scales. This model allows more complex and precise information provisions to provide better guidance to commuters in move, and support planners/decision-makers to data management, network planning, and information services. In order to develop a multi-scale and multi-modal transportation GIS data model, some key aspects could be reviewed:

- Transportation geographical entities are usually characterized by multiple properties, involving space, time and attributes. Moreover, they are often multi-modal and exist across many different jurisdictions, and have different logical views, e.g., static or dynamic. Therefore, proper representations of the transportation entities are essential to data integration and representation, and to

support the implementation of transportation applications (Huang, 2003).

- In a multi-modal transportation network, transportation GIS applications usually consider lots of data that interact with spatial and temporal entities and relationships involved in different networks. The data could involve public transit network, street network, walking facilities, dynamic data (such as schedules), and surrounding non-network data (such as land-uses, landmarks address, socio-economy, etc.). This implies that the complex and multiple relational linkages among these data are needed to address in data analysis (Peng and Dueker, 1995). In a case of bus transit network planning, bus lines and stops need to be correlated on the structure of the given road networks, taking into account traffic rules and restrictions applied on the networks, and connections with other transit networks.
- As the transportation GIS applications to represent multi-modal transportation activities involve different data themes and characteristics, a multi-modal transportation GIS data model should encompass all the semantics of the represented system to be compatible with the data themes and characteristics reflected by different transportation activities. This requires a modelling approach that can complete and seamlessly use coupled methods to represent the themes and characteristics of transportation data. This implies that a modelling framework is needed to provide ample semantics to express transportation objects and relationships.
- As different multi-modal transportation GIS applications may require different levels of aggregation and precision of data for their specific purposes, transportation networks should be represented at multiple levels of granularity, i.e., scales. The method of representing data at one level of granularity may yield sufficient information to meet a given type of transportation GIS applications, such as vehicle navigation, however, the transportation GIS model usually needs to be redesigned and re-constructed to address new application purposes. Therefore, a multi-scale transportation GIS data model is needed to meet different applications purposes without a redesigning or reconstruction of the model.

Regarding these aspects outlined above, a multi-scale and multi-modal transportation GIS data model need to integrate and represent multiple transportation modes at conceptual and logical views, and allow for multiple data representations resulted from cartographical or topological changes. The data model could be the core of an adapted GIS-T which provides an essential set of datasets and functionalities to meet the users' needs.

2.4 Transportation GIS data modelling approach

In order to develop a multi-modal and multi-scale transportation GIS data model, modelling approaches need to be reviewed and investigated. Therefore, this section provides a review of current practices of transportation GIS data modelling. The modelling approaches were studied and applied with respect to, and incorporation with the transportation network which interacts with different transportation modes, spatio-temporal properties and topological rules. These approaches involve transportation spatio-temporal data integration, multiple data representations, and network topology modelling.

2.4.1 Transportation data representation

2.4.1.1 Multiple data representation

In order to implement transportation data representation, the characteristics of transportation objects need to be explicitly defined and represented. Transportation objects usually have spatial and temporal properties, and are associated with attributes and topology relationships with other objects. Fletcher (1987) organized these multiple characteristics of transportation data into two primary points of views, i.e., logical and physical perspectives (Table 2.8). In the real world transportation objects are covered in a logical concept or a conventional definition, for example, streets can be defined as a street network. Network data structures are also defined by logical concepts, e.g., “networks”, “chains”, “links” and “nodes”. The physical mode corresponds to transportation actual facilities (e.g., “rails”, “roads” and “intersections”) as constructed and used in the real world. Their spatial properties are described according to the shapes and scales (i.e., the levels of abstractions). The logical and physical modes to describe transportation object are not separated. The relationship between them is often one-to-many, and occurs in both directions. For example, two bus routes may share the same streets. Conversely, a bus route can, and often will traverse several physical streets in urban areas. A one-to-many relationship also exists when two or more network links correspond to the same graphical line that is used to represent the network at a given scale. For example, a two-way street is represented logically by two directed arcs at large map scales, while a single cartographic line at small map scales. Also, several cartographic lines can be use to represent one link. For example, the routes of a bus line may be represented by a link.

Logical mode	Physical mode
<i>Conventional definitions</i>	<i>Actual facilities</i>
<ul style="list-style-type: none"> • Route • Bus transit network • Rail transit network • Street network 	<ul style="list-style-type: none"> • Rails • Roads • Interchanges • Intersections
<i>Data structures</i>	<i>Geographical features</i>
<ul style="list-style-type: none"> • Networks • Chains • Links • Nodes • Lattices 	<ul style="list-style-type: none"> • Lines • Points • Polylines • Polygons • Attributes

Table 2.8 Transportation GIS modelling mapping (Fletcher, 1987)

The definitions of transportation objects present that the characteristics of transportation data are multi-mode. This implies that the transportation data representation is complex and diverse, and one way to implement multiple data representations in a GIS-T is required. Multiple data representations result from exploring the world from different levels of abstraction and points of views of geographical themes, shapes and scales. Research in multiple data representations has so far focused on the development of data structures (Bédard *et al.*, 2002). In most cases, these structures allow a geographical object to have different shapes (features) that vary according to the level of abstraction and scale, importantly explicitly describe the interrelationships between these features. The connections between these features imply multiple topological relationships are also explicitly defined and represented. This presents that multiple data representations could

maintain the consistency of topological relationships between transportation entities. Moreover, as each spatial data model may have its own needs regarding the representation of transportation objects, multiple data representations could vary according to different users' needs, and consequently at different levels of abstractions which indicate a range of scales, respectively.

The current transportation GIS data models have implemented multiple transportation object representations with a special data structure. The UNETRANS (Unified Network for TRANSPORTation) model is a notable effort to accomplish multiple representations (Curtin *et al.*, 2003). In the UNETRANS model, the road networks can be stored and displayed in a variety of ways (Figure 12). Commonly, road networks are represented by single centrelines. This line symbol can theoretically be infinitely thin yet still represent the entire navigable way. Nevertheless, a given user may require more than one type of representation for the same street. Other applications may require carriageway representation (that is usually represented as two centrelines, each representing one side of the street, or one direction of travel) where the street is represented by two centrelines. Each centreline defines one carriageway and contains information about flow in a single direction along the centreline of the street. Still, more detail may be necessary to capture specific flow information along the street. In that case, a lane representation may be most appropriate.

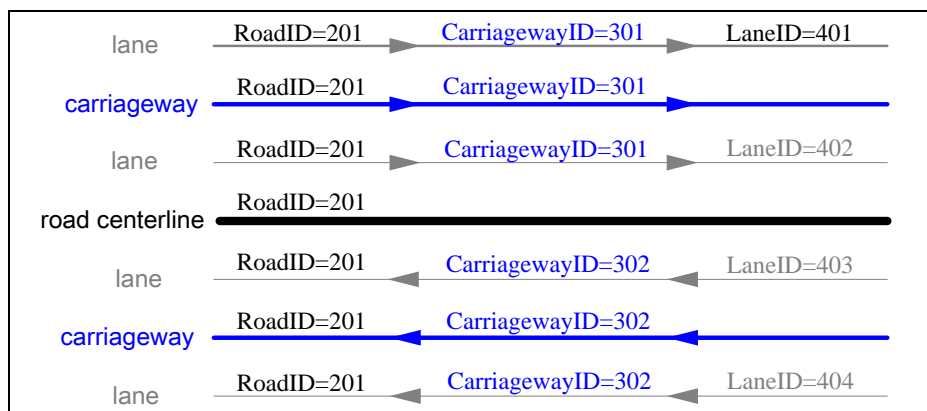
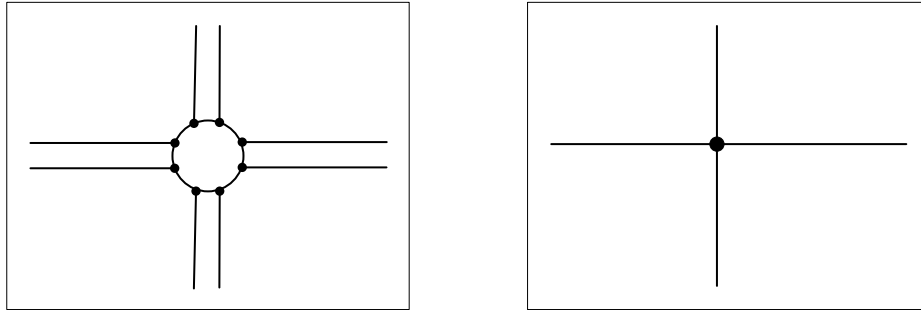


Figure 2.12 Multiple representations of transportation networks (Curtin *et al.*, 2003)

Another transportation data model to accomplish multiple data representations is the International Standards Organization–Geographic Data Files (GDF) (GDF, 1995). GDF has been developed in Europe, to describe road and road-related data. The model specifies rules for data capture and the attribution of objects. GDF specifies topological relationships, and has several levels of description for different representations of objects. In the model, for example, the road networks are described at multiple representations regarding different transportation GIS applications. Figure 2.13(a) presents the most used level of the GDF which contains simple features, such as road elements, rivers, boundaries, and signposts. Features can have attributes that are specific (i.e. one way, road width, number of lanes) as well as relations that are important for car navigation systems. In Figure 2.13(b), the “simple features” are aggregated to a higher-level feature. For instance, all road elements of an intersection are only represented with a single point. This level of representation is mostly used when a simplified description of the road network is sufficient. For example, inter urban route calculation does not require a high level of detail, but vehicle location by means of a GPS receiver does need the detailed description of the road network.



(a) Level 1 representation of a roundabout (b) Level 2 representation of a roundabout

Figure 2.13 Representations of a roundabout at different levels of abstraction

2.4.1.2 Transportation network modelling and representation

In the current transportation data models, e.g., the GDF data model and UNETRANS model, the multiple representations of transportation networks are implemented by node-link network structures which are composed of as nodes and links in a geographical network. In the geographical network, nodes are point locations where traffic activity originates, terminates or delays, while links connect nodes and model traffic activity between nodes. A “node-link” transportation network model deals exclusively with directed networks due to the directional flow properties of transportation networks. This tackles the connectivity relationships among nodes and links and graph interactions between network components. For a street network, for example, nodes are generally referred to street intersections while links are defined by street segments between intersections. Generally, two directed links made of the same nodes, but oriented in opposite directions represent a two-way street with opposite directed paths.

The node-link transportation network can be applied to represent not only the road sub-networks (such as carriageways or lanes), but also the public transit networks (such as bus and metro). As different transportation networks are interconnected, some important operations (such as routing or planning) usually involve different logical or topological relationships between different modal nodes and links. This implies that the modelling and representation of the transportation networks should deal with multiple relationship representations in an integrated manner that does not impose an artificial separation. This implies that an integrated topological structure is needed to implement the integration of different modal links and nodes, and support the representation of multi-modal transportation activities (e.g., trip planning), taking into account the impedances of individual links and nodes.

The notion of impedance is an important difference between a transportation network and a graph network. In a transportation network, each link or node has impedance that represents the cost resulted from traversing the link or the node. The cost can be a non-negative numeric attribute associated with a link or a node, such as time or distance. These values are important criteria in some applications related to the networks, such as trip planning. For example, the identification of a shortest path between two nodes depends on the minimum distance cost from the origin node to the destination node. In these applications, a single cost factor, such as driving time or driving distance, can be specified, but not be limited to. Nevertheless, the connectivity of a transportation network is not inherently related to the spatial proximity (spatial connection) between the nodes

or the links, as traffic rules are applied to the transportation networks. In particular, in a public transportation network, fixed routes and stops result in the non-spatial connection between two stops. The connection derived from traffic-oriented restrictions and rules may be referred as traffic connectivity. Although the spatial connectivity is the fundamental and prerequisite for traffic connectivity, the traffic connectivity is the core of the topological structure of transportation network. For example, as barriers are usually deployed within a street, and when two bus stops are on opposite sides of the street, the shortest path based on spatial proximity (a straight line across the middle of the street) is not relevant if passengers want to walk from one bus stop to the other. This implies that in an integrated transportation network structure, the spatial connectivity and the traffic connectivity need to be modelled, integrated and represented.

An example is taken to illustrate the modelling, integration and representation of turning rules applied to the intersection. One approach to model and represent the turning rules on the intersection is introduced by Miller and Shaw (2001). The approach model and represents an intersection by varying levels of granularity. In Figure 2.14(a), the intersection is aggregated to a single node. Although parsimonious, this method is simplistic and does not capture a critical intersection property. Therefore, the varying turn impedances associated with different directions of travel should be implemented through the intersection, as a left turn may require more time than a right turn or travelling straight through the intersection. In addition, turn restrictions should be presented (e.g., "no left turn"). In order to capture these properties, single node representation of an intersection can be expanded, as shown in Figure 2.14 (b). This method expands the intersection to four nodes with connecting links representing direction-specific travel.

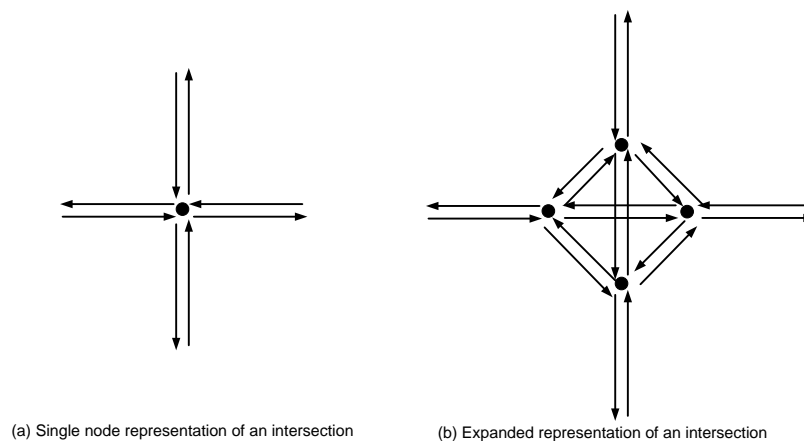


Figure 2.14 Representations of an intersection

2.4.2 Current multi-modal transportation GIS data models

In many modern cities, such as Paris, London, Hong Kong and Guangzhou, the urban transportation network is a complicated multi-mode-based network, including multiple streets (carriageways, vehicle lanes, bicycle lanes and pavements), bus lines and rails (metro lines). Several attempts and practices have been made to develop multi-modal transportation GIS data models to incorporate in the growth of multi-modal transportation systems.

Miller *et al.* (1995) designed a virtual network for representing the topological relationship of a multi-modal transportation network. This multi-modal network was designed by a collection of route classes, such as bus routes and streets, generated from basic topologic network. This approach separates the multi-modal network from the physical network for specific transportation mode attributes, and maintains data consistency. Ho *et al.* (1998) practiced a similar design of virtual network on the multi-modal mass transit system in Singapore. In the design of a GIS-based automatic trip planning system, Peng (1996) modelled the public transit network by decomposing the physical transportation network into segments. A form of pattern composed of one or several segments was used to build up public transit network. These efforts seek to construct an integrated network which can record the topological relationships among different transportation networks. However, the conceptual models oriented to a multi-modal transportation network are needed to be further investigated.

The UNETRANS model is a notable multi-modal transportation GIS data model that was conducted by ESRI (Curtin *et al.*, 2003). One purpose of the model is to generate an initial conceptual object model of transportation features incorporating multi-modal transportation modes with an accommodation of multi-scale representations. This object-oriented model is specified in an industry-standard modelling notation called the Unified Modelling Language (UML) and is intended as a starting point for structuring transportation data. A logical data model view is also provided to present the basic structure of the UML model in an easy-to-read poster format. However, the UNETRANS model is limited to a given environment of ESRI ArcGIS. Although the UNETRANS model provides multiple data representations for different transportation networks (including roads and rail networks), temporal properties of transportation data are not considered.

The USA National Cooperative Highway Research Program (NCHRP) has supported an effort (commonly referred to as the 20–27 models based on the NCHRP Project number) of dealing with the temporal referencing methods. In particular, the transportation multi-modal, multi-dimensional location referencing system (MDLRS) data model was developed through NCHRP Project 20-27(3) for meeting the need of the transportation community to implement the temporal referencing systems and multi-modal transportation location referencing systems (LRS) (Koncz and Adam, 2002). The research of this model was benefited from other existing transportation data modelling methods (e.g., linear or temporal referencing systems), and to develop a generic data model which could be adopted by transportation agencies, by transportation geographical data standards groups, and by GIS-T software vendors.

The MDLRS is supported and extended by the NCHRP 20-27(2) Linear Referencing System data model (Vonderohe *et al.*, 1997). A Linear Referencing System is a data structure that can be defined as a method for storing geographic data by using a relative position along an already existing linear feature (Curtin *et al.*, 2003). The NCHRP 20-27(2) Linear Referencing System data model is used in the MDLRS data model as the framework to manage and transform linearly referenced data, and is extended to include locations in both space and time. The MDLRS data model fulfils accommodation of a temporal datum that relates the database representation to the real world. It provides the domain for transformation among temporal referencing methods. These efforts achieve a comprehensive, multi-modal, and multi-dimensional LRS data model. Figure 2.15 illustrates a high-level view of the MDLRS data model. The transportation feature object, subclasses, and inter-relationships are explicitly defined in this conceptual and logical UML class schema. In this schema, the spatio-temporal object consists of a spatial object with an associated time object. The time object describes when the spatial object is valid. In order to allow for multiple spatial representations resulting from historical, cartographic, or topological changes, a transportation feature can have one or more

spatio-temporal objects. Temporal relationships between transportation features, and between, spatio-temporal objects are through the use of explicit temporal relationship objects: temporal topology and temporal proximity, i.e., temporal referencing systems.

The MDLRS data model addresses an important topic in transportation data modelling that is to build and represent spatio-temporal topological relationships in transportation networks, which act through geographical/temporal connectivity and the defined traffic connectivity in practice. However, the development of the MDLRS data model is limited to the conceptual modelling levels, the modelling and representation of the multi-modal network topology model needs to be further investigated at the logical levels. For example, the functions related to path finding, route guidance, travel time prediction, stochastic processing (e.g., predictive traffic estimates), or dynamic programming do not be validated and verified in the MDLRS data model, although the model does provide the data constructs to support the methods.

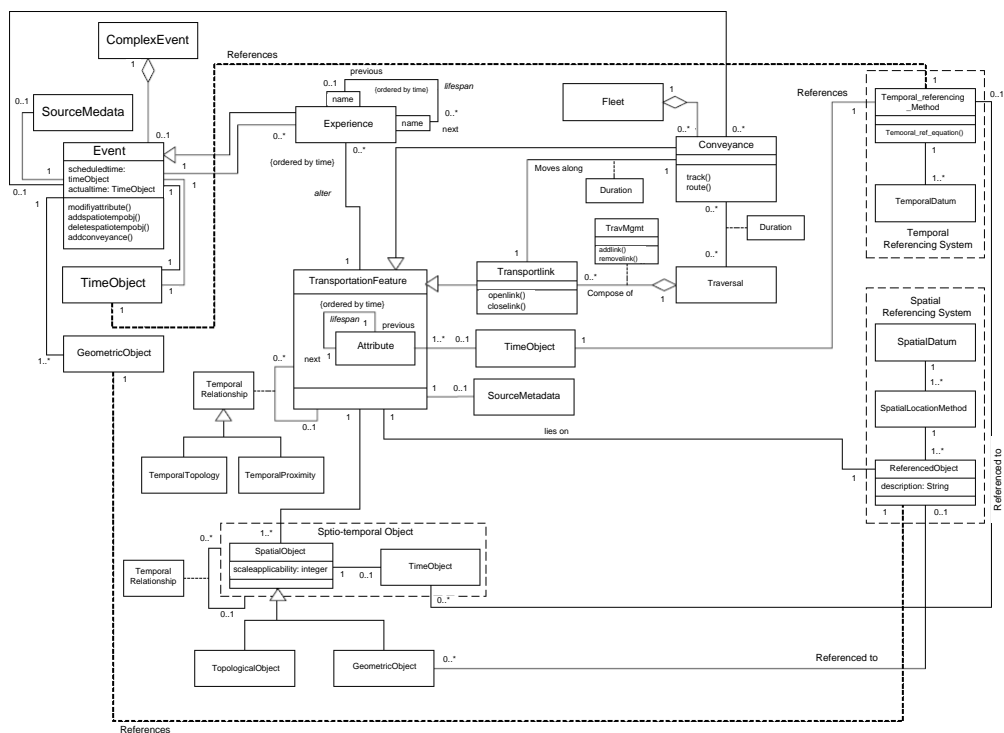


Figure 2.15 High-level view of MDLRS data model (Koncz and Adam, 2002)

2.4.3 UML-based GIS data modelling

2.4.3.1 Object-oriented modelling methods

One of the available data modelling methods currently is to rely on object-oriented principles. Besides of the advantages that object-oriented methodology brings to software analysis and design, it is particularly adapted to the modelling of the complex GIS data (Liu *et al.*, 2004). The advantage of object-oriented data modelling is the fact that data objects encapsulate state expressed by attributes and behaviour specified methods or

operation, and they are able to communicate by sending and retrieving messages. This implies a data object model of custom features.

Nowadays, object-oriented modelling methods have been widely used in GIS data modelling, and have significantly contributed to existing data models in the fields of transportation GIS, including the NCHRP 20-27(3) MDLRS Data Model (Adams *et al.*, 2001), GDF (GDF, 1995), NCHRP 20-27(2) LRS data model (Vonderohe *et al.*, 1997), and the GIS-T/ISTEA PFS model (Fletcher, 1995). These data models apply the object model approach extended to the semantics of the Unified Modelling Language (UML) for modelling and representing transportation data and relationships. The UML is a notable object-oriented modelling language, and is referred to as the industry standard visual modelling language and used to specify, visualize, construct, and document software systems or data models (OMG, 2005). Visualizing, specifying, constructing, and documenting object-oriented systems and models are exactly the purpose of the UML. The UML-based visual object-oriented data modelling helps us to (1) understand and describe more precisely the intended content of a client's datasets; (2) master the complexity of the problem, and facilitate the exchange and the validation of ideas; (3) improve the programming process, and to ease the maintenance of the model (Booch *et al.*, 2006; Bédard, 1999).

Object-oriented modelling concepts in the UML have been clearly identified by many efforts in visual software and data modelling (Rumbaugh *et al.*, 1991; Fletcher *et al.*, 1995; OMG, 2005; Booch *et al.*, 2006). In order to apply the UML in transportation GIS data modelling, the fundamental concepts and semantics of the UML need to be reviewed. These involve the concepts of class and object and relationship definitions.

The UML provides a graphical representing of class that is a description of a set of objects that share the same attributes, operations, relationships and semantics. Figure 2.16 illustrates an example of the representation of a class. An attribute is a data value held by objects in a class. An operation is function that may be applied to or by objects in a class.

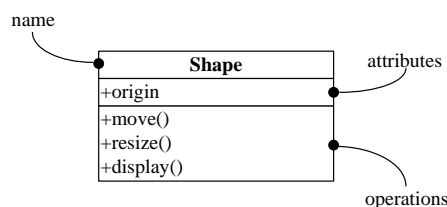


Figure 2.16 Example of class diagram with name, attributes and operations

Relationship representation is an important topic in the UML, as every signal object class does not stand alone in the object modelling. Relationships defined in the UML are employed to model how these classes stand in relation to one another. There are three kinds of relationships that are especially important in object-oriented modelling: “dependencies”, which represent using relationship among classes and is rendered as a dashed direction line; “generalizations”, which link generalized classes to their specializations and is shown as a solid directed line with a large open arrowhead pointing toward the parent; and “associations”, which represent structural relationships among objects (instances) and is rendered as a solid line connecting the same or different classes. These three relationships cover most of the important ways in which classes collaborate with on another. The UML also provides a graphical representing for each relationship, as shown in figure 2.17.

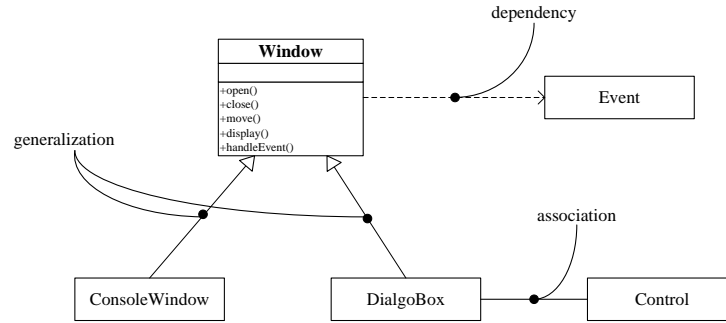


Figure 2.17 Example of relationships

An association can have a name, and it is used to describe the nature of the relationship. In order to avoid ambiguity about its meaning, the name may be given to a direction by providing a direction triangle that points to the direction, as shown in Figure 2.18. Furthermore, when a class participates in an association, it has a specific role that it plays in that relationship. The role played by an end of an association is called an end name. For example, Figure 2.18 illustrates that the class Person playing the role of employee is associated with the class Company playing the role of employer.

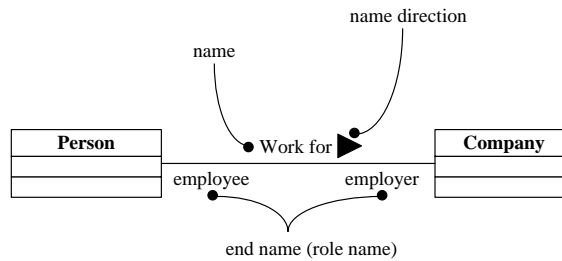


Figure 2.18 Example of association name and its direction

While an association represents a structural relationship among object classes, it may present how many objects may be connected across an instance of an association, i.e., the multiplicity of an association’s role. This role states a range of integers specifying the possible size of the set of related object. A multiplicity specification is shown as a text string of integer intervals in the format “lower-bound..upper-bound”, as shown in Figure 2.19. Figure 2.20 illustrates an example of multiplicity of relationships. In this UML scheme, each company object has as employee one or more person objects (multiplicity 1..*), but each person object has as employer zero or more company objects (multiplicity 0..*).

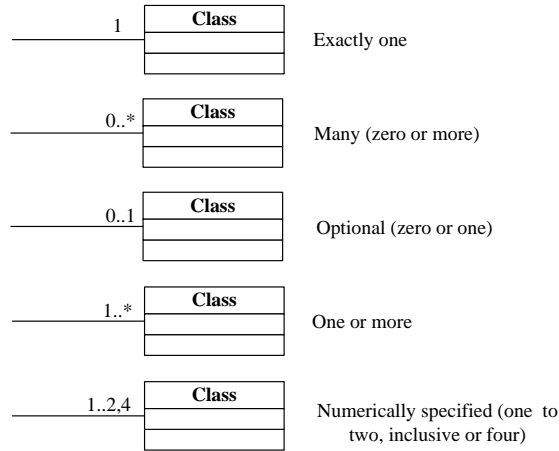


Figure 2.19 Multiplicity of relationships

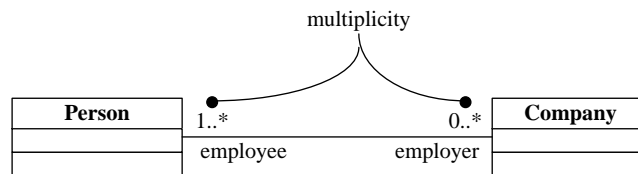


Figure 2.20 Example of multiplicity of relationship

Dependencies, generalizations and associations with names, multiplicities and roles are the most common features needed in modelling. However, the UML also introduces some relationships to visualize or specify other features, such as “whole/part” relationship or “contained/containing” relationship. These relationships include “association class”, “aggregations” and “compositions”. An “association class” is designated to represent an association that has class like properties (such as attributes, operations, and other associations). Figure 2.21 illustrates that an association between “person” and “company” classes has a class “hires”. This association class states that a company can hire one or more persons and one person can be hired by zero or more companies.

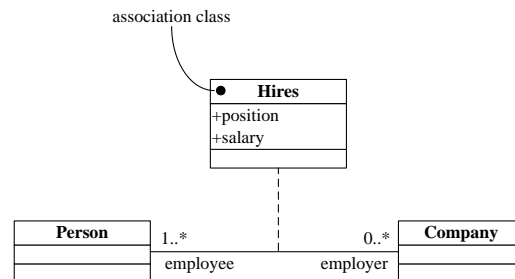


Figure 2.21 Example of an association class

“Aggregation” is introduced to model a “whole/part” relationship, in which one class represents “the whole”, which consists of “the parts”. Aggregation is really just a special type of association that is specified by adorning a plain association with an unfilled diamond at the whole end. Figure 2-22 illustrates an example of an aggregation relationship between a Car and a Wheel. However, if a class cannot exist by itself, and instead must be a member of another class, then that class has a composition relationship with the containing class. The composition relationship is just another form of the aggregation relationship, but the subclass’s instance lifecycle is dependent on the superclass’s instance lifecycle, as shown in Figure 2.23.

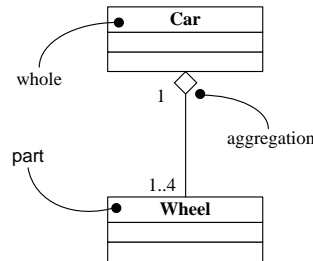


Figure 2.22 Example of an aggregation association

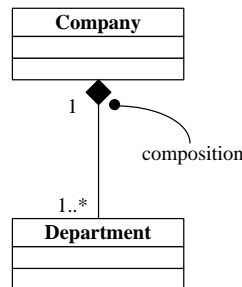


Figure 2.23 Example of a composition association

2.4.3.2 Spatio-temporal GIS data modelling

Several efforts of applying the UML in GIS data modelling have been motivated during the last decade (Price *et al.*, 1999; Bédard, 1999; Brodeur *et al.*, 2000; Liu *et al.*, 2004; Svinterikou and Kanaroglou, 2006), which are targeted for specifically addressing the need for a conceptual modelling language suitable for analysis and specification of spatio-temporal data.

Bédard (1999) argues major trends of visual modelling languages and related research in GIS data modelling. The analysis of these trends seeks to provide extensible, spatially- and temporally-aware, and standard object-oriented modelling languages with formal and rich dictionary. The UML incorporates with these trends due to its extensibility mechanisms, i.e., stereotype, tagged values, and constrains. This implies spatio-temporal UML that may be referred as an object-oriented modelling language for geographical information applications based on the UML built-in extensibility mechanisms (Price *et al.*, 1999). Amongst the UML’s extensibility mechanisms, stereotypes can be used to extend

the vocabulary of the UML, and allows for creating new kinds of class diagrams. These diagrams are derived from existing ones but that are specific to the problem. Stereotypes also allow for introducing new graphical symbols in order to provide visual and graphical views to specify special properties of an object in the UML (Figure 2.24). A stereotype can be also rendered as a name enclosed by “<< >>” and placed above the name of another element.

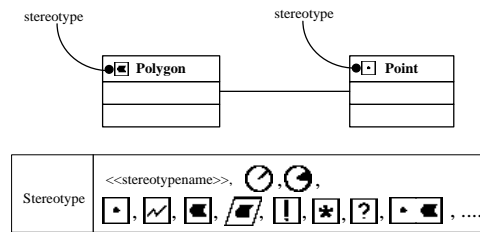


Figure 2.24 Example of extensibility

A notable extension of the UML to express spatial and temporal data in a GIS environment is a freeware Computer Aided Software Engineering (CASE) tool called *Perceptory* (Bédard and Proulex, 2006). The *Perceptory* employs plug-in for visual languages (PVL) as stereotypes to extend the UML’s semantics to accommodate the representations of spatial, temporal or spatio-temporal data (Brodeur *et al.* 2000). Therefore, the *Perceptory* can be applied in the depiction and design of GIS data models. In order to apply PVLs provided by the *Perceptory* in the transportation GIS data modelling, some principles of the PVL need to be reviewed, particularly the constructs of PVL.

In the GIS data modelling by applying *Perceptory*, PVL are introduced as stereotypes to define and illustrate spatial, temporal or spatio-temporal object classes and their hierarchies and inheritances by using object model diagrams. In the *Perceptory*, the plug-in for visual languages (PVL) provides a set of basic constructs including “simple geometry” and “simple temporality”, as shown in Figure 2.25. The basic constructs is rendered as graphical notations called “pictograms”. The pictograms can be used along to describe a simple spatial or temporal object, i.e., spatial pictograms or temporal pictograms. As for spatial pictograms, in particular, if the aggregation involves shapes of a same dimension, a simple spatial pictogram box can be followed by the cardinality 1, N (A cardinality of 1, 0 means a facultative shape; 1, N a group of shapes; default is 1,1). For example, while a geographical network is described by an aggregation of lots of linear features, the pictogram, i.e. $\square_{1,N}$ can be used to express such a network. Temporal pictograms, i.e., instantaneous time (\odot) and durable time (\odot) are linked to the temporal dimension of transportation object. As the temporal dimension is based on the temporal axis graduation (i.e., hour, day, month and year), temporal pictograms can be used to define instantaneous events if they have a dimension \leq than the graduation, and durable events if they have a dimension $>$ than the graduation.

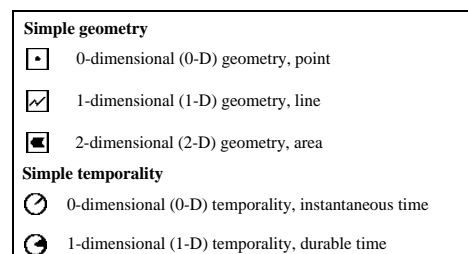








Figure 2.25 Basic constructs of PVL with graphical notations (named “pictograms”)

As a geographical object can have multiple themes, scales and shapes, furthermore, the basic pictograms outlined above can be combined to describe the multiple properties. In the case of representing a hydrographical network, a pictogram box includes a 1-D and a 2-D symbol (i.e. ) is used to describe an aggregation of several lines (rivers) and polygons (lakes). Moreover, temporal pictograms can be combined with spatial pictograms to specify the spatio-temporal objects. For example, a durable polygon is expressed as a combination of geometry and temporality pictogram, i.e. , to describe the capability of the geographical object which have a durable evolution in space. Other spatio-temporal pictograms can be also referred to the instantaneous description of object in space. For example, while a bus is running along a path through time and space, the position and time of each vertex can be represented by the pictogram, i.e. .

Moreover, the attributes of transportation object may have spatial or temporal characteristics. The pictograms can be also used to describe these characteristics of the attributes. For example, for a transportation network, it is a common rule to use a linear referencing system for certain road attributes such as “number of lanes”. Another specific case is that starting from intersection A, the road has 4 lanes up to a distance of 200 meters; then 2 lanes from the distance 200 meters to the distance 1800 meters. When such an attribute within an object class is considered as a component of an object instead of a sub-object, it is simply to use spatial pictograms next to the value of the attribute to represent its spatial characteristics. This is also useful for the attributes with a temporal or spatio-temporal characteristic within a class object.

As the pictograms can be used to enrich the representation of spatio-temporal geographical objects by an integration in the UML, the *Perceptory* defined them a precise location into a UML class diagram: (1) a spatial stereotype of a class is placed on the left side of the name of object class; (2) a spatial stereotype of an attribute is placed directly nearby the defined attribute; (3) a temporal (existence) stereotype of a class is placed on the right side of object class; (4) a spatial evolution of a class is placed on the left side of the name of object classes instead of the spatial stereotype; (5) a descriptive (non-spatial) evolution stereotype of an attribute is placed directly beside the defined attribute; (6) a spatial evolution of an attribute is placed directly nearby the defined attribute. Figure 2.26 illustrates a class diagram with the PVL pictograms. A spatial pictogram () represents a metro line composed by two 1-D lines with oppose directions. A temporal pictogram () beside the attribute “status” specifies a metro line may change its status on time, such as the value of “in service” or “off service”. A spatio-temporal pictogram () of the attribute “construction” indicates that a metro line might be under construction. A metro line can be mapped progressively while allowing the user to record the new geometry and position as well as the corresponding periods.

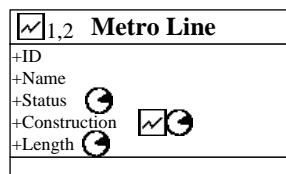


Figure 2.26 Example of a class diagram of metro line

2.5 GIS-T development and routing application

2.5.1 Transportation GIS development

A transportation GIS data model could allow for the development of specialised applications designed in a software system according to the users' needs. Application customisation is a key to a successful GIS, but also, it is recognized as one of the most time-consuming and expensive elements of GIS implementation (Maguire, 1995). Therefore, GIS software system development often heavily relies upon the existing GIS software platforms or object libraries, such as ESRI ArcGIS or ESRI MapObjects. These GIS development components and readily available object libraries provide opportunities for GIS developers to be able to customize different GIS applications rapidly (Hu, 2004).

GIS has relevant software packages to deal with transportation problems. These software packages provide visualization, data management and spatial analysis tools for GIS applications applied to different transportation fields, such as logistics, planning, navigation and pre-trip guidance. Amongst these packages, some consider special problems of optimizing the delivery or collection routes (i.e., logistics), such as ArcLogistics Route of ESRI, Visual Control Room of MapInfo, LogisticsPRO of Interpa LLC and logistics decision support systems of CAPS Logistics Inc.. Some concentrate on transportation planning issues, such as TransCAD. A few packages provide a complete set of tools for modelling geographic information to meet GIS needs in different fields. These packages provide one common platform that allows for an integrated collection of GIS software products and servers for building and deploying a complete GIS, particularly custom applications. For instance, ESRI GIS and mapping platform is designed as an integrated system. Such a platform offers tightly integrated solutions that cover the full spectrum of GIS requirements from small applications designed for casual users to sophisticated multi-user enterprise applications.

A specific GIS configuration can be created by selecting appropriate software or development components from the ESRI GIS platform, including ArcInfo, ArcView, ArcObjects and MapObjects. In particular, ESRI MapObjects is a set of mapping and GIS components for application developers (ESRI, 2008). Developers can use MapObjects to create applications that include dynamic live maps and GIS capabilities (ESRI, 2008): (1) Add mapping components to enhance existing applications; (2) Build lightweight data viewing applications; (3) Create customized mapping and GIS programs that fulfil specific tasks and requirements; (4) Develop simple query-based applications that easily enable access to data generated by sophisticated GIS solutions.

Software application development has been greatly facilitated by the use of interactive forms and structures for developing reusable software modules in the "visual" object-oriented programming environment. ESRI MapObjects is a powerful programming tool that can enable developers to incorporate mapping capabilities in their application within a "visual" programming environment, such as Microsoft Visual Basic 6.0 (Lombard, 1997). Under a "visual" programming environment, ESRI MapObjects offers the advantage of providing a complete set of vivid GIS-based analysis/management tools and methods, which can be readily utilized in transportation GIS software application development. Therefore, ESRI MapObjects could be an appropriate software development tool to develop a multi-modal and multi-scale transportation GIS.

2.5.2 Transportation GIS routing application

Routing application is an important functionality of the transportation GIS, as many traffic questions or activities are related to path identification, computing and tracking, involving shortest-path finding, trip planning, pre-trip guidance and vehicle navigation or surveillance. This implies to the important applications related to transportation networks, in particular path finding with minimizing costs, e.g., travelling distance, transfer or travelling time.

As transportation networks can be represented by a directed graph composed of links and nodes, the theoretic foundation of routing on transportation networks may be considered as a graph theory. Some algorithms based on graph theory have been introduced to perform routing on a transportation network with a widespread application since the 1960s (Lupien *et al.*, 1987). The algorithms, particularly Dijkstra algorithm (Dijkstra, 1959), Bellman-Ford algorithm (Cormen *et al.*, 2001), Johnson's algorithm (Black, 2004), and Floyd-Warshall algorithm (Floyd, 1962), have been constructed to solve various routing problems: (1) Dijkstra algorithm for single-source shortest-path problem on a nonnegative graph; (2) Bellman-Ford algorithm (Cormen *et al.*, 2001) for single-source shortest-path problem on a graph with negative weights; (3) Floyd-Warshall algorithm (Floyd, 1962) for all-pairs shortest-path problem on a common graph, and; (4) Johnson's algorithm (Black, 2004) for all-pairs shortest-path problem on a large sparse graph.

Although shortest-path finding is an essential precursor to many transportation operations (Waters, 1999), it is not all routing applications can be considered as shortest-path searching problems on a graph. In the urban areas, roads extend in all directions and form a complicated network that connects every corner of the city. Referencing of the road network, public transportation networks are provided to assist dwellers in moving around the city. Under a common condition, there are several different modes integrated to serve the travel demands. Therefore, routing created in transportation GIS is often concentrated on more than one transportation mode. Moreover, the routing applications should involve different desires with different minimizing travel costs. This implies that transportation GIS routing application should be designed and developed with respect to deal with multi-modal and multi-criteria path finding problems.

2.6 Discussion

2.6.1 Application requirement

The widespread uses of automobile in the 20th century changed the way we live our life and do business. Nevertheless, the high automobile ownership and usage also brings serious traffic issues to the cities around the world. These problems particularly involve traffic congestion, energy shortage, air pollution and traffic accidents. In order to specify the issues and needs of urban transportation development, we particularly review and investigate the current patterns of the urban transportation systems and travel behaviours in the city of Guangzhou. The change of transportation modal split estimates presents the rapid growth of urban mobility demand in the city of Guangzhou, which has led to a high level of private car ownership and usage. In order to deal with these issues, the city of Guangzhou has moved away from the "build it and they will come" and

infrastructure- and capital-intensive transportation policies, toward more effective and economic solutions. This includes the need to implement the policies that prioritize public transportation systems above road investment, and in particular the need to apply information means to bring forward the role of integrated information systems which can be a source to provide decision-makers, planners and end-users the appropriate applications at the right time.

The approach to meet the needs is to implement an efficient multi-modal urban transportation system which can deal with the shortcoming derived from high automobile ownership and usage, and meet urban mobility demand. Nowadays, multi-modal urban transportation modes, either public or private, have been developed in many big cities around the world, including Paris, London, New York City, Hong Kong, Beijing and Guangzhou. In these cities, the multiple transportation networks are usually composed of streets, pavements, rapid mass transit network (here identified as metro lines) and bus-based network. The combination of these transportation networks has provided more freedom in personal transportation, and form a multi-modal urban transportation network which is the connection of different transportation modes, including bus, metro, walking and car. Some problems, such as traffic congestion, energy shortage, air pollution and traffic accidents are not of particular points in the research context of this thesis. Nevertheless, the study and implementation of an integrated information system of multi-modal transportation network are of interest. Such a system can provide reliable data and information to support the applications of multi-modal data management, multi-level data representations, network planning and multi-modal trip planning, taking into account the quality of public transportation services. Government agencies, research institutions, private sectors and commuters are among the transportation actors who look forward availability of these applications to facilitate the development of an efficient multi-modal transportation system. This requires an appropriate data structure to support the implementation of multi-modal transportation applications. The application requirement presents the need of an essential transportation GIS, which can provide a multi-modal and multi-level network topology structure, and a source of reliable data and information to support the applications towards the users' needs. This reflects the research objectives of the thesis.

2.6.2 Related work

In order to facilitate the transportation GIS data modelling, related work are discussed by reviewing and examining the existing transportation GIS models and standards, involving the NCHRP MDLRS model, GDF and UNETRANS model. These models have provided some key elements to build a GIS data model applied to the multi-modal transportation systems. These elements include location referencing methods, spatio-temporal data structures, multiple data representations, and multi-level topological representations. Amongst the existing data models, the MDLRS and UNETRANS model are the notable multi-modal GIS-T data models which provide the modelling elements. However, these two models are still in the design phase with proposals. For example, although both of the UNETRANS and MDLRS models do provide the data constructs to support routing methods, the applications related to multi-modal transportation routing issues are still not implemented. The GDF model is oriented to the road network modelling, and to facilitate the navigation and routing applications for the car drivers. However, the GDF model is not initially proposed to meet the need of multiple transportation modes, although the model can be adapted to this extended scope.

The models outlined above have provided the principles to implement multiple cartographical representations for particularly describing the street network at different granularity levels (carriageway- or lane-based levels). Nevertheless, in the MDLRS,

UNETRANS and GDF models, the primitive objects (e.g., individual stop sites and directional routes) of public transit network are not described with details at a given scale. This leads to the topology structures of the models can not be compatible with a synthesis of multi-modal and multi-scale transportation data, and handle valid spatial and traffic connectivity with restrictive impedances between individual links and nodes. Therefore, the principles to multiple cartographical representations of the street network need to be adapted to implement the multi-level representations of a multi-modal transportation network which could involve streets, walking paths, bus lines and metro lines. Moreover, the development of an efficient transportation system requires the design of an adapted transportation GIS that could clarify the primitive objects of multi-modal transportation networks at different levels of abstractions (i.e., scales), and maintain consistency of multiple topological relationships. More detailed representation of data and integrated topology structure is essential to implement the functionalities to match the applications of multi-modal transportation modes. Table 2.9 shows the criteria to build an adapted transportation GIS data model, i.e., a multi-modal and multi-scale urban transportation GIS (MDMSTGIS) data model, as compared with the existing GIS-T models.

Model Criteria	GDF	UNETRANS	MDLRS	MDMSTGIS
Location referencing methods	Linear referencing methods	Linear referencing methods	Temporal referencing systems and multi-modal transportation location referencing systems	Temporal referencing systems and multi-modal transportation location referencing systems
Spatio-temporal data modelling	Need to be extended	Need to be extended	Spatio-temporal data structure	Spatio-temporal data structure
Multiple cartographical and topological representations	Several levels of description for representations of road network	Multiple representations of transportation features and objects (road network, assets and activities)	Use scale applicability as the central notion for maintaining consistency of multiple geometric and topological representations	Use scale applicability as the central notion for maintaining consistency of multiple geometric and topological representations
Multi-modal transportation systems	Need to be extended	Road and rail networks	Allow for the connectivity of modal transportation systems (including road, bus, metro and walk networks)	Build the connectivity of modal transportation systems (including primitive objects of road, bus, metro and walk networks)
Detailed data representation and topological structure	Need to be extended	Need to be extended	Need to be extended	Implement detailed data representation and integrated topological structure
Application related to multi-modal routing issues	Need to be extended	Provide data structure to support path finding and proximate analysis	Provide data structure to support path finding and proximate analysis	Implement multi-modal path finding and proximate analysis with special data structure

Table 2.9 Key criteria to build a multi-scale and multi-modal urban transportation GIS

The modelling approaches applied in the GDF, UNETRANS and MDLRS models are provided by a visual object-oriented modelling method, i.e. the UML. The UML provides a

standard language for writing data model blueprints. Nevertheless, the complex characteristics of transportation data are not limited to spatial and temporal dimensions, but also include the direction of transportation link provides. This also implies multiple relationships of transportation components. The issues of transportation GIS data modelling are still existed in the UML-based modelling approaches to deal with the complex characteristics and multiple relationships of transportation data.

The approaches to deal with GIS data modelling have been studied and implemented by several efforts. One effort is the *Perceptory* CASE tool based on the plug in for visual languages, i.e., the PVL. The reviews of the *Perceptory* are explored to lay some principles of UML-based GIS data modelling. Although the PVL implements more effective and straightforward object-oriented GIS data modelling in UML, it is not proposed towards the transportation data modelling. In the *Perceptory*, the UML extended with PVL is not one language to ever be sufficient to express all possible nuances of all spatial data models across all domains. In order to meet the modelling objective in the domain of multi-modal and multi-scale transportation GIS, it is necessary to identify alternative UML-based modelling fundamental, concepts and features to an essential transportation network data model. Therefore, the PVL needs to be extended to meet the need of transportation data modelling in a GIS environment. On the basis of the principles provided by the *Perceptory*, spatial and temporal UML-based semantics could be extended and adapted to accommodate the multi-level cartographical representations of transportation data and topological structures in the context of a multi-modal transportation network.

Regarding the routing applications of multiple transportation modes, an attempt should be practiced in an adapted transportation GIS to handle multi-modal trip planning. In order to provide more reasonable, accurate and complete multi-modal trip planning, the path identification algorithms need to be reviewed and adapted. Amongst these algorithms, Dijkstra algorithm is a classic and basic shortest-path routing algorithm. It also is one of most widely adopted methods for routing on networks, and accessed as a way that has advantages in handling shortest-path problems (Cormen *et al.*, 2001; Zhan, 1996). Based on Dijkstra algorithm, various types of traffic routing problems have been explored by researchers (Chen and Hsueh, 1998; Fu and Rilett, 1998; Kaufman *et al.*, 1998; Spiess and Florian, 1989; Wong and Tong, 1998). However, the major disadvantage of Dijkstra algorithm is the fact that it does a blind search thereby consuming a lot of time waste of necessary resources. That is, for a given single vertex (node) in the graph, Dijkstra algorithm finds the path with lowest cost (i.e. the shortest path) between that vertex and every other vertex until the destination vertex (node) has been determined. This implies that the algorithm could consume a lot of resource (time) to determine the destination vertex. Particularly, the multi-modal transportation network involves complex topological structures which involve a large number of transportation links and nodes. As a result, the efficiency of the Dijkstra algorithm may be limited due to consume a lot of time in searching the destination node. This requires the design and development of more efficient routing methods to implement multi-modal routing applications in an adapted transportation GIS.

Chapter 3

MULTI-SCALE AND MULTI-MODAL TRANSPORTATION GIS DATA MODEL

This chapter describes the designing and development of a multi-scale and multi-modal transportation GIS data model by the conceptual object modelling and network topology modelling. The conceptual object modelling lays fundamental concepts to the definitions and interpretations of transportation objects, and their spatio-temporal characteristics and relationships. In the network topology modelling, the modelling process starts with identifications of the primitive objects and topological relationships of and between transportation networks, and continues with investigation of the modelling and multiple representations of transportation objects in the multi-scale context. Last, an integrated topology structure of multi-modal transportation networks is accomplished. On top of the special data structure, multi-criteria routing applications in the multi-modal transportation networks are studied and implemented.

3.1 Modelling process

The modelling process of a multi-modal and multi-scale transportation GIS data model is based on a visual object-oriented data modelling process accessed by the UML. In this process, the UML takes into account the extension of spatial and temporal semantics, and the integration of the plug in for visual languages (PVL) to express transportation data and relationships at different levels of granularities. The stages of the modelling process and the associated output of these stages are illustrated in Figure 3.1.

Amongst these stages, the first stage is to identify the requirements that the data model is intended to meet. The requirements have been explicitly synthesized from the users' needs and extensive study of the current urban transportation systems and patterns in the city of Guangzhou. The specific requirements to the transportation GIS data model are represented in the Guangzhou ITS Development Project conducted by the Guangzhou Committee of Transportation in 2006. These requirements are listed as follows:

- Integrated network topology. This is required to integrate the spatial connectivity and traffic connectivity between transportation objects and even

networks. This implies an integrated topology structure which is needed to support the applications related to multi-modal transportation networks.

- Temporal relationship model. The model is needed to represent the temporal relationships between objects (or events), and validate the differences in time between dynamic objects, such as schedule and actual events, occurring at a particular location.
- Multiple spatial data representations. This is needed to support multiple cartographic and topological representations to model and represent the transportation spatial data to be compatible and flexible with different application purposes, as different applications usually require different levels of data abstractions.
- Multi-modal trip planning. The approach to implement multi-modal trip planning is required to facilitate the multi-criteria routing and path finding applications. These applications are needed to deal with the optimal path questions resulted from different transportation actors' expectations, particularly the commuters. Moreover, multi-modal trip planning is also needed to facilitate the planning and analysis applications related to multi-modal transportation networks for the planners and decision-makers.

Followed by the first stage, the second stage of the modelling process is to build and identify the fundamental transportation concepts in the data model. These concepts involve transportation objects and their spatio-temporal characteristics and topological relationships. The output of this stage is a conceptual object model. Based on the object model, the third stage is to describe the transportation primitive components and their connections in the context of multi-modal transportation networks. These connections involve spatial perspectives and the traffic connectivity determined by the traffic-oriented rules and restrictions applied to transportation networks. This lays a fundamental to an integrated network topology structure. In order to express the transportation GIS data model, the fourth stage is to extend and adapt the spatial and temporal semantics of the UML, and to integrate the PVL and the UML, to accommodate multiple transportation spatial data and topology representations. The output of the third and fourth stages is a multi-scale and multi-modal transportation GIS data model. The data model represents the user's view of the interrelationships between objects, and use scale applicability as the central notion for maintaining consistency of multiple geometric and topological representations. Based on the integrated network topology structure, the fifth state is to implement multi-modal routing applications, taking into account different criteria as different users' expectations. With an integration of routing algorithms and network topology model designed, it is readily to be applied to a prototype that could implement the functionalities to meet different users' needs and application purposes.

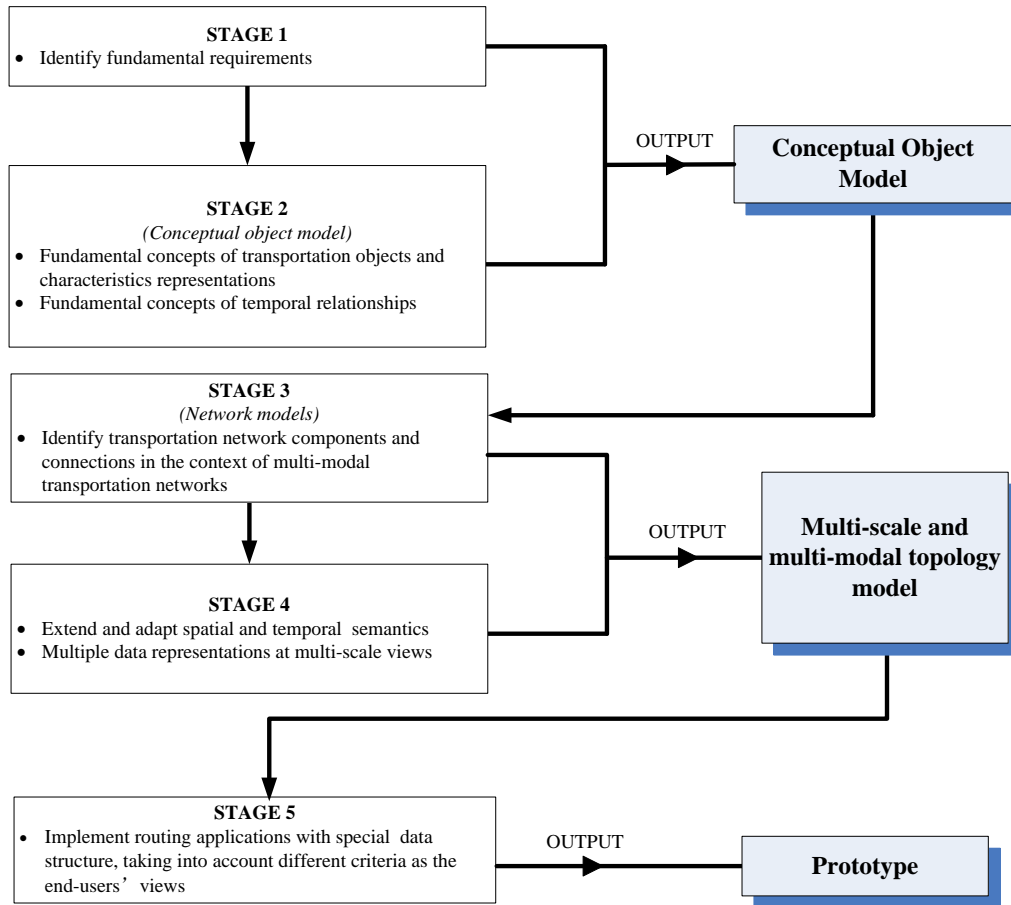


Figure 3.1 Modelling process

3.2 Conceptual object model

3.2.1 Transportation object

A conceptual object model is used to develop a first cut conceptual structural object architecture for a given modelling domain. In Figure 3.2, a conceptual object model of multi-scale and multi-modal transportation GIS is presented based on a UML schema. In the UML schema, transportation data are presented as objects, which are instances of classes. “Transportation object” is the core concept of the model which is defined as a feature to represent a real-world or logically defined transportation geographical entity. A transportation object may comprise different properties, involving spatiality, temporality and attributes. Spatial properties are represented as geometric features that are valid for a certain scale. These geometric features can be a point (zero-dimensional), a line (one-dimensional), a surface (two-dimensional), or a complex, according to different shapes, scales and themes. Since transportation network is commonly considered as a linear graphic network that is composed of vertexes and links. In the object model, such vertexes and links are represented as anchor points and anchor sections (i.e., point and line features), respectively. While transportation spatial networks are represented as a series of anchor points and sections, the connections of these static spatial objects should

be maintained, and explicitly identified, taking into account different levels of abstractions. Spatial transportation objects can be referenced to location referencing systems, including linear referencing systems (LRS) or cartographic coordinate systems. In linear referencing systems, spatial transportation objects are located by a linear referencing method, and a cartographic representation can be mapped to a linear feature. In nonlinear referencing systems, spatial transportation objects have one or more geometric representations that reference a cartographic coordinate system.

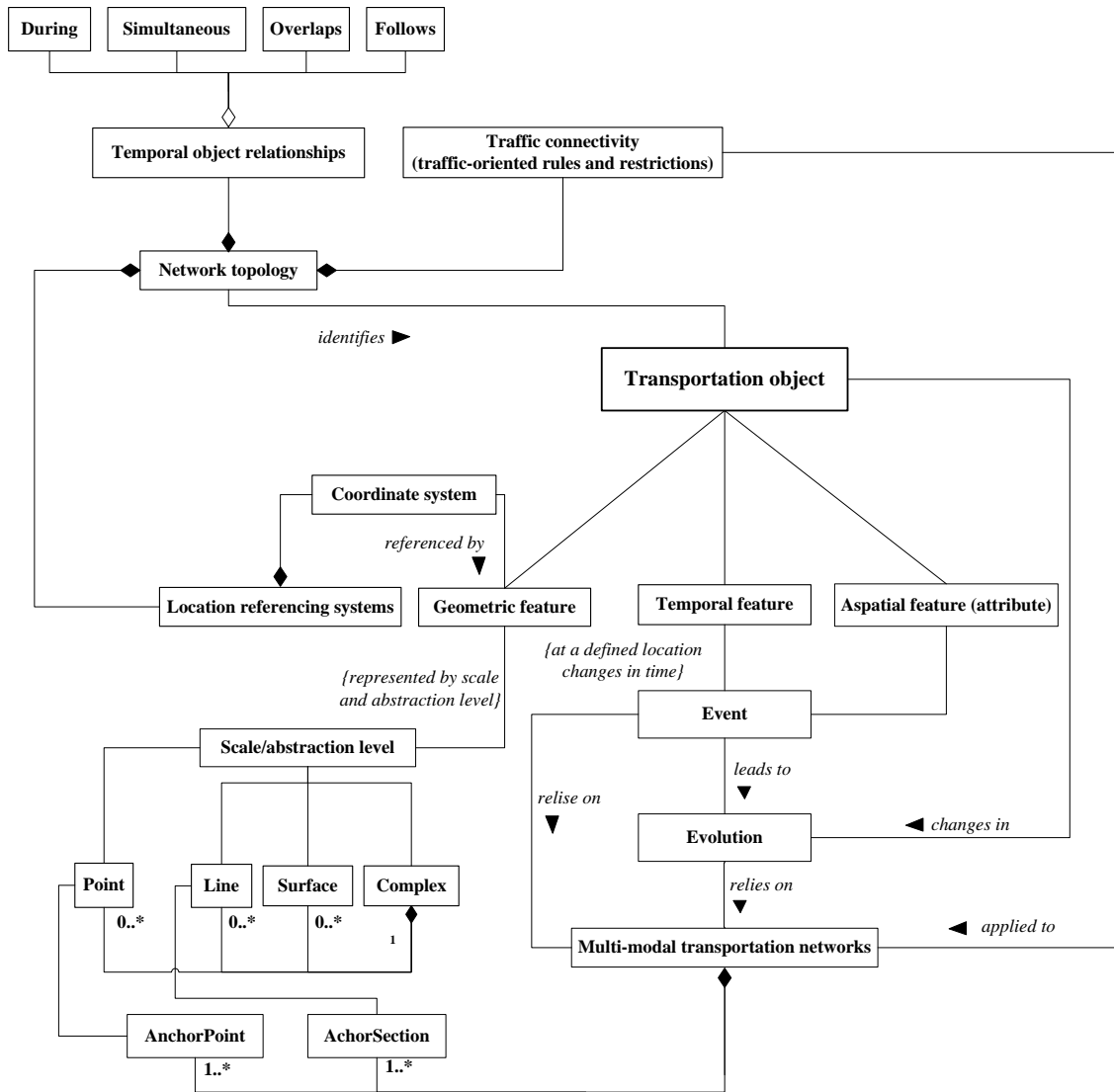


Figure 3.2 Conceptual object model

The spatial connections consist of the spatial topology structure of transportation network. However, different transportation networks usually are applied to traffic-oriented restrictions and rules. This implies that the connections between transportation objects are not limited to the spatial connectivity. For example, the rules of public transit network present that each route is restricted to connect to a sequence of stops. This implies a particular non-spatial relationship between the routes and stops. The turning rules applied to the street network present the restricted connections of the street segments on an intersection. The connections restricted by the traffic-oriented rules and

restrictions are referred as traffic connectivity (or semantic connectivity), which structures the core topology of transportation networks. This implies that both spatial connectivity and traffic connectivity are the essential elements to an integrated network topology structure. In particular, traffic connectivity presents the differences between a transportation network and a graphic network.

A transportation object could be valid for a period of time (i.e., temporal properties). One method to represent the temporal properties is to introduce a "TimeObject" (Adam *et al.*, 2001), as shown in Figure 3.3. TimeObject provides metric descriptions of the temporal properties of transportation objects and events. It represents a specific or relative portion of a time line, and associated temporal referencing system for which an object is valid. This method adopts and extends the concept of three-domain spatio-temporal data models (Peuquet and Qian, 1997; Yuan, 1997). In these three-domain spatio-temporal data models, the attribute domain ("what") is stored in the Transportation Feature object, the spatial domain ("where") is stored in the SpatialObject, and the temporal domain ("when") is stored in the TimeObject. The separate domains eliminate redundancy, as spatial objects have the same geographical meaning can be linked to a single semantic description (Yuan, 1997).

However, the separate semantic description also leads that the modelling of spatial, temporal, and spatio-temporal data is great complexity and low efficiency. One approach to deal with this issue is to provide an alternative integrated representation of spatial and temporal semantics, which does not consider temporal domain as a sub-object, but a component of transportation object. A UML conceptual view of the integrated representation of spatio-temporal transportation object is illustrated in Figure 3.4. The attribute domain ("what"), spatial domain ("where"), and temporal domain ("when") are referred to the components of a transportation object. This approach simplifies the representation of spatio-temporal transportation data, as spatial and temporal transportation objects have the same geographical, temporal and thematic concepts. The approach also provides spatial and temporal UML-based semantics by adapting and extending relative notations (e.g., PVL pictograms) to describe the concepts. This implies an integration of "what", "when", and "where" domains into the concept of transportation object. This presents the combination of temporal and spatial semantics within an integrated modelling framework (Claramunt and Jian, 2000). In this framework, while the questions of "where a spatial feature is?" are addressed, a temporal question, i.e., "when does a spatial or aspatial (i.e., attributes) feature occur in time and space?" may be also completely considered.

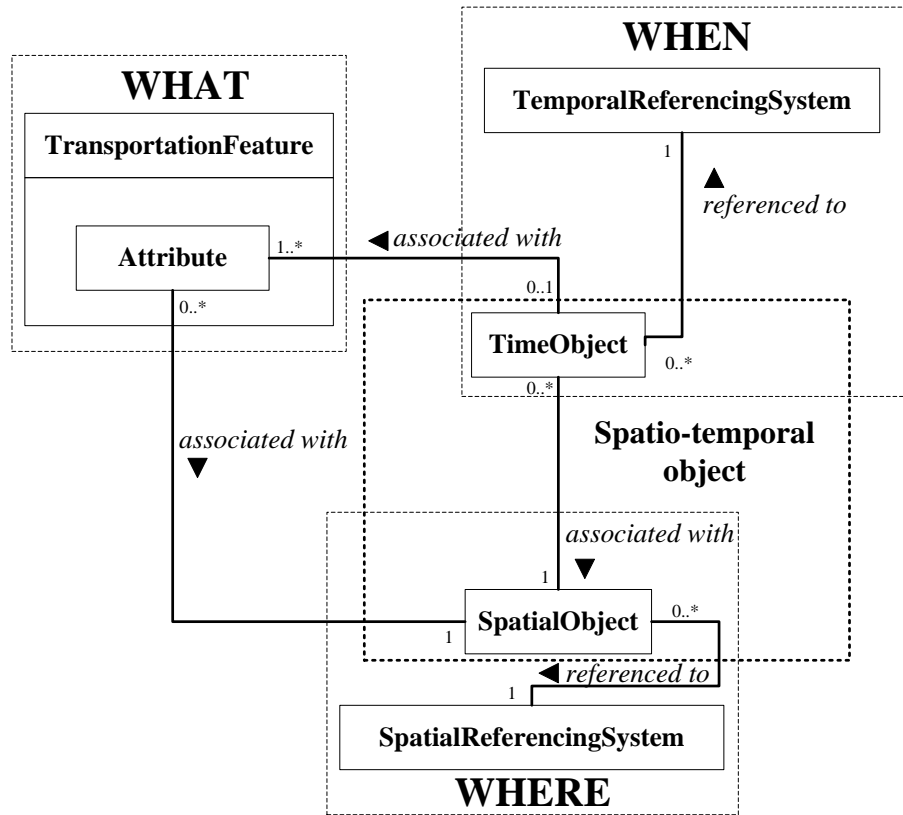


Figure 3.3 UML conceptual view of temporal characteristic representation (adapted from Koncz and Adam, 2002)

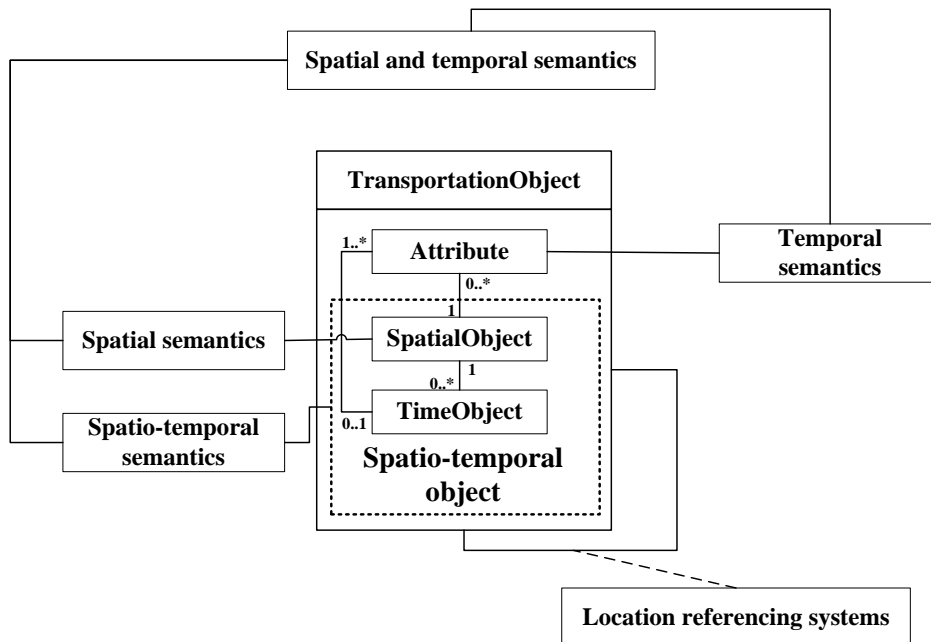


Figure 3.4 UML conceptual view of temporal characteristic representation

3.2.2 Temporal relationship definitions

The temporal properties of transportation objects imply that temporal relationships should exist between transportation objects while they are measured based on a continuous time line. The possible temporal relationships can be defined by follows, simultaneous, during, and overlaps (BCMELP, 1995). These concepts can be applied to a transportation object (e.g., to find the most recent spatio-temporal object), and two transportation objects (e.g., to determine if one transportation object was created before another feature).

In the conceptual object model, each temporal relationship of transportation objects is considered as a conceptual object. One approach to represent the temporal relationship has been introduced by the CGIS-SAI model (BCMELP, 1995). This approach defines two transportation objects, e.g., transportation object *a* and *b*. Time is assumed to be continuous. Let *T* is a continuous time line. *T_a* indicates the time interval between the start (i.e., birth) and end (i.e., dead) of transportation object *a*. *T_b* represents the time interval between the start and end of transportation object *b*. The values of *T_a* and *T_b* are a durable time or an instantaneous time, i.e., $T_a, T_b \in T (T_a \leq T_b \text{ or } T_a \geq T_b)$. The start of *T_a* is defined by *T_a^S*, and the end of *T_a* is *T_a^E*. Accordingly, *T_b^S* and *T_b^E* are the start and end of transportation object *b*. The time-intervals (*T_a* and *T_b*) of these two objects may be temporally disjoint, when one part of *T_a* is simultaneous with part of *T_b*, or intersect. The relationships in which two temporal intervals may intersect, or disjoint temporally are defined from the CGIS-SAI model (BCMELP, 1995). Table 3.1 illustrates all possible temporal relationships based on a continuous time line, and provides the pseudocode to allow the generation of temporal topology operations.

Temporal relationships		Illustration	Condition
Disjoint	<i>T_a</i> before <i>T_b</i>		$T_a \cap T_b = \emptyset$ and $T_a^S \cap T_b^E = \emptyset$ and $T_a^E \cap T_b^S = \emptyset$
	<i>T_a</i> after <i>T_b</i>		$T_a \cap T_b = \emptyset$ and $T_a^S \cap T_b^E = \emptyset$ and $T_a^E \cap T_b^S = \emptyset$
Intersect	<i>T_a</i> is at start of <i>T_b</i>		$T_a \cap T_b = \emptyset$ and $T_a \cap T_b^S \neq \emptyset$
	<i>T_a</i> is at end of <i>T_b</i>		$T_a \cap T_b = \emptyset$ and $T_a \cap T_b^E \neq \emptyset$
	<i>T_a</i> follows <i>T_b</i>		$T_a \cap T_b = \emptyset$ and $T_a^S \cap T_b^E \neq \emptyset$
	<i>T_a</i> overlaps <i>T_b</i> at start of <i>T_b</i>		$T_a \cap T_b \neq \emptyset$ and $T_a \cap T_b^S \neq \emptyset$
	<i>T_a</i> overlaps <i>T_b</i> at end of <i>T_b</i>		$T_a \cap T_b \neq \emptyset$ and $T_a \cap T_b^E \neq \emptyset$
	<i>T_a</i> occurs during <i>T_b</i>		$T_a \cap T_b \neq \emptyset$ and $T_a^S \cap T_b^S \neq \emptyset$ and $T_a^E \cap T_b^E \neq \emptyset$
	<i>T_a</i> occurs during <i>T_b</i> from start of <i>T_b</i>		$T_a \cap T_b \neq \emptyset$ and $T_a^S \cap T_b^S \neq \emptyset$ and $T_a^E \cap T_b^E \neq \emptyset$
	<i>T_a</i> occurs during <i>T_b</i> to end of <i>T_b</i>		$T_a \cap T_b \neq \emptyset$ and $T_a^E \cap T_b^E \neq \emptyset$ and $T_a^S \cap T_b^S \neq \emptyset$
	<i>T_a</i> and <i>T_b</i> are simultaneous		$T_a \cap T_b \neq \emptyset$ and $T_a^S \cap T_b^S \neq \emptyset$ and $T_a^E \cap T_b^E \neq \emptyset$

Table 3.1 Temporal relationships

However, the approach introduced in the CGIS-SAI model is not an effective and straightforward mean which cannot incorporate in visual object-oriented transportation data modelling. This implies that a graphical view is needed to provide supports to such a way in visually and graphically representing the temporal relationships between transportation objects. A graphical view based on the PVL which provides simple temporal pictograms could be an alternative mean. Nevertheless, PVL temporal pictograms are not proposed to the representations of precise temporal relationships among objects. PVL just includes a simple temporal representation to indicate transportation features' or attributes' "presence", "bird", and "dead". Therefore, the graphical view for visual temporal topology representations is still needed to investigate and explore. In this thesis, the PVL temporal pictograms (i.e., instantaneous time (\odot) and durable time (\ominus)) are extended and adapted with a set of variations to accommodate temporal topology representations, which are illustrated in Table 3.2.












Temporal topological relationship		PVL-based temporal relationship pictogram
Disjoint	T_a before T_b	 ($T_a = \odot, T_b = \ominus, T_a \cap T_b = \emptyset$)
	T_a after T_b	 ($T_a = \ominus, T_b = \odot, T_a \cap T_b = \emptyset$)
Intersect	T_a is at start of T_b	 ($T_a = \odot, T_b = \ominus, T_a \cap T_b^S = \odot$)
	T_a is at end of T_b	 ($T_a = \ominus, T_b = \odot, T_a \cap T_b^E = \ominus$)
	T_a follows T_b	 ($T_a = \ominus, T_b = \odot, T_a^S \cap T_b^E \neq \emptyset$ and $T_a \cap T_b = \emptyset$)
	T_a overlaps T_b at start of T_b	 ($T_a = \odot, T_b = \ominus, T_a \cap T_b = \odot$)
	T_a overlaps T_b at end of T_b	 ($T_a = \ominus, T_b = \odot, T_a \cap T_b = \ominus$)
	T_a occurs during T_b	 ($T_a = \odot, T_b = \ominus, T_a \cap T_b = \odot$)
	T_a occurs during T_b from start of T_b	 ($T_a = \odot, T_b = \ominus, T_a \cap T_b = \odot$)
	T_a occurs during T_b to end of T_b	 ($T_a = \ominus, T_b = \odot, T_a \cap T_b = \ominus$)
	T_a and T_b are simultaneous	 ($T_a = \odot, T_b = \ominus, T_a \cap T_b = \odot$ or \ominus)

Table 3.2 PVL-based temporal relationship pictograms

The PVL-based temporal relationship pictograms can be integrated into the UML to incorporate in visual object-oriented transportation data modelling. Each temporal relationship is modelled to construct a temporal relationship object using a UML class

(Figure 3.5). This implies the extension of the UML temporal semantics to facilitate the representation of transportation activities and phenomena. In order to provide a consistent understanding of the temporal relationship representations in a UML scheme, some definitions are introduced as follows:

- A temporal topological relationship is defined by a UML class;
- A PVL-based pictogram is placed on the left side of the name of class to represent a temporal relationship;
- Each class owns two temporal attributes, e.g., T_a and T_b . A PVL temporal pictogram is placed directly beside the value of attribute to identify a period of time;
- The temporal operations, i.e., intersect or disjoint are defined by an operation in the operation section of the UML class, termed as “Intersect(condition)” or “Disjoint(condition)”, respectively.

According to above definitions, a case of temporal relationship “Follows” representation is illustrated in Figure 3.5. “Follows” represents that a transportation object occurs while a transportation object ends. Such an object encompasses two temporal intervals (e.g., T_a and T_b) derived from a same temporal measurement. A temporal operation, i.e., “Intersect()” is used to specify a connection of these two temporal intervals. Figure 3.6 shows a UML schema to represent different temporal relationship objects and their connections in the conceptual object model.

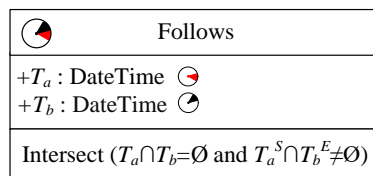


Figure 3.5 UML class of temporal relationship

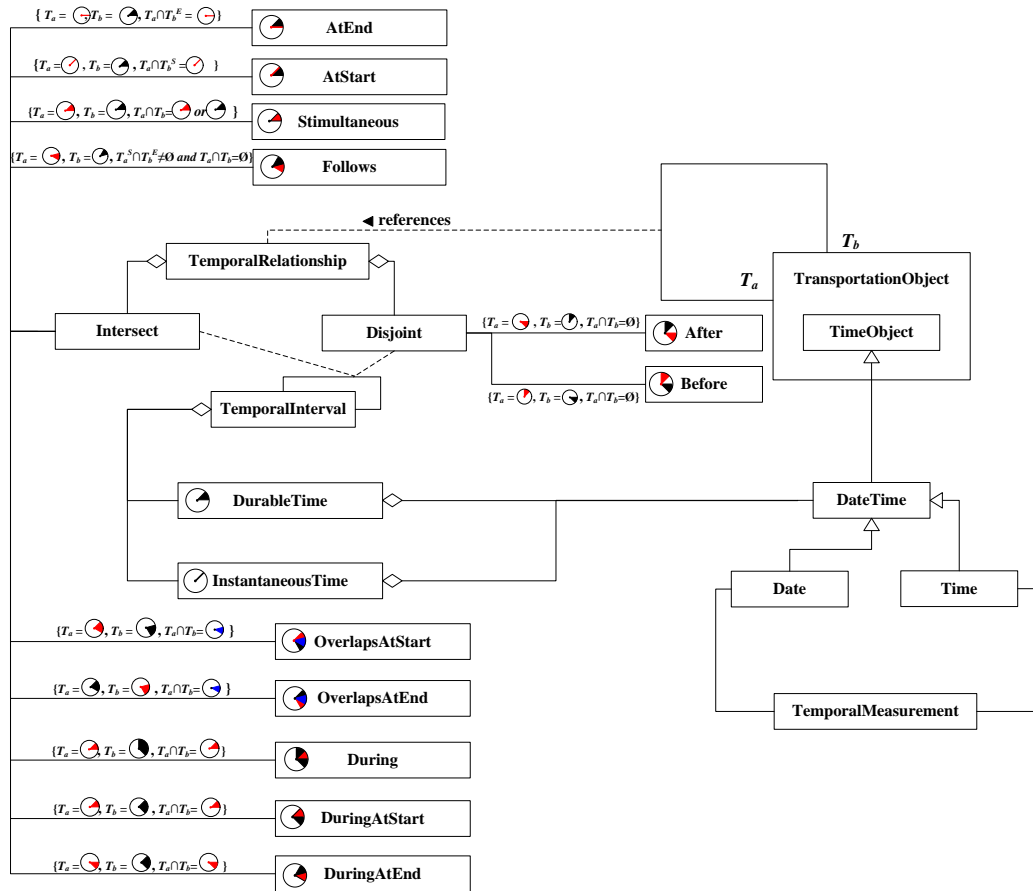


Figure 3.6 UML conceptual view of temporal referencing system

3.2.3 Event and evolution

Temporal properties imply that a transportation object may change in a durable or an instantaneous time. The behavioural changes of transportation object can be modelled and represented by the concepts of “events” and “evolutions”. Events are the concepts that are used to describe dynamic transportation objects. An event usually occurs during a defined period (temporal feature) at a defined location (geometric feature). This is usually valued by the temporal dimension, such as time cost. For example, while a moving point represents a motor vehicle moving along a path between a pre-defined pair of origin and destination, a period of time to finish this trip should be considered. Therefore, in an event a transportation object may change in space and time. The concept of “evolution” is introduced to represent the historic states of such a transportation object, and indicates which event lead to changes of the object. This implies the representation of behavioural evolution of transportation object. Therefore, evolution is also an important feature to model and represent the behavioural changes of dynamic transportation objects. Over time, transportation object may participate in several events, producing additional evolutions. The collection of evolutions represents the history of the transportation object. Namely, the history of the transportation object is the result of the evolutions of the transportation objects that make up the transportation system. Herein, a case is taken to present the behavioural evolution of a transportation object, i.e., bus stop. While a bus stop is relocated on a bus route, the events may include the change of position and the

update of connections to relative bus routes. The bus stop takes participate in all these events that lead to the behavioural changes of the bus stop. These behavioural changes construct the evolutions, i.e., the historic states of the bus stop. Therefore, an evolution of the bus stop resulted from a sequence of events can represent what bus stops have been in an area, what changes have occurred to those stops, and how those changes occurred (Figure 3.7). In short, the combination of events and evolutions implies a representation of the behavioural changes which occurs in and among transportation activities.

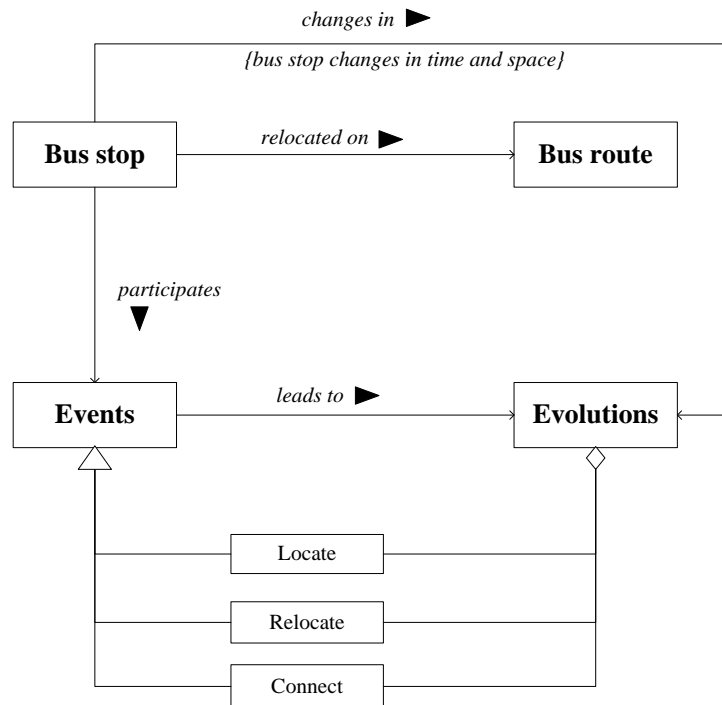


Figure 3.7 Example of evaluations of a bus stop

3.3 Multi-scale and multi-modal network topology model

While the objects and concepts are clarified in the conceptual object model, this section introduces the principles retained for the design and development of the multi-modal transportation network topology model. The network topology model is applied in the urban system of the city of Guangzhou. In the model, the main modelling components include the streets, bus lines and metro networks, taking into account walking paths related to the street network. This implies several important tasks to implement multi-level network representations, build an integrated topology structure of multiple transportation networks, and maintain consistency of multiple topological relationships at different levels of abstractions.

3.3.1 Bus line network

The bus mode infrastructure is a complex network system with multiple relationships that are derived from traffic-oriented rules and restrictions. Such a network is commonly composed of bus lines and stops. Each bus line spreads on the streets with two paths

restricted. Each directional path is restricted to connect to a sequence of bus stops, as shown in Figure 3.8. In order to explicitly specify the components of bus line network, two key terms, i.e., “bus route” and “bus platform” are introduced. The differences among the components are presented as follows:

- A bus route is a directional path of a bus line, and is described by a line with reference to one side of the street.
- A bus stop site indicates one location of the generally presented “bus station” that contains at least two stop sites on the opposite sides of the street. In correspondence to the concept of “bus route”, each individual stop site is referred to as a “bus stop”. Accordingly, the general presented station is termed as “bus platform”.
- A segment of bus route is partitioned by two sequential individual stop sites (i.e., bus stops) along the directed bus route. Such a segment is referred to as a term “bus route segment”.

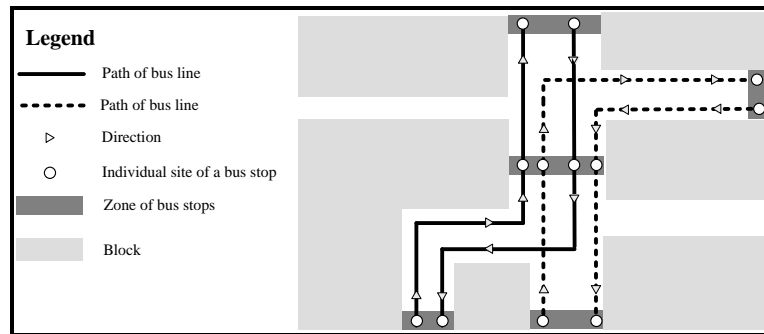


Figure 3.8 Example of static structure of the bus line network

Taking into account different shapes, scales and themes, the components can be represented by graphic features, i.e., points, lines, polygons or surfaces. Within a GIS, the spatial components of bus line network can be specified as the point and line features:

- Points: bus stops, bus platforms.
- Lines: bus lines, bus routes, bus route segments.

There are a variety of connections between the components of bus line network, which are derived from not only spatial connectivity, but also traffic connectivity. Figure 3.9 provides a conceptual view to represent the topology structure of bus line network by extending and adapting the UML notations. In the topology structure, a bus line is a transportation object composed of two directional bus routes. A bus line is restricted to connect to a sequence of bus platforms. Bus stops represent the individual stop sites of a platform, and are described as points located along the directional bus routes. Accordingly, a bus route is also a transportation object that is identified by a set of interconnected directional bus route segments. The start or the end of each route segment is referenced to a bus stop.

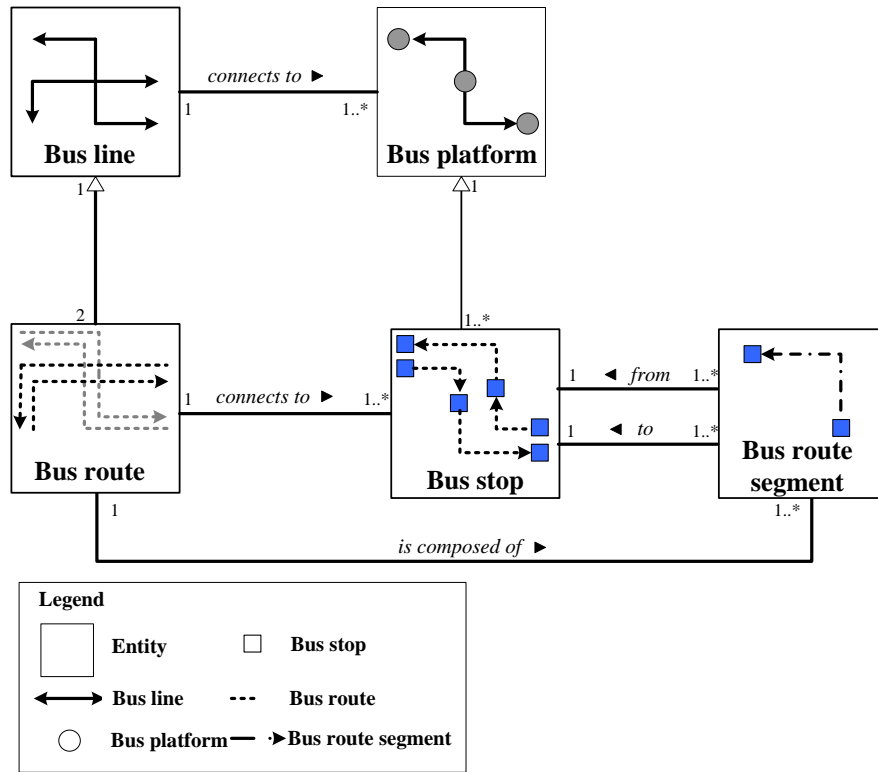


Figure 3.9 Topology structure of the bus line network

3.3.2 Metro line network

The metro transit network is an underground rapid rail network system which has fixed routes and stations, and provides precise schedules. Generally, a metro station covers a large area, and could be composed of three components: station halls, platforms and tunnels. Figure 3.10 illustrates an example of metro station at a planar view in the city of Guangzhou. A metro platform is a boarding site alongside railroad tracks. Tunnels can lead passengers from underground station to several different locations, i.e., entrances/exits on the ground. Station hall provides ticket services to passengers, and is also the connection of metro platforms and tunnels. According to the role that a station hall plays, station hall can be considered as a part of tunnels to provide a connection to lead passengers to get to the metro platforms or leave a metro station.

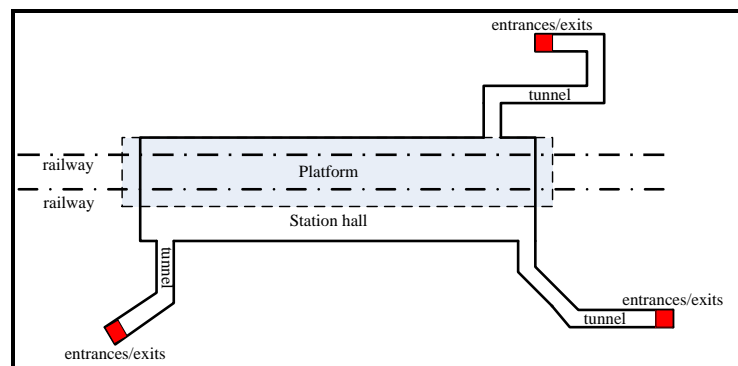


Figure 3.10 Example of a metro station at a planar view

Similarly to bus line, a metro line is composed of two directional paths with opposite directions. While a metro line is represented by a linear feature, in a metro station the landing site, i.e., platform can be represented by a point located on the metro line. When a metro station is a junction of metro lines, the metro station can have several platforms responding to different metro lines. Moreover, in order to define the tunnels between metro platforms and entrances/exits in a metro station, a transportation object “metro passageway” is introduced, and represented as a linear feature. A term “metro way” is proposed to represent the directional paths of metro lines. Each metro way is composed of a sequence of interconnected segments, i.e., “metro way segment”. The start or end of a way segment connect to a “metro way stop”. The metro way stop is referred to the individual stop sites along a metro way. In a GIS, these spatial components can be represented by points, lines, and polygons:

- Points: metro way stops, entrances/exits, metro platforms.
- Lines: metro lines, metro ways, metro way segments, metro passageways.
- Polygons: metro stations.

Figure 3.11 illustrates a conceptual view of the topology structure of metro line network by adapting UML notations. In the topology structure, a metro line is restricted to connect to a sequence of metro stations. Metro station is defined as a composition of metro platforms and entrances/exits. Metro platform is represented by an aggregation of the metro way stops which server the same metro line in a metro station. A metro way is also restricted to connect to a sequence of metro way stops.

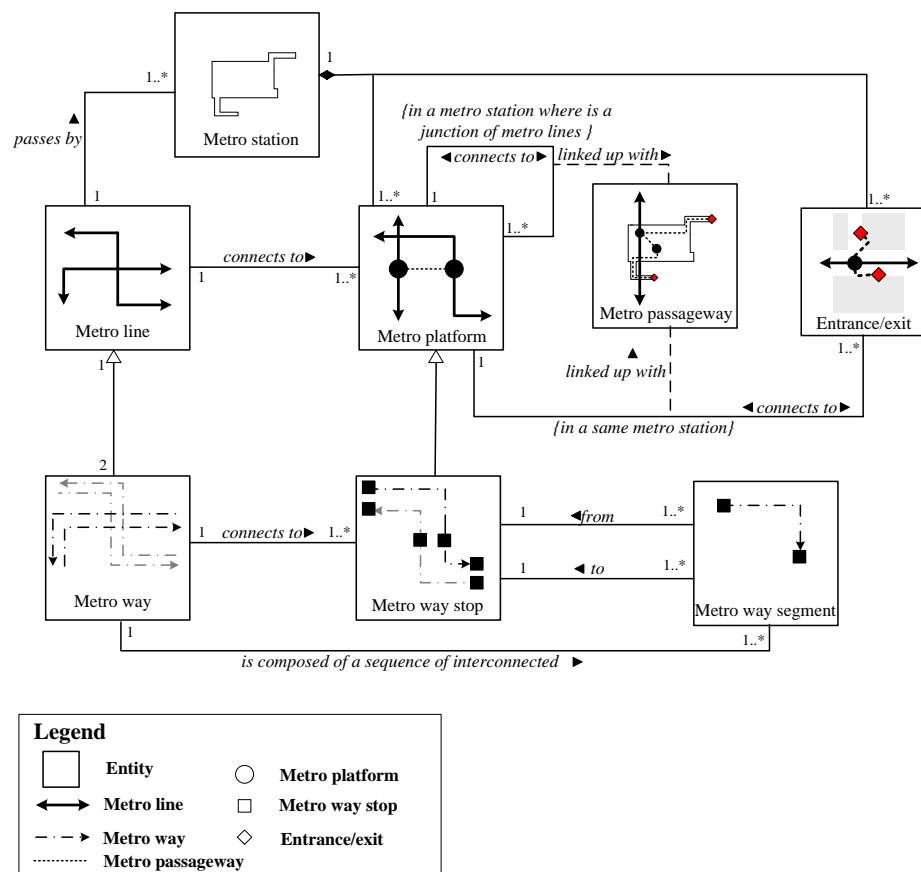


Figure 3.11 Topology structure of the metro line network

3.3.3 Urban street networks

Public transportation networks should rely on the given street networks. This implies that the modelling of urban street network needs to be compatible with the representation of directional public transit routes, taking into account particular applications applied to the street network, such as motor vehicle navigations. Figure 3.12 illustrates an example of the components of streets network. The denotations and interconnections of the components are presented as follows:

- Every street is composed of a set of interconnected segments portioned by intersections. Such a segment is described as a road segment.
- A road segment may be divided into two (or more) parallel strips by median or other dividing strips (e.g., barriers). Each parallel strip is represented as a carriageway. A carriageway includes one or several dividing traffic lanes with same moving direction.

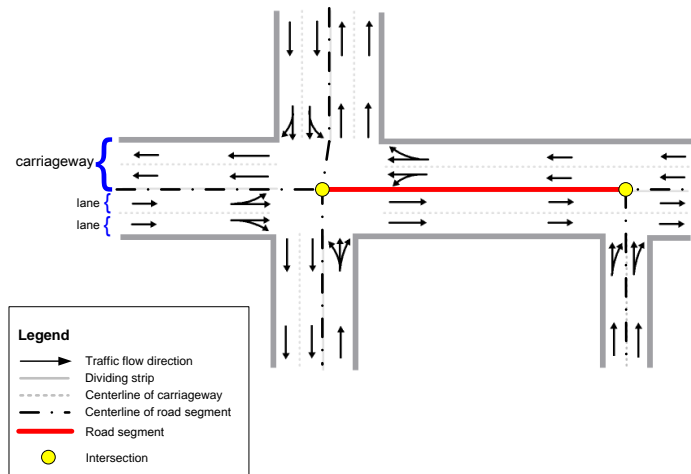


Figure 3.12 Example of the streets network

Different application purposes require different sub-networks of the street network, such as roads, carriageways or lanes networks. This implies different levels of granularity in the modelling and representation of the street network. In the multiple representations, the streets are abstracted at different levels, i.e., road centrelines and carriageway centrelines, which are represented by terms “Road Segment Centre Line” (RSCL) and “Carriage Way Centre Line” (CWCL), respectively. Accordingly, at high-level of abstraction, i.e., the road segment centrelines network, an intersection is abstracted as a transportation object, i.e., “RSCL intersection point” (RSCLIntPnt). But at low-level of abstraction, i.e., the carriageway centrelines network, the intersection is identified by a sequence of “CWCL intersection points” (CWCLIntPnt). This implies that the multi-level representations of the street network are responded to the level 1 and level 2 of GDF standard.

Figure 3.13 illustrates multiple cartographical representations of the street network. At low-level of abstraction, the number of CWCLs of a road segment results from traffic controls. For example, a one-way street is represented by one CWCL, and two-way street by two CWCLs (Figure 3.13(a)). At high-level of abstraction, carriageways of a road

segment are aggregated to a higher-level feature, i.e., a road segment centreline (RSCL) (Figure 3.13(b)). RSCLIntPnt is defined to a generalization of CWCLIntPnts, and stores turning information. In order to visually and graphically represent the turning information of an intersection, a transportation object, i.e., virtual directional turning link is introduced at high-level of abstraction. A term “RSCL Virtual Directional Turning Link” (RSCLVDTL) is used to represent such a link. On an intersection, the start and end of each RSCLVDTL connect to a RSCL, respectively. According to the turning information, RSCLVDTL may be bi-directional or single-directional. Figure 3.14 shows an example of turning information representation using directional RSCLVDTLs. The components of street network can be represented by point and linear features:

- Point: RSCLIntPnts, CWCLIntPnts.
- Line: RSCLs, CWCLs, RSCLVDTLs.

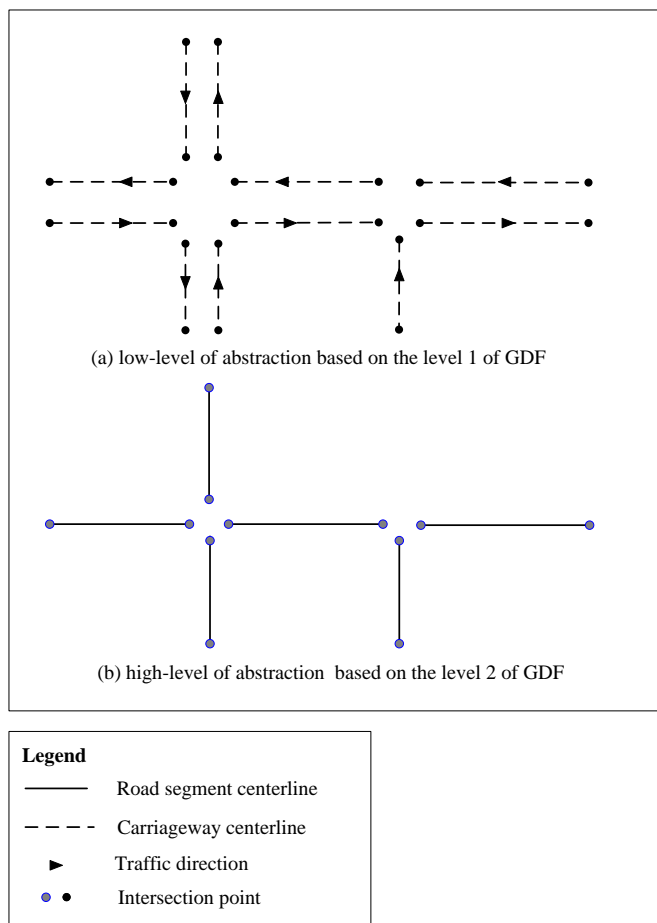


Figure 3.13 Representations of the streets network

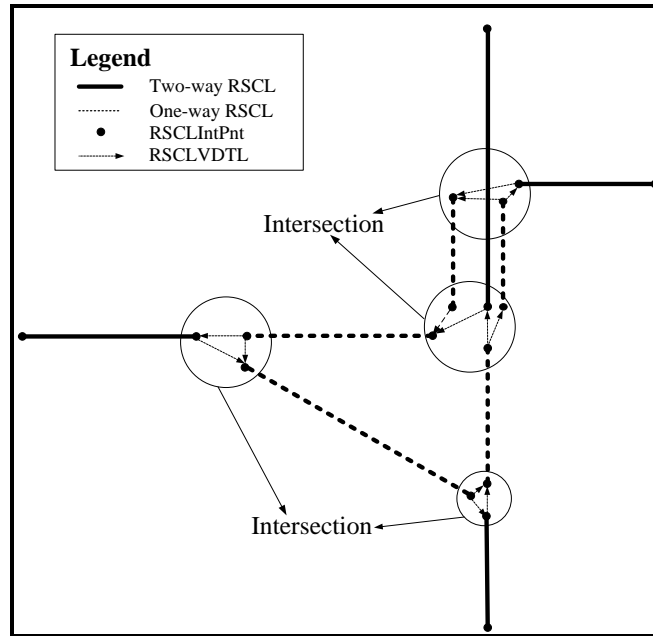


Figure 3.14 Example of visual and graphic turning information representations of intersections

In term of the directional characteristics associated with RSCL, CWCL and RSCLVDTL, the turning information between any pair of CWCLIntPnts at an intersection can be representation without increasing the complexity of the data model. For example, while at an intersection there is a barrier deployed to block motor vehicles to cross the intersection freely, the turning information of the intersection may be represented by a look-up turning table. Figure 3.15 illustrates one of these cases. In Figure 3.15(a), each road segment centre line (i.e., RSCL) has two carriageway centre lines (i.e., CWCLs) with opposite directions. One carriageway leads motor vehicles to enter the intersection, the other leads to depart. At the intersection, the turning restrictions between any pair of CWCLIntPnts can be determined from the directional CWCLs and RSCLVDTLs. Figure 3.15(b) illustrates a look-up turning table to represent the turning information of the directional CWCLs at the intersection. In term of the analysis and definitions of the components and relationship in the urban street network, a UML schema is introduced to provide a UML conceptual view for expressing the topology structure of the network (Figure 3.16).

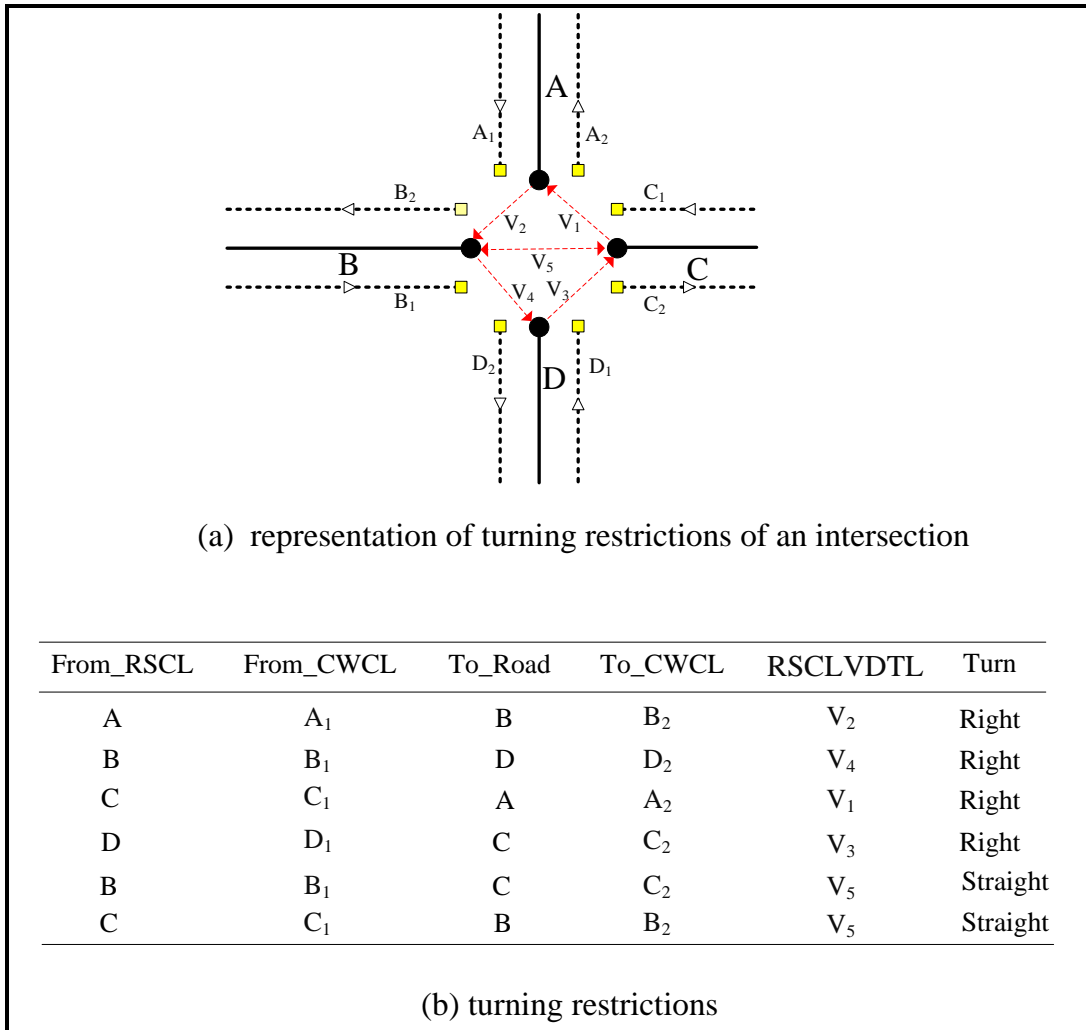


Figure 3.15 Example of building connections between CWCLs

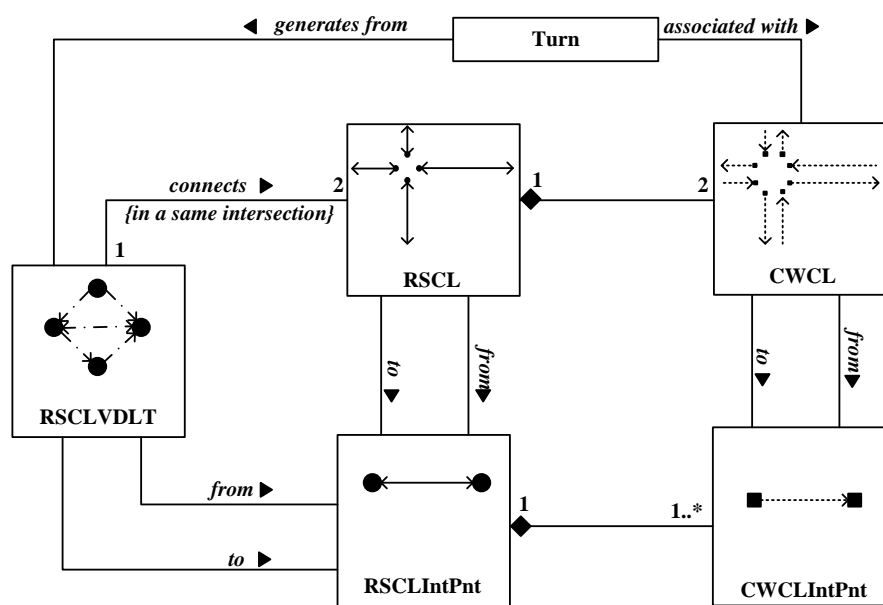


Figure 3.16 Data structure of the street network

3.3.4 Walking links network

Walking opportunities are important to change routes. Each public transit route (e.g., bus route or metro way) has a sequence of stops for passengers boarding or alighting. Stops of different routes can be located at a same site, or are close for passengers to alight from one route, and walk to other stops to take another route. In this case, these two routes can be joined together at the stops with a same site, or the stops with different sites that can be connected with walking paths.

Generally, most of urban streets provide sideways for pedestrians. These sideways can be referred to walking paths. A term “walking link” is introduced to represent the paths. In order to reduce data redundancy and avoid increasing the complexities of the data model, CWCLs are designated to the concept of bi-directional walking links, taking into consideration different traffic-oriented rules and restrictions applied to CWCLs and walking links. The turning information between CWCLs should be different from those between walking links. For example, on an intersection motor vehicles may be forbidden to make a right turn, but this control may not be valid for pedestrians. Therefore, a look-up turning table can be used to present the turning information between the walking links at an intersection, in order to avoid the increasing of the complexities of the data model.

Although pedestrians usually can make turns freely at an intersection, some intersections deploy barriers to separate motor vehicle lanes from pedestrian lanes for traffic safety (Figure 3.17). In this case, pedestrian facilities, such as pedestrian bridges, pedestrian tunnels and zebra crossings are important to provide a passage for pedestrians crossing a street or intersection safely. Figure 3.18 illustrates an example of the representation of a pedestrian bridge which is also represented by a walking link. The start and end of such a link is referenced to a point, respectively. This type of point is termed as “transfer point” located on the related walking link.

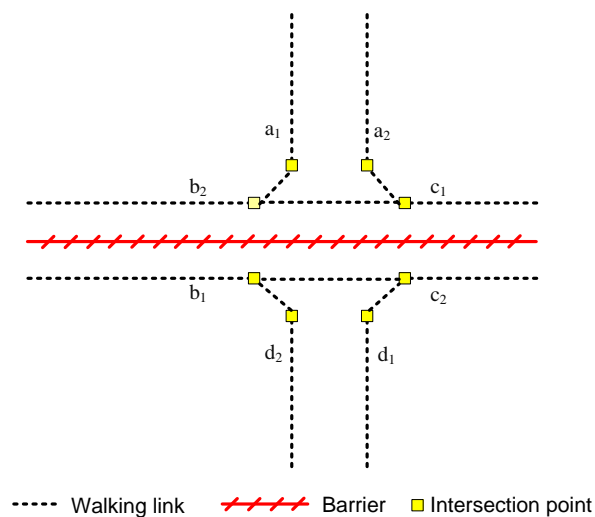


Figure 3.17 Example of an intersection of the walking links network

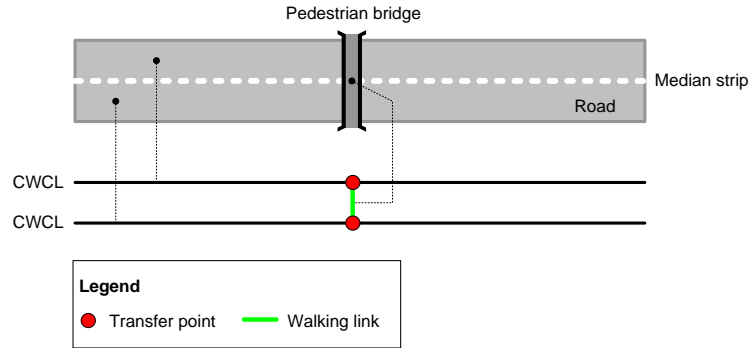


Figure 3.18 Case of pedestrian bridge representation

The modelling concept of walking link covers a wide range of transportation facilities, including sideways and pedestrian facilities, and particularly the metro passageways towards and inside metro stations (Figure 3.19). Although the metro line network is underground, these passageways lead passengers to walk the entrances/exits or enter the metro station. As metro entrances/exits are located on the ground, and should be connected to the CWCLs by walking paths. Therefore, in the walking links network model, the walking paths between the entrances/exits and CWCLs or CWCLIntPnts are also determined as walking links. In this case, a transfer point is used to represent an intersection of the walking link and CWCL. This implies that transfer point concept also covers a wide range of transportation facilities, including the starting and ending nodes of pedestrian facilities (e.g., pedestrian bridges), and the starting node of a walking link towards to a metro entrance.

In order to represent the combination of the multi-modal transportation networks, at the low levels of abstraction, the road segment represented by two lines oriented in opposite directions, i.e., the parallel carriageways are used to reference the limited access bus routes. A bus route segment is referenced to the same directional carriageways. Figure 3.19 also illustrates the representation of bus routes that are depicted as a line with reference to different or parts of CWCLs. Bus stop are represented by a point that is located on the related CWCL. According to the roles of walking links and transfer points, walking links are the walk connection facilitators for the multi-modal transportation modes. Transfer points thus indicate these connections between the transportation modes. Walking links and transfer points are essential means to support the connections of different transportation modes. Figure 3.20 illustrate a UML-based conceptual view of the integrated topology structure of the multi-modal transportation networks in the city of Guangzhou.

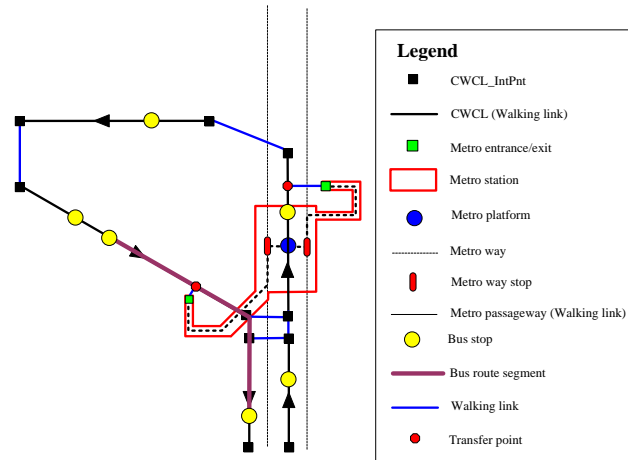


Figure 3.19 Example of walking links between transit networks

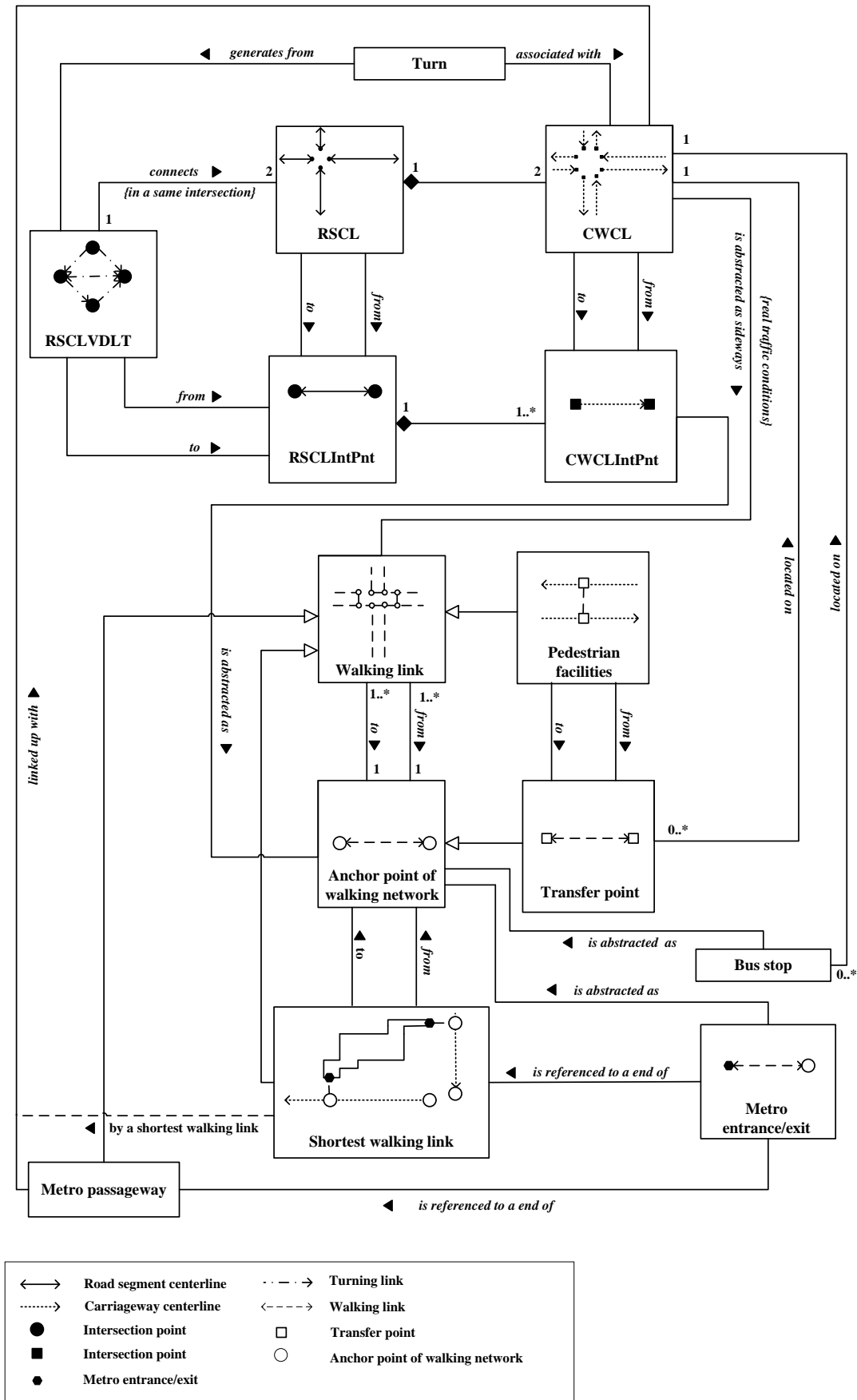


Figure 3.20 Integrated topology structure of multi-modal transportation networks

3.3.5 Multi-scale data modelling and representations

In the transportation network modelling, the directional characteristics of transportation links require the extended spatial semantics for visually expressing transportation data in object-oriented modelling framework (Koncz and Adam, 2002). Although the CASE tool *Perceptory* has provided a richness of spatial PVL expressions to describe the spatial properties of geographical objects (Bédard and Proulex, 2006), the spatial pictograms need to be extended and adapted to incorporate in transportation spatial data representations, particularly the spatial properties of transportation linear features. For example, in *Perceptory*, a bus line may be represented by a 1-dimentional pictogram with a cardinality, i.e., $\square_{1,2}$. As this pictogram does not include the depictions of directional characteristics, the expression cannot sufficiently and effectively represent the directional characteristics of the bus line which is commonly composed of two routes with opposite directions. Therefore, the spatial semantics provided by *Perceptory* are adapted to accommodate the expression of the transportation linear features, as shown in Table 3.3. The table illustrates the variations of PVL spatial pictograms to describe different transportation linear objects which have been identified in the data model.










Pictogram	Definition	Linear spatial object
	Two solid directed lines with a filled arrowhead pointing toward opposite directions, respectively.	Bus line
	A solid directed lines with a filled arrowhead pointing toward a direction. The 1, N cardinality indicate a route is composed by a sequenced of interconnected directed lines.	Bus route and metro way
	A solid directed lines with a filled arrowhead pointing toward a direction.	Bus route segment and CWCL
	A solid line with two filled arrowheads pointing toward opposite directions, respectively.	Walking link
	A solid line with two filled arrowheads pointing toward opposite directions, respectively, OR, two solid directed lines with a filled arrowhead pointing toward opposite directions, respectively.	Metro line
	A solid line with two filled arrowheads pointing toward opposite directions, respectively, OR, a solid directed lines with a filled arrowhead pointing toward a direction.	RSCL and RSCLVDTL

Table 3.3 Representations of transportation linear objects

Figure 3.21 presents an example of the modelling of transportation object (e.g., bus line). This UML notation is adapted with the PVL pictograms. In the class, the spatial dimension of the bus line is represented by an adapted 1-dementation spatial pictogram (i.e., ). This indicates that the bus line is composed by two directed linear features (i.e., bus routes). On the other hand, a temporal pictogram (i.e., ) at the right of class name represents the temporal dimension defined by a descriptive (non-spatial) evolution, i.e., a durable time. This durable time begins at a date of validation (i.e., birth), and ends at a date of abolishment (i.e., dead) of the bus line. Both of attribute “Company_Name” and “Status” possess temporal characteristics represented by using temporal pictograms (i.e., ). The value of attribute “Status” describes whether a bus line is in services, or stop services in a period of time. The status usually changes through time in view of the assignments based on a proposal to provide bus service between different origins and destinations. The UML with an extension of adapted PVL pictograms enriches the spatial and temporal semantics. This provides an efficient modelling framework which can be incorporated in the integration of spatial and temporal features defined in the concept of transportation object.

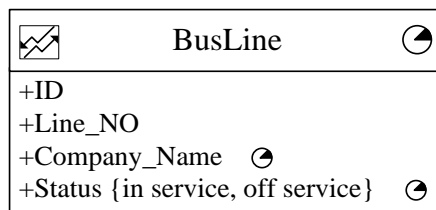


Figure 3.21 Example of UML-based expression of transportation object

In the data model, the urban street network are modelled at two levels of abstractions (i.e., low-level and high-level) which indicate the ranges of granularity, i.e., scales. Accordingly, at low-level of abstraction, i.e., a large scale (e.g., 1:1000), a metro station can be represented by a polygon. While at a smaller scale (e.g., 1:8000), the metro station may be represented by a simple point with reference to a location on metro line (Figure 3.22). While the ranges of granularity (scales) for the multi-level transportation object representations are valid, information conversion between different scales may be implemented by zooming in (large scale) and zooming out (small scale) on map in a GIS environment.

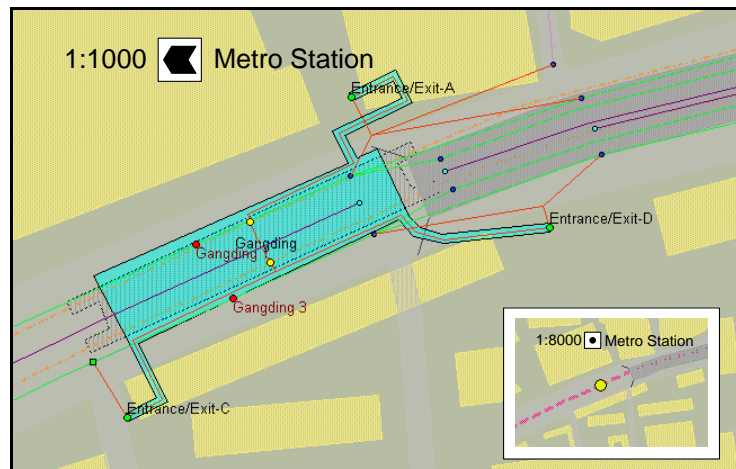


Figure 3.22 Example of multi-scale representations

In order to model and represent multi-scale transportation data, each process for multiple representations is defined by an operation in the operation section of UML class. A representation process is defined by a unique operator, named as “REP”. In an operator, the level of abstraction is identified with largest and smallest scales. Figure 3.23 illustrates an example of multiple representations of the transportation object of metro station. Metro station is represented by a point or surface according to a defined map scale. The concept of low-level of abstraction (LL) is depicted by “LL[largest scale, smallest scale]”, and high-level of abstraction “HL[largest scale, smallest scale]”. In this case, the operators are described as “REP(LL [0.1k,1k])” and “REP(HL [8k, 15k])”. The spatial properties corresponding to the levels of abstractions are indicated by PVL pictograms, such as “◼” and “◻”.

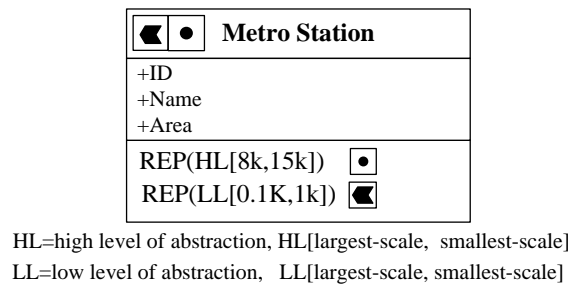


Figure 3.23 multi-scale representations of transportation object

Table 3.4 lists the multi-level cartographical representations of the transportation network components which have been identified in the data model. Multiple cartographical representations are determined at a range of scales corresponding to a low level of abstraction or a high level of abstraction. In term of the modelling and representation of multi-scale transportation data, Figure 3.24 shows an example of a multi-scale data model, which provides a UML-based view of multi-level cartographical representations to the bus line network.

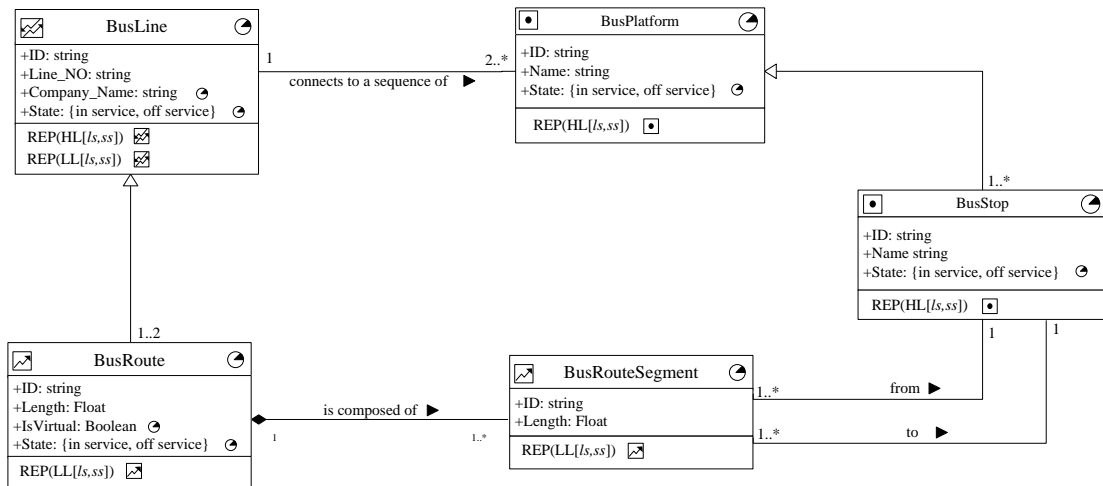


Figure 3.24 Case of the logical data model of bus line network

Transportation network spatial entity		Shape			Abstraction	
		Point	Line	Surface	High level	Low level
Bus transit network	Bus line		•		•	•
	Bus route		•			•
	Bus stop	•				•
	Bus Platform	•			•	
	Bus route segment		•			•
Metro transit network	Metro line		•		•	
	Metro platform	•			•	•
	Metro way		•			•
	Metro way segment		•			•
	Metro way stop	•				•
	Metro station			•	•	•
	Entrance/exist	•			•	•
	Metro passageway		•		•	•
Urban road network	RSCL		•		•	
	CWCL		•			•
	RSCLIntPnt	•			•	
	CWCLIntPnt	•				
	RSCLVDTL		•			
Walking links network	Walking link		•			•
	Transfer point	•				•

Table 3.4 Multiple levels of abstraction of transportation objects

3.4 Multi-modal and multi-criteria routing

3.4.1 Data structure to multi-modal routing

A traversal may be a path or route in a road network from an origin node to a destination node, and is represented by a sequence of directional links (Spear and Lakshmanan, 1998). In the context of multi-modal transportation networks, the definition of “traversal” is broad to cover all meanings of routes or paths. Bus and metro service routes and walking paths are typical examples of traversals. As a result, a collection of traversals can be referred to a “multi-modal route” that may involve different modal transportation links, such as CWCLs, bus routes, metro ways and walking links. Accordingly, the anchor points of a traversal may involve multi-modal transportation nodes, such as bus stops, CWCLIntPnts, metro entrances/exits, metro way stops and transfer points. This implies

that a node-link traversal network is composed of multiple transportation links and nodes. Figure 3.25 illustrates an UML schema to represent the traversal network data structure. As the traversals network data structure simplifies and synthesizes the topological relationships of a multi-modal transportation network, it lays out an essential support to multi-modal trip planning.

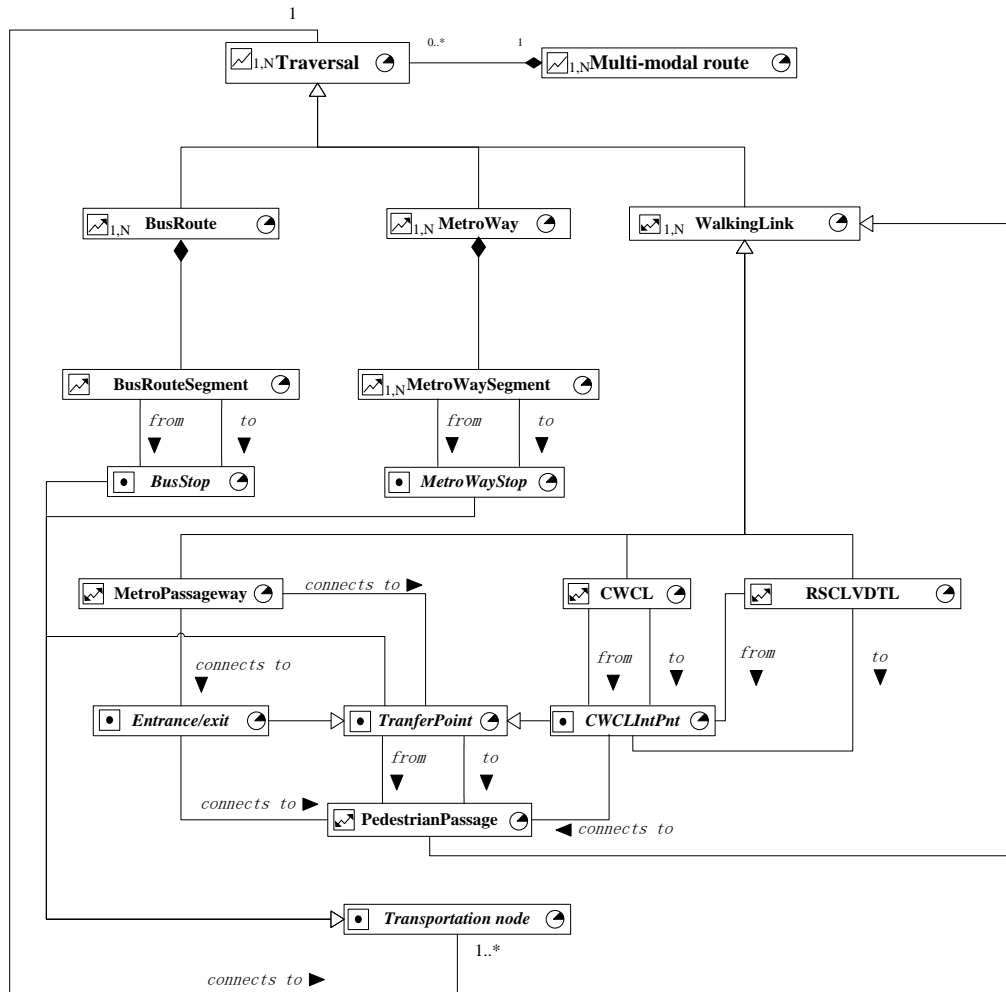


Figure 3.25 Topology structures of the traversal transportation network

3.4.2 Travel costs in multi-modal routing

However, trip planning is a complex process involving network topology structures and evaluation of travel costs, including travelling distances, travelling time, travelling fare and transfer. The approach to trip planning is capture in Figure 3.26. This illustrates a typical multi-modal route that involves a bus route, a metro way and several walking links. In the multi-modal trip planning, a commuter represents a “mobile object” and takes on the characteristics of the surrounding transportation system. The behavioural changes of the mobile object in the multi-modal trip can be represented by an UML-based conceptual schema (Figure 3.27) provided by the data model. This schema clarifies the spatial and temporal relationships of different dynamic objects

(including commuter, bus and metro) to enhance means of communication between model designers and transportation professionals.

In the multi-modal trip planning, when a commuter makes a trip using public transit, the commuter travels a walking link on a pedestrian mode with a defined method of movement to the bus stop. The commuter gets on to the bus mode and rides a bus, taking on the bus's movement characteristics. The commuter then gets on to the pedestrian mode walking link to the metro, gets on to the metro mode, and rides the metro. Finally, the commuter uses a walking link to a destination. Such a multi-modal route involves several constraints that include connection possibilities at the physical level (i.e., possibility of performing a multi-modal connection using walking links and logical connection between different transportation modalities) and temporal constraints (i.e., derived from public transportation timetables). These constraints reflect the travel costs to finish the trip.

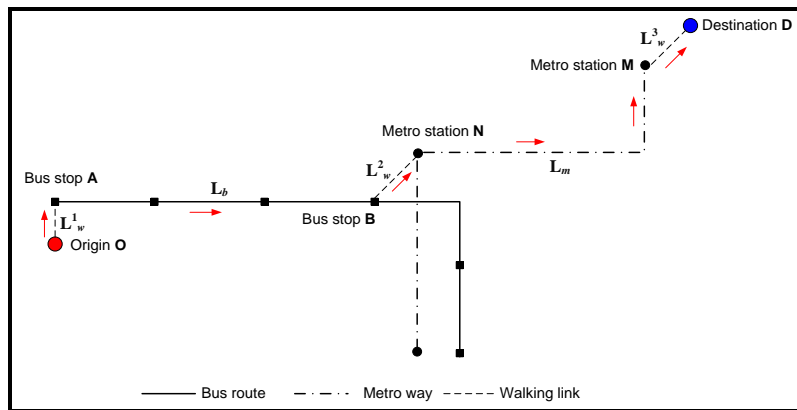


Figure 3.26 Example of multi-modal trip planning

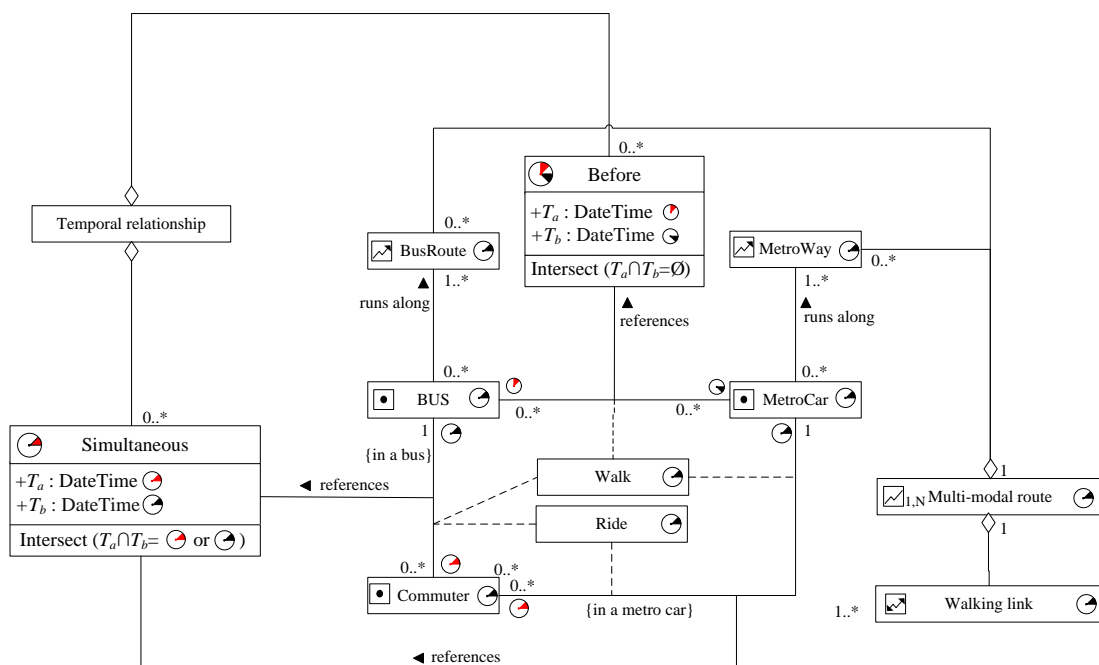


Figure 3.27 Example of UML-based conceptual view of multi-modal routing

Moreover, for planners the focus is usually upon service quality, which is influenced by many aspects such as coverage (e.g., portion of households and jobs within 5-minute walking distance of a 15-minute transit service), service frequency, punctuality, comfort (e.g., portion of trips in which a passenger can sit and portion of transit stops with shelters), affordability (e.g., fares as a portion of minimum wage income), information availability, and safety (e.g., injuries per billion passenger-miles), and travelling time. Although non-exhaustive, these indicators provide many significant inputs for identifying the service quality of public transportation. Some of these indicators can be also evaluated by the output of the multi-modal route planning model that provides information of travelling (walking) distance, travelling time, transfer time and travelling fare of a trip. In particular, the trip planning and evaluation perspectives intersect in the evaluation of the “cost” of multi-modal transfers, which is an important criteria when searching for multi-modal routes. Transfer costs reflect different impedance parameters that can be matched to the logical representation of the multi-modal transportation network. The time of route change (or transfer) should be limited to a reasonable number in order to not discourage commuters.

The travel costs reflect different criteria in routing, which correspond to different commuters’ expectations. This implies that a trip planning system should be considered as a decision support system, not a definitive solution provider to a multi-criteria decision process. This also presents that the “metrics” in an optimal route planning rely on the commuters’ expectations.

3.4.2 Multi-modal and multi-criteria routing model

In response to multi-criteria routing, a look-up table is built to trace and calculate the impedance parameters of all possible traversals between two transportation nodes. The impedance parameters present different travel costs, involving travelling distance, travelling fare, number of stops, and even time of route change. An example is given to illustrate the look up table applied in the multi-modal and multi-criteria routing model.

Figure 3.28 presents the pattern of a bus route, e.g., bus line 41A, with bus stop A, B, C, D and E. At bus stop E, there is another bus route, e.g., bus line 60, with bus stop G, E, F, H and I. For each bus line, all directional route segments with impedance parameters are stored in the look up table. Figure 3.28 also illustrate the look-up table of bus line 41A. Using this table, the through bus routes between two bus stops can be easily determined in a computer system. If the traversals between the stops need to change routes, the interconnected bus routes are also ease to identify, as the through routes between two stops are clarified in the table. While the possible bus route segments are identified, the travel costs of these segments can be determined from the table. As for the metro line network, its look-up table can be also accomplished in this way, as these two networks have the same data structure achieved in the data model to identify the connection of routes and stops.

The approach to implement public transportation routing is based on the network data structures which have been specified in the data model. The approach can avoid the blind search of all transportation nodes, i.e., stops, to determine the desired path. This improves the efficiency of path finding, as compared with Dijkstra algorithm. Moreover, the approach implements the more effective acquisition and evaluation of the travel costs of the public transportation service routes between an origin stop and a destination stop.

This facilitates the determination of an optimal path according to different passengers' desires.

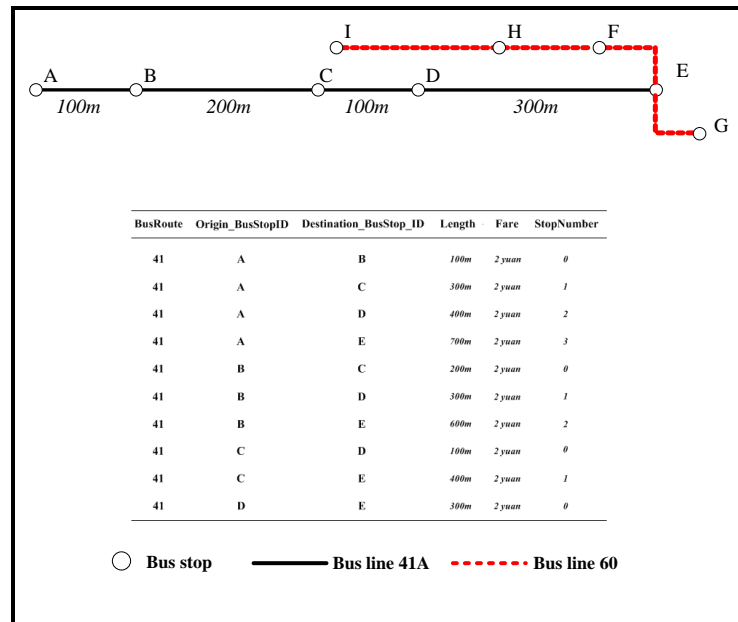


Figure 3.28 Example of a look up table

However, in a multi-modal trip planning the travel costs particularly include walking distance. Figure 3.29 illustrates a case of routing process between two given bus stops. A basic value for using public transportation mode is the walking distance that passengers can bear, in order to ride a public transit vehicle, to exit a route for route change, or to get to the destination. Some passengers can bear walking a long distance (e.g., 500m) to use public transportation modes, while others like to cover only a short distance (e.g., 100m). In the city of Guangzhou, this distance is commonly referred to 300m, according to the travel behaviour surveys in 2005. Therefore, walking distance is a key impedance parameter for passengers to select a desired route. Particularly, walking distance is an important criteria to determine the possibility of using public transportation modes in a trip planning. While the centre of an area is a stop, the area determined by the bearable walking distance can be recognized as the available service coverage area of the stop. Moreover, this area can be also referred to a transferring coverage area of the stops which are located in the area, as in some cases of routing walking opportunities (i.e., shortest walking path) should be considered to change other routes from a stop (e.g., bus stop A) to a stop (e.g., bus stop B). This implies that in the cases stop A or stop B must be located at the service coverage of the other in order to satisfy the conditions of route change. As the locations of these two stops are close, a shortest walking path between the bus stops can be efficiently determined using the Dijkstra algorithm. This routing process is based on the data structure of walking links network which have identified in the data model.

In short, the practical case of multi-modal trip planning should rely upon multiple criteria which include: (1) endurable walking distance from origin to ride or change route, and to reach destination; (2) temporal constraints (i.e., timetables); (3) minimizing travel costs (travelling fare, transfer time and travelling time). As these criteria can be used to evaluate and determine an optimal route from different commuters' perspectives, the optimal route may be a path with minimizing travelling time, travelling fare, transfer time, travelling distance, or walking distance. The multi-modal and multi-criteria trip planning process mentioned in the following paragraphs of this section represents the

identification of a multi-modal route with minimizing travel costs between a given origin and destination.

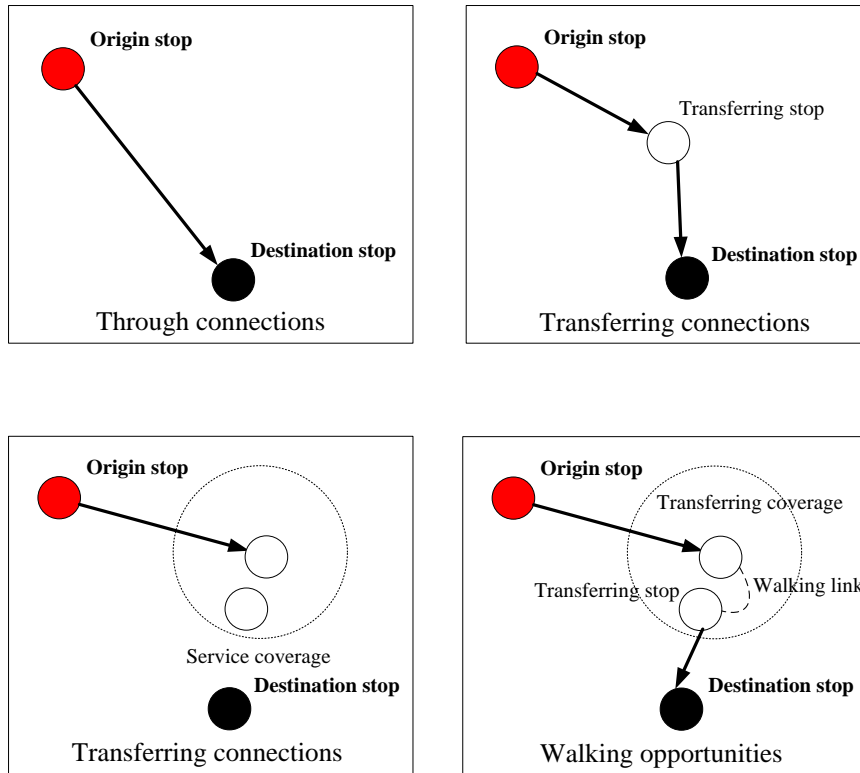


Figure 3.29 Example of routing conditions

As walking opportunities reflect the pre-conditions of public transportation routing, the routing process is started to identify if the walking opportunities of a given origin and destination are available for using public transportation modes. Figure 3.30 gives an example that shows the walking opportunities are available for the origin and destination: (1) the origin is in bus stop service coverage determined by the criteria of endurable walking distance (e.g., 300m); (2) the destination is in metro station service coverage determined by the criteria of endurable walking distance (e.g., 300m). This implies that the traversals between the origin and the destination could involve walking, bus and metro service routes.

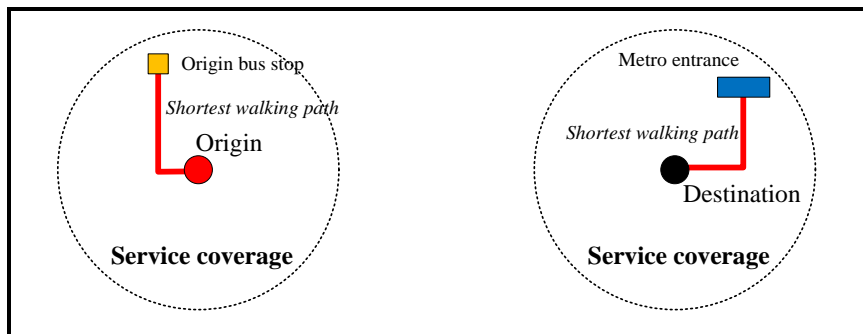


Figure 3.30 Example of the pre-conditions of routing

After the identification of shortest walking paths to origin bus stops from the origin, the routing process is to identify destination bus stops which should serve the same bus

routes with origin bus stops. This implies the identification of through bus routes between origin bus stops and destination bus stops. While the adaptive destination bus stops are identified, the service coverage of these stops can be provided in a GIS environment (Figure 3.31(a)). In a GIS, the service coverage provides a buffer area to validate origin metro entrances which are located in the service coverage. If the metro entrances are available, the shortest walking paths between destination bus stops and origin metro entrances can be achieved in the routing model (Figure 3.31(b)).

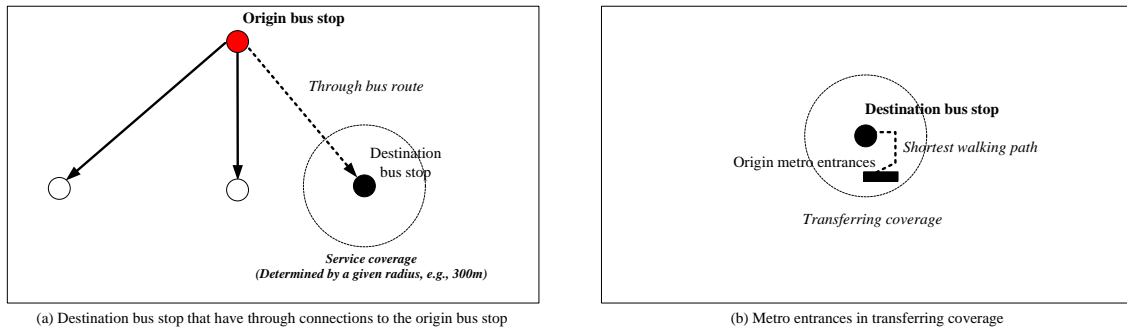


Figure 3.31 Example of the multi-modal routing process

As origin metro entrances and destination metro entrances are validated, the multi-modal routes (including bus routes, metro ways and walking links) can be traced and calculated in the routing model (Figure 3.32). The multi-modal routes between the origin and the destination may involve different qualities of travel costs, namely, some of these routes are least travelling time paths; some are shortest walking paths; some are least travelling fare shortest. This implies a question to an optimal route based on different criteria corresponding to different commuters' expectations. These criteria should involve least travelling time, shortest walking distance, shortest travelling distance, least travelling fare, least time of route change (transfer time), or least number of stops. While a routing criteria is validated, the optimal route planning can be implemented. This implies that an optimal route should be resulted from the commuters' expectations which provide the metric to validate the optimality of a trip.

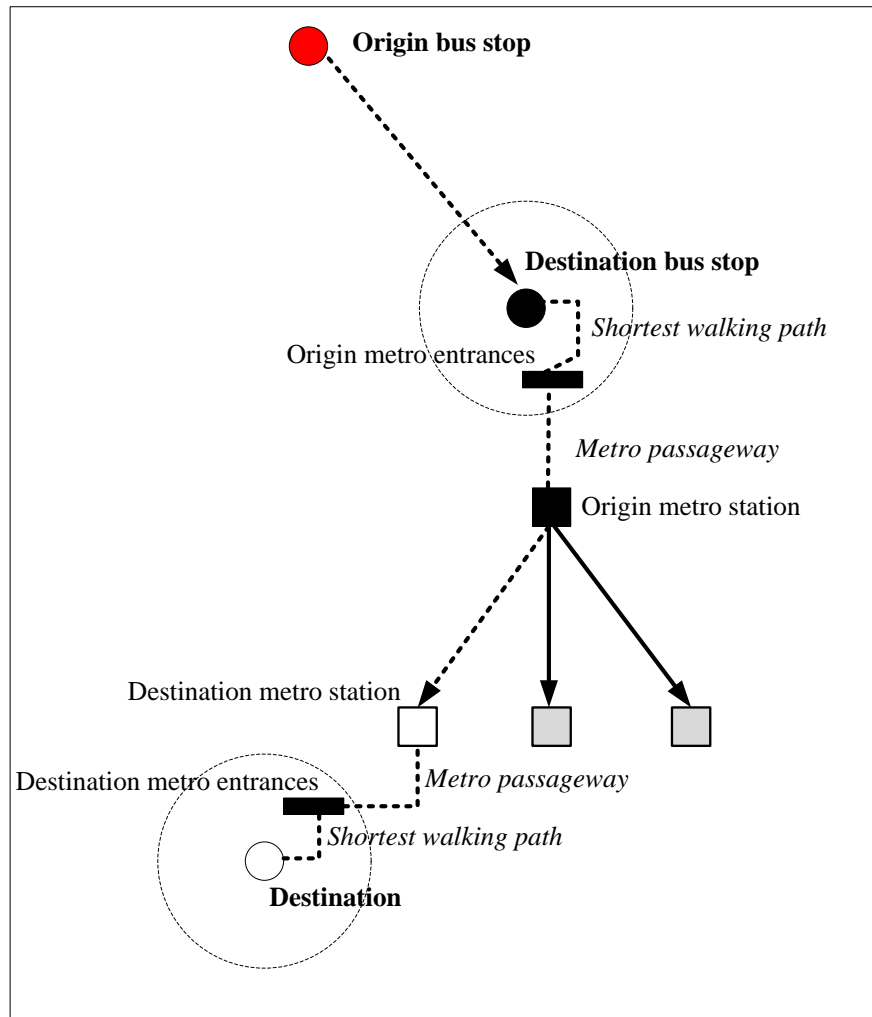


Figure 3.32 Example of multi-modal route

The multi-modal routing model provides a set of principles to support multi-criteria trip planning for the commuters. Furthermore, it can be also used to evaluate the connections (transferring or through) and walking opportunities between two given sites in the context of multi-modal transportation networks. In particular, this information allows evaluation of traffic connectivity between two given stops. Moreover, as observed in the spatial distributions of through- and transferring-trips, adjustments (oriented to the origin) can be made to compare with route planning scenarios and suggestions. This helps to optimize the connectivity of stops, thereby facilitating any needed re-engineering of the spatial structure of the current transit network for planners and decision-makers.

3.5 Conclusion

A crucial issue for sustainable development is to promote efficient urban transportation systems while reducing their negative impacts. This entails the need for effective transportation policies and services. They can be enhanced by GIS-T models. One step in this direction will be to use and adapt GIS-T model to provide service information which can also evaluate current practice and policy. The multi-scale and multi-modal transportation GIS data model presented in this chapter has those capabilities. The model

provides several data management and integration facilities, such as integration of multi-modal transportation modes, either public or private, and multiple level data representations.

The modelling approach is supported by an object-oriented GIS data modelling method, i.e., the unified modelling language (UML) extended with plug-in for visual languages (PVL). In this visual modelling process, the UML was adopted and extended to provide enrich spatial and temporal semantics to represent transportation objects and relationships. This involves the adaption of UML notations and spatial and temporal PVL pictograms which have been retained for GIS data modelling. The adapted UML notations and PVL pictograms provide efficient, straightforward and integrated means to support the transportation GIS data modelling. In particular, the integration and extension of spatial and temporal semantics implement the representation and maintain of the multiple properties, relationships and behavioural changes of transportation objects. The UML-based modelling framework oriented to transportation GIS promotes the cognition of the complex process of transportation activities and phenomena, particularly the representation of multiple transportation modes. Also, it offers a media to enhance means of communication between model designers and transportation professionals.

The multi-modal and multi-scale transportation GIS data model takes into consideration the availability of current transportation network components, involving streets, bus lines, metro lines and walking links networks. A set of principles, including location referencing methods, multiple cartographical representations and spatio-temporal data structures, are adopted and promoted to support the data modelling. Taking into account an extensive study of the transportation patterns and travel behaviours of the city of Guangzhou, the data model is designed and developed to meet the needs of multi-modal urban transportation applications. These needs are listed as follows:

- An integrated topology structure of multi-modal transportation networks;
- Spatio-temporal transportation data structure and temporal relationship model;
- Multi-level transportation data modelling and representations;
- Multi-modal and multi-criteria routing model and application.

The approach to meet the needs outlined above is to design and implement the conceptual object modelling and network topology modelling in the context of multi-modal transportation networks. The conceptual object model provides a structural object architecture to the modelling of multi-scale and multi-modal transportation GIS. In a GIS environment, the conceptual object model clarifies the fundamental concepts and principles of transportation objects (involving static and dynamic data), temporal topology relationships and representation of transportation objects' behavioural changes. This lays out fundamental to further investigate and explore the data structure of multi-modal transportation networks, and implement multiple data representations. The network topology model provides an essential multi-modal and multi-scale transportation data structure, and maintains consistency of topology relationships of multi-level transportation objects. This enhances the flexibility and reusability of the adapted transportation GIS to meet different needs and application purposes of multi-modal transportation systems.

The modelling principles outlined in this chapter simplify and synthesize the topology structure of a multi-modal transportation network, and support multi-modal GIS-T applications. The implementation of these principles is a key to a GIS-T for a multi-modal transportation network. These principles can underpin applications such as trip planning, pre-trip guidance and prediction of travel costs to passengers, as well as evaluation of accessibility to, or interaction of, different transportation modes. The case study outlined

in the following section represents these principles and their applications in a multi-user computer environment.

Chapter 4

A PROTOTYPE FOR MULTI-MODAL TRANSPORTATION GIS

A multi-modal and multi-scale transportation GIS data model has been designed and implemented in the urban transportation system of the city of Guangzhou. The model is developed to allow for developing specialised services designed after the survey and study of users' and planners' requirements. Experiments of multi-modal transportation GIS applications are validated to meet the need of the urban systems of the city of Guangzhou. This implies to develop a prototype system to carry out the applications. This chapter focuses on the development of a multi-modal and multi-scale GIS-T prototype, which is applied to a study area, i.e., the centre of Tianhe District in the city of Guangzhou. This experimental system represents the multi-modal and multi-scale transportation GIS data model in a multi-user computer environment, and demonstrates a decision support system to enable transportation planners and decision-makers to take better decisions effectively, and provide high-quality geospatial information-based services to final end-users.

4.1 Study area: the centre of Tianhe District

In the city of Guangzhou, Tianhe District is bordered by Yuexiu District on the West, Baiyun District on the North and Huangpu District on the East. Haizhu District is on its south, though they are separated by Pearl River (Figure 4.1). The district of Tianhe covers an area of over 96 square km and with a population of about 0.65 million. Nowadays, the district has been developed as a new centre of the city of Guangzhou with a great number of modern transportation and traffic facilities, particularly in the centre of the district.

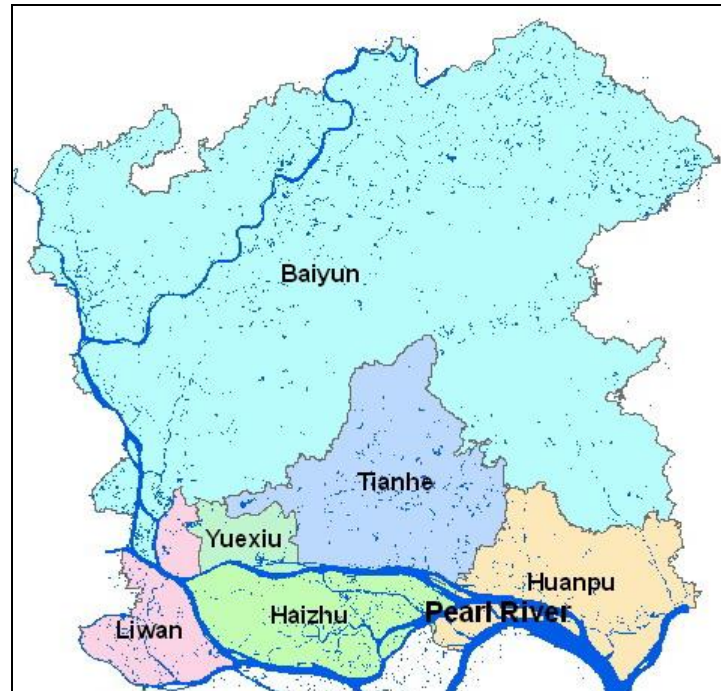


Figure 4.1 Tianhe District location

This centre area just covers about 12.5 square km. Although this area is quite small as compared with the total area (over 7000 square kilometres) of the city of Guangzhou, it is a typical built-up area with busy traffic activities. This is the reason to select this area as the study area. As shown in Figure 4.2, in this area the road network is composed of three main roads that run in East-West direction (i.e., Tianhe Bei road, Tianhe Road, and Huangpu Boulevard), over ten mains roads that run in North-South direction (such as Guangzhou Boulevard, Tiyue Dong Road, and Tianhe Dong Road), and some secondary roads. Moreover, the public transit system is also well developed in the centre of Tianhe District. As shown in Figure 4.3, the paths of bus lines and stops in the study area are spreading on the urban streets network to serve the public. Over 60 bus lines and 100 bus stops are deployed over the streets network to provide bus-based transportation services. In particular, in this area the complex public transportation network is multi-modal based, including not only the bus line network, but also the metro line network. For the metro line network, in the centre area there are 2 metro lines to provide public transportation services, which include Metro Line 1 and Metro Line 3. Figure 4.4 shows the metro line network of the city of Guangzhou.



Figure 4.2 Road network in the study area

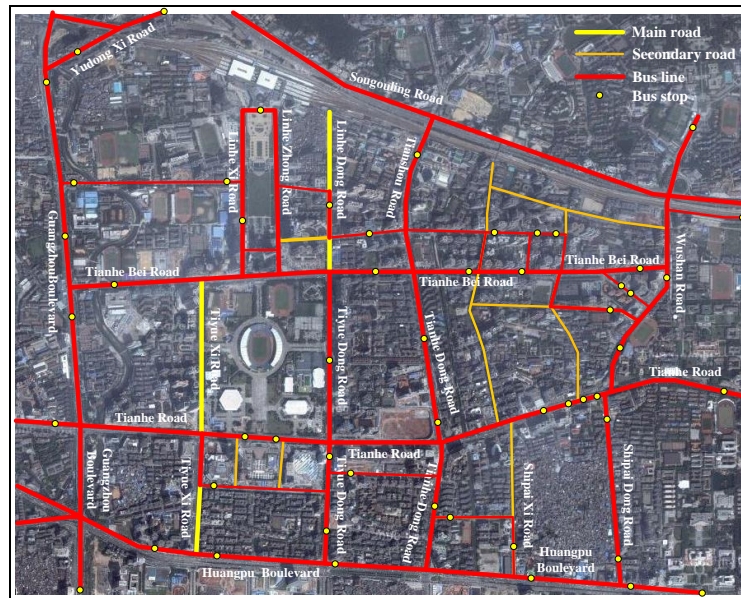


Figure 4.3 Bus lines and bus stop locations in the centre of Tianhe District

(Note: Red lines represent the running paths of bus lines spreading on roads; bus stop locations are represented as yellow points without consideration of individual stop sites)

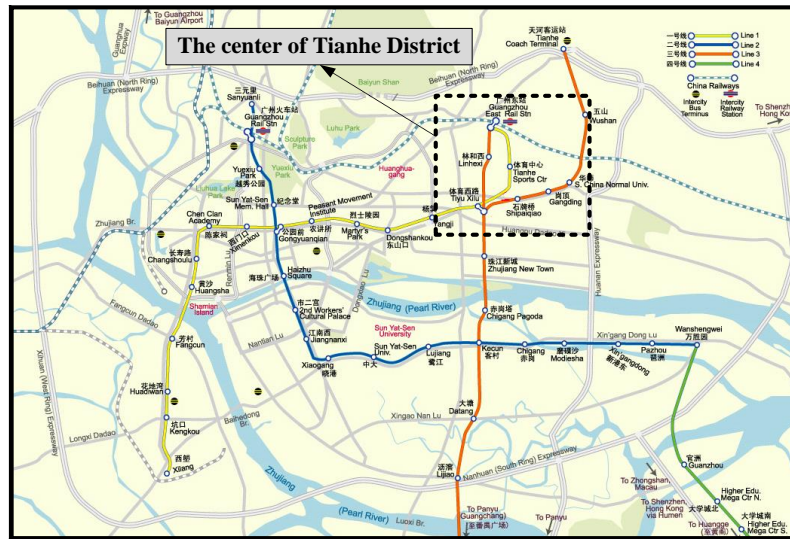


Figure 4.4 Metro transit network of the city of Guangzhou

In this area, the busy traffic can be demonstrated from current traffic flow volume and vehicle velocity on the streets. Average traffic flow on Huangpu Boulevard reached nearly 8000 vehicles per peak hour in 2006, according to a survey conducted by the Guangzhou Municipal Technology Development Corp (Table 4.1). Nevertheless, the average bus velocity on the main roads in the study area is less than 13 km per peak hour. This presents poor quality of time cost of bus-based transportation service. This motivates crucial applications to deal with the busy and complex traffic circumstance to improve the efficiency and quality of public transportation services in the city of Guangzhou. The application requirements have been investigated and explored from the extensive survey and study of current transportation patterns and travel behaviours in the city of Guangzhou. This presents an objective of high-quality public transportation provisions, which is to attract more transportation actors to use public transportation modes to travel, instead of private car modes. This entails a task to evaluate and improve the accessibility to public transportation modes and the connectivity/interaction of multiple transportation modes, thereby promoting the quality and efficiency of public transportation services.

Road name	Traffic flow (vehicles per peak hour)	Bus velocity (km per peak hour)
Tianhe Road (8 lanes)	3200	10.83
Tianhe Bei Road (8 lanes)	2000	13.37
Huangpu Boulevard (16 lanes)	8000	14.73
Average	4400	12.98

Table 4.1 Average traffic flows and bus speeds on main roads in the study area (Wang *et al.*, 2006)

(Note: According to the Code for Transport Planning on Urban Road (Ministry of Construction, 1995), the range of prescriptive bus speed is between 16 and 25 km per peak hour)

4.2 A GIS-T prototype applied to the study area

One approach to develop a GIS is to employ current GIS development components and readily available object libraries which provide opportunities for GIS developers to be able to customize different GIS applications rapidly. Therefore, the development of transportation GIS prototype is supported by ESRI MapObjects and ArcGIS, and is implemented under a visual software development environment, i.e., Microsoft Visual Basic 6.0. Moreover, in order to improve the efficiency of data transmission and exchange between the GIS application system and the geo-database. The database of prototype was designed and implemented on top of a relational database management system (RDBMS), i.e., Microsoft SQL Server 2000. The RDBMS is spatially enabled by ESRI ArcSDE which is an application server to facilitate storage and management of spatial data in a RDBMS Form. ArcSDE also allows the RDBMS to integrate spatial data seamlessly. Therefore, in the prototype Microsoft SQL Server 2000 is referred to as an ArcSDE-based RDBMS to integrate spatial and non-spatial data.

The development components and software outlined above are the fundamental elements to develop a transportation GIS which needs to be designed with an appropriate architecture. The software structure of transportation GIS prototype is designed based on the three-tier client/server (C/S) architecture. In comparison with the two-tier (i.e., the client and the server) architecture, the three-tier architecture introduces a server (or an "agent") between the client and the server (Eckerson, 2005). The roles of the agent can provide translation services (as in adapting a legacy application on a mainframe to a client/server environment), metering services (as in acting as a transaction monitor to limit the number of simultaneous requests to a given server), or intelligent agent services (as in mapping a request to a number of different servers, collating the results, and returning a single response to the client. Therefore, as compared with the two-tier, the three-tier C/S architecture can provides increased performance, flexibility, maintainability, reusability and scalability, while hiding the complexity of processing from the user. These characteristics facilitate software development because each tier can be built and executed on a separate platform, thus making it easier to organize the implementation. Also, the three-tier architecture readily allows different tiers to be developed in different languages. Based on the concepts of three-tier client/server (C/S) architecture mentioned above, the structure of the transportation GIS prototype can be defined as three essential components

(tiers), including user interface, process management and data management. The components and relationships can be presented as follows:

- User interface (representation tier)

This is the topmost level of the application. This presentation tier displays information related to such services as searching facilitators. It communicates with other tiers by outputting results to the browser/client tier and all other tiers in the network.

- Process management (Business Logic/Logic Tier)

The middle tier provides process management services that are shared by multiple applications. This tier is also referred as the application server that improves performance, flexibility, maintainability and reusability by centralizing process logic. Centralized process logic makes administration and change management easier by localizing system functionality. As a result, changes may be written once and placed on the middle tier server to be available throughout the systems.

- Database management (Data Tier)

This tier consists of Database Servers. Here information is stored and retrieved. This tier keeps data independent from application servers or business logic.

According to the components outlined above, a diagram can be given to represent the software structure of the prototype system (Figure 4.5). In the proposed system, users connect to the system from graphical user interfaces. Figure 4.6 shows a main graphical user interface of the prototype. Data are delivered to processing units to implement data representation, management, or analysis. The resulting information is visualized and/or transmitted to the GIS-based database management (i.e., the Arc SDE-based RDBMS) for updating or storing and data analysis. Moreover, the database management provides dynamic information for GIS which is usually extracted from travel surveys (e.g., the passengers/vehicles flow information). The implementations of processing units are also supported by the database management. As shown in Figure 4.6, graphic representation of the transportation network data delivered from the data management is implemented by the processing units. The processing units can be described and understood as below.

- Data management and integration: With the aid of GIS, the process is able to visually represent transportation geographical data. Also, it can process the passengers/vehicles flow information to offer a mean to analyze flow patterns with respect to current transportation patterns, i.e., the carriageway centreline-based network.
- Data query: With user interfaces, users can connect to the system to get information services. They can find specific transportation facilities (streets, transit routes or stops) and can also retrieve a path (e.g., shortest walking path) to a desired position. Combination of service coverage and walking path finding illustrates the accessibility to public transportation modes.
- Multi-modal and multi-criteria routing: In the busy and complex traffic situations, multi-modal trip planning is essential process to guide people to choose a desired path with minimizing travel costs. Such path finding is oriented to the question of optimal multi-modal path which can be identified based on different criteria, i.e., different commuters' expectations.
- Transportation network analysis: The routing (path finding) process to an origin and a destination on public transit networks can also be used to detect different

OD (origin-destination) trips. For example, the trips involve several times of route change. This process also implies an evaluation of the connectivity of multiple transportation networks. Using this process, moreover, bus route volume and traffic survey information can be represented and compared, particularly with respect to current public transportation patterns and their intensity. Adopting the GIS-T approach and transportation network topology designed together, the planners/administrators of transportation agencies can more effectively perform network planning, adjustment (e.g., expansion, location, or relocation) of facilities, or arrangement of schedules.

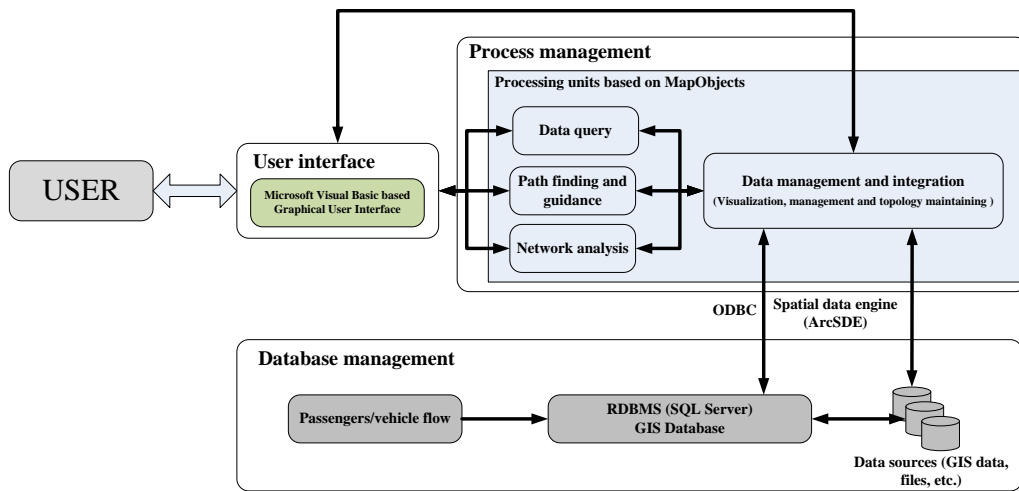


Figure 4.5 Diagram of the prototype

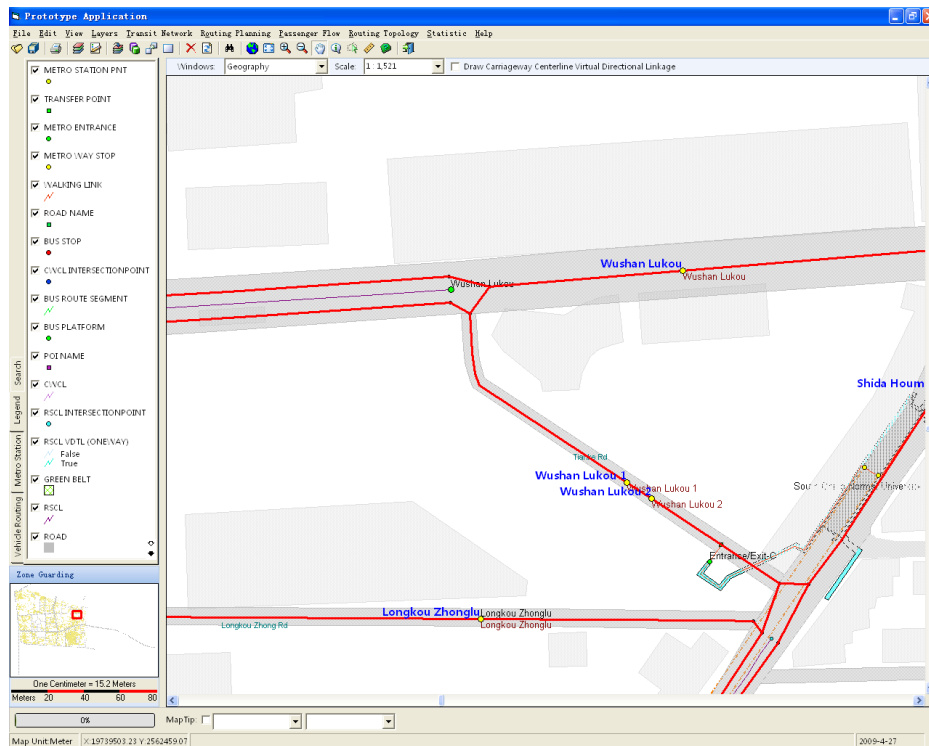


Figure 4.6 Example of graphical user interface

4.3 Transportation data management and representation

GIS data in the transportation GIS are identified by different spatial features that may be represented by points, lines or polygons, according to their shapes, themes and scales. In an Arc SDE-based GIS database, each feature dataset is a collection of related features that share a common theme, shape, and coordinate system. This implies that related features can be organized into a common dataset for building a topology, a network dataset, or a geometric network. Table 4.2 illustrates all feature datasets involved in the transportation GIS. These datasets reflect multiple spatial objects which are involved in the streets, walking links, bus lines and metro lines networks, and are abstracted and represented at different scales. At different ranges of scales, the transportation objects sharing a common theme can be abstracted at different levels of granularity. For example, a metro station can be represented as a polygon if the mapping scale is large, or a point if the scale is small. As multiple data representations are the crucial principle of the transportation GIS data model, in the prototype each feature dataset is represented in a range of scales to accommodate the principles of data representations defined in the model. Figure 4.7 gives an example of a system interface which is developed to specify and identify different levels of granularities (scales) to represent the transportation GIS data.

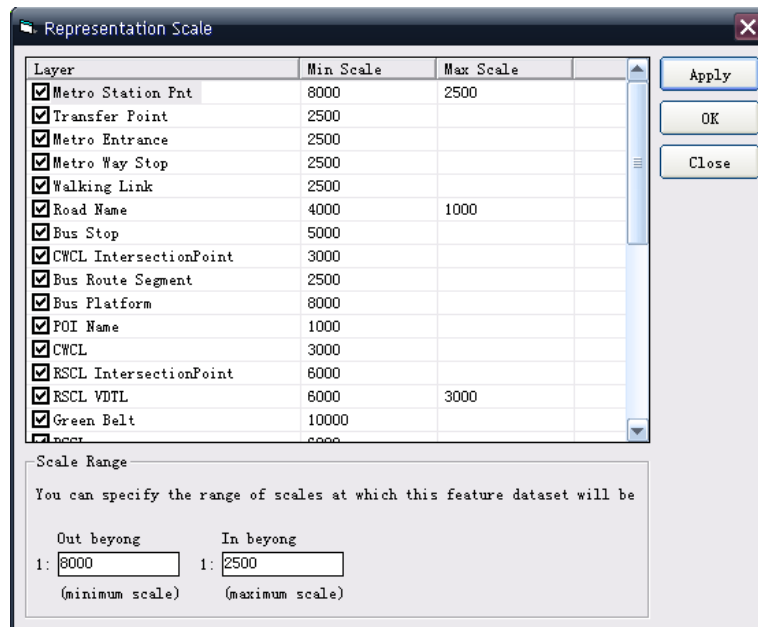


Figure 4.7 Range of data representation scale

Features	Feature dataset	Shape
Urban spatial features	Point of interest (POI)	Point
	Road Surface	Polygon
	Playing field	Polygon
	Green belt	Polygon
	Block	Polygon
	River	Polygon
	Pool	Polygon
Transportation spatial features	Road segment centreline (RSCL)	Line
	Carriageway centreline (CWCL)	Line
	RSCL virtual directional turning link	Line
	RSCL intersection point	Point
	CWCL intersection point	Point
	Bus platform	Point
	Bus stop	Point
	Bus route	Line
	Metro line	Line
	Metro way	Line
	Metro station surface	Polygon
	Metro station point	Point
	Metro way stop	Point
	Metro entrance	Point
	Walking link	Line
	Transfer point	Line
	Railway	Line

Table 4.2 Datasets involved in the multi-modal transportation GIS

Moreover, the function of data management and representation deals with an integration of the transportation GIS data and other data, particularly including dynamic data (i.e., passenger/vehicle flow) and urban spatial features. Passenger/vehicle flow data can be identified as the attributes of related transportation linear features. This helps to represent the flow data with respect to the patterns of related transportation networks. Urban spatial features (e.g., rivers, green belts, and points of interest) are used as a background of the transportation spatial information. In a GIS, the connection between transportation spatial features and urban spatial features can be validated by spatial connectivity. Figure 4.8 illustrates the representations of urban spatial features at different scales, e.g., 1:15000 and 1:5000. While the scale is 1:5000, roads and points of interest (e.g., building, hotels, restaurants, and shops) are labelled with names. This detailed information helps people to point quickly a position on map.

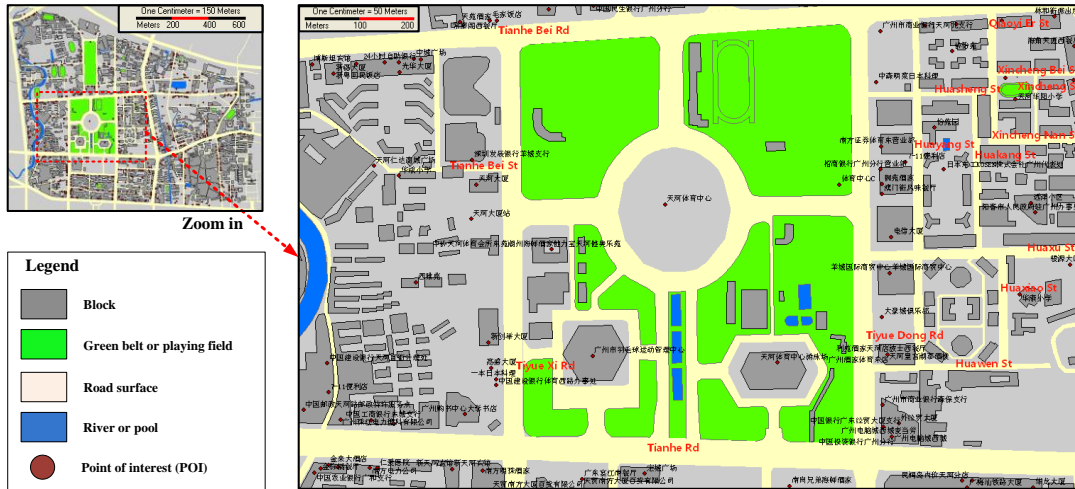


Figure 4.8 Representation of urban spatial features

In term of the principles of multi-level data representations defined in the data model, the street network is particularly represented at different levels of abstractions which reflect different transportation themes. As shown in Table 4.1, the geospatial features of street network can be classified into different datasets, involving road segment centre lines (RSCL), carriageway centre lines (CWCL), RSCL intersection points, CWCL intersection points and RSCL virtual directional turning links. Figure 4.9 illustrates an example of the multi-level representations of the streets network in a given area (named as “Teemhe City”) validated in the prototype. As shown in Figure 4.9(a), at each intersection turning restrictions are stored as the attributes of the intersection points, and visually represented as the virtual directional tuning links, i.e., RSCLVDTLs. Figure 4.9(b) illustrates a low-level representation of the street network in the same area. This implies that the carriageway centre lines are represented.

As public transit routes depend upon physical infrastructures (e.g., streets and railways) which already exist, the bus route segments and stops are referenced to the carriageway centrelines network (Figure 4.9(c)), and the distributions of the metro way segments and stops are restricted by the railways (Figure 4.9(d)). Figure 4.10 illustrates an example of the multiple representations of metro transit network validated in the prototype. At the scale of 1:15000, the metro lines are represented a single lines that connect to a sequence of metro stations represented as points. At the scale of 1:5000, metro stations may be represented as a zone (polygon) which is referred to a background for locating two parallel directional metro ways, way stops, entrances and tunnels. In the metro station, each way stop is located on the metro way.

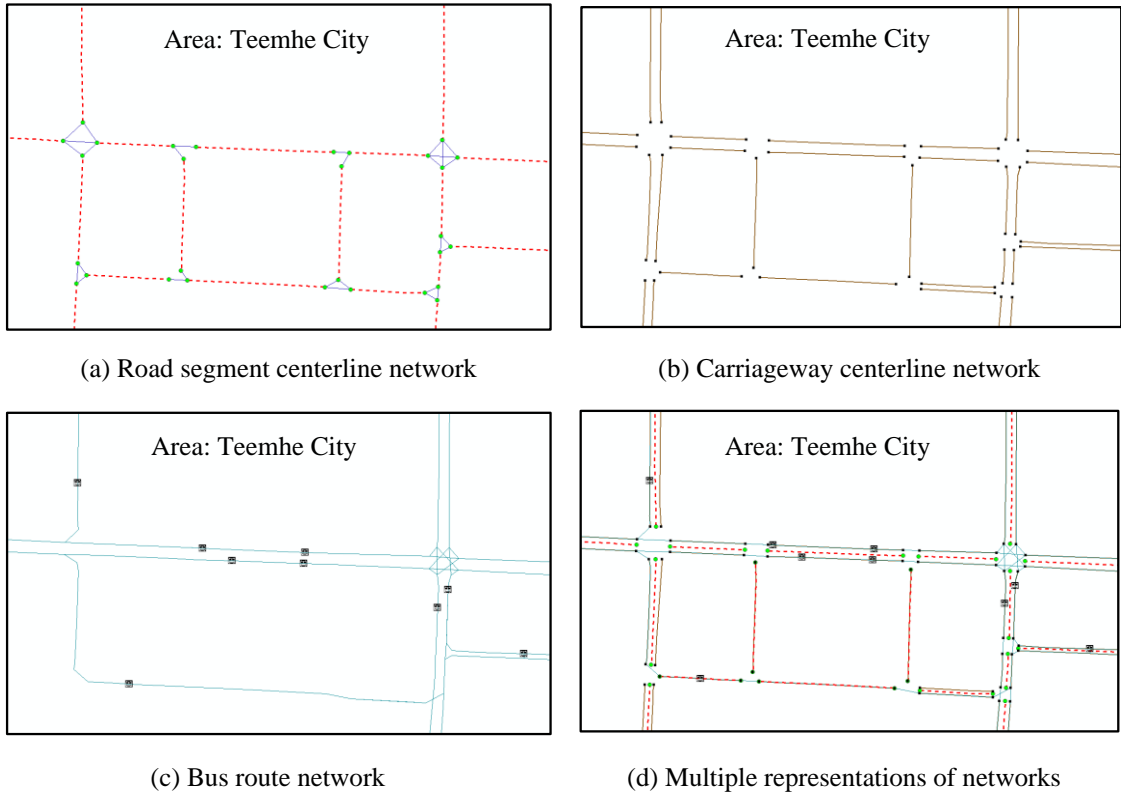


Figure 4.9 Representations of the transportation networks

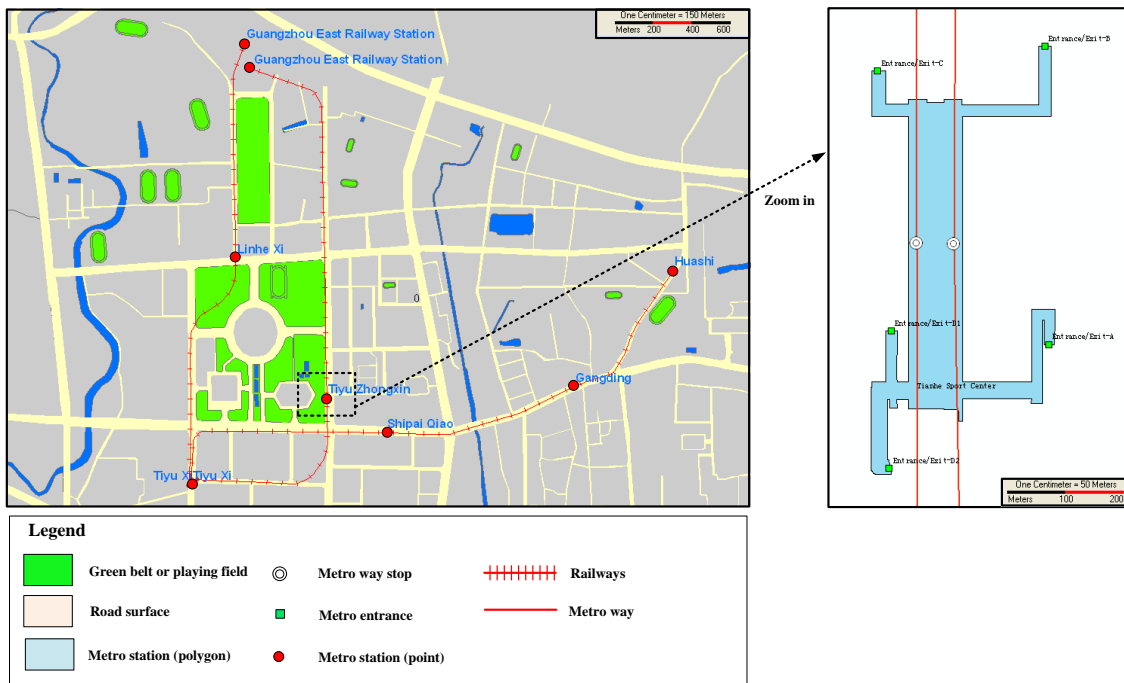


Figure 4.10 Multi-scale representations of the metro transit network

In the transportation GIS data model, the walking links are identified by a wide range of transportation links, including CWCLs, pedestrian facilities (zebra crossing, overpass or underpass) and passages in or towards to metro stations. Accordingly, the anchor points of walking link network cover a wide range of transportation nodes, including transfer points, bus stops, CWCL intersection points, metro entrances and metro way stops. Figure 4.11 illustrates a case of the representation of node-link walking link network in the area of “Teemhe City”. Multi-modal transportation objects are described and integrated in the concept of walking link network. The walking link network data model simplifies the data structure of multi-modal transportation networks, and provides an integrated topology to facilitate shortest path finding and multi-modal trip planning between multiple modal-based components. This also presents walking opportunities to support related functions and utilizations that mainly include evaluations of accessibility to, and connectivity and interaction of, multiple transportation modes.

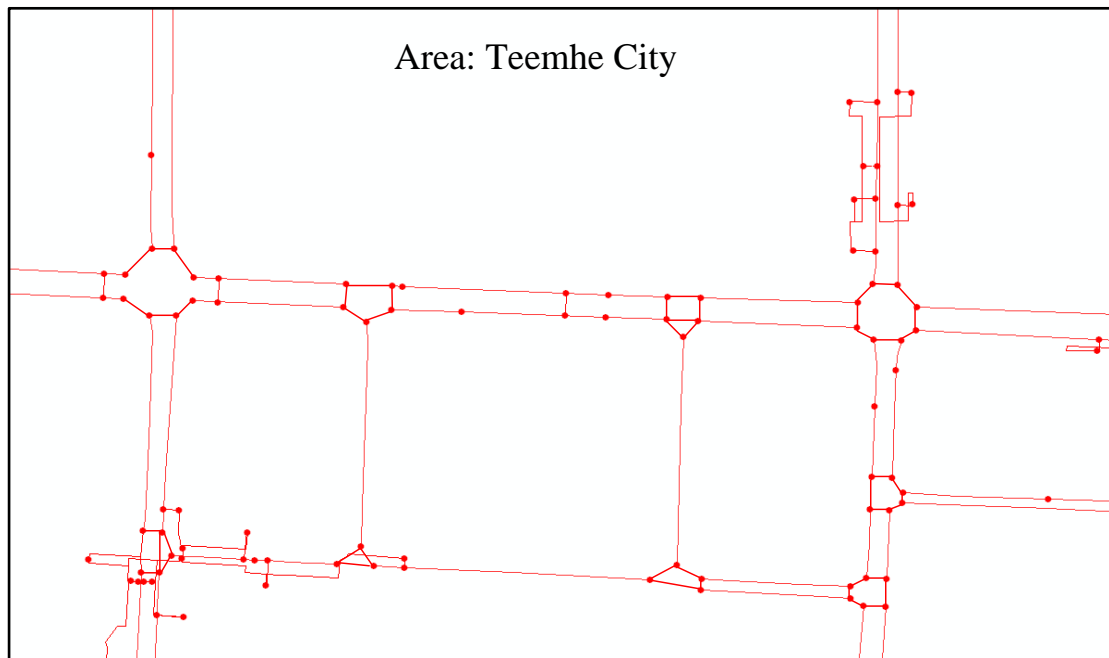


Figure 4.11 Multi-scale representations of the metro transit network

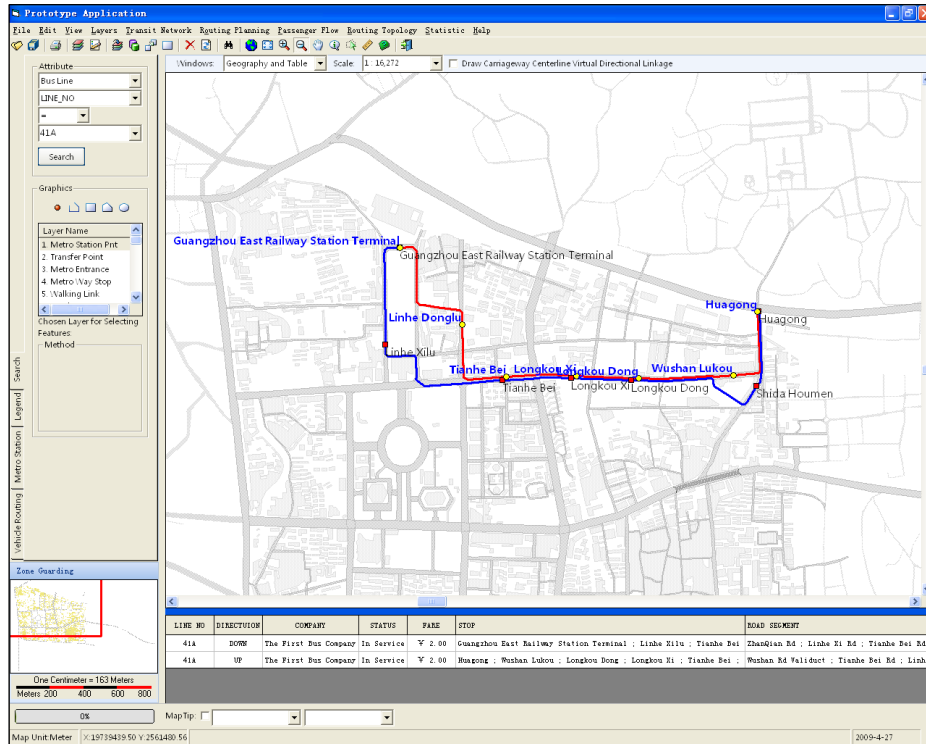
The multi-modal and multi-level data management and representation validated by the prototype is able to deal with the storage, updating, organizing and representation of transportation GIS data, and maintain the consistency of their topology relationships at different levels of abstractions. This implies that the transportation GIS data model proposed can handle the complex urban transportation patterns and the representation of multiple transportation systems. This provides an essential support to the process of multi-modal transportation routing information and network planning information through spatial data analysis with the aid of GIS.

4.4 Transportation data analysis and evaluation

4.4.1 Data Query

In the multi-scale and multi-modal transportation GIS data model, each bus route is modelled and described by linkage information to its corresponding bus route segments and stops. This contains not only basic information, such as names of stops and lengths of route segments, but also spatial and traffic topology information of the bus routes and stops whose locations are restricted to the carriageway centreline network patterns. The topology information is important for the commuters to identify if it is a right bus line for a destination. This also helps the planners to evaluate the patterns of each bus line. Figure 4.12 illustrates an example of data query to retrieve the information of bus line. A system graphical user interface is developed to provide accesses of various parameters, such as direction or name of bus line to return the information of a desired bus line. In a GIS environment, the resulting information can be represented with two directional routes on map (e.g., red line denotes the route of “UP” direction, blue line “DOWN” direction, as shown in Figure 4.12). Moreover, all stops of each route of the bus line are highlighted and labelled by their names. The attributes of the bus routes are also presented, including the name, company, direction, fare and so on. The representation of directional bus route with individual stop sites provides more detailed information to meet the users’ needs, e.g., which is the right directed bus route to the destination, or where is the exact site of the bus stop.

Moreover, as the representation of bus route segments is referenced with the centre lines of directional carriageways, this can more effectively and precisely generate such information than traditional methods that represent a bus line by a single or two directional linear features spreading along the centre lines of road segments. The length of individual bus routes is important information to evaluate bus-based services. The Chinese national standard for length of bus route in a built-up area is up to 12 km (Ministry of Construction, 1995). Statistics on existing bus routes can be applied to compare with this standard, thereby indicating if these bus routes are operating over a longer distance compared to the one suggested by the standard. Moreover, as the length of individual bus routes and relevant properties can be precisely determined in the prototype, other variables can be estimated. One case is the Vehicle Miles Travelled (VMT), generally used in transportation evaluation. As most bus schedules are fixed during a given period of time, the VMT for each bus in a day can be obtained by multiplying its route length in two directions by its running frequencies. By accumulating the value, the VMT for all buses in a city can be estimated.



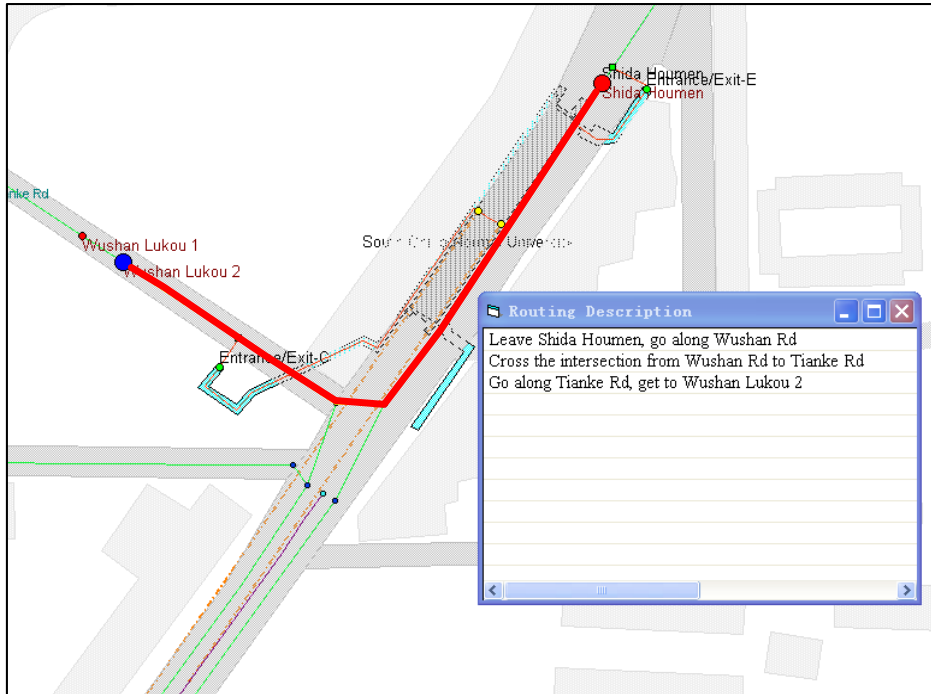
Legend

- Bus stop ("UP" direction)
- Bus stop ("DOWN" direction)
- Bus route ("UP" direction)
- Bus route ("DOWN" direction)

Figure 4.12 Query of bus line

4.4.2 Shortest path finding

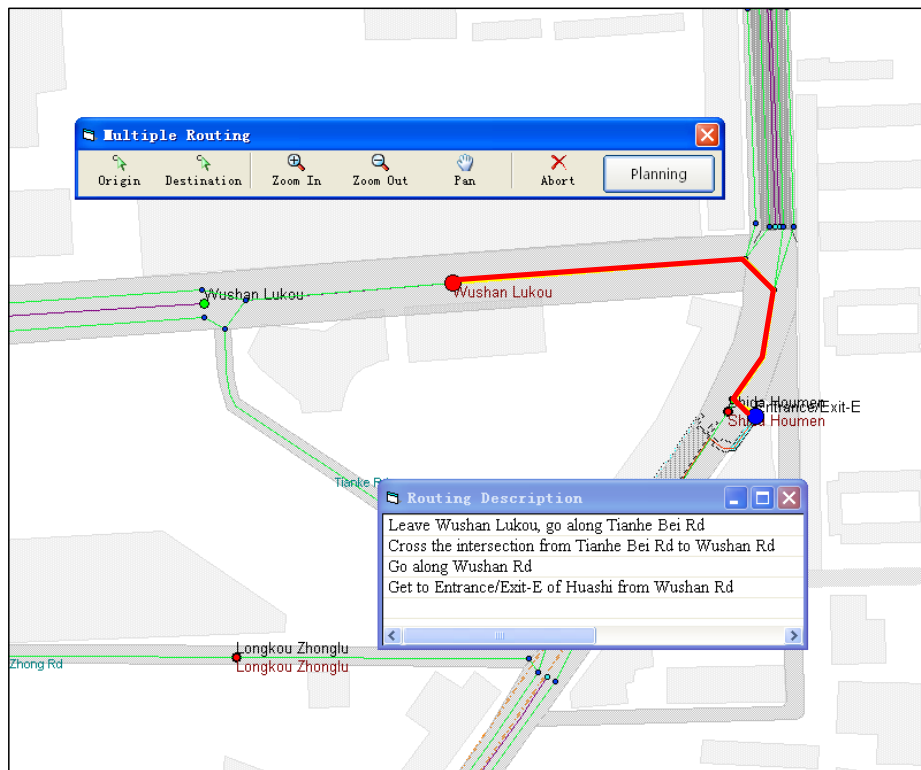
A route usually is a modal-based path, which may involve bus, metro and walking modes. This implies several constraints to include connection possibilities (i.e., possibility of performing a multi-modal connection using walking links and traffic-oriented connections between different transportation modalities) and temporal constraints (i.e., walking time, travelling time spending on public transit vehicles, or derived from timetables). This presents that the “cost” of walking in multi-modal transfers is an important constraint when searching for a relevant route. Figure 4.13 illustrates an example of shortest walking path finding between two individual bus stop sites. The guidance of this walking path is also presented. The walking connection explicitly indicates the cost, i.e., walking distance or time. The guidance information may be important to guide passengers to change a route from a stop to a stop. If the cost is compatible with the commuters’ expectations, this implies the possibility of route change between these two stops. This also presents that shortest walking path finding can be used to evaluate the connectivity of stop sites. Furthermore, in the context of multi-modal transportation networks, the possibility of route change between different modes (i.e., bus and metro) can be presented by the shortest walking path between a given bus stop and a given metro entrance. Figure 4.14 illustrates a shortest walking path finding between a metro entrance/exit (e.g., Entrance/Exit-E of South China Normal University) and a bus stop (e.g., WuShan). Taking into account the walking cost for this route change, multi-modal transfer reflects the interaction of multiple public transportation modes.



Legend

- Original stop
- Destination stop
- Walking path

Figure 4.13 Shortest walking path between bus stops



Legend

- Original stop
- Destination metro entrance
- Walking path

Figure 4.14 Shortest walking path between metro entrance/exit and bus stop

Shortest walking path identification outlined above is implemented based on the walking link network topology model, which are realized as a series of actions interacted with multiple nodes (bus stops, metro entrances or transfer points) and links (carriageway, pedestrian passageways or underpass) between an origin and a destination. However, as for the car drivers, the identification of shortest path should be oriented to the movement or navigation of motor vehicles on the street network. The prototype has also validated the routing function based on the carriageway centreline network topology model. This implies the routing application needs to take into consideration the traffic-oriented rules and restrictions applied to the street network, involving traffic controls (e.g., one way or two way streets), directions of carriageways and turning restrictions at intersection. Figure 4.15 illustrates an example of the identification of shortest-path to a motor vehicle. System interface is developed to locate an origin and a destination with a reference to the carriageway centreline network. The resulting path is highlighted by a red line, and provides a textural form of pre-trip guidance. As the shortest-path is restricted by the current traffic connectivity of the given street network, this information is useful for the planners to optimize the patterns and topology of carriageway centreline network in future network planning and management.

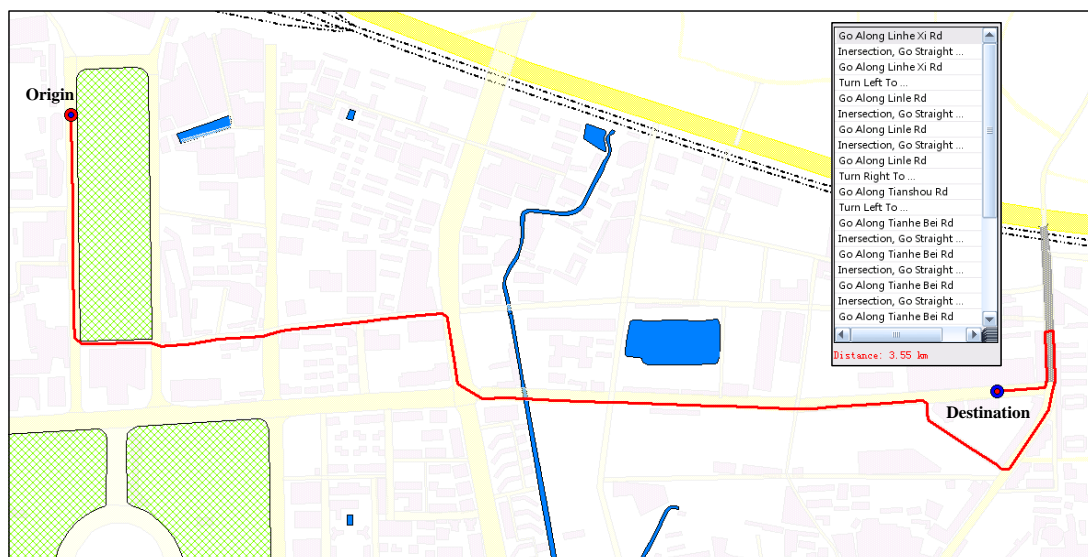
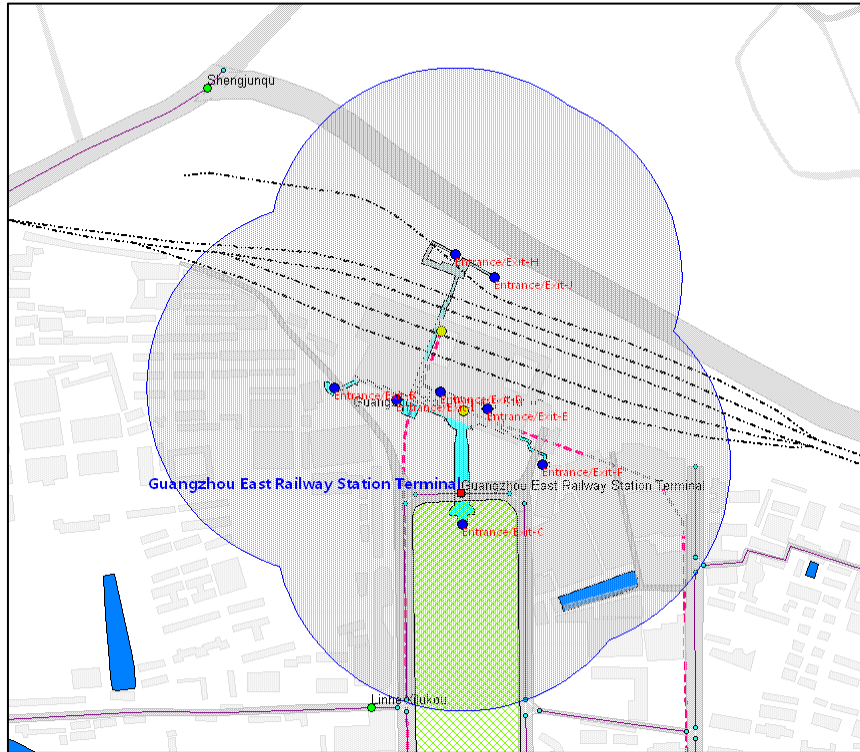


Figure 4.15 Example of shortest-path finding for motor vehicle

4.4.3 Service coverage

Service coverage analysis is a typical showcase for GIS applications in urban transportation. With the aid of GIS, the process is characterized by creating buffer zones based on a defined radius around service routes or stops, and by overlaying the zones with streets or land uses (Nyerges, 1995; Thorsen and Rasmussen, 1999). For a given public transportation mode, the notion of service area is of crucial importance as it defines the coverage with respect to a population area. Figure 4.16 illustrate an example of a service area defined using a radius of 300 meters, and where metro and bus stops are highlighted as possible transfer nodes. This service coverage area presents a transfer area of bus and metro modes. This is particularly relevant when the origin and destination of a given route are given as search criteria. In the area, there is a shortest walking path among all walking possibility between bus stops and metro entrances. In this case, such a walking path is identified between the bus stop of “Guangzhou East Railway Station Terminal” and the metro entrance of “Entrance/Exit C”, as shown in Figure 4.17. This

walking possibility may present a parameter to support bus stop or metro entrance/exit location or relocation in network planning, or help commuter to choose the right metro entrance/exit or bus stop for multi-modal transfer.



Legend

- Bus stop inside service area
- Metro entrances/exit
- Service area

Figure 4.16 Service area of a metro station

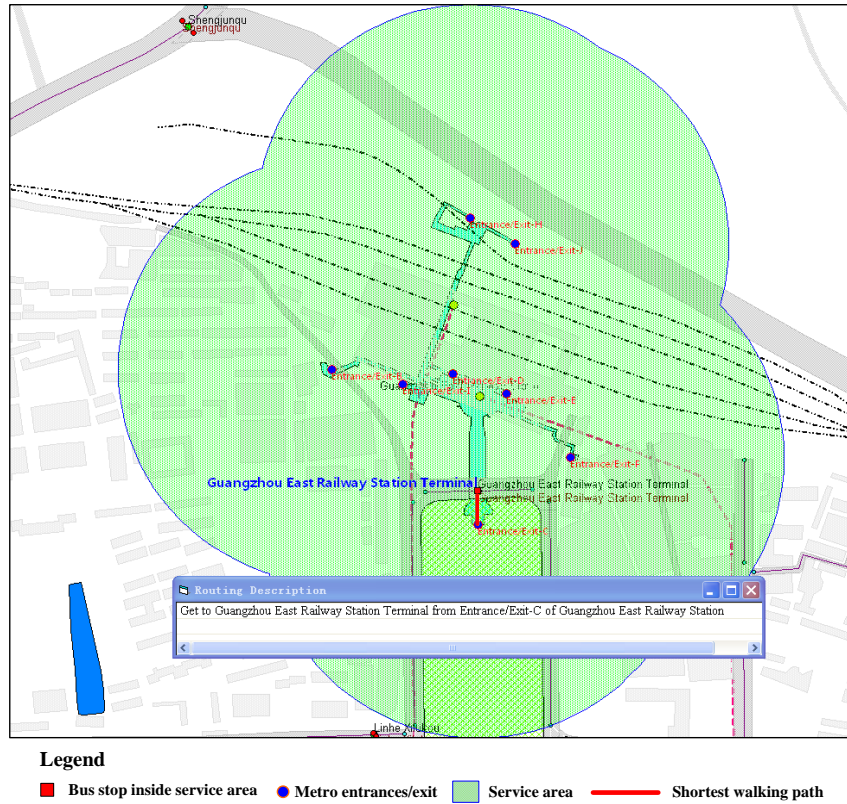


Figure 4.17 Example of shortest walking path between bus and metro modes

Moreover, service coverage can identify the areas where public transportation opportunities are available. This information can be used to evaluate the accessibility to public transportation modes. The experiments made in the city of Guangzhou clearly show that a combination of several public transportation modes (i.e., bus and metro) extend the urban service coverage of public transportation. This implies that the public transportation opportunities are enhanced. However, some zones (including population areas) cannot be covered in the combination of multi-modal service coverage areas. Figure 4.18 shows the public transportation opportunities derived from a combination of metro and bus service coverage areas. Accordingly, some urban areas are clearly excluded outside the service coverage. This implies that the accessibility to public transportation modes need to be improved in future planning studies.

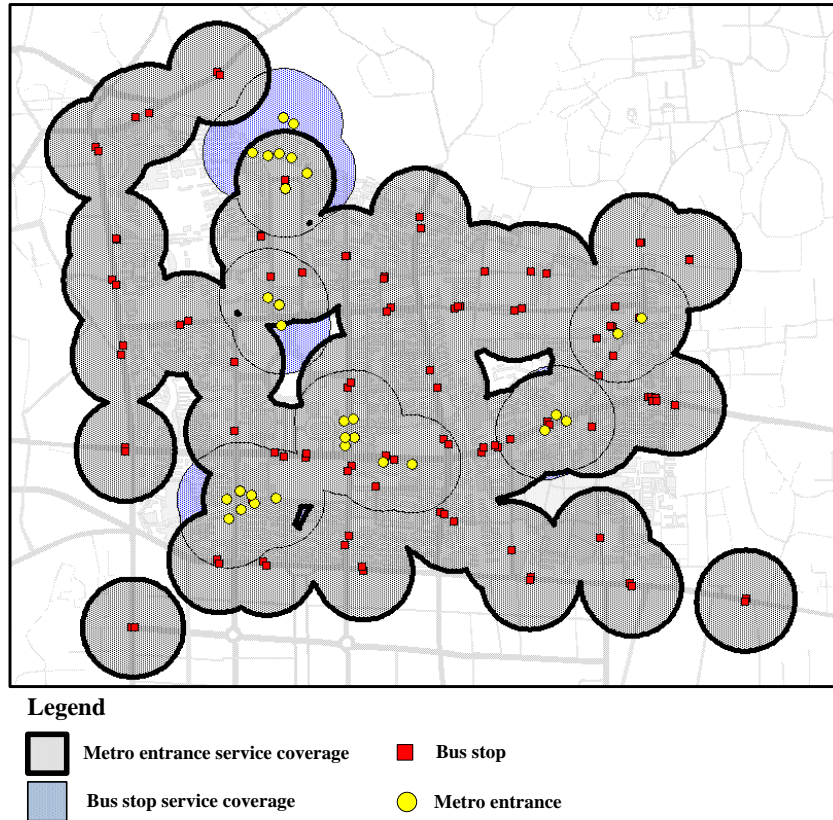


Figure 4.18 Service areas of bus and metro networks

As observed in the travel behaviours of the city of Guangzhou and the related studies of building decision support systems for traffic and transportation GIS (Peytchev *et al.*, 2001), a given commuter might also prefer to take transportation opportunities with reliable travelling times (e.g., metro), rather than potentially faster solutions but dependent on traffic conditions (e.g., private car or bus). Therefore, and to a certain degree, it appears that common service coverage of multiple public transportation modes is a key factor regarding the quality of public transportation services provided to the commuters. Figure 4.19 illustrates the urban areas which can be covered in the common service coverage areas of multiple public transportation modes in the study area. These areas can be referred to the transfer zones where walking opportunities exists to route change between bus and metro modes. The cost of walking can be used to evaluate the interaction of bus and metro modes, and needs to be minimized in future planning studies of multi-modal public transportation networks.

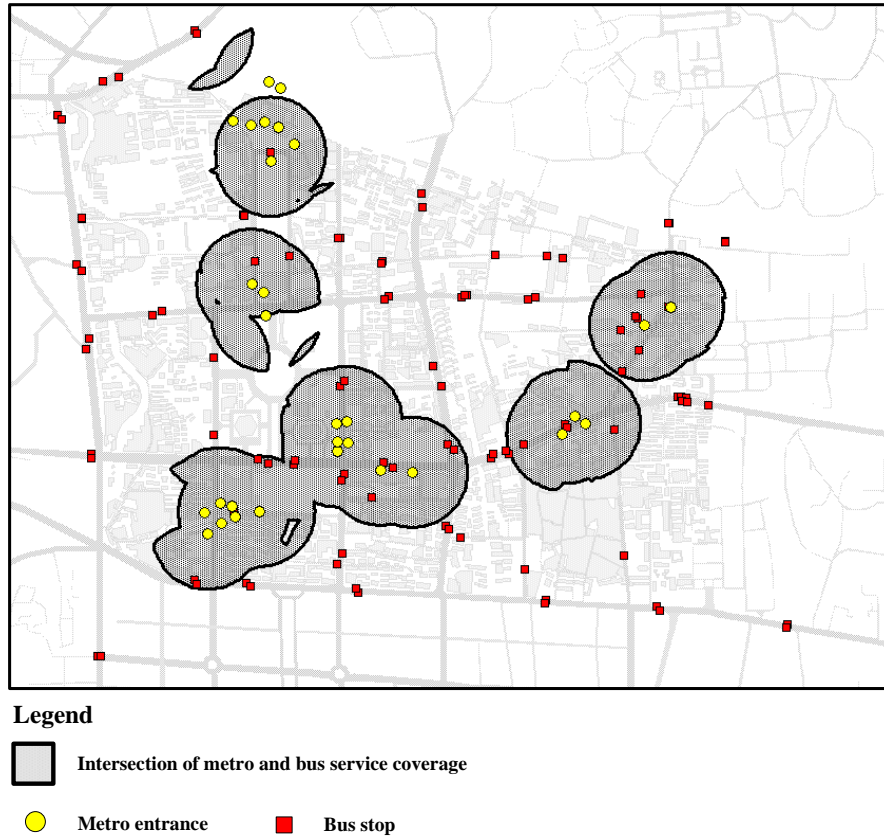


Figure 4.19 Intersection of bus and metro service coverage area

4.4.4 Multi-modal trip planning

4.4.4.1 Routing criteria

In the multi-modal and multi-criteria routing model, multi-modal trip planning needs to take into account the fact that the routing criteria are spatial (e.g., walking distances), time-dependent (e.g., travel time and timetables), and affordable (e.g., fare). The spatial criteria have been discussed in shortest (walking) path finding and service coverage analysis. Time is commonly considered as a key measurement and variable for trip planning and transportation service efficiency. Time consumption is determined by a function of distance and speed. Nevertheless, ways to determine time cost for different transportation modes are different. For metro mode, transit vehicles run on the fixed routes that are designed only for their own uses and operated in a rather separated system, therefore, they can operate at a stable speed, and be limited to a strict schedule. This implies that each metro way segment has a fixed time cost according to the schedule. Although metro timetables are generally respected, much different from metro modes, buses share roads with other motor vehicles. This implies that they are affected by traffic conditions and traffic controls, especially in overcrowded urban area. This presents that the time cost of waiting for a bus need to be determined by practical experiences. Although the distance of each bus route segment is given, the speed of vehicles is not sure to determine the time cost. Determination of real-time bus speed in an urban area is not the research point of this study, but the estimation of travel time taken to ride bus in peak

and non-peak hours are required. This implies that the time cost of each bus route segment can be reached simply by dividing the distance of the segment by an average or expected speed in peak or non-peak hour. Therefore, average speeds are given to buses in peak and non-peak hours, and this is at the bus route segment level and fixed according to a study made in the district of Tianhe, following a study of Wang *et al.* (2006). Time cost on a multi-modal route includes not only the time taken to ride public transit vehicles and to wait for a vehicle coming, but also the time cost of walking, including walking to origin stop, between stops to route change, and to destination. Time costs of walking links are also given according to an average speed of 5 km per hour in plain area. In the prototype, the maximum walking distance can be validated by a commuter who is ready to perform for a given transfer.

Besides the criteria of walking distances and time cost outlined above, transfer time and travelling fare are also key criteria in trip planning. Public transportation services are usually oriented to the policy of low price, in order to establish against high-cost of private automobile use. According to the travel behavioural surveys in the city of Guangzhou, time of route change is referred to a crucial criteria in trip planning, especially in multi-modal trip planning. This implies that a prior consideration in trip planning should be to reach destination with minimizing time of route change. This appears that the number of transfer time need to be limited to a reasonable number in order to not discourage commuters. This value is denoted as 1 in the city of Guangzhou.

4.4.4.2 Routing applications

Different people may have different expectations on the question of optimal in travel planning. This stresses the fact that in all cases such a system should be considered as a decision support system, not a definitive solution provider to a multi-criteria decision process.

Washington Metropolitan Area Transit Authority (WMATA) has implemented a trip planning system, i.e., the WMATA Trip Planner (WMATA, 2009). The system is a web based system to provide trip planning service for the end-users, in particular commuters. The trip planning criteria include minimized travelling time, walking distance and transfer time. Nevertheless, an origin or destination cannot be located on a digital map of the urban street network, although it has an interactive map that allows a user to see the full station map and click on a station to use in either the Travel From or Travel To fields. The resulting itinerary is depicted in text-based instructions, and lacks map-based instructions. When complicated service network appears as a maze in front of passengers, especially new comers and tourists for the city, it is essential that the transportation GIS data model should be an interactive digital guide map to help passengers plan journeys.

In response to the issue outlined above, the prototype provides more flexible and interactive interface and digital guide map to represent the multi-modal and multi-criteria routing model in a GIS environment. Figure 4.20 illustrates a user interface of multiple criteria representation to multi-modal trip planning validated in the prototype. The multiple criteria representation provides a flexible interface which helps a commuter to define an appropriate trip corresponding to his/her expectations. This implies the validation of multiple criteria to trip planning. This includes walking opportunities, public transportation opportunities and transfer. In a routing scenario, validation of walking opportunities depends upon finding an acceptable length of walking path to travel between modes and to the origin and destination. Data shown in the latest travel behavioural survey in the city of Guangzhou, such a length is denoted as 300 metres (GTP, 2006). The prior possibility of public transportation is through bus mode or metro mode,

namely, privileging a bus route only or a metro route only. Another possibility is the support of transfers between bus routes, or between bus and metro modes. Furthermore, the trip planning based on the criteria outlined above may generate different paths with different travel costs, such as travelling distances, walking distances, travelling fare, travelling time and number of stops. The system interface of multiple criteria representation also provide an access for commuters to identify the expectation of minimizing travel cost, such as shortest-path, shortest walking path, least travelling fare, least travelling time or least number of stops.

Routing Pre-condition: Service Radius

Service Coverage Radius: 300 (meter)

Criteria

Walking, if a distance is less than 300 (meter)

Through Connection (Without route change)

Taking bus without transferring

Taking metro without transferring

Transferring Connection

Taking bus, and may transfer to other bus routes

Taking bus, and may transfer to metro OR taking metro, and may transfer to bus

Shortest-path Shortest walking path Least fare Least time Least stop number

Figure 4.20 Multiple criteria representation

As compared with the WMATA Trip Planner, a graphical user interface is introduced to freely locate origin or destination on the map (Figure 4.21). With the aid of the system interface, user can look through the transportation networks, and locate a desired origin or destination with a reference to the walking links in the district of Tianhe. Figure 4.22 illustrate an example of locating an origin and a destination on the walking link network with interaction of digital map. After the process of routing application, all public transportation possibilities corresponding to the given routing criteria are listed with comparisons of travel costs, e.g., travelling fare, travelling time, and walking distance, as shown in Figure 4.23. This implies that the routing application deal with different answers to the question optimal path identification, which include the path with a through bus route, the path with a through metro way, or the path with minimizing travelling distance, walking distance, travelling time, travelling fare, or number of stops.

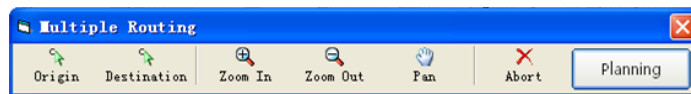
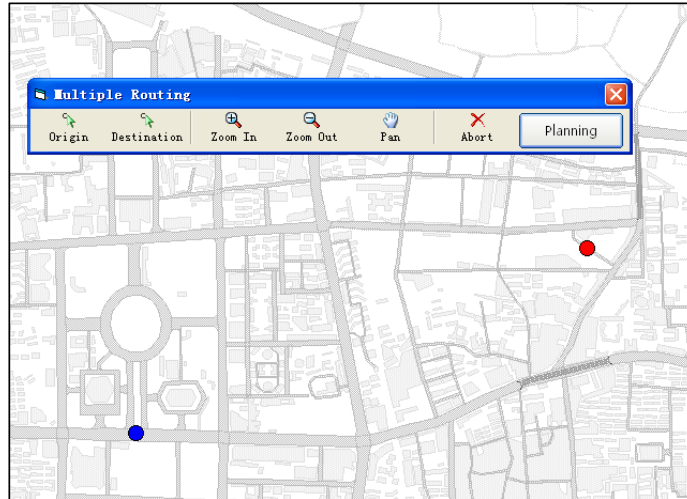


Figure 4.21 Graphical user interface of routing



Legend

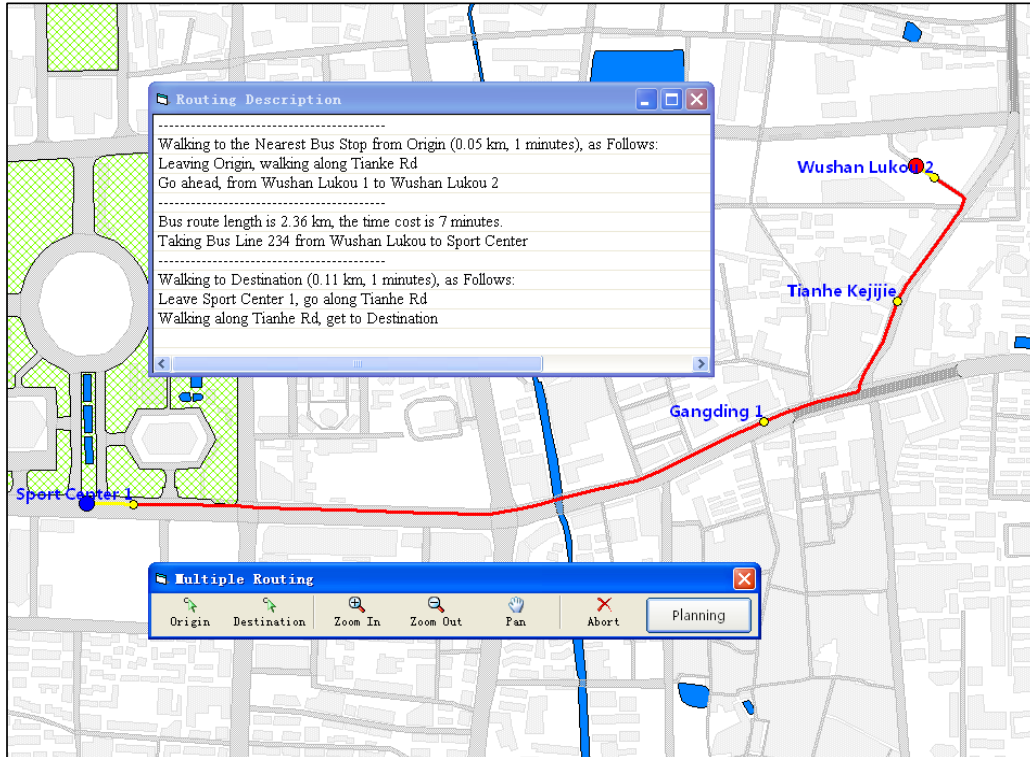
● Origin ● Destination

Figure 4.22 Validation of origin and destination

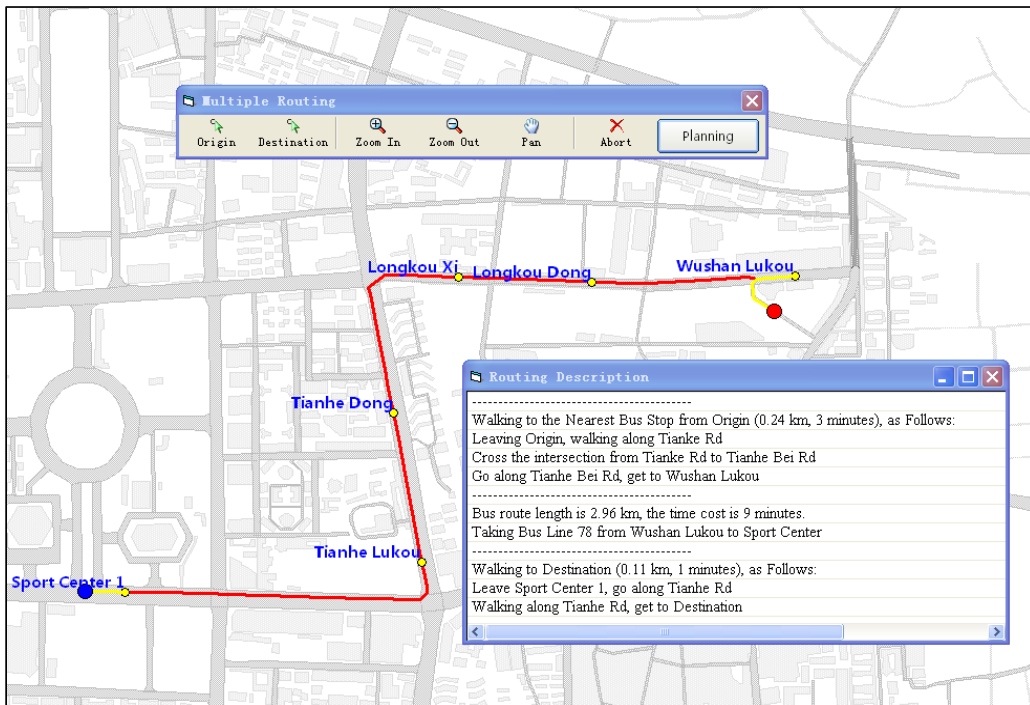
Bus Mode:							
Bus R...	Fare (...)	Stop ...	Bus Route Length	Walking Path Len...	Whole Path Len...	Time (Minute)	
234	2	2	2.36 km	.28 km	2.64 km	10	
22	2	2	2.36 km	.28 km	2.64 km	10	
78	2	4	2.96 km	.35 km	3.31 km	13	
Metro Mode:							
Metro Route	Fare (...)	Stop ...	Metro Route Len...	Walking Path Len...	Whole Path Length	Time (Minute)	
Metro Line 3	3.00	3	3.03 km	0.45 km	3.48 km	8.4	

Figure 4.23 Resulting information of path finding

In this routing scenario, the through transportation possibility with minimizing travelling time (about 10 minutes) includes two bus routes, i.e., Bus Line 234 and Bus Line 22, as compared with the other possibility which needs to take about 13 minutes to reach the destination, i.e., Bus Line 78. The resulting routes with minimizing travelling time also present the least travelling distance (2,64 km), shortest-walking path (0,28 km) and least number of stops (the value is 2), as compared with 3,31 km, 0,35 km, and 4 bus stops from the route proposal of Bus Line 78. In comparison with the WMATA Trip Planner, moreover, route proposals can be returned using different forms: either using textual-based instruction forms or using a map presentation that outlines the resulting route (Figure 4.24). The resulting information also presents a route proposal based on the metro mode, as shown in Figure 4.25. With a comparison of the bus- and metro-based through transportation opportunities, regarding the expectation of minimizing travelling time, the metro-based route proposal is more competitive, i.e., about 8,4 minutes. However, this alternative route proposal needs a longer distance of waking (about 0.45 km), and is more expensive.



(a) Route proposal by riding Bus Line 234



(b) Route proposal by riding Bus Line 78

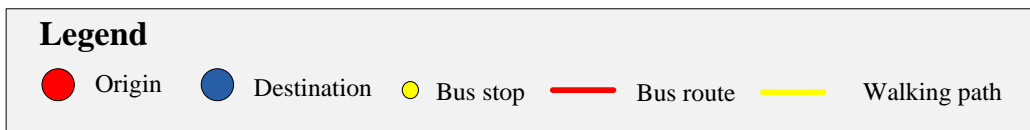


Figure 4.24 Example of bus-based travel planning

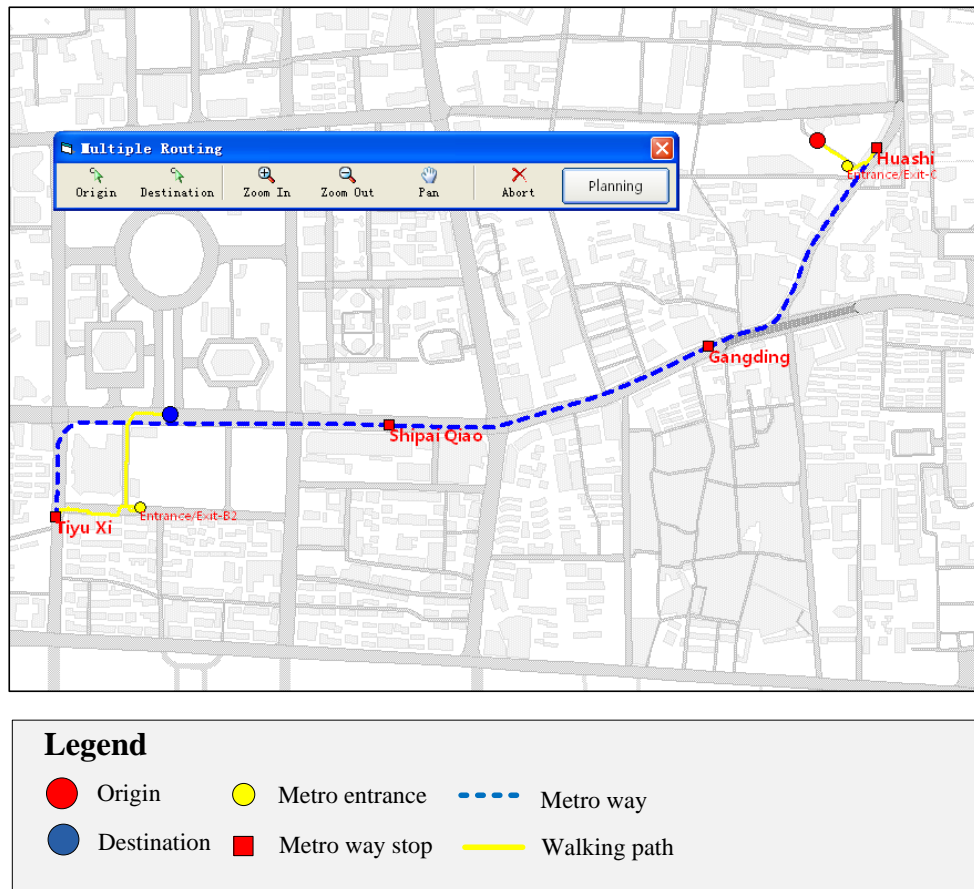


Figure 4.25 Route proposal by riding metro

In some cases of public transportation routing, the trip between an origin and a destination is supported by transfer of bus routes, or of multiple modes. Figure 4.26 illustrates a trip planning that involves a transfer between two bus routes. Bus stop Tianhe Dong represents a transferring site where commuters can change other routes to the destination without walking cost. Furthermore, Figure 4.27 illustrates a case of multi-modal transfer that presents a multi-modal route composed of walking paths, bus routes and metro ways. This routing scenario presents a multi-modal trip planning to reach the destination from the origin with minimizing travelling time, by riding a metro way, and exiting the metro mode, then walking to board a bus route, finally exiting the bus mode and walking to the destination. Instructions of the trip planning are also represented using graph-based and textural-based forms, as shown in Figure 4.27.

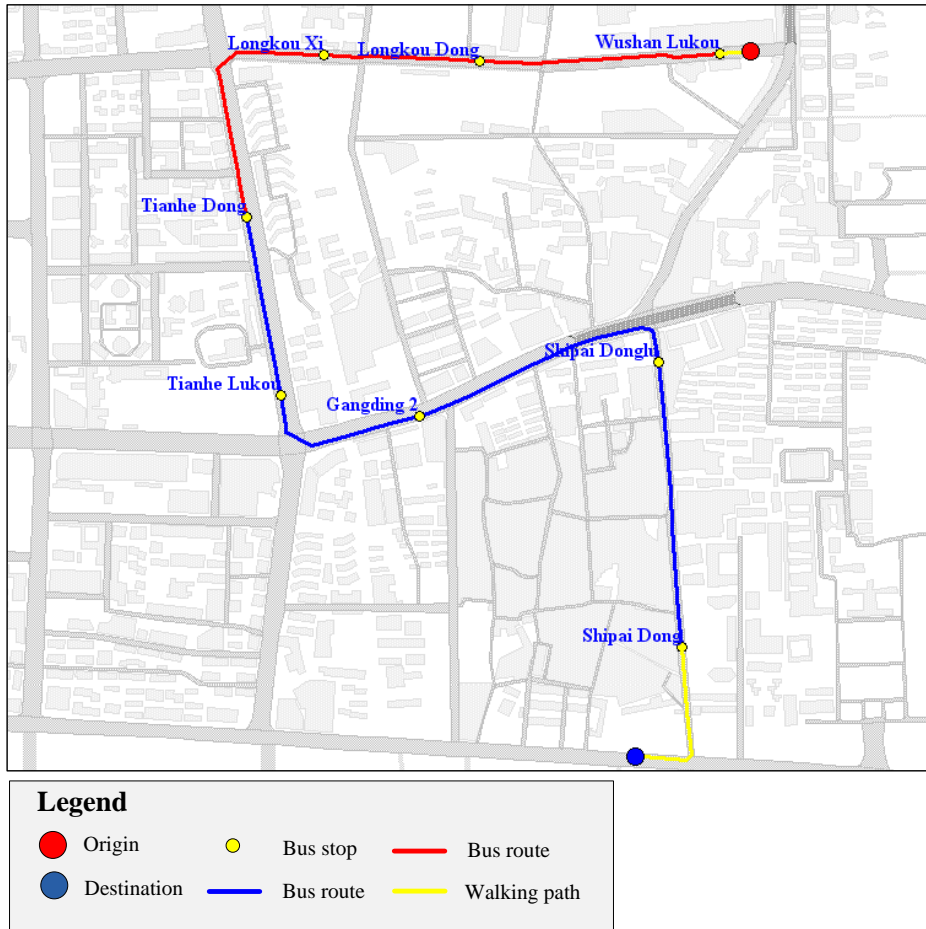


Figure 4.26 Transfer between bus routes

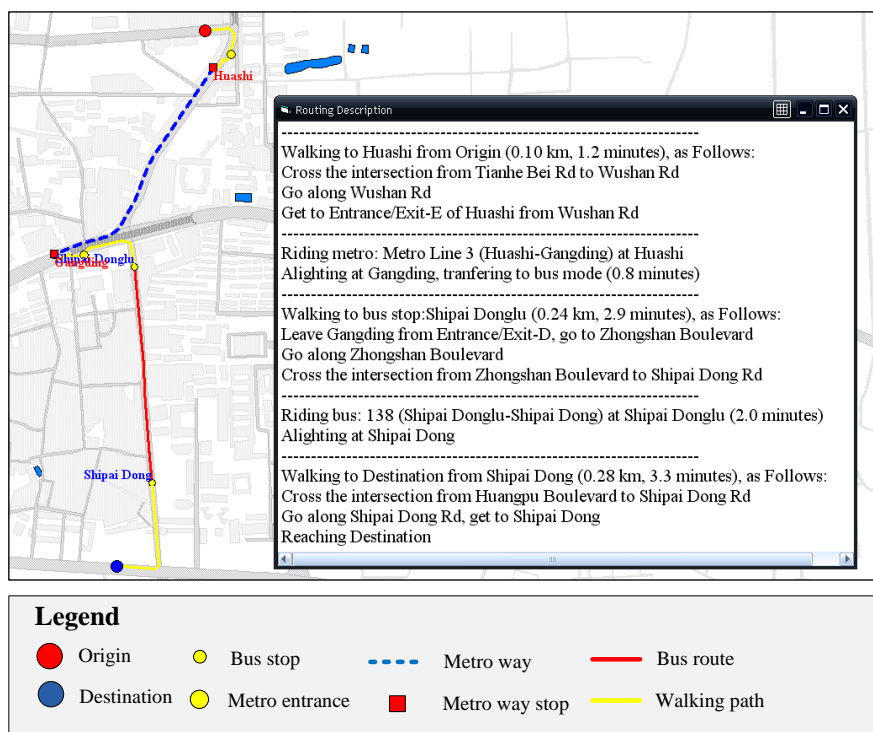


Figure 4.27 Transfer between bus and metro modes

The routing applications outlined above contain single or multi-modal routes in operation. A trip planning usually occurs according to different commuters' expectations reflected by the selected routing criteria. This implies that route proposals are generated according to the selected routing criteria in trip planning, when necessary, by considering the schedules of the routes involved. The resulting routes are generally referred to as an optimal-path question that helps to increase travel efficiency. Such a result is usually a multi-criteria and compromised proposal, such as a faster but not expensive route. In short, routing applications outlined above deal with the question of optimal path identification in the context of multi-modal transportation networks, as the decision support system validated in the prototype provides different answers (route proposals) to commuters to identify an appropriate route which is responding to his/her expectations. This also demonstrates that the transportation GIS data model can favour the objective of optimal path finding, and the validated multi-modal and multi-criteria trip planning can be adapted to support the connectivity analysis of transportation networks.

4.4.5 Transportation network data analysis

The implemented prototype system also provides a decision support system for urban planners and decision-makers. This is crucial to facilitate planning and management of transportation networks. Experiments of service coverage derived from a given radius have presented the way to evaluate the accessibility to public transportation modes. Trip planning reflects the connectivity of transportation networks. In particular, routing applications are dedicated to multi-modal and multi-criteria trip planning which can be a statistical function to evaluate the traffic connectivity of a set of origins and destinations, named as "OD". In this case, while a bus stop is defined as an origin, other bus stops (100 in all) are represented as the destinations. This generates 100 pairs of OD (that is from a bus stop to a bus stop, respectively). The statistics include the diversity of OD trips utilising single- or multi-modal transportation modes supported by the routing model. Figure 4.28(a) uses a large area of the district of Tianhe to illustrate the spatial distributions of the destinations (named as through-destination stops) that can be reached by a through bus route, from an origin stop. The service coverage areas of the through-destination stops can be compared to destinations that require transfers. Figure 4.28(b) presents the spatial distributes of the transfer destination stops. This information allows evaluation of traffic connectivity between stops. Moreover, as observed in the spatial distributions of through- and transferring-trips adjustments (oriented to the origin) can be made to compare with route planning scenarios and suggestions. This helps to optimize the connectivity of stops, thereby facilitating any needed re-engineering of the spatial structure of the current transit network. This comparison can continue by considering the transportation opportunities associated with transfers between bus and metro modes, as shown in Figure 4.28(c). This information also acts as a key measurement to evaluate the coordination between bus mode and metro mode. A combination of the diversity of OD trips can be generated (Figure 4.28(d)). A system interface is also developed to identify an origin stop, and provide a textural-based form to present the statistics of connectivity information, as shown in Figure 4.29.

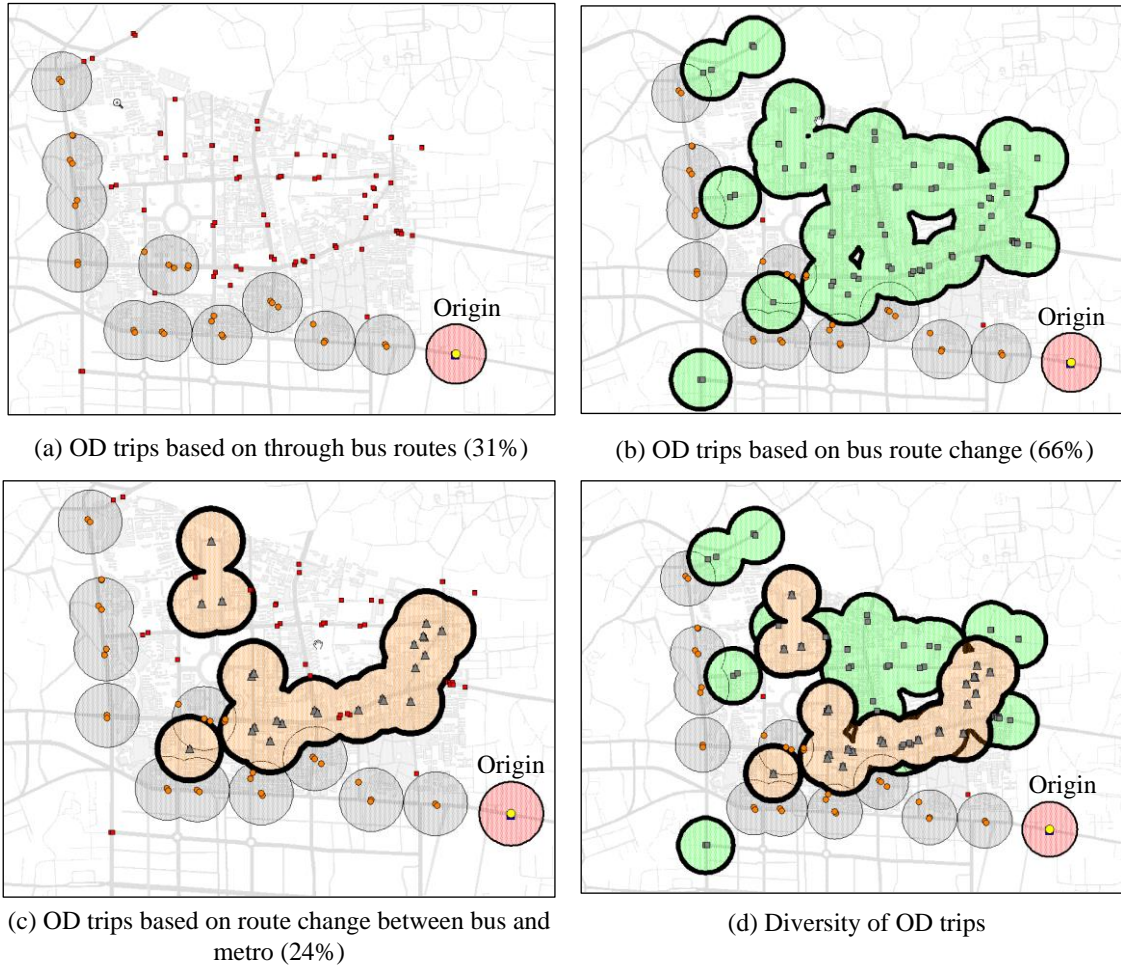


Figure 4.28 Statistics of OD trips based on a same origin

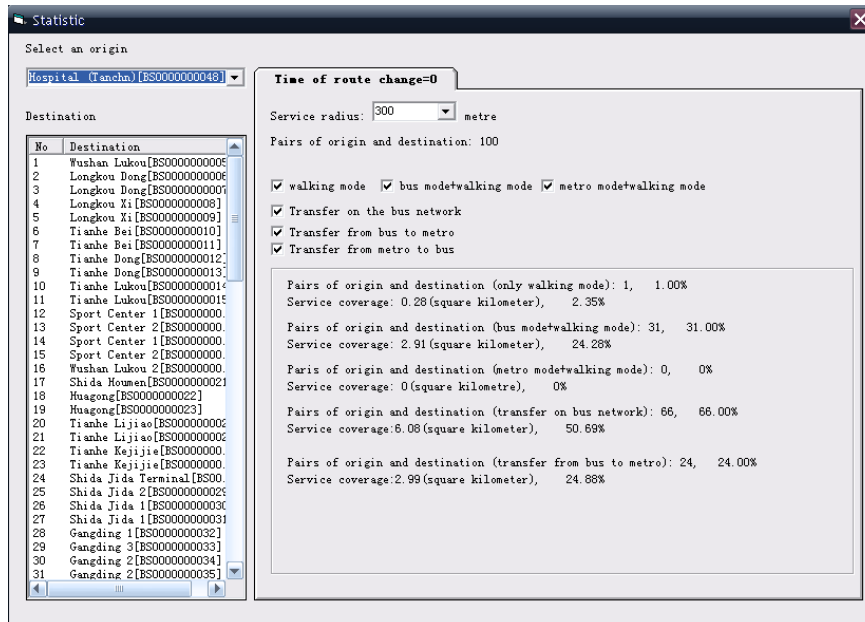


Figure 4.29 System interface for the statistics of OD trips

In addition, the assignment of bus passengers to routes produces forecasted route bus flows which can be compared with existing patterns on the transportation network. The model also facilitates the analysis of existing bus route flows on each road segment in both directions, as individual bus routes are referenced to directed carriage way centre lines of road segments. Bus route flows on each directed carriage way indicate the current situation of public transportation services. Regarding a user's request, a system generated bus route volume could be compared to bus service conditions, particularly with respect to the spatial distribution of the current transportation patterns, and their intensity. This information also acts as another way of evaluating travel demands. Moreover, by comparing common suggested routes with existing bus route flows, refinements can be made with respect to route scenarios and suggestions regarding the re-engineering of the structure of the current transit network. For instance, Figure 4.30 illustrates a heavy concentration of bus routes in a street corridor (i.e., Tianhe Road) in the centre of Tianhe District. This indicates that current bus route volume of Tianhe Road is under heavy pressure, and thus not as a good candidate to be part of a commuter's multi-modal route plan, and that it also needs to be considered in future transportation planning studies.

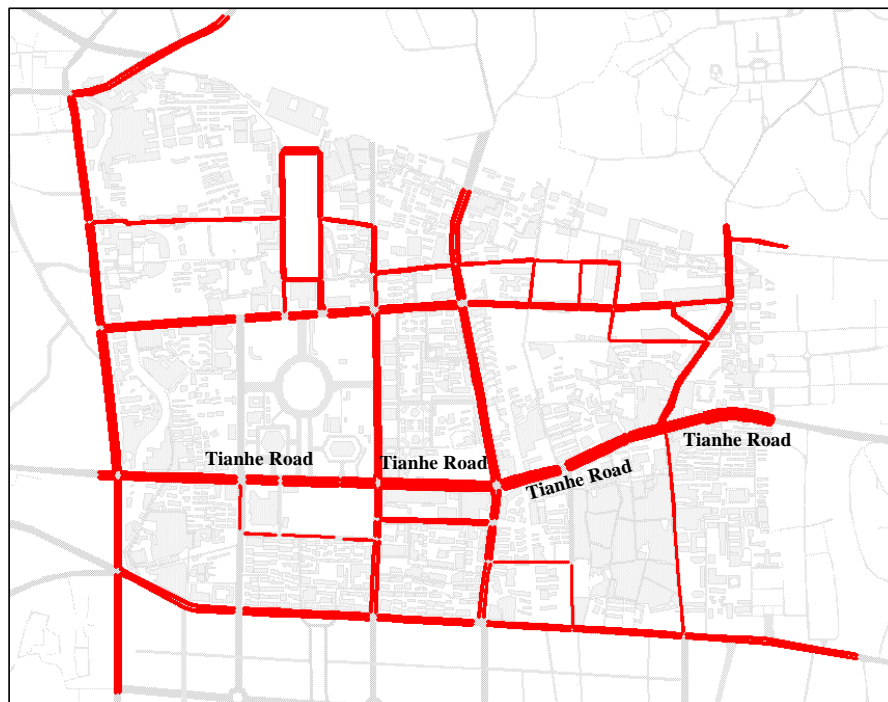


Figure 4.30 Directional bus route volumes along road segments

Traffic survey information, including traffic flow data should be also compared with the current patterns of the street network. As the collection of traffic flow is not involved in this study, the data is collected from the surveys conducted by different transportation organizations of the city of Guangzhou. Traffic flow data are obtained from the Guangzhou Municipal Technology Development Corp. As the transportation GIS data model involves the modelling and representation of directed carriageway centreline network, the data structure designed facilitates the representation of directional traffic flow. The prototype system can be developed to generate directional traffic flow volume with respect to the spatial distribution of the carriageway centreline network, and their intensity, as shown in Figure 4.31. As observed in comparison with bus route volume reflects personal and public transportation demands, and presents the current urban traffic environment. This information can help the planners to optimize the patterns of public transportation

networks, in order to reduce the frequency of traffic congestions, and increase the average speed of bus.

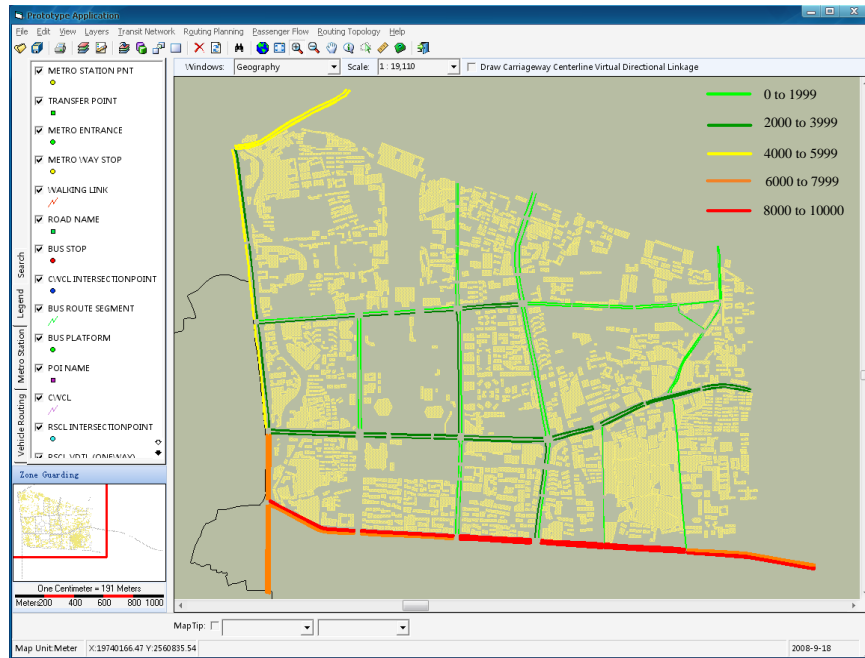


Figure 4.31 Traffic flow characteristics in the centre of Tianhe District

4.6 Discussion

Transportation sustainable development entails the need of efficient multi-modal transportation information applications and services. This implies an adapted transportation GIS to provide multi-modal GIS-T applications. Table 4.3 illustrates a summary comparison of transportation GIS applications and data representation in the prototype and the existing Guangzhou public transportation GIS. The new scheme of the prototype system is based on phenomena that exist in the large transit-oriented city of Guangzhou. It meets the objectives to integrate different modal transportation data as a federated system, and implement multi-level data representations and multi-modal GIS-T services.

The multi-modal and multi-scale transportation GIS prototype developed so far provides several functions and evaluations, such as multiple data representations, shortest-path identification, service coverage, multi-modal trip planning and transportation network aided analysis. In comparison with the applications and services provided by the existing Guangzhou public transportation GIS, the functionalities of the prototype system are adapted and extended to implement multi-modal GIS applications. The prototype is retained for a decision support system that can produce reasonable outcomes for travel planning by end-users, and for network analysis and planning by planners. The functionalities and evaluations outlined above represent the principles of the transportation GIS data model and their applications in a multi-user computer environment. In short, the implemented approach and system provides several levels of services: a decision-aided system for urban planners and decision-makers, and a flexible

interface for multi-route planning at the end-user level. Table 4.4 illustrates a comparison of the functions provided by the transportation GIS prototype and the existing public transportation GIS of the city of Guangzhou.

However, multi-modal topological structures require consistent updates to maintain the consistency of topological relationships between transportation objects. For example, when data (involving traffic controls or spatial information) of a road segment changes, contents of the related routes need to be also updated. Furthermore, multi-modal transportation GIS takes into account different transportation modes which should be always performed into the system during operation, which may require more system resources than a stand-alone but less integrated transportation GIS.

A PROTOTYPE FOR MULTI-MODAL TRANSPORTATION GIS

Transportation network System	Road network			Bus transit network				Metro transit network
	Road segment centre line	Carriageway centre line	Turning restriction	Single stop representation	Individual stop site representation	Directed bus route		
						Along road segment centre lines	Along carriageway centre lines	
Multi-modal urban transportation GIS	•	•	•	•	•		•	•
Guangzhou public transportation GIS	•			•		•		

Table 4.3 Comparison of transportation network representation introduced by the prototype and existing Guangzhou public transportation GIS

Application & Service System	Routing		Service coverage			Network analysis			
	Multiple routes planning	Single-route planning	Based on individual stop sites	Based on single stop	Multi-modal service coverage	Statistics of multi-modal OD Trips (traffic connectivity analysis)	Bus route volume attached to directional carriageway centrelines	Survey data integration	
								Attached to directional carriageway centrelines	Attached to road segment centrelines
Multi-modal urban transportation GIS	•	•	•	•	•	•	•	•	
Guangzhou public transportation GIS		•		•					•

Table 4.4 Comparison of applications and services provided by the prototype and existing Guangzhou public transportation GIS

Chapter 5

CONCLUSION

5.1 Research purpose

The constant growth of urban transportation has largely impacted on the economy, society and environment. Urban transportation development in particular reflects socio-economic growth, as it increases motorized mobility, and is expected to improve quality of life. However, urban transportation development generates serious problems, including air pollution, traffic congestion, energy consumption, noise and deterioration of the natural environment. The concept of sustainable transportation development has been developed to address these problems, and has become a key factor in the planning of modern cities. Sustainable urban transportation policy is closely related to the improvement of the quality of life in a city, including ecological, cultural, political, institutional, social and economic components, without leaving a burden on the future generations. This implies a crucial issue that needs to be dealt with is to balance the conflicting challenges to promote the efficiency of urban transportation systems while reducing their negative impacts.

One approach to this issue by transportation planners and decision-makers involves considering multi-modal urban transportation strategies. A multi-modal or inter-modal urban transportation system can be defined as the use of two or more modes involved in the movement of people or goods from origin to destination. Large cities around the world, such as London, Paris, New York City, Tokyo and Hong Kong, have developed multi-modal urban transportation systems that usually involve bus, metro, light rail and tram. In these cities, the main objective of urban transportation units is not only to design, build, manage, and extend transportation networks, but also to emphasize the achievement of high-level accessibility to, and interaction between, these transportation systems, taking into account the value and quality of services provided to their inhabitants. Experience in these cities shows that the quality of multi-modal urban transportation networks is not determined just by the availability of the main transportation modes, but also by accessibility to, and interaction between, different modes and services. This implies that new planning methods and approaches are needed to support the development and planning of multi-modal urban transportation systems.

In particular, this brings forward the role of integrated information systems which can provide decision-makers, planners and end-users with the appropriate information at the right time. Therefore, the general research purposes of this research presented in this thesis can be concluded as follows:

- Different urban transportation modes, either private or public, have different network systems which have complex spatial and traffic connectivity and spatio-temporal properties. Moreover, the multiple transportation network systems are interconnected with multiple topology relationships resulted from not only spatial and traffic connectivity, but also temporal connectivity. This implies that a multi-modal transportation GIS data model is needed to explicitly and effectively integrate and represent the topology relationships of multiple transportation objects and networks.
- Different users' needs reflect different requirements to transportation applications which usually require multiple data representations at different levels of granularities. This presents an important topic in the transportation data modelling to implement multi-scale transportation data representations, and to maintain the consistency of multiple topology relationships, thereby facilitating the incorporation of transportation applications and users' needs.

Although much work has been achieved in the transportation data modelling, the research purposes outlined above still presents many efforts which need to be emphasized on the modelling of a multi-scale and multi-modal transportation geographical information system (GIS). One approach to deal with these efforts is to introduce novel modelling principles and concepts to design and develop an adapted transportation GIS for meeting the research purposes. This implies to the contribution of the research, which is presented in the following section.

5.2 Contribution

The study presented in this thesis introduced a multi-scale and multi-modal transportation GIS data model. The designing and development of the model are incorporated in the conceptual object and logical topology modelling. In the model, transportation networks are involved in different transportation modes, either public or private, and are integrated as a federated system. Furthermore, the model implements multiple spatial data representations, taking into account the representation of multiple properties of transportation data, and the maintaining and representation of multiple connectivity, including spatial, traffic and temporal topology relationships. Therefore, the model can facilitate the development of specialised tools for integrating transportation data, and favours topology- and time-based analysis. On top of the principles and concepts provided by the data model, a multi-modal transportation GIS is accomplished. The experiments are carried out in the prototype, and are applied in the urban transportation system of the city of Guangzhou to demonstrate the transportation GIS data model designed.

In the modelling of a multi-scale and multi-modal transportation GIS, a framework based on the application of GIS-T approach is investigated and proposed. The modelling framework retains a visual object-oriented modelling system, i.e., the unified modelling languages (UML). Although an integration of plug-in for visual languages (PVL) and UML has laid out the fundamental to support GIS data modelling, it is not oriented to the modelling of transportation GIS data. Therefore, one contribution made are dedicated to

an integration of UML and PVL, and particularly to adapt and extend the UML-and PVL-based constructs (semantics) to accommodate object-oriented modelling of transportation data and relationships in a GIS environment. This contributes to facilitate visual object-oriented modelling of multiple properties, spatio-temporal data structure, multiple representations and topology relationships in the context of multi-modal transportation networks.

The study of the modelling framework presents some important perspectives which should be explicitly defined to facilitate the modelling of a multi-modal and multi-scale transportation GIS. These perspectives present the transportation GIS modelling concepts and principles. The study emphasizes on the achievement of conceptual object modelling and logical topology modelling in the context of multi-modal transportation networks. The conceptual transportation object model and network topology data model are incorporated in an essential GIS-T model to meet the need of multiple transportation modes. In particular, the adapted transportation GIS model supports multi-modal transportation GIS applications taking into consideration multiple topology relationships of transportation objects. In short, the important principles and concepts of the modelling of a multi-modal and multi-scale transportation GIS can be concluded as follows:

- At the conceptual levels, transportation objects are considered as the conceptuality of physical features from a “real-world” point of view. The conceptual object modelling of transportation data provides a conceptual view complemented by geographical and temporal views which reflect the spatio-temporal data structures of transportation systems.
- Temporal properties are resulted from the behavioural changes of transportation objects in space. This implies that besides spatial object category transportation data can be organized into temporal and spatio-temporal objects categories. In the transportation spatio-temporal data modelling, various temporal connections between objects are represented as temporal relationship objects. This favours the representation of the behaviour states of transportation dynamic objects and activities which are represented as events and evolutions. Using the temporal concepts and principles of temporal relationship identifications, the behavioural changes of transportation objects can be indicated explicitly.
- From a traffic perspective, different transportation networks rely on existing transportation infrastructure which encompass different restrictions and rules, and incorporate with the need of multiple transportation modes. Although spatial connectivity is the preliminary topology of transportation networks, traffic connectivity presents the core of the topology structure. An integrated topology structure is retained for the representation of multiple transportation modes in the urban areas. The topology model promotes the multi-modal transportation GIS applications to meet the need of multiple transportation modes. In particular, the model lay out the fundamental to support and implement the full range of algorithms and services of multi-modal trip planning, thereby facilitating networks planning and information services.

The prototype system developed implements the research objective which is to provide several levels of multi-modal transportation GIS services: (1) a decision support system for urban planners and decision-makers; (2) a flexible interface for multi-modal trip planning for the end users, particularly the commuters. Amongst the applications validated, multi-modal and multi-criteria trip planning is referred to essential transportation GIS applications and services, and presents an important contribution of the research. The routing model approaches the issue of optimal-path finding based on the integrated topology data structure of multi-modal transportation networks.

Furthermore, it promotes all of GIS applications which involve the use of path identification for some aspect of transportation network analysis. This emphasizes on the evaluation of the accessibility to transportation modes, interaction between different transportation modes, or spatial distribution and connectivity of transportation objects and networks. Routing experiments made significantly demonstrate that the multi-modal transportation GIS services validated in the prototype beyond the functionality carried out by the existing Guangzhou public transportation GIS in the city of Guangzhou. Furthermore, the multi-modal transportation GIS application scenarios are dedicated to a decision support system by generating more reasonable outcomes for making decisions on trip planning at the end-user level, and facilitating transportation network planning and management at the planner level. This implies that the need of multi-modal transportation modes is addressed.

5.3 Further research

This thesis presents a study of designing and developing of a multi-modal and multi-scale transportation GIS data model. The current work focuses on the integrated and detailed view of multi-modal transportation network modelling and representation. Nevertheless, there are still many issues involved in integrating the GIS-T approach with specific process models, e.g., real-time data models and simulation models used in the dynamic analysis of multiple transportation systems. This does seem to be a very fruitful area for future research that mainly involves three aspects:

A. Integration of real-time transportation data

In urban transportation networks, real-time transportation data (e.g. passenger or traffic flow volumes) may be directly linked to spatial linear features, such as lanes; some are related to the total amount for the whole urban area, such as vehicle speeds and ownership, and total capacity of transportation networks. Another possible data is intermediate data produced by data inference or data summarizing, such as schedules or the probabilities of travel choice from statistical choice models. Real-time transportation data provides a more wide range of traffic information for planners and decision-makers to facilitate strategic urban transportation planning. For instance, evolution of traffic flow volumes for a given time reflects the critical points of particular traffic situations (such as traffic congestions) on the roads. This important information helps to evaluate the transportation infrastructure and public transit facilitators related to the roads, and needs to be promoted in future studies of transportation network planning. Moreover, data from long term, static, predefined public transportation schedules need to be amended with continuous, dynamically determined schedule deviations. The integration of real-time schedules may favour exchange of real-time traffic data for updating the planned schedule information. This implies that such information integrated in the transportation GIS could be intended to inform commuters about currently available services.

B. Application of GIS-T approach to planning scenarios oriented to public transit system development

A number of real-time transportation data inputs are acquired from different transportation actors, including commuters, planners or agencies, and are used to formulate the strategic planning scenario. Application of the GIS-T approach dedicates to allow planners to quickly begin running and testing various planning scenarios. This process should be iterative in that a number of draft scenarios are formulated and compared before the final scenario is derived.

Moreover, the formulation of each of the draft planning scenarios required application of the GIS-T approach to help planners to specify which suitability factors would affect the future development of specific transit networks. This implies the representations for the planners with an intuitive and easy-to-use graphical user interface. This allows alternative transportation planning scenarios to be generated oriented to the development of public transit systems. Also, this enables the planner to easily test out possible alternatives by adjusting “weightings of importance” and rerunning new planning scenarios.

C. Integration of GIS-T approach with simulation models

An integration of the GIS-T approach with simulation models aims to study and examine the changes of network efficiency over time by tracking real-time spatial distribution of network capacity, traffic flow, and congestion. As transportation network planning decisions made at one point of time can have profound impacts in the future, a better understanding of the natural growth pattern of the transportation networks will provide valuable guidance to planners who try to shape the future network. This also helps to analyze the relationships between network supply and travel demand, and describes a network development and degeneration mechanism microscopically at the lane-based or route-based level. In short, with the application of the GIS-T approach, the simulation models may be applied to simulate the topological evolutions of complex multi-modal networks, and examine the changes of network efficiency over time by tracking real-time spatial distribution of transportation network capacity, traffic/passenger flows, or traffic congestions.

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