Data Organization for Routing on the Multi-modal Public Transportation System: A GIS-T Prototype of Hong Kong Island

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ABSTRACT

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Multi-mode based public transportation system is an obvious phenomenon in Hong Kong. However, the twisted routes, thousands of stops, and complicated transfers often confuse passengers in finding their ways in the city. Although information for the public transportation is fairly rich in Hong Kong, it is mostly in a format of text or paper-based map, and these are not good methods of information organization for passengers' convenient use. With the blooming development of GIS and its growing implementing on transportation, GIS applications on Transportation (GIS-T) is considered as a good approach to manage the multi-modal public transportation data. And this thesis is focus on using GIS-T to organize the multi-modal mass transit data of Hong Kong in order to provide public transport information and give suggestions on route finding on such a network for passengers, setting Hong Kong Island as the study area.

Two steps of works are completed to reach the purpose. Since the representation of the multi-modal transportation network is still a difficulty in GIS-T research, designing a data model that can handle the conditions encountered in the multi-modal public transportation system becomes the work of the first step in the thesis. A layer-cake model is used to describe the different contents of a public transportation system. Node/link based model is adopted in representing the transportation network. In the data model, a service network is generated to represent the multi-modal transport service network together with the topologic information, and transfers are defined in the network to record the extra costs when route change happens during the travel. The second step of works is to construct a GIS-T prototype of the study area based on the data model discussed in the thesis. TransCAD, a special software package of GIS-T, is used as the platform of the prototype and some programming works using its developer's kit are done to construct the prototype. The prototype can give shortest path analysis on a pair of origin and destination concerning on different routing criterion, taking the mode information into consideration. Using the prototype, passengers can get suggestions on route selection based on the multi-modal mass transits.

From the implementation of the prototype and the routing results, we can find out that GIS-T is a feasible and effective approach to organize the multi-modal public transportation data in Hong Kong. With the data model designed in the thesis, the GIS-T prototype can provide a convenient access to the public transportation information and reasonable suggestions on route finding for passengers. Such a system is useful to help passengers in understanding and making full advantages of the public traffic service network.

摘　要

多交通模式是香港公共交通系統的特徵。然而，複雜的公交綫路常使乘客迷失方向。雖然香港有相當豐富的公共交通信息，但絕大部分的信息是以文字或紙制地圖的形式存在，而這些信息組織方式並不利於乘客得到所需要的信息。隨著地理信息系統的快速發展及其在交通方面應用的蓬勃興起，更多人認爲交通地理信息系統是一種組織多交通模式公交系統信息的有效方式。本文將以香港島作爲研究區域，致力於運用交通地理信息系統來組織香港多交通模式下的公交信息，用來向乘客提供獲取香港公交信息的有效途徑以及多交通模式下路徑選擇的合理建議。

首先，本文設計了一個能用於處理多交通模式下的公交系統所遇情形的數據模型。在數據模型中，一個基於節點和弧段的公交服務網絡被用來表達多交通模式下的公共交通網絡及其拓撲關係。網絡中一些被定義成爲轉乘點的節點記錄了乘坐公交系統出行時，在綫路轉換過程中所產生的額外費用。根據所設計的數據模型，作者建立起一個交通地理信息系統原型，用於向乘客提供研究區域內的公交信息以及根據不同的規則進行最短路徑搜尋。由於在路徑搜尋過程中考慮到了不同交通模式及綫路的因素，因此，得到的結果更爲合理。

原型系統的實現以及路徑搜尋的結果證明，交通地理信息系統是對香港多交通模式下的公交信息進行組織的一種可行及有效的途徑。

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CHAPTER I

INTRODUCTION

1.1 Problem Statement

Travel is an indispensable activity in human being's daily life. Going to work place, back home, doing shopping, visiting a tourist place, all these activities cannot be separated from travel. In an urban area, roads extend in all directions and form a powerful network that connects every corner of the city. Over the well-connected transportation network, powerful public transportation services are provided in many cities to assist people in moving around the city. Such a well-built mass traffic network provides a cheap and convenient way for people's travel. However, the complicated service network appears as a maze in front of passengers. Passengers, especially new comers and tourists for the city, are likely to have difficulties in finding their way out. Passengers may often find out that they have lost their directions at transfers or confused by the twisted bus routes network. Some efforts should be done to help passengers out of such troubles.

Hong Kong is a modern metropolitan in southern China. It has built up a powerful transportation infrastructure system covering a broad area of its territory. By the end of year 1999, Hong Kong has 1,885 kilometers constructed road distributed on Hong Kong Island, Kowloon, New Territories, and other islands. Also, more than 160 kilometers track, including railway and tramway, and water routes are in use at present (Transportation Department of Hong Kong SAR, 2000). In order to protect the environment and alleviate the air pollution, Hong Kong government advocates people using public transportation services instead of private cars for travel. Over the transportation infrastructures mentioned above, Hong Kong has built up a powerful public transportation service system based on multiple traffic modes and operated by different companies. Hundreds of service routes are served by different traffic modes, including bus, subway, train, ferry, and tram (see Table 1.1). Nearly every built-up area is served by at least one public traffic route. At some important subway stations, such as Admiralty and Central, over thirty public traffic routes served by different modes connect to them. In such a multi-modal public transportation system, when passengers go out of their home, they will encounter dozens of twisted service routes, thousands of stops distributed along the streets, and hundreds of interchange stops converging multi-modal service routes. Facing so many choices, passengers, especially those new comers and tourists to Hong Kong, can hardly choose the right routes to get to their destinations. Even those people who have been living in Hong Kong for a long time may be only familiar with a few routes that they ride frequently. When talking to visit a new place, they also have difficulties in finding the right route. Is there not enough information for passengers to make their decision? The answer is 'no'. Quit accurate base maps of Hong Kong territory can be reached from Hong Kong government in both paper and digit formats, and fairly complete public transport information can be accessed from mass transit service companies or transportation directory books. However, most public transport information only exists in text or paper-based map. Paper-based maps cannot hold all public traffic routes together with their information for their limited space, and text-based information are rather ambiguous in showing spatial information without the support of maps. Organized in these methods, information required by passengers is either lost in the mess of all kinds of annotations or not enough for route decision. Therefore, it is necessary to set up a new way of data organization to integrate and handle the spatial and non-spatial information of multi-mode-based public traffic routes together, and to provide the information in a clear way to help passengers choose the reasonable routes for their travels.

Table 1.1 Main public transportation services in Hong Kong

Traffic Mode		**Operator**	**Service**
Railway	Mass Transit Railway (MTR)	Mass Transit Railway Corporation	5 routes (total 77.2km): Kwun Tong Line; Tsuen Wan Line; Island Line; Tung Chung Line; Airport Express Line.
	Kowloon-Canton (East Rail), KCR	Kowloon-Canton Railway Corporation	1 route (total 34km): Hom Hung ↔ Lo Wu.
	Light Transit Rail	Kowloon-Canton Railway Corporation	Total length: 31.75km serving Tuen Mun and Yuen Long new towns.
Bus		Citybus Limited	Total 108 routes: 65 in Hong Kong Island; 26 cross-harbour routes; 16 Tung Chung/Airport routes.
		New World First Bus Services Limited	Total 93 routes: 61 routes in Hong Kong Island; 32 cross-harbour routes.
		Kowloon Motor Bus Company Limited	Total 446 routes: 385 routes in Kowloon and New Territories; 61 cross-harbour routes.
		Long Win Bus Company Limited	15 routes to north Lantao and Airport.
		New Lantao Bus Company Limited	18 routes on Lantao Island.
Tram		Hong Kong Tramways Limited	A 16km track: 8 routes along the north shore of Hong Kong Island.
Peak Tram		Peak Tramways Company Limited	A 1.4km line: Central ↔ the Peak.
Ferries		14 ferry operators	32 regular routes to: Outlying islands; New towns in the north-western New Territories; Across the Harbour.

Data source: Transportation Department of Hong Kong SAR (2000)

Geographic Information System (GIS), which has special power on spatial data handling, is growing rapidly since its appearing in the early of 1960s (Clarke, 1997; Foresman, 1998). It has been widely adopted in many fields, helping people deal with problems relating to space and place (Kosters, Pagel, & Six, 1997; Openshaw, 1998; Zeiler, 1999). In GIS, attributes of ground features can be easily joined into their spatial information and the latter can be used in analysis concerning space and location. There is a branch of GIS implementations focusing on transportation, which is now recognized as GIS-T (GIS application for Transportation). Vivid examples of using GIS on transportation are given by Lang (1999). In GIS-T, transportation features, such as roads, railways, intersections, and stations, are abstracted into lines, points, sometime polygons, which finally compose a network that can be easily handled by computer system. By representing transportation system in the real world with link/node based network, GIS-T includes network analysis and transportation models to help people navigate in the transportation network or make transportation planning (Sarkozy, 1997; Shaw, 1997). Furthermore, with a user-friendly interface, GIS-T can play a role as an efficient and effective disseminator of transportation information (Dewar, Fenno, Garvey, Kuhn, Roberts, Schieber, Vincent, Yang, & Yim, 2000; Western & Ran, 2000). Some efforts by Azar, Grayson, Hancock, and Knonz (Koncz & Greenfeld, 1995) and Peng (1996) in the USA, and Ho (Ho & Parthiphan, 1998) in Singapore, have been made to provide mass transits information to the public using GIS. Also, such a capability of GIS has been noticed by Hong Kong government, and a strategy of using GIS to manage transportation data comes into forming in the Transport Department of Hong Kong (Leung, 1999). Furthermore, based on graph theory, GIS-T provides a basic and important function for transportation – shortest path analysis.

It can help passengers find a shortest path on the network in terms of the weights defined to links. With the help of GIS-T, spatial information and service information of public transportation system can be readily integrated and, further more, the information can be used by passengers in making a path choice. Many works have been done contributing to the representation of transportation networks (Miller, Storm, & Bowen, 1995; Goodchild, 1998; Lu, 1999). However, 'few efforts have been made to create database combining different modes, but these would be essential for multi-modal routing' (Goodchild, 1999b, p.5). The public transportation network of Hong Kong is also multi-mode based. Moreover, there are no projects using GIS to organize the data of such a network in Hong Kong. It is a big challenge to organize Hong Kong multi-modal mass transits information with GIS-T in order to help passengers choose shortest routes on the network. In this paper, attempts are made to give a solution to the problem in Hong Kong.

1.2 Research Purpose

There are two main goals to be reached in this research. In order to meet the request for routing on the multi-modal public transportation network, mass transit data need to be organized by GIS-T with a proper data model. As there is no proper and standard data model for the representation of such a network, modeling the multi-modal public transportation system becomes the first goal of this research. The second goal is to construct a GIS-T prototype with the data model to help passengers find shortest path on the mass transit network in Hong Kong, using Hong Kong Island as the study area.

According to the reviews on the former researches and applications of GIS-T, it can be found that representation of the multi-modal transportation system is still a tough problem in the research of GIS, although some researchers are attempting to make a breakthrough on it recently (UNETRANS, 2000). In this research, in order to assist passengers to find shortest routes on the multi-modal mass transit service network, a conceptual data model is introduced with the attempt to represent the route service network combined with various traffic modes. The conceptual data model not only deals with the basic attributes of route service network provided by multiple traffic modes, but also handles the extra information and factors happened at transfers. With the extra information for transfers organized in the traffic service network, the data model is able to take these factors into consideration when searching the shortest path on the multi-mode based network for passengers.

Based on the data model designed for the public transportation system, a GIS-T prototype for the mass transit system on Hong Kong Island is built up using TransCAD, a powerful software package for GIS-T, to test the feasibility of the data model and to provide an interactive way for passengers to get transport service information and route choice suggestions. Dispersed information for public transportation service on Hong Kong Island are collected from different sources, such as road central line data in the Land Department, bus routes information in bus service companies. All the collected data are organized under the framework of the data model discussed in the thesis. Part of the public transportation service routes, including the multi-modal information, on Hong Kong Island are included to construct a prototype system of GIS-T. Further on, the prototype is used to make shortest path analysis to assist passengers in finding reasonable routes.

1.3 Significance

At first, this paper attempts to find a new approach to deal with the multi-modal public transportation information using GIS. Currently, representation of the multi-modal transportation system in GIS is still a difficulty to be overcome. Many scholars are making their efforts studying on this topic (Peterson, 2000; UNETRANS, 2000). A public transportation system is a subset of a transportation system, and it also involves the situation of multiple traffic modes. This paper attempts to introduce a data model that can organize the multi-modal mass transit service information using state-of-the-art techniques and methods of GIS, and be suitable for making shortest path analysis on such a multi-mode-based network.

Secondly, this paper provides some experience on constructing a GIS-T for the multi-modal mass transit system. Using Hong Kong Island as the study area and TransCAD as the tool to construct a GIS-T prototype to handle spatial information of transportation system, this paper describes the procedures of building a database for the multi-mode-based public transport service network, from data collection, data processing, data organization, till the construction of the prototype.

Finally, a GIS-T prototype for the public transportation system on Hong Kong Island is developed to help passengers in route finding. By collecting the basic geographic data from the Land Department of Hong Kong SAR government and public transport service information from mass traffic service companies, using the data model discussed in the paper to organize and manage the data, a prototype is constructed. It can provide passengers with recommendations on route selection. Because taking the transfer information into the consideration for shortest path analysis, it can help passengers find reasonable shortest paths for traveling on the multi-modal public transit service network of Hong Kong Island in various criteria, such as time, fare, and route change. It can help passengers get a better understanding of the complicated public transportation system and, moreover, take further advantages of the service.

1.4 Methodology

To construct a GIS, like any information system, a series of steps should be completed. Following an elaborated process for GIS design, efforts are made on modeling the multi-modal public transportation system. Based on the data model designed, a prototype of GIS-T is built up for the mass transit system on Hong Kong Island to assist passengers to search the reasonable route for traveling.

Elaborated from common processes for information system design, five steps are completed for GIS design (Worboys, 1995): define application domain, represent the interested phenomena in application domain model, set up the conceptual model based on system analysis, develop the logical model and, finally, the physical model that can be implemented on a computer system. In this paper, modeling for the multi-modal public transportation system is processed in these steps. After the application domain – multi-modal public transportation system – is defined, network data model is adopted as the application domain model to represent the transportation network abstracted from real world, and a layer-cake based GIS model is used to organize different layers of the public transportation information. At the stage of conceptual model design, node/link based network model is adopted to construct the topology information for the network. Then, relevant logical and physical implementation is discussed according to the conceptual model.

In data modeling process, Entity Relationship (E/R) diagram is used to assist the model design of the multi-modal public transportation system due to its clear interpretation on entities and their relationships, especially in conceptual modeling and logical modeling stages.

In shortest path analysis, Dijkstra's algorithm is used for routing on the multi-modal public transportation system due to its satisfied performance on dealing with single-source shortest-path problems. In order to consider the multi-modal information for routing, extra costs that happen at transfers are joined into the calculation of shortest path analysis.

1.5 Outline of the Thesis

This paper is composed with six chapters. The coming five chapters are going to talk about the literature review on GIS-T, data modeling for the multi-modal public transportation system, data preparation for the study area, implementation of prototype GIS-T for routing on the multi-modal mass transit network of Hong Kong Island, and conclusions achieved in this research.

In Chapter II, brief history of GIS and development of GIS-T are introduced at the beginning. Data models and techniques used in a GIS-T are discussed in the following part. Then current research on data model for the multi-modal transportation system and popular GIS-T software packages are introduced. Based on the review, the significant of research on data model for routing on the multi-modal public transportation network is pointed out at the end of the chapter.

In Chapter III, data modeling for the multi-modal public transportation system is discussed in detail following the five stages for GIS design mentioned by Worboys. Information of extra costs at transfer is organized in the data model, in order that it can be used for shortest path analysis. Also, routing criteria and algorithm are described in detail for shortest path analysis on such a network.

Chapter IV is going to talk about data preparation for the study area – Hong Kong Island – in the prototype. Basic information about the transportation situation, especially public traffic service, on Hong Kong Island is introduced briefly at the beginning of the chapter. Then, corresponding data preparation for the prototype construction is given in the main part of this chapter, including the data source, data collection, and works on data conversion.

Implementation of a GIS-T prototype for routing on the mass transit system on Hong Kong Island is the main content of Chapter V. Following the data model discussed in Chapter III and data prepared in Chapter IV, the multi-modal public transportation service information of Hong Kong Island is organized in the prototype and ready to help passengers find the shortest path. The generation of the most important layer – service network layer – of the prototype is done at the beginning of this chapter, including the generation of transfers. After the built-up of the prototype, main functions of the system are interpreted in the second part of the chapter and the results for shortest-path routing on the multi-modal mass transit system are illustrated, and compared with the results without consideration of the multi-modal information.

In the last chapter, Chapter VI, research findings are given based on the work of this paper, and the limitations of the research and suggestions for further studies are provided at the end of the chapter.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Geographical Information Systems (GIS) is fairly a new term in the field of geography. But, due to its powerful functions on spatial data handling, it has been rapidly involved in many fields that care about spatial information. Transportation is such a field. And now, a special term, GIS-T, is used to indicate GIS applications for Transportation. In this chapter, brief history about the origin of GIS is described at the beginning, and research backgrounds of this paper are introduced in detail in the following eight parts, concerning the development of GIS-T, its capabilities, structure and main techniques adopted in GIS-T, key routing models on networks, frontiers of research on GIS-T for the multi-modal transportation system, and main GIS-T packages. Finally, a summary on research status is given, and problems to be handled in this paper are pointed out.

2.2 Origin of GIS

Geographical Information Systems now plays an important role in many fields. Clarke (1997) interpreted the four roles of GIS from different aspects. The first role of GIS can be seen from its functional aspect as a set of tools for analyzing spatial data. Many GIS definitions are given according to its functions. The second role of GIS is a special information system which is a database system with specific capabilities for spatially referenced data (Maguire, 1991; Star & Estes, 1990). Also, GIS is considered as a science – GIScience (Goodchild, 1992; Goodchild, 1999a), which was first addressed by Goodchild on the fourth International Symposium on

Spatial Data Handling (Worboys, 1995). And, as a cross-disciplinary research domain (Mark, 1999), which emphasizes more on a scientific aspect (Li & Zhou, 1998), it has been further studied under a project named Varenius (Goodchild, Egenhofer, Kemp, Mark, & Sheppard, 1999). At last, GIS can be regarded as a Multibillion-Dollar Business as it is developing into an information-rich stage. Generally, GIS is defined as computer systems which are designed to handle geo-spatial data, including data capture, storage, management, operation, and display (Aronoff, 1989; Chrisman, Cowen, Fisher, Goodchild, & Mark, 1989).

GIS has become a widely used term nowadays, but it is rather a phenomenon that appeared in the second half of the century (Chrisman et al., 1989; Maguire, 1991). Although some researchers (Clarke, 1997; Demers, 2000; Foresman, 1998) argued that its roots in cartography can be traced back to the emergence of thematic overlay maps in early twentieth century in Europe and North America, it is only four decades since the advent of the term 'geographic information systems'. The exact record of the first use of the term 'geographic information systems' is lost in the sands of time. Goodchild (1999b, p.1) attributed much of the initial impetus to 'the group of graduate students in quantitative geography at the University of Washington in the late 1950s'. In the 1960s, with the sponsor of Canadian government, Dr. Roger Tomlinson led a team to develop the Canadian Geographic Information System (CGIS) (Bernhardsen, 1999; Tomlinson, 1998), which was marked as the milestone of the advent of GIS. Nearly at the same period, some faculty and students led by Howard Fisher at Harvard University's Laboratory for Computer Graphics and Spatial Analysis made some major theoretical contributions and developed and implemented several new systems (Clarke, 1997; Coppock & Rhind, 1991). Also, David P. Bickmore at the Experimental Cartography Unit in the United Kingdom attempted to solve the map updating problem with the help of computer in the early 1960s (Coppock et al., 1991). After the success of Canada Geographic Information System, the term 'geographic information system' became widespread (Foresman, 1998).

With the development of computer technology and decrease of computing cost, digital approach for fast and efficient conduct of operations on spatially referenced data is viable. A mushrooming of GIS packages appeared in the 1980s, such as Arc/Info, IDRISI, and GRASS. Continually in the 1990s, GIS matured as a technology (Clarke, 1997). Today, GIS are widely used in many government, business and private activities, which fall into three major categories (Maguire, Goodchild, & Rhind, 1991; Stefanakis, Vazirgiannis, & Sellis, 1999):

1). Socio-economic applications (e.g. urban and regional planning cadastral registration, archaeology, natural resources, market analysis, ect.) (Clarke & Gaydos, 1998; Hendriks, 1998; Sui, 1998);

2). Environmental applications (e.g. forestry, fire and epidemic control, ect.) (Goodchild, Steyaert, Parks, Johnston, Maidment, Crane, & Glendinning, 1996; Zhang & Quine, 2000);

3). Management applications (e.g. organization of pipeline networks and other services, such as electricity and telephones, real-time navigation for vessels, planes and cars, ect.) (Golledge, Klatzky, Loomis, Speigle, & Tietz, 1998; Xu, 1999).

2.3 Development of GIS-T

Geographic Information Systems in Transportation (GIS-T) is a main branch of GIS applications and dates from the very earliest interest in GIS in the 1960s (Goodchild, 1999b). A fairly completed definition of GIS-T is given by Fletcher (2000): GIS-T are interconnected systems of hardware, software, data, people, organizations, and institutional arrangements for collecting, storing, analyzing, and disseminating information about areas of the earth that are used for, influenced by, or affected by transportation activity. As a branch of GIS, 'GIS-T benefited from developments in management information systems and database techniques in general, and relational database in particular' (Waters, 1999). Many efforts, for example, the development of 'stand alone' packages for carrying out specific operations such as shortest path analysis and location-allocation modeling and more recently the Mctrans programs in University of Florida, Transportation Research Center, are considered to be contributed to the development of GIS-T by Waters (1999).

Depending on the study of Goodchild (1999b), the evolution of GIS-T can be revised from three perspectives: the map view, the navigational view, and the behavioral view.

Due to its root in cartography, GIS has map presentation as its basic function (Goodchild, 1999a). Then, GIS-T also provides an easy way to store, manage, edit, and display the geographic information in digital version (Shaw, 1999; Xiong, 1999). Appearing as map symbols in paper-based map, the transportation features on the ground can also be abstracted into symbol sets that can be accepted by computer.

Currently, points, lines, and polygons are popular symbol sets for representation in GIS-T. Points are used to represent stops, stations, or important objects. Lines indicate roads, tracks, or rivers. Polygons express buildings, car parks, lakes, or special areas. This method deals with the transportation system using only zero- or one-dimensional reference. In the network, points and lines to form the network are usually called nodes and links. Several systems have been built up for the purpose of transportation information management and display (Laffey, 1996).

For navigational view, links and nodes have remained the prevailing view of networks, driven partially by the almost mythical significance given to topology in the traditions of GIS. And link/node model has a noteworthy advantage in supporting navigation, since a path through a network is easily represented as a series of decisions at nodes. However, GIS-T demands an extra data structure to obtain this function. For routing purpose, the system should have the ability to identify one-way streets, and barriers to the traffic flow. New data structure should to support information about turns between links, conditions of access from one link to another, or different lanes leading to various destinations (Goodchild, 1998). More generally speaking, use of street centerline databases to support navigation requires a more complex view of topology than that of the DIME and TIGER files, which used it simply to establish consistent representations of planar features. In order to make an effective of navigation, new extension of attributes is required, such as dynamic attribute of levels of congestion and travel speeds, temporary obstructions, and temporary turn restrictions.

The third view, behavioral view, deals explicitly with the behavior of discrete objects – vehicles, people, trains or boats – on and off the linear network, considering both time and space facets of geographic information (Egenhofer & Golledge, 1998; Langran, 1992). Hagerstrand (1970) was one of the first to examine the behavior of discrete objects moving in time with persistent identity. He introduced the notion of time as a third dimension, with the trajectories of objects tracing paths in this three-dimensional space, constrained such that each object had exactly one intersection with any plane of constant time. Mark and Egenhofer have termed such object trajectories geospatial lifelines (Goodchild, 1999b). Some works on mathematical modeling of behavior are also made (Fischer, Nijkamp, & Papageorgiou, 1990). Yuan (2001) gave a fairly detailed discussion on the representation for supporting queries about 'life' and 'motion' of socio-economic units recently. A GIS to support the behavioral view, and thus the modeling of complex behavior, must also deal with data types other than aggregate variables. Disaggregate objects must be included in the research scope (Goodchild, 1999b; Shaw, 1999).

All these three perspectives of GIS-T represent different application aspects. The map view implies an essentially static perspective of the transportation system, the navigational view assumes that information of a dynamic nature must be represented on the static geometry of the network, and the behavioral view deals with the mobile characteristics of discrete objects on or off the linear network (Shaw, 1999). All of them need further develop to meet their full requirements, and many researchers are making their efforts to promote GIS-T in all three facets.

2.4 Capabilities of GIS-T

Besides common operations that can be found in any GIS, for example, presentation, general spatial analysis such as buffer and overlay, GIS-T has special capabilities on solving problems on transportation system. The main capabilities of GIS-T can be described in the following parts (Caliper Corporation, 1996; Waters, 1999):

1) Shortest path analysis: an essential precursor to many GIS-T operations (Waters, 1999) used to find the best route in terms of length, time, fare, or other defined weights. It can be used for en-route navigation or trip planning (Jiang & Tan, 1997; Keenan, 1998; Western et al., 2000), or together with the help of GPS for car navigation sometimes (Chao & Ding, 1998).
2) Vehicle routing: to determine the routes or tours for deliveries and/or pickups from one or more depots at one or more stops, for example, delivering gasoline to several filling stations and further using in logistics planning (Ralston, 1997; 1999).
3) Arc routing: to find optimal routes that can cover a set of arcs in the transportation system, such as an optimal route to collect waste along streets (Parafina, 1995).
4) Network flow model: to solve assignment problems of optimal matching, one-to-one or many-to-many basis, of demand and supply points within the network.
5) Partitioning: to create zones of a database with restrictions applied to the transportation network of that area.

6) Location-allocation modeling: it seeks to determine optimal locations for facilities.
7) Spatial interaction and gravity model: a classic model of transportation planning.
8) Urban transportation model system: it is a powerful capability of GIS-T on transportation planning with the help of the above operations (Wong & Thong, 1997). Matrices are introduced into the GIS-T to store the information of travel time, distance or flows between each pair of origin and destination, which are basic form of analysis on transportation research. The four steps (trip generation and trip attraction, trip distribution, model split, and traffic or network assignment) are processed with the help of operations of GIS-T.

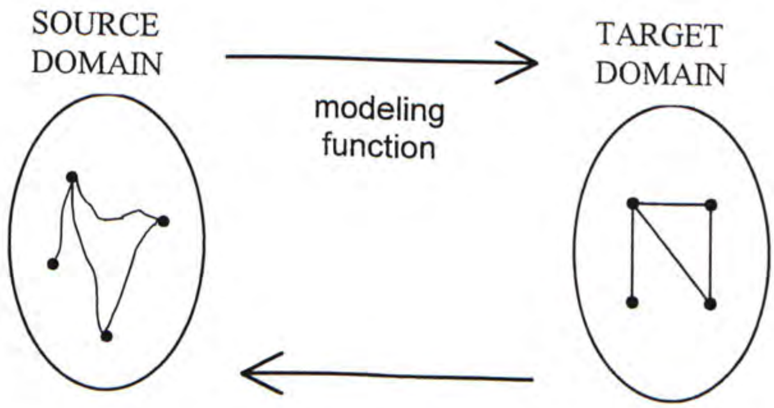
Among the capabilities of GIS-T, some are about various routing problems on the network and others are implementations of traditional transportation planning model on GIS-T. Most operations perform their analysis on transportation network composed of one mode, and further complicated conditions are discussed in their models within this range. But few works have been done on handling transportation network combined with more than one traffic mode (Goodchild, 1999b).

2.5 Structure of a GIS-T

2.5.1 Data Models for GIS-T

As a kind of digital computer application, a geographic information system is designed for the input, storage, manipulation, and output of geographically referenced data of the Earth's surface. Two main categories of spatial data are used in GIS system, raster data and vector data (Laurini & Thompson, 1992; Lin, 1998; Worboys, 1995). Many ways are used to represent the variation of phenomena on the surface of the Earth using raster or/and vector data. However, due to the limitation of representation methods of computer, only some of them can be applied by the GIS designer in practice.

As Worboys (1995) defined, a model is an artificial construction using parts of a source domain to represent a target domain, in which the source domain may be any phenomena of interest in the real world and the target domain is abstraction symbols for of real world phenomena (see Figure 2.1).



Source: Worboys, 1995, p143

Figure 2.1 The modeling process as source domain, modeling function and target domain

Goodchild (1992) classified the methods of ground surface representation into three broad categories in the context of transportation applications:

a. field models that represent continuous variation over the surface, one parameter at a time, for example, representation of the elevation of the land surface;

b. discrete entity models that represent collections of discrete point, line or area features, and their associated properties, such as landmarks, roads, or lakes;

c. network models that represent variation over a linear network embedded in the surface, such as transportation networks, or hydrologic networks.

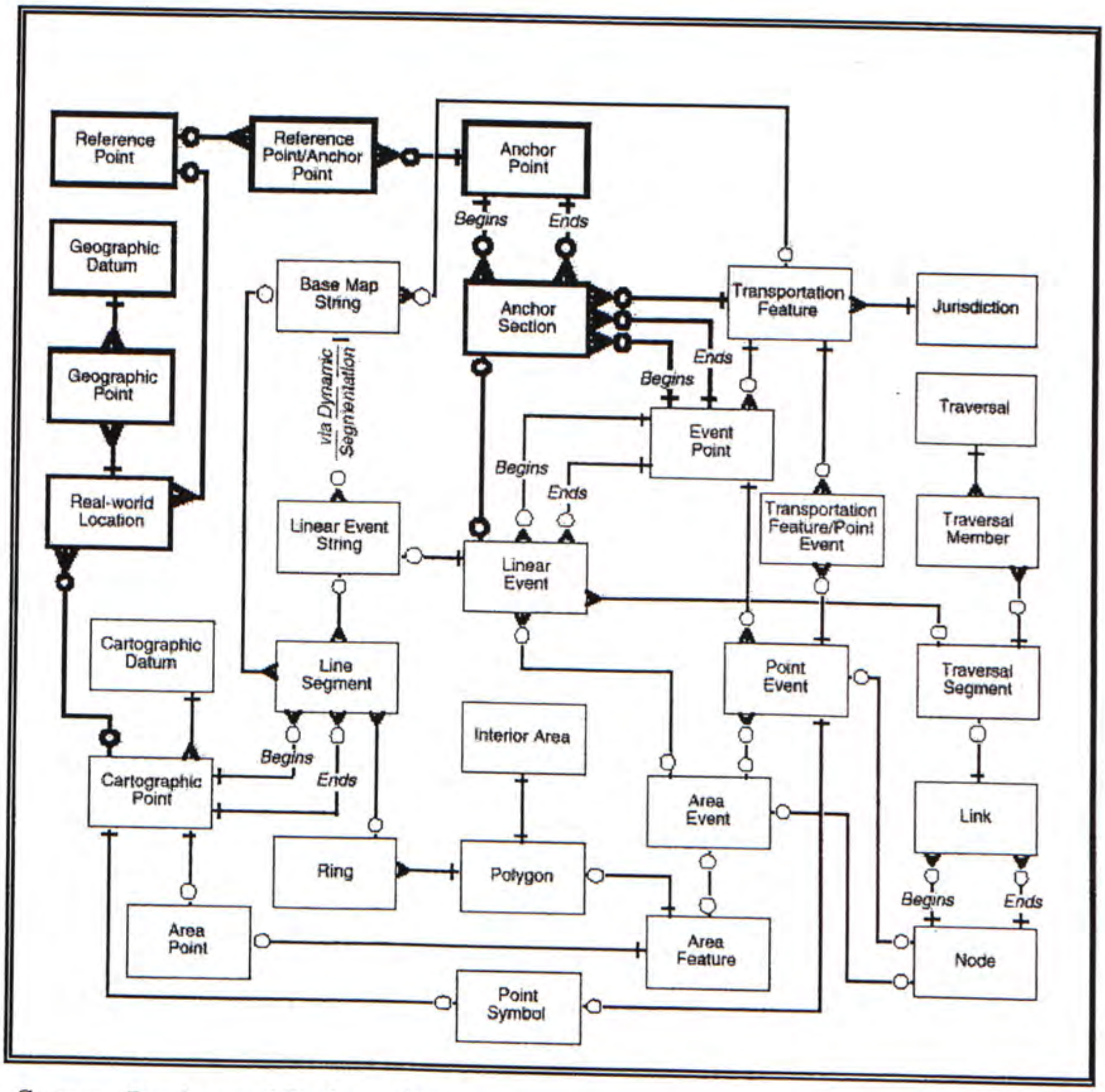
These three schemes are not entirely mutually exclusive, but have some overlaps. Field models are widely adopted in many GIS applications, especially in environmental science, but they are of less interest in transportation modeling (Goodchild, 1998). For discrete entity models, they are used to represent the discrete identified ground features from zero-dimension to two-dimension, which are referenced as points, polylines, and polygons. In transportation applications, points can represent bus stops, signs, or traffic accident places; polylines can indicate bus routes, channels, or bridges; and polygons can symbolize railway stations or car parks. Network models, due to their perfect matching with the linear network of transportation systems, are of great importance in transportation applications of GIS. In fact, our world is highly organized into networks. For example, most our daily movement occurs within vast systems of connected linear channels (Lupien, Moreland, & Dangermond, 1987). Roads, railways, tramlines are easily abstracted into connected networks with special attributes attached with them.

Although transportation research requires a wide range of models and forms of analysis, it makes use of a comparatively small part of types of data, the vast majority of which have some form of geographic reference (Goodchild, 1999b). Discrete entity models and network models, especially the later, are commonly adopted for GIS designers to apply transportation applications. Link/node based network model is widely used in representation for the transportation system by many applications, such as the National Highway Network (NHN), National Waterway Network (NWN), Railway Network, and, recently, CFS multi-modal network of the Oak Range National Laboratory (Center for Transportation Analysis, 1996; Peterson, 2000).

2.5.2 Relational DBMS and Dueker-Butler's Data Model for Transportation

Database Management Systems (DBMS), as general software systems for manipulating database (Teorey, 1994), are an integrated and crucial component of most successful GIS to handle map attribute data and digital cartographic data both (Healey, 1991). These systems can be broadly categorized into four main types: inverted list systems, hierarchical systems, network systems, and relational systems. Among these four types of DBMS structure, relational systems are widely used in commercial DBMS software and coming to dominate the GIS field (Healey, 1991). However, none of today's commercial DBMS includes the data type for spatial information (Egenhofer, Glasgow, Gunther, Herring, & Peuquet, 1999). GIS designers have been trying to expand the structure of relational system in order to well deal with the spatial data under its framework. A hybrid or an integrated data model has been developed for their differing emphasis on the advantages of the file system approach or the database approach for storage of digital map coordinates

(Bracken & Webster, 1989). Integrated approach puts all the data (both spatial and non-spatial) in the relational database, while hybrid approach separates the spatial from the non-spatial data (Worboys, 1999). In theory, the integrated approach is perfectly possible. However, in practice the pure relational geospatial model has not up to now been widely adopted because of unacceptable performance (Healey, 1991; Worboys, 1999).



Source: Dueker and Butler, 1998

Figure 2.2 Dueker and Butler's logical model for enterprise GIS-T

Dueker and Butler (1998) proposed a GIS-T enterprise data model that included all the perspectives of transportation information, including transportation features, the cartographic data, topology information and geographical reference (see Figure 2.2). Different from most other data models used to represent networks, which integrate the cartography, the network link and attributes of the link into a single linear spatial object, Dueker and Butler's data model is set up based on the independence of graphics, topology, position, and characteristics (Butler, 1995; Dueker et al., 1998; Dueker & Butler, 2000). Then data sharing and updating can be readily processed under such a framework. With the stored connection information among various transportation features, this data model makes attempt to deal with the route-finding problem using only the relational database operation without the complex cartographic topology information. Thirty entities are in the E/R diagram of their logic data model. These entities can be grouped into four sets to show the different aspects of transportation system: information of transportation features, including the linear events, points events, area events; routing information, such as traversal, traversal segments, links, and nodes; geographical information of transportation system; cartographic information of transportation system. This data model gives a perfect way for the management of transportation data under the relational approach, especially for data sharing among different sections. However, some difficulties need to overcome for practicing such a data model on a pure relational database by now with state-of-the-art techniques, particularly for route finding.

2.5.3 Object-oriented Approach

Besides the entity-relationship-attribute approach for GIS modeling, the object-oriented approach arises in this decade, for example, Mainguenaud's (1995) work on modeling the network component of GIS, Liu and Zhou's (Liu & Zhou, 1998; Zhou, Wan, & Liu, 1999) attempt to set up a conceptual model for the virtual network, and discussions on the method from Helokunnas (1995) and Leung, Leung, and He (1999).

The fundamental idea of object-oriented approach is encapsulation, which places a wrapper around an identifiable collection of data, and code, which operates upon it to reduce an object. Then, features sharing similar characteristics in the real world can be considered as the same object class with certain attributes and behavior, instead of separated entities. By doing so, features of the same class can easily share the common characteristics and have special operations particularly working on them. Object-oriented approach has shown its power in dealing with complex natural entities (Egenhofer et al., 1999). It can construct a data model in a way much closer to human's concepts of the world, and then, such a data model can be readily understood by users. In terms of flexibility and accuracy in representing the real world, object-oriented approach takes advantages over entity-relational approach. However, object-oriented approach is so complex that it has not yet crystallized into a set of universally agreed constructs (Worboys, 1999). When talking to implement such a data model on a computer system, it is rather a tough task to complete. Some of currently claimed object-oriented systems are more or less object handlers which are essentially relational database systems in disguise (Leung et al., 1999). However, some attempts are made to combine features of object-based and record-based models together into object-relational models (Kang & Choy, 1995), which enhance the standard relational mode with some object-oriented features (Egenhofer et al., 1999; Worboys, 1999). It still needs sometime for the coming of a real applicable object-oriented system.

2.6 Main Techniques of GIS-T

As transportation system is a special kind of ground features, which is mostly considered as a network composed of directed linear features and compound node features, it needs some special cares to deal with the problems arising in it. Several techniques in GIS have been developed and adopted to handle the cases encountered in transportation system.

2.6.1 Linear Location Reference System

When passengers travel in a transportation system, generally, geographic coordinates, which show the absolute position in the world, are not so important to them. In stead, relative location information of a required position, such as direction and distance referring to a known site, is of greater importance to passengers and can be much easier accepted by human's understanding (Goodchild, 1998). Such a system, which is based on a location reference method of referencing a location to a known point, is called a location referencing system (LRS) (Adam, Vonderohe, Butler, & Koncz, 1999). Data on transportation and utility networks are often stored in a measurement from a fixed reference point along a route. This method of storing location information is also named linear reference system (Caliper Corporation, 1996). Linear and point events are elements or characteristics of a partial or whole transportation feature (Butler & Dueker, 1998). It is of great convenience to adopt linear LRS to refer a location to a known position in a network. Furthermore, it can be helpful to integrate transportation data from different sources (Fletcher, Expinoza, Mackoy, Gordon, Spear, & Vonderohe, 1998). The linear LRS is the glue that binds linear and point events to their transportation features, as well as to the geographic datum of anchor points and anchor sections that place the transportation features on the surface of the Earth (Butler et al., 1998). Several primary methods used by transportation agencies include route-mile-point, route-reference-post-offset, route-mile-post-offset, route-reference-point-offset, and methods based on link-node models (Adam et al., 1999). The difference of them is the methods to set the reference points. Route-mile-point method uses the measured distance from a given or known point, usually the point of a route entering a jurisdiction area, to the referenced location. Route-reference-post-offset method and route-mile-post-offset method use signs posted in the field to indicate the known locations. The former posts a sign at a special place, while the later sets signs at every mile. Route-reference-point-offset method uses special stable ground entities as reference points, for example, bridges and monuments. Then, link-node method adopts the intersections as the reference points.

2.6.2 Dynamic Segmentation

In a transportation network, different segmenting to the link and inserting new nodes are required to represent different attributes of the same network. In order to show more information based on different segmentation to a network, avoiding exhausted update work, dynamic segmentation technique is introduced by some GIS designers (Goodchild, 1998). In a linear LRS, a zero-dimensional entity, such as a bus stop, a sign, or an accident place, can be located using a single offset distance from a reference point and a one-dimensional entity, such as a delivery route or a congestion road section, can be located using a pair of offset distances (beginning and ending). The basic link/node structure is preserved, and a new structure representing zero-dimensional or one-dimensional entities, which are located at arbitrary locations on the network, is added above it. Dynamic segmentation allows a property to vary along a network segment, rather than remain constant (Goodchild, 1998).

2.6.3 Planar and Non-planar Networks

A network can be considered as a one –dimensional space embedded in a ground surface. A network is modeled as a collection of polylines with nodes at connections. In a planar network, nodes are forced at all intersections, that is, there is surely a node when two or more polylines gather. Planar data model is too simple to match the common situation of a transportation network with over-pass bridges, in which a road can overpass the other without intersection. To solve this problem, a non-planar network is needed. Non-planar data model allows overpass and underpass situations in a network. It breaks the restriction of plane, and provides a partial solution to the problem of connectivity.

2.6.4 Turn-table

It is commonly assumed that the linear network is homogeneous between nodes or junctions (Goodchild, 1998; Lupien et al., 1987), but the real world is definitely more complex than the assumption. In a modern metropolitan transportation network system, traffic regulations always attempt to break the free traffic flow at junctions. Drivers have to face turn restrictions. A new structure called the turn-table has been extended to the basic GIS data model to deal with such a problem. A table records the attributes of connections from each edge to others at the same junction, indicating appropriate properties of the turns.

2.7 Algorithms for Finding Shortest Paths on a Network

When traveling on the transportation network, passengers and drivers are most likely to ask how to reach the destination and, moreover, how to complete the trip with the least cost. So, finding shortest paths (in term of passengers' reference) on a network is a key problem in network and transportation analyses (Zhan, 1996), and shortest path analysis is an essential precursor to many GIS-T operations (Waters, 1999). Many GIS-T software packages provide a basic function to find a shortest path on the network, such as TransCAD, ArcView Network Extension, and MapInfo DriveTime.

2.7.1 Overview of Routing Algorithms

Algorithms used to perform routing on a network are well established and have been in widespread used since the 1960s (Lupien et al., 1987). The theoretic foundation of routing on the network is graph theory, as transportation network in real world can be abstracted into a directed or non-directed graph composed of vertices and edges. Then, route finding on the transportation network can be considered as path searching problems on a graph. Numerous algorithms have been constructed to solve various shortest paths problems. For example, Dijkstra's algorithm for single-source shortest paths problem on a nonnegative graph, Bellman-Ford algorithm for the same problem on a graph with negative weights, Floyd-Warshall algorithm for all-pairs shortest paths problem on a common graph, and

Johnson's algorithm for the same problem on a large sparse graph. Among these algorithms, algorithms for single-source shortest paths problem attract more researchers' concern, because many other problems, including single-destination shortest-paths problem, single-pair shortest-path problem, and all-pairs shortest-paths problem, can be transformed into single-source shortest-paths problem and solved by these algorithms (Cormen, Leiserson, & Rivest, 1990).

In solving single-source shortest-paths problem, Bellman-Ford algorithm can deal with more general case in which edge of the graph can be negative or nonnegative, a linear-time algorithm based on depth-first search is used to handle the situation in a directed acyclic graph, and Dijsktra's algorithm aims at nonnegative graph. When taking public transit service, passengers mostly consider the nonnegative reference such as time, fare, or transfers for route choice. Then, the situation for passengers' route finding between their origin and destination stops on the public transportation network referring to the selected factor (time, fare, or transfer) can be abstracted as the single-source shortest-paths problem on the nonnegative directed graph, which falls right in the scope of Dijkstra's algorithm.

Dijsktra's (1959) algorithm, with another name as label-setting algorithm, is a classic and basic routing algorithm. It is one of most widely adopted methods for routing (Cormen et al., 1990; Li & Qian, 1982), and has been embedded in some GIS-T software for network analysis after slightly modification. Various types of routing problems have been explored by researchers based on Dijskstra's algorithm (Chen & Hsueh, 1998; Fu & Rilett, 1998; Kaufman, Nonis, & Smith, 1998; Spiess & Florian, 1989; Wong et al., 1998). In order to deal with multiple modes in transportation system, some researchers (Spiess et al., 1989; Wong et al., 1998; Ziliaskopoulos & Mahmassani, 1996) also worked on routing models that can take mode information into consideration for decision of route choice.

2.7.2 Dijkstra's Algorithm

Dijkstra's algorithm is considered as the most classic and basic method for routing, and is assessed as a way that has advantages in handling a one-to-one shortest path (Zhan, 1996). Some complex routing problems have been transfromed into the format that can be dealt with Dijkstra's algorithm and given with solutions, such as shortest path routing on dynamic and stochastic traffic network (Fu et al., 1998), and minimum path on a schedule-based transit network (Wong et al., 1998).

Dijkstra's algorithm is based on an assumption that optimization of partial leads to an optimization of total (Lu, 1999). Using this method, every time making a search in the network, a shortest path from the origin to the current node is found, and then till the destination is found, the procedure of searching ends.

Cormen et al. (1990) clearly describe the algorithm. Considering the service network as a weighted, directed graph $G = (V, E)$ for the case in which all edges weights are nonnegative, that is $w(u, v) \geq 0$ for each edge $(u, v) \in E$, Dijkstra's algorithm maintains a set S of vertices whose final shortest-path weights from the source s have already been determined. For all vertices $v \in S$, we have $d[v] = \delta(s, v)$. The algorithm repeatedly selects the vertex $u \in V - S$ with the minimum shortest-path estimate, inserts u into S, and relaxes all edges leaving u. The procedure continues till the destination node n is in the set S. Then the result is $d[n] = \delta(s, n)$.

If a priority queue Q that contains all the vertices in $V - S$, keyed by their d values, is maintained during the implementation of the algorithm, we can represent the procedure of the implementation of the algorithm as the following list.

```
DIJKSTRA (G, w, s)
1 INITIALIZE-SINGLE-SOURCE (G, s)
2 S ← ∅
3 Q ← V [G]
4 while Q ≠ ∅
5       do u ← EXTRACT-MIN (Q)
6          S ← S ∪ {u}
7          for each vertex v ∈ Adj[u]
8          do RELAX (u, v, w)
```

When we find the shortest-path from the origin s to the destination n, we even need not search all the edges in the network as the fourth procedure in the list. While the destination vertex n is in the set S, or n is not included in the set Q, the result we wants comes out and the process is ceased.

2.7.3 Routing Models for the Multi-modal Network

For routing on the multi-modal network, Spiess et al. (1989) had described a model for the transit assignment problem with a fixed set of transit lines based on consideration of single traveler's reaching the destination with shortest path on multi-modal transit routes. Ziliaskopoulos et al. (1996) proposed a new approach to take intersection movements in calculating best path with a modified label correcting shortest path algorithm. The former one is used to transportation planning of transit assignment, and the latter is applied to navigation on road with prohibitions. Although they are not designed directly for routing on the multi-modal route service network, they are useful to the design of data model for multi-modal public transportation system.

2.8 Recent Researches on GIS Data Models for the Multi-modal Transportation System

GIS-T has become a main branch of GIS applications. However, most data models of GIS for transportation are deal with conditions of single traffic mode (Goodchild, 1999b), and it is too limited to represent and handle the complicated cases of real world. In the real world, transportation system is composed of various traffic modes, including roads, railways, water routes, and airways. Also, a journey in the real world most likely involves travel by different traffic modes. Transportation network in fact is a complicated multi-mode-based network with different characteristics and rules applying on different sub-networks of traffic modes. More and more GIS researchers are focusing on this characteristic of transportation network and finding ways to deal with the problem in the framework of GIS (Miller et al., 1995; Peng, 1996; Ho, 1998; Zhou et al., 1999; Okabe, 2000).

Several attempts and practices have been made by the researchers from different groups. By linking GIS with RDBMS for accessibility analysis on a public transit system, Grayson put forward a comprehensive framework of three levels of network to represent the multi-modal public transportation system in 1993, which includes a geographic level for the road network, a transit level for the bus routes and stops, and a supernetwork for the abstraction of transit routes facilitating network analysis (Koncz et al., 1995). However, his prototype used only buses and did not allow transferring between nearby stops by walking. In order to develop a GIS-based simultaneous transportation equilibrium model (GIS-STEM) on a multi-modal network, Miller et al. (1995) designed a virtual network for representing the topological relationship of the multi-modal transportation network, which was a collection of route classes, such as transit routes and streets, generated from basic topologic network. This approach separates the multi-modal network from the physical network for mode-specific attributes, and contributes to a better data consistency. Zhou et al. (1999) made a try for the representation of Miller's virtual network from an object-oriented approach, and 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 (ATPS), Peng (1996) modeled the transit network from a different approach. By decomposing the physical transport network into segments, Peng set up a form of pattern, which is composed of one or several segments, and later, these patterns are used to build up mass transits. However, to find out suitable patterns is rather a difficult work. All these efforts are made to construct an integrated network which can record the topologic relationships among different traffic modes or transit routes. Studies of the Center for Spatial Information Science in the University of Tokyo, who are tackling the spatial analysis on an inhomogeneous network, may give a more general outline for dealing with the problem. By transforming an 'inhomogeneous' network into a 'homogeneous' one, analysis on a homogeneous network can be applied on it (Okabe, 2000).

Recently, a data consortium called UNETRANS (Unified Network for TRANSportation), led by ESRI staff and researchers at University of California at Santa Barbara (UCSB), including members from North America, Europe and the Pacific Rim, is working on developing a generic data model for transportation application using ESRI's new software (UNETRANS, 2000). One main purpose of this one-year-last project, which will be ended in the end of 2001, is to generate a conceptual object model of transportation features incorporating multiple traffic modes and accommodating multiple scales. Thirty-odd points are listed as problems that the data model 'should' or 'must' deal with on modeling multi-modal, transit, and travel demand forecasting (Kratzschmar, 2000). Their attempts of constructing the GIS framework are based on the basic data structures provided by ArcGIS 8. It is a tough task to meet all the requests. However, the rough conceptual model is coming into being.

While the scholars in University of California at Santa Barbara are working for the state-of –the-art of data model for application on multi-modal transportation system, some other researchers are working on providing data source for the multi-modal transportation system (Bureau of Transportation Statistics, 2000). The Oak Ridge National Laboratory's (ORNL) Center for Transportation Analysis (CTA) has been working for the Bureau of Transportation Statistics (BTS) to create a multi-modal network. The products from this effort include both a combined multi-modal network and a separate network for each individual transportation mode. In order to simulate routes taken by freight shipments in the 1997 Commodity Flow Survey (CFS), CTA generated a database for CFS multi-modal network, including highway, rail, and water, along with a set of intermodal terminals and a terminal model to connect them. As they consider the multi-modal network is composed of several single-mode networks, each occupying a horizontal plane, with intermodal terminals connecting two modes at the transfer, they use vertical access links to connect each independently constructed single-mode network at intermodal terminals (Peterson, 2000). CTA has created a database known as the Oak Ridge National Highway Network (NHN) for major highways in the United States, which is designed for not only vehicle routing and scheduling but also other studies on geographically based highway network (Center for Transportation Analysis, 1996). Similarly, updated databases for railway network, waterway network, and intermodal terminals in United States are created by CTA (Bureau of Transportation Statistics, 2000). They are linked by mode-specific 'vertical access links' at transfers with universally encoded ID for each link to form the CFS multi-modal network.

2.9 Main Software Packages for GIS-T

As more and more people interest in spatial information, software that can help people handle spatial data is becoming more and more common. As a main direction of GIS applications, GIS-T has relevant software packages to deal with transportation problems. Some deal with special problems of optimizing the delivery or collection routes, now known as 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 work on transportation planning issues, such as the production of CAPS Logistics Inc. for transportation planning, and TransCAD of Caliper Corp.. Also, a few packages provide more powerful functions to model and analyze transportation networks. ArcInfo 8 with its extension of ARC NETWORK of ESRI and TransCAD of Caliper are such packages.

ARC/INFO and TransCAD are considered as the fully developed GIS and GIS-T packages respectively (Waters, 1999). The recent version of ARC/INFO, ArcInfo 8, together with ARC NETWORK extension, is enhanced on representation of network features (ESRI, 2000). Cooperated with UCSB's GIS specialists, ESRI is working on general transportation data model in ARC/INFO environment. Now, ARC NETWORK has functions as generating complicated networks, route-finding, assigning portions of a network to a resource supply location. However, as an extension of general GIS software, it is too simplistic, inflexible and slow to compete with state-of-the-art network modeling algorithms (Wegener, 2000). And it even cannot be as powerful as TransCAD, a special package for transportation. With extended data model, TransCAD can handle more complicated situations in transportation systems, such as directed roads, underpass and overpass, route system over transportation infrastructures, and connectivity of links at nodes (Caliper Corporation, 1996). It has more flexibility than ACR NETWORK to deal with transportation features. More over, embedded with most operations and analytical models for transportation, TransCAD can solve the widest transportation problems. By now, it perhaps is the best-known software specialized for GIS-T (Waters, 1999).

2.10 Summary

Based on the review above, GIS-T is suitable for representation of transportation feature due to its well-developed data models and techniques in handling spatial data. Link/node based network model is a proper target domain to abstract and represent the transportation network in the real world. Also, routing algorithm based on graph theory is easily to apply on the network model for shortest-path analysis. However, network created in most GIS-T system is concentrated on no more than one traffic mode. Under a common condition, there are often several different traffic modes integrated to serve the demand of the public. Goodchild

(1999b) indicated that few efforts have been made to create databases that combine modes, but these would be essential for multi-modal routing. Although universal network connectivity is becoming a reality, no universally accepted data structures, formats, syntax, terminology, or quality standards exist by now (Fletcher, 2000). Problems for representation of the multi-modal transportation system are getting more and more concerns from GIS specialists, transportation sectors, and other traffic facility users. Consortiums are organized working on general data model for transportation, with handling multi-mode-based travel as one of its purposes.

Shortest path analysis, as an important and basic function of GIS-T, is included in nearly every GIS-T application. Well-developed algorithms are ready to be implemented in GIS-T for finding best routes. However, shortest path analysis function in most GIS-T packages is fitted to work in single-mode network environment. Facing the multi-mode-based complicated situations of transportation system in real world, the current method seems limited. Concerning conditions in public transport service field, the same facts also exist. Especially in big cities, for example, Hong Kong, it is common that more than one traffic mode serve passengers. Without a general network that combines different traffic modes together, GIS-T can hardly give a proper suggestion on optimal route analysis. A proper approach to deal with the multi-modal public transportation service is requested by the public. It is also a challenge in the development of GIS-T. With the existing principles and techniques, an attempt is practiced in this paper to handle the data organization of the multi-modal public transportation service information, which can be used for providing more proper path-finding results based on such a mass transit service network. In this paper, Hong Kong Island is selected as the study area.

Mass transit system of this area is considered as the study object for modeling, and then, a GIS-T prototype is implemented for the area. Details are discussed in the following chapters.

CHAPTER III

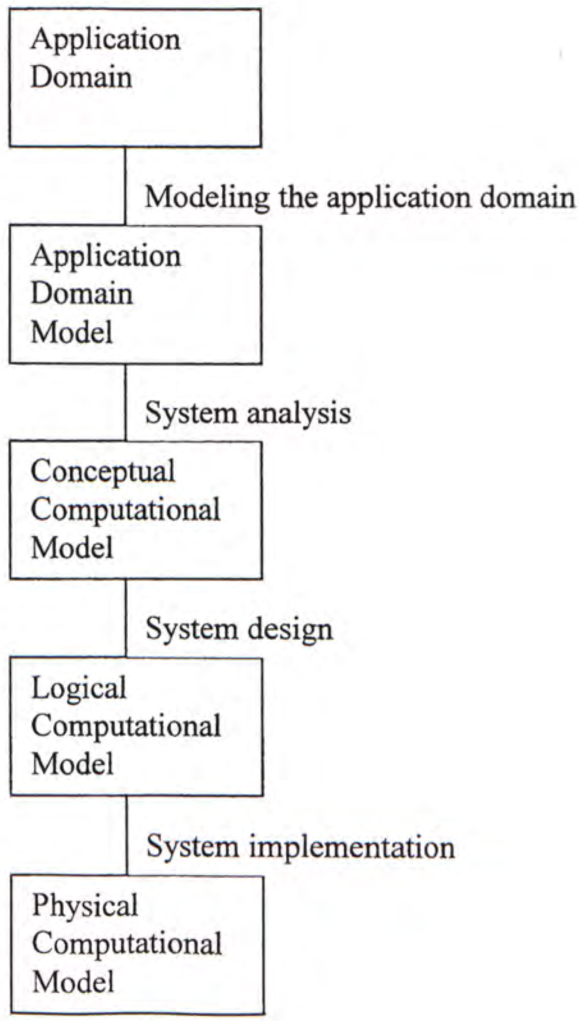
MODELING THE MULTI-MODAL PUBLIC TRANSPORTATION SYSTEM

3.1 Introduction

In this chapter, data model for the multi-modal public transportation system is discussed in detail considering the existing methods and techniques. At the beginning of this chapter, a process of five stages for GIS modeling brought up by Worboys is introduced. Following the process, a data model for the multi-modal public transportation system is constructed in this chapter. At first, the application domain of this research is described and analyzed. Based on the analysis of the application domain, a conceptual data model is formed for the multi-modal public transportation system. Then, corresponding logical and physical implementation of the data model are discussed in the following part. Routing criteria of shortest path analysis on such a network are discussed subsequently. At the end of the chapter, a summary is given for the content of this chapter.

3.2 Elaborated Stages and Methods for GIS Modeling

As a kind of complicated computer-based system, GIS-T has several stages during model design. Elaborated process for GIS is given by Worboys (1995). In Figure 3.1, five stages will be completed for model design of a GIS. In this chapter, data modeling for the multi-modal public transportation system will follow this process.



Source: Worboys, 1995, p22

Figure 3.1 Elaborated modeling stages in GIS

At first, according to research interests, application domain of the real world is determined. Research objects and domain scope are clearly pointed out. Some typical scenarios may be described specially in order to get a well understanding on the application domain.

Then, phenomena in the application domain are abstracted and represented in a proper application domain model (Smyth, 1998). The objects in the real world are simplified roughly for easy analysis later.

After the application domain model is set up, data model design can be started. In this phase, the application domain model is transformed into the conceptual model that is computationally tractable but independent of any special database (Worboys, 1995). Conceptual model is the framework of the following efforts, indicating the direction of the system. If the conceptual model is not built correctly, the likely outcome will be an inefficient database structure with unnecessary redundancy in data storage and a poor match to user's requirements for data access and retrieval (Healey, 1991).

In a logical model, further detailed descriptions are needed to fulfill the conceptual model. Components and their definitions will be considered for each entity in the conceptual model. At the same time, the relationships between different components (data sets) will be clearly defined.

A physical model is concerned with the location of different parts of the database within the file system of computer. Different from a logic model, which represents the user's view of the interrelationships between data sets stored in the database, a physical model concerns how to practice the model in hardware with special data structure. With a physical model designed, it is readily to be applied on a computer.

Various data analysis or data modeling techniques can be used, but the entity-relationship (E/R) model approach, which was first introduced by Chen, has met with the widest acceptance (Adam & Gangopadhyay, 1997; Healey, 1991; Lorents & Morgan, 1998). 'Over the 15 years, the Entity-Relationship Approach (E/R) has evolved as an almost *de facto* standard for conceptual and logical design of databases and information systems' (Pantazis, 1997, p. 348). E/R model, as a popular method to provide a description of a database in visual form (Lorents et al., 1998; Teorey, 1990), can provide a clear view of how the various things about which we want to store and retrieve information are related to each other. With the fundamental concepts, it is possible to develop sophisticated models of data interrelationships. The availability of diagramming methods linked to the concepts allows graphical representations of models to be drawn. These are powerful aids to model articulation and as a means of communication (Healey, 1991). So E/R diagram is used in the processes of conceptual and logic model design in this paper.

3.3 Application Domain: The Multi-modal Public Transportation System

3.3.1 Definition of a Multi-modal Public Transportation System

Generally, a multi-modal transport or intermodal transport is defined as the use of two or more modes involved in the movement of people or goods from origin to destination (Dewitt & Clinger, 2000). This definition mainly deals with freight transportation. In a mass transit system, the cost of a passenger transferring among different transit routes is the same as among different traffic modes. For example, a passenger will spend some time and expense to transfer from one bus route to another one, the same as he/she transfers from a subway route to a bus route. So, in this paper, the term 'multi-modal' also includes the situation of different public traffic service routes. Accordingly, a multi-modal public transportation system indicates a complicated mass transit service network comprised of numerous service routes that are operated by different traffic modes. Then, a transfer is a special stop in the service route where several traffic service routes meet and passenger can change from one route to another.

3.3.2 Descriptions of the Multi-modal Public Transportation System

Many passengers probably encounter the following scenarios when traveling on public transportation system in a big city:

Andy is a visitor to city H. He needs to meet a friend in a restaurant. He finds out the location on a map with mass transit service routes, but there is not a direct mass transit route serving between his hotel and the restaurant. After searching most mass transit routes on the map for half an hour, he finds out that two routes running at his hotel and the restaurant respectively both drive to the city center. Then he takes the route to the city center first. However, the second route has only very few vehicles for service and runs at a thirty-minute headway. He waits for nearly twenty minutes to catch a bus for the second route to the restaurant. The trip takes him totally nearly an hour, although there exists another path that takes only half an hour to get the destination.

Bob is a resident of the city K. He goes to work everyday by subway. During his trip, he need change the lines three times. As the subway runs at a high speed, he thinks that the current route he selects is the best choice. In fact, another route served by bus and subway can save ten minutes than his current route, because he need only change once in the new route and that will reduce more waiting time.

The above two scenarios indicate that a public transportation system constructed on the multi-modal network is a complicated system. Passengers can hardly well understand the multi-modal mass transit service network or even hold sufficient information to make their decisions. As a basic and important function of current GIS-T, shortest path analysis can well solve path-finding problems based on single-mode network. For routing on the multi-modal network, there are still obstacles to overcome.

Works have been done on car navigation (Chao et al., 1998; Claussen, 1991; Maassen, 1996; Xu, 1999), and some products are using in cars for road guidance (Hartley, 1996). For routing in public transportation systems, it is different from navigation for a single driver in a car, especially in a multi-modal based public transportation system. In navigation for a car, a driver faces the network of transportation infrastructures, mostly the roads, and regulations applying on them. In route finding on the multi-modal public transportation system, passengers face twisted service routes, numerous stops, and different traffic modes. Definitely, all service routes are based on some kind of transportation infrastructures, such as roads, railways, and water routes, but they are hidden from passengers. So, the data organization for routing on the multi-modal public transportation system should be different from that for car navigation.

In a metropolitan, the multi-modal based public transportation system is composed with traffic service routes operated by different kinds of traffic modes. Every service route depends on a certain kind of transportation infrastructure, such as road network or railway network. Along each service route, there are many stops at which passengers can board or alight the service route. Mostly, stops are set at some noticeable sites that can be easily found by passengers. Among the stops, there are some special stops at which passengers can change their service routes from one to another, for example, from a bus route to another bus route, or from a bus route to a subway route. Extra cost will be generated at a transfer stop. All these features are the objects in application domain of this research.

3.3.3 Objective of the Modeling Work

Facing so many service routes, complicated transfers, and different traffic modes, passengers have difficulties in well understanding the mass transit service, and they need helps to make reasonable decisions. GIS-T has successes in dealing with transportation problems, especially for single-mode network. Now its capability for handling the multi-modal network is being explored. After the data modeling process, a model is expected that can properly represent the multi-modal public transportation system and basically support the multi-modal routing on such a network.

3.4 A Layer-cake Based Application Domain Model for the Multi-modal Public Transportation System

As mentioned in Chapter 2, there are three broad categories for representation of ground features: field model, discrete entity model, and network model. The latter two models are widely adopted in GIS-T, especially for network model (Goodchild, 1992; Goodchild, 1998). Discrete model can be used to represent stops, intersections, and transfers in a transportation system. Network model can be used to represent various networks of transportation system.

Based on the description and analysis on the multi-modal public transportation system mentioned above, an application domain model for it can be constructed in a layer-cake structure as following (see Figure 3.2).

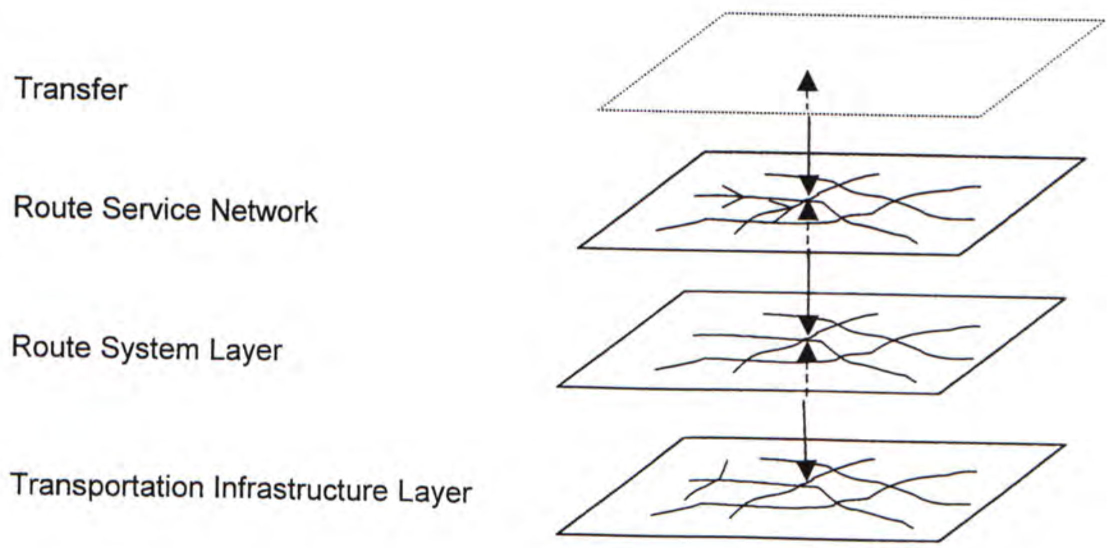


Figure 3.2 An application domain model for the multi-modal public transportation system

All vehicles run on transportation infrastructures, such as highways, railways, and waterways. These physical infrastructures are basic facilities for a mass transit system. A transportation infrastructure layer is a collection of link/node based networks for all traffic modes, including road centerline, railway, subway, tramline, and waterway. Commonly, they are represented respectively, according to different types. This layer contains the geographical information of the points and lines. The coordinates of the features can be transferred to real world coordinates, longitude and latitude. Transportation infrastructures are the physical base of a mass transit service and they also provide a service scope for the mass transit routes. So transportation infrastructure layer is the basic layer to create the mass transit system.

Above the transportation infrastructure layer is a route system layer, which includes all mass transit service routes of different modes. This layer is generated from the basic transportation infrastructure layer. Some points and lines are collected to form mass transit service routes. Then, some points and lines may be selected more than once to form different service routes, that is, several routes pass these physical transportation features. Also, some points and lines are never been included in a single service route. If a physical stop of the route locates at a position where no point stands in the transportation infrastructure layer, a new point may be added to the infrastructure layer to give its corresponding base. Or, if a linear location reference system (LRS) is set up for the network, the method named dynamic segmentation can be used to record its position by means of distance from the starting point. The route system only records the segment composition information of each mass transit service route, not the topology information. So this layer is only used to give a clear view of mass transit service routes and store the general information for service routes.

A route service network contains topologic information of the multi-modal mass transit system. In this layer, each service route is represented as a separate line and connected with others at transfers and, then, they form a general network for the mass transit service, which presents the scope that passengers can travel by all public traffic modes. Mode information, direction information and penalty for mode changing are attached to the link. Some special nodes in the network, which connect links more than one type, are defined as transfers. At these nodes, passengers can change from one service route to another one. Corresponding costs happening at these nodes are recorded together with the link changes in the network. As the nodes work as transfers and extra costs only have effects when transferring actions exist, they are represented the same as other nodes in the network. If necessary, a transfer table which records the cost for each pair of mode changes can be constructed to show detail interchange information of the network.

Such a model, well known as a layer-cake model, uses several co-registered representation layers of geographic variation over an area, and it is easy for us to keep the consistency among different layers and ready to update the information of different layers.

3.5 A Conceptual Model for the Multi-modal Public Transportation System

Based on the application domain model, detail structures of each layer are explored and spatial entities and relationship among them mentioned in the application domain model are embodied in the conceptual model phase. In Figure 3.3, network structures of each layer and association among different layers are represented clearly.

Further on, a conceptual implementation of the application domain model can be readily described with Entity-Relationship (E/R) diagram after the structures of each layer are determined.

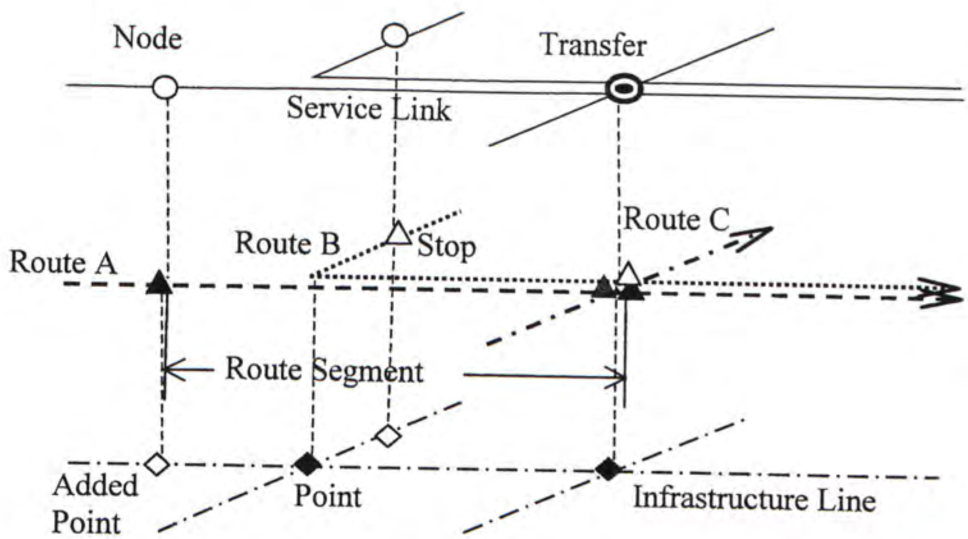


Figure 3.3 Structure of transportation features in three layers

Each layer in the application domain model can be embodied with several entities. The entity composition of each layer is given in the following part, respectively.

The transportation infrastructure layer, a collection of physical networks of different traffic modes, is composed of transportation feature, linear string, and point entities. Their definitions are given as bellow:

a) **Transportation feature**: an identified physical element of transportation infrastructures. It can be a road, a highway, a railway, or a waterway, such as Fleming Road, Tolo Highway, Kowloon-Cantonese Railway, and Center-Kowloon waterway.

b) **Line string**: line units that form transportation feature. Usually, they are segments of transportation infrastructures.

c) **Point**: a zero-dimension element that records the beginning or end position of a line string. Often, it is an intersection or special site.

The transportation feature, line string, and point entities compose the transportation infrastructure network. Such an infrastructure set includes several single-mode networks, such as highway systems, railway networks, or waterway networks. Each transportation feature is composed of one or more line strings. For example, a highway may be built with tens of line strings. For each line string, there must be two points attached to it, one for the beginning and the other for the end. However, for each point, it may not just work as one endpoint of a line string. It may be the endpoint of several line strings. For each line string, it must belong to one transportation feature.

The route system layer, a set of mass transit routes, is composed of route, route segment, and stop entities.

d) **Route**: a service line of any mass transit mode, such as a bus route, a railway route, or a ferry route.

e) **Route segment**: partial of a service line. Mostly, it is the segment between two sequential stops along a route.

f) **Stop**: stops are sequential point features along a route, serving as boarding and alighting places for passengers.

The route, route segment, and stop entities together record the public traffic service information of the route system layer. A traffic route is constituted with one or more route segments. A route segment has two stops for beginning and end. A stop may work as stop for more than one route segment, and a route segment must belong to one traffic route.

A route service network layer is made up of link, node, and transfer entities to record the topologic information of the multi-modal mass transit system.

g) **Link**: a line topologic feature of the multi-modal mass transit system which records the mode information, direction of traffic flow, and the transportation cost of the relevant route segment.

h) **Node**: a zero-dimensional topologic feature standing at the location of a corresponding stop. It works as the start or end point of a link, with the connectivity information of adjacent links attached.

i) **Transfer**: a special kind of node, standing at a stop where a route change may occur. It records the connectivity information between different route links, together with the penalty when such a change happens.

These three entities form a general public traffic service network for multi-modal routing. A link is composed with a *from* node and *to* node, while a node works as an endpoint of links. As a special type of node, a transfer contains connectivity and penalty information between each pair of route links. By connecting links of different routes or different modes, transfers join separate routes together and extend the passengers' travel scope to the whole public transportation service network. For each transfer, a node must stands there, while only a special node that connects two different types of links can form a transfer.

Then entities of a multi-modal public transportation system and their relationships can be clearly described in an E/R diagram. (See figure 3.4)

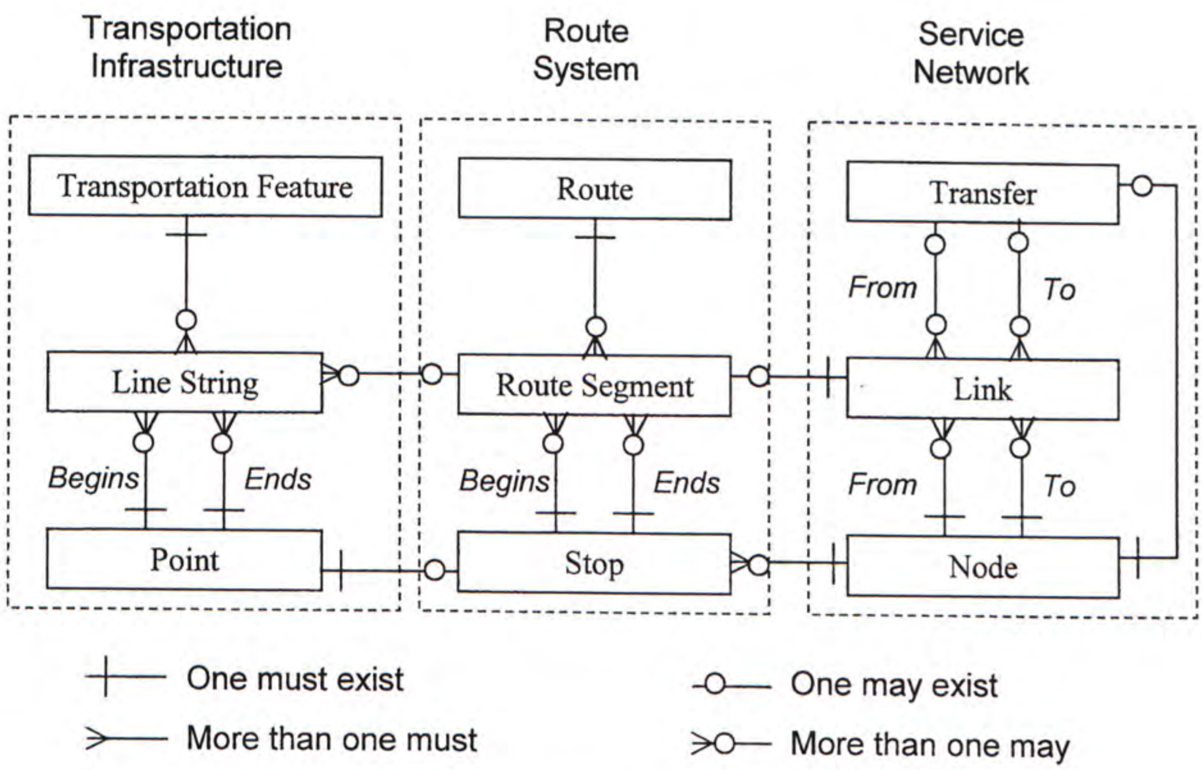


Figure 3.4 A conceptual model for the multi-modal public transportation system

Relationships between different layers can also be read from the E/R diagram. Layer-cake model depends on a serial of co-registered map layers, so relationships between different layers record the co-registered information of the system. The route segment is composed with one or more line strings, but some strings may not appear as a route segment. For each route segment in the route system layer, there must be a corresponding link in the service network. It is the same for zero-dimension entities. Each stop stands on a point, but not all points appear as stops. Each stop has a corresponding node in the service network, and a node may have more than one relevant stop.

3.6 Logical and Physical Implementation of the Data Model for the Multi-modal Public Transportation System

For each entity, two main categories of information are used to describe its characteristics, spatial and non-spatial data. Spatial data indicates an entity's location in a specified coordinate system and non-spatial data contains its other attributes. Spatial data are pairs of coordinates. For a point feature, one pair of coordinates refers its location. For a line feature, a sequential series of coordinates pairs records its track. Various types are used to represent attribute data, such as character, number, date. A relational database, as the main stream of database type, has powerful function on attribute data management. But it has some difficulties in handling spatial data. So extended relational database is explored by specialists to enhance relational database to deal with spatial data (Egenhofer et al., 1999; Healey, 1991; Worboys, 1999). Usually, an extended relational database provides long fields with variable length for spatial data, and handles non-spatial data and spatial data respectively, with RDBMS managing attributes data and a specified program to interpret the spatial data. Then common identities of entities are used to link the spatial data and attribute data together (Egenhofer et al., 1999). Most GIS software adopts this method in managing these two types of information, such as TransCAD and Arc/Info. It is also used for modeling the multi-modal public transportation system here.

Based on the conceptual data model discussed in former part, logical relationships of entities are represented in a logical data model shown in figure 3.5.

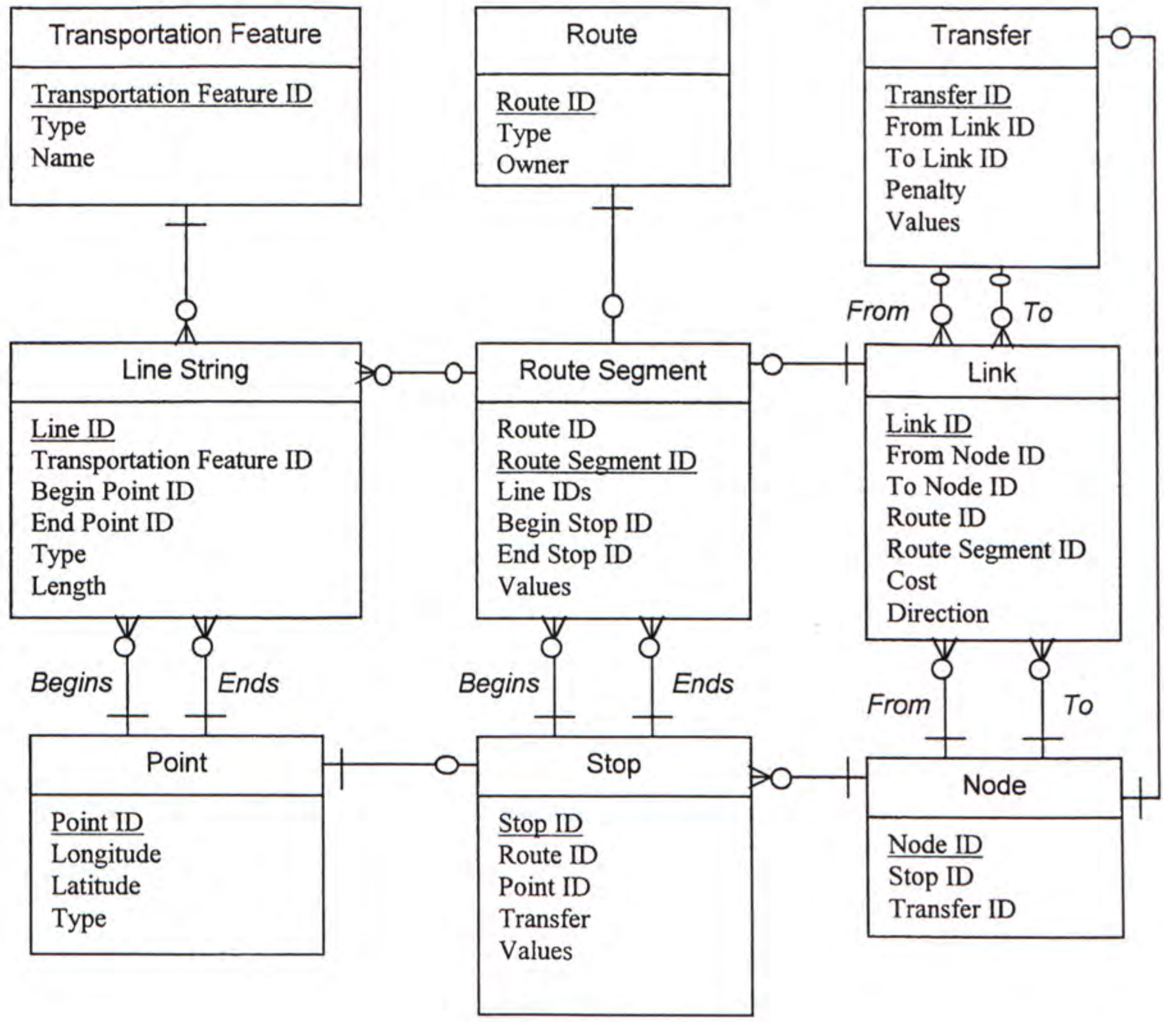


Figure 3.5 A logical model for the multi-modal public transportation system

The table for transportation feature uses transportation feature ID to give each transportation feature a unique identity in the whole system. Other fields record the type for the transportation infrastructure, such as road, railway, or water route, and the name of the feature. A line table stores the line ID, the beginning and end point ID, and the attributes attached to the line. In a point table, point ID and the coordinates (longitude and latitude) are stored.

A route table records the route ID, route type (bus route, railway route, or tram route), and the attributes applied to the whole route. A route segment table contains the line IDs that comprise it, route ID, corresponding stop IDs, and its own values. In a stop table, it records the stop ID, route ID, point ID, which can set up joint information with point table, and its type (a simple stop or a transfer).

In a link table, because it should provide topologic information, it has a field in which the traffic direction (one-way or double-way) is indicated. Also, a type field stores the traffic mode for this link. A cost field will be used to show the time or length for traveling through this link. A node table has not only fields of node ID and stop ID, through which it can maintain a relationship with stop table, but also a transfer ID, which indicates whether the node is a transfer (by checking whether its value is null or not) and which transfer it refers to. In a transfer table, a penalty field will tell us the cost for a mode change between each pair of route links.

A Physical model deals with how information is stored in a computer (Mannila & Raiha, 1992). It is a further step of implementation of a data model, and determines how an application can finally be implemented on a computer system. Due to its mature development and vase supports from several commercial software companies, relational data model still has its advantages in solving all kinds of data. Extensions for spatial data handling have enabled relational database to deal with geo-spatial problems to a certain extent. Hybrid and integrated data models, which are derived from pure relational data model, are developed for GIS, and adopted by several GIS software developers, such as ESRI, INTERGRAPH and Caliper (Caliper Corporation, 1999; Healey, 1991). In this research, TransCAD, a transportation GIS software package of Caliper Cooperation, is used to implement the data model. It uses an extended relationship database to manage the spatial data. It has its own format to record spatial data of transportation network, and use relational database to store attribute data of transportation features (Caliper Corporation, 1999). Also, as it has fairly exhaustive functions on handling GIS-T problems, flexible and powerful function on network editing, and is considered as probably the best-known software specialized for GIS-T (Waters, 1999), it is adopted as the platform for the study of GIS-T prototype. Under the environment of TransCAD, the data model for the multi-modal public transportation system can be practiced on a computer.

3.7 Criteria for Routing on the Multi-modal Public Transportation System

Passengers' decision process for a trip is very complicated. Every person may have his/her own criterion for route choice. Moreover, even the same person may have different criteria under different conditions. In a multi-modal based public transportation system, the condition becomes even more complex. Passengers may face different traffic modes. Some may like to travel by train instead of bus, while others prefer to take a bus rather than a train. It is a kind of habit. These have much to do with behaviour study. Many studies have been done in this field (Hickman & Wilson, 1995; Ndoh, Pitfield, & Caves, 1990; Vaziri & Deacon, 1985), and still keep on going. This paper does not attempt to touch these issues for limited time and energy. So a few routing criteria are presumed that are adopted by passengers for decision making of a route choice. Time and cost are considered as the most important aspects of transportation (Tate-Glass, Bostrum, & Witt, 2000). Also, travel time and fare are very important factors for the public transportation and often be used as the measurement of route choice. In a mass transit system composed of multiple modes, another factor cannot be omitted, that is transfer, because it means that extra time and efforts are needed. So, based on the above factors that are usually considered in route choice on the multi-modal public transportation system, three routing criteria are presumed in this paper. They are least-time, least-fare, and least-transfer criteria for route choice.

3.7.1 Least-time Routing

Time is one of the mostly accepted measurements for travel efficiency (Tate-Glass et al., 2000). When finding a least-time route on a network, usually, costs at nodes are ignored and only time consumptions of links are included in least-time routing, especially for a car driver. Among all feasible routes that connect the origin and the destination, the route that has the minimum total time costs of its links is considered as the routing result. This can be presented as following,

$$T = \underset{i}{Min}(\sum_{j} L_{ij})(i = 1,2,...,m; j = 1,2,...,n_i) \qquad (1)$$

in which, m is the number of feasible paths, n_i is the number of links in the ith feasible path, and L_{ij} is the time cost for the jth link of the ith path.

However, the cost at nodes (usually indicate intersections) can hardly be ignored in most cases. Especially for routing in a small scale, time cost on intersections take quite a portion of the total travel time. It should be included in the travel time. Delays of intersection movement are considered for calculating shortest paths with the following functional equation (Kirby & Potts, 1969; Ziliaskopoulos & Mahmassani, 1996):

$$C(l_l, l_k) = \min_{l_i \in B(l_k)} \{C(l_l, l_i) + c(l_i) + p(l_i, l_k)\}, l_k \neq l_l \quad (2)$$

$$C(l_l, l_l) = 0 \quad (3)$$

where $C(l_l , l_k)$ is the cost of an admissible path from the end of link l_l to the beginning of link l_k, $c(l_i)$ is the travel time on link l_i, $p(l_i , l_k)$is the delay associated with the movement from link l_l to link l_k and $B (l_k)$ is the set of links upstream of l_k.

The same condition happens in a multi-mode based public traffic service network. Time consumption happens not only at links, but also at some special nodes, that is, transfers. Sometimes, passengers transfer to other public traffic service route for several times to get their destinations. At transfers, they may spend several minutes to walk from one stop on current service route to another stop on a new service route, and they have to wait for a while waiting for the vehicle coming on the new service route. So the total time consumption for passengers travel on a multi-modal public transportation system can be divided into three parts:

1) time cost of route links (*L*), or in-vehicle time;

2) time used for walking from current service route to a new service route at transfers (*W*);

3) time of waiting for vehicles coming at transfers (*D*).

Thus, the least-time route in a multi-mode based public traffic service network should be

$$T = \underset{i}{Min}\{\sum_{j}^{n_i - 1}(L_{ij} + W_{ij} + D_{ij}) + L_{in_i}\}(i = 1,2,\ldots,m; j = 1,2,\ldots,n_i) \quad (4)$$

in which, n_i is the number of links in the ith feasible path, W_{ij} and D_{ij} are the walking time and the waiting time at the jth link's end node in the ith path, respectively. If there is no route change at the jth link's end node, values of W_{ij} and D_{ij} will be both set zero.

3.7.2 Least-fare Routing

Under least-fare routing, passengers try to finish their travel with least money. Fares for different public traffic service routes during a travel are added up to give a result. Because fare determination of mass transit service depends on a series of complicated factors, it is not simply a linear variable to distance. The value of fare cannot be simply attached to a links as its attribute. It will be better to use a matrix to record fares for each mass transit route. Then, for every pair of stops on that route, a value is clearly given. For every path in the multi-modal public transportation system, it can be broken down into several segments served by different routes (each segment involves only one traffic route). Boarding and alighting stops for each service segment are used to get the value of fares from fare matrix of each route. The sum of all fares of different routes is the total cost of the travel. The path that has the least cost is the routing result.

3.7.3 Least-transfer Routing

For least-transfer routing, passengers like to encounter as least transfers as possible in order to avoid the efforts of walking between stops and waiting for vehicles. The number of service route changes is recorded during travelling. Information recorded for transfers can help us to do it. A new field named change can be added to record the mode (route) changes in the transfer table. If the route type of *From* link is different from *To* link at a transfer, 1 is given to this field. Otherwise, 0 is given. During routing, the number of route changes is accumulated by this field to give a result.

It is not an easy work for passengers to select a reasonable path among numerous routes in the service network based on the criterion mentioned above. Then GIS-T, with the help of proper routing algorithms, can perfectly solve the problem. For every pair of origin and destination, the system will give a result path with the minimum value measured in time, fare, or the number of transfers. Because all these weights of the network are nonnegative and links in the network are directed, this kind of routing problem can be considered as a single-source shortest-paths problem on a nonnegative weighted, directed graph. Then, Dijkstra's algorithm for single-source shortest path problems can be applied. Adding the components for transfers, using relevant attributes as the factor to be considered, the algorithm can give the shortest path on the multi-modal public transportation system according to different routing criteria in GIS-T.

3.8 Summary

In this chapter, efforts are focused on the modeling process for the multi-modal public transportation system, following the five stages of an elaborated GIS modeling process discussed by Worboys. Based on the definition of the multi-modal public transportation system, which is a complicated mass transit service network served by different traffic modes or routes, a layer-cake based application domain model and a conceptual model in E/R diagram are discussed following the analysis of the mass transit system in the real world. Subsequently, attempts are made on corresponding logical and physical implementation of the data model with extended relational database. As routing is one purpose of constructing a general network for the multi-modal public transportation system, routing criteria on such a network are mentioned after the modeling process. In this paper, three types of criteria are assumed that can be accepted by passengers for route decision. They are least-time routing, least-fare routing, and least-transfer routing, caring about time, fare, and change factors during traveling, respectively. Problems that should be noticed in multi-modal routing under different criteria are mentioned in the discussion. The data model discussed in this chapter will be implemented with a GIS-T prototype for the multi-modal mass transit system on Hong Kong Island later.

CHAPTER IV

DATA PREPARATION FOR THE STUDY AREA

4.1 Introduction

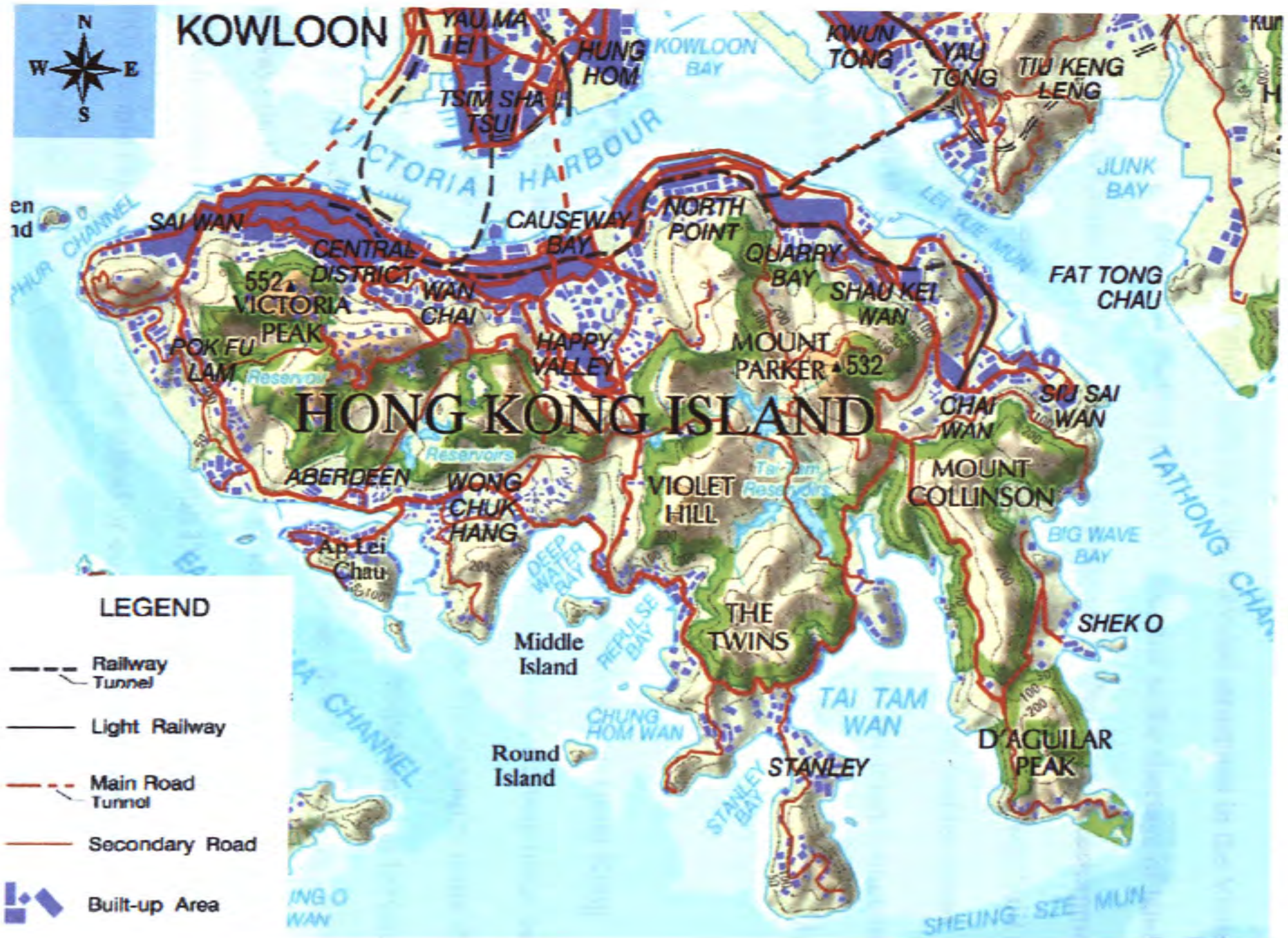
This chapter aims at preparation works for constructing a GIS-T prototype for routing on the multi-modal public transportation system on Hong Kong Island. As the study area, the basic geographical information of Hong Kong Island and its mass transportation system are introduced at the beginning of this chapter. Part of its mass transit system, including multiple modes, is used to construct the prototype. Preparation works on geographical and attribute data about selected routes are described in the following part, including data collection, data transformation, data integration, and data input. After these works, the data are ready for the prototype construction.

4.2 The Study Area: Hong Kong Island

4.2.1 General Information of the Transportation System on Hong Kong Island

Hong Kong Island is the most developed area in Hong Kong. The area of Hong Kong Island is 80.30 square kilometers, only 7.3% of total area of Hong Kong territory. The total length of road network on Hong Kong Island is 425 kilometers by the year of 1999, which is 22.7% of total constructed roads of Hong Kong (Census & Statistics Department of Hong Kong, 1999).

The road framework on Hong Kong Island can be abstracted into three lines that run in north-south direction and one line running in west-east direction (see Figure 4.1). First road built in Victoria on Hong Kong Island now goes round the



Source: Land Department of Hong Kong SAR

Figure 4.1 Transportation network on Hong Kong Island west of the island via Pok Fu Lam to Aberdeen in the south. Two more roads were built running north-south on the island. one across the middle of the island through Aberdeen Tunnel, which was put into action in 1982 and connects Aberdeen and Happy Valley directly, and the other round its eastern end. The west-east running road is on the north shore, mainly built on either elevated structures in the Victoria Harbour or as a ground level road on reclaimed land, due to the shortage of land. The road runs from Central to Causeway Bay, and extends to Chai Wan in easternmost part. An aided west-east scheme to alleviate the congestion at Central was built along Connaught Road through Central via the Rumsey Street Flyover, Pedder Street Underpass and the Harcourt Road Flyover. These roads form the main framework of road network on Hong Kong Island (Highways Department of Hong Kong SAR, 2000).

The public transportation system is also well developed on Hong Kong Island. Along the transportation infrastructures including roads, subway track, and tramline, hundreds of service routes are serving the public. For example, more than 100 bus routes running within the island, around sixty bus routes running between island and outside island through Cross Harbour Tunnel, five subway lines and eight tramways on the north part of island, and about thirty ferry routes taking passengers to Kowloon and other islands (Transportation Department of Hong Kong SAR, 2000). People can easily travel in the island or outside the island by these mass traffic services.

4.2.2 Reasons for Choosing Hong Kong Island as the Study Area

Several reasons can be given for using Hong Kong Island as the study area to set up the GIS-T prototype for the multi-modal public transportation system:

1. A closed and limited area: Hong Kong Island is a small island surrounded by sea. It has a clear and natural boundary and is comparatively a separate area. The area of the island is 80.3 square kilometers, which can be considered quite small. It is easy to get familiar with the area and understand its situations.
2. A typical area: Although Hong Kong island is quite small, it is not harm to its representativeness. Hong Kong Island is the first built-up area of Hong Kong. Road network and public traffic service are well developed. Its public transportation system is multi-modal based, including bus, subway, tramline, and ferry routes.
3. Information available: data is very important element for a GIS system. Without suitable data, the system is of no use. Hong Kong Island is the busiest area of Hong Kong, and detailed information can be captured from many sources, such as government, traffic service companies, and transportation directory books.

For the above reasons, Hong Kong Island is feasible as a study area for this study. Then data capture and preparations of this area for the prototype are processed subsequently.

4.2.3 Mass Transit Routes Selected for the Prototype

As there are nearly 200 bus service routes, five subway routes, eight tramlines, and tens of ferry routes on Hong Kong Island, it is impossible and not necessary to put all the service routes into the prototype, due to the limited time and energy. Part of the mass transit system is selected to construct the prototype. It includes thirty bus routes, five subway routes, and eight tramline routes. The set of selected routes contains different kinds of traffic modes (bus, subway, and tramline), and also different routes of same traffic mode (different routes of bus, subway, and tramline), so it has basic characteristics of multi-mode and can be considered as a representative of the multi-modal public transportation system. Information of selected mass transit routes is listed in Table 4.1.

4.3 Data Source and Data Collection

Information appears as data in a GIS system, which is readily processed by computer. Data is basic element of a GIS system. It not only contains information it shows, but also implies information not discovered yet. Having the right data in right format is of great importance for study and analysis (Turner & Bespalko, 2000). So collection of suitable data is preliminary step for constructing a database. Data category can be divided into two broad classes, spatial data and non-spatial data. Spatial data is what indicates position information and later can be used for cartographic purpose, such as the series of coordinates of road central lines. Non-spatial data, also called as attribute data, is what records the characteristics of ground entities, for example, route number of a bus service route. Also, data can be classified as their functions in the system. The data needed in the system are:

Table 4.1 Public transportation service routes selected in this study

Bus service route (by CityBus Company)				
Route No.	**From**	**To**	**Time***	**Headway (Min)**
1	Central (Rumsey Street)	Happy Valley (Upper)	06:45-23:03 (06:30-23:33)	10-20
3B	Central (Rumsey Street)	Pokfield Road	06:30-23:52 (06:57-23:25)	7-13
5	Causeway Bay (Whitfield Road)	Kennedy Town	06:00-00:00 (05:25-23:36)	10-15
6	Central (Exchange Square)	Stanley Prison	06:00-01:00 (06:00-00:00)	10-30
7	Central (Ferry Piers)	Shek Pai Wan	05:45-01:00 (05:15-00:30)	10-15
8X	Siu Sai Wan	Admiralty (Rodney St.)	05:30-00:00 (06:00-00:45)	10-15
10	North Point Ferry	Kennedy Town	05:00-00:00 (06:25-01:00)	5-10
11	Jardines Lookout	Central (Ferry Piers)	06:30-23:50	6-15
12	Central (Ferry Piers)	Robinson Road	06:45-23:30	9-15
25A	Wan Chai (HK CEC Extension)	Braemar Hill	06:37-00:22	10-15
37A	Chi Fu Fa Yuen	Admiralty	06:36-23:06	6-12
40	Wah Fu (North)	Wan Chi Ferry Pier	06:00-23:00 (06:37-23:48)	7-15
41A	Wah Fu (Central)	North Point Ferry Pier	06:30-23:00 (06:45-23:00)	10-15
47A	Wah Fu (North)	Admiralty MTR Station (West)	06:15-23:00 (07:00-23:45)	10-15
48	Wah Fu (North)	Wong Chuk Hang	06:00-00:00 (05:40-23:45)	5-15
70	Central (Exchange Square)	Aberdeen	05:50-00:10 (05:30-23:50)	6-15
71	Central (Ferry Piers)	Wong Chuk Hang	06:15-00:10 (05:35-23:30)	10-15
72	Wah Kwai	Causeway Bay (Moreton Terrace)	05:10-00:00 (06:00-00:30)	4-10
73	Wah Fu (North)	Stanley Prison	05:30-23:00 (06:20-23:45)	15-25
77	Tin Wan	Shau Kei Wan	06:00-23:06 (07:09-00:15)	12-23
85	Siu Sai Wan	North Point Ferry Pier	06:30-23:30 (06:30-00:00)	6-12
90	Ap Lei Chau Estate	Central (Exchange Square)	05:55-00:25 (05:20-00:25)	5-15
96	Lei Tung Estate	Causeway Bay (Moreton Terrace)	05:50-00:00	8-15
99	South Horizons	Shau Kei Wan	06:45-00:00 (06:00-00:00)	12-15
260	Central (Exchange Square)	Stanley Prison	07:12-00:00 (06:36-23:40)	10-15

Table 4.1 Public transportation service routes selected in this study (Cont'd)

Bus service route (by CityBus Company) (Cont'd)

Route No.	From	To	Time	Headway (Min)
515	Sai Wan Ho	The Peak	19:30-23:30 (20:15-00:15)	15-20
780	Siu Sai Wan	Central	05:30-23:16 (06:10-00:00)	6-16
788	Siu Sai Wan	Central (Macau Ferry)	06:00-23:08 (06:40-23:51)	5-12
N72	Wah Kwai	Quarry Bay (Hoi Chak Street)	00:10-05:00 (00:30-05:40)	10-20
M5	Kennedy Town	Central	06:00-00:00	12-15

Subway route service (by MTR)

Route	From	To	Time	Headway (Min)
Tsuen Wan Line	Tsuen Wan	Central	06:00-00:30 (06:06-00:54)	2-6
Kwun Tong Line	Yau Ma Tei	Quarry Bay	06:01-00:50 (06:04-00:44)	2-6
Island Line	Sheung Wan	Chai Wan	06:05-00:56 (05:55-00:35)	2-6
Tung Chung Line	Hong Kong	Tung Chung	06:01-00:50 (06:01-00:50)	2-6
Airport Express	Hong Kong	Airport	05:50-00:48 (05:54-00:48)	2-6

Tramline service (by Tramway Hong Kong)

Route	From	To	Time	Headway (Min)
1	Shau Kei Wan	Sheung Wan Market	06:00-22:04 (06:08-22:40)	4
2	Shau Kei Wan	Happy Valley	06:06-22:31 (06:38-22:44)	6
3	North Point	Whitty Street	06:00-23:12 (05:24-22:32)	4-8
4	Happy Valley	Kennedy Town	06:03-00:31 (05:59-23:55)	4-8
5	Causeway Bay	Sheung Wan Market	07:39-17:56 (07:33-17:59)	3
6	Shau Kei Wan	Kennedy Town	06:28-18:13 (07:26-18:13)	5-8
7	Causeway Bay	Kennedy Town	07:10-17:30 (07:30-17:30)	8
8	North Point	Kennedy Town	13:09-20:57 (12:16-19:57)	12

* Running time for weekdays (running time for weekends)

1) Basic geographical data of Hong Kong Island: such as coastal line of Hong Kong territory, roads and buildings on Hong Kong Island, using as a background of the transportation network. Although they are not important in routing analysis, they are useful for people to find the position with the help of familiar environment.
2) Transportation infrastructure information: for example, road central lines, railways, and tramlines on Hong Kong Island. They are physical facilities for the public traffic service.
3) Route service information: including service routes, stops, and schedules of public transit services.
4) Transfer information: such as position of a transfer and cost for transferring.

Spatial and non-spatial data needed in this thesis shown above exists in various formats. Geographical information data mainly exists as maps, such as the base map of Hong Kong Island and transportation infrastructure network maps, but also some is in text. Non-spatial public traffic service information data mostly exists in text, such as service schedule, names of service routes and stops.

The Lands Department of Hong Kong SAR government is a professional department for surveying and mapping in Hong Kong. It provides a series of base maps and thematic maps on different map scales, from 1:1000 to 1:20000, both in paper and digit. The public can easily purchase maps by filling a certain application form. So base maps of Hong Kong Island and road central lines can be reached from the Lands Department of the government.

Public traffic services are shared by several different companies, either private or governmental. Each company holds only information of public traffic routes served by itself. Service routes, service schedules, fares, and stops information can be reached from these companies, respectively. They provide text-based information for their service, and some even distribute information through the Internet.

Also, there are published maps and directories on transportation in Hong Kong. Some have detailed information on roads, buildings, and public transport information. These can also be considered as good data sources.

In brief, data of the mass transit system on Hong Kong Island can be collected from various sources in different formats. Data sources of the prototype in this paper are listed in Table 4.2.

4.4 Geographical Data Preparation

The geographical data collection is in different types, such as digital map, paper-based map, and text-based coordinates. All the data should be transformed into a unique format and managed together. Most GIS packages use extended relational database to store and manage GIS data. So is TransCAD, the tool for the study. It is used to manage the data for the study area in this paper.

Table 4.2 Data sources for the study area

Data	Provider	Format	Remarks
Base map of Hong Kong	The Lands Department of Hong Kong	Digital	• 1: 20,000 • Hong Kong coastal line
Base maps of Hong Kong Island	The Lands Department of Hong Kong	Digital	• Two map sheets of B20000 series: T11, T15 • 1: 20,000 • Including buildings, railways, tramlines, and double-line-based streets of Hong Kong Island.
Road central line of Hong Kong Island	The Lands Department of Hong Kong	Text	• Four map sheets of G1000 series: T11SW, T11SE, T15NW, T15NE • 1:1,000
Citybus service routes information	Citybus Limited	Text	• Including routes, schedules, and fares.
MTR routes information	MTR Corporation	Text	• Including routes, schedules, and fares.
Tram routes information	Hong Kong Tramways Limited	Text	• Including routes, schedules, and fares.
Public transportation information	Hong Kong Directory, Hong Kong City Guide 2000	Text/map	• Including routes, fare, and transfer information

Among the different types of geographical data colleted, maps are the most commonly used type for geographical data storage, such as base maps of Hong Kong Island. With a series of principles and methods, ground features are drawn on maps in abstracted symbols and their positions can be accurately measured referring to mapping parameters. Also, some spatial information exists in coordinate pairs to indicate positions in a specified two-dimensional coordinates, such as road central lines are recorded in coordinate pairs of longitude and latitude. These data can be located on a map under proper projection. Another type of geographical information is text-based location descriptions. It usually records relative positions of ground features referring to land marks, such as 200 meters east to the railway station. It is widely accepted by the public. This method is adopted by public traffic companies showing mass service routes. Special techniques are needed to change these data into maps. Moreover, the data are in different computer formats. In order to organize the data in the environment of TransCAD, some conversion works should be finished before geographical data input.

4.4.1 Data Conversion

Data collected for the study area are in various types and different formats. They should be converted into TransCAD format and co-registered in order to work together. Figure 4.2 shows the general process for the geographical data conversion of the study area. It indicates the common processes, so not all data transformation processes restrictedly following the steps. Some data can be transformed directly to co-registered TransCAD geographical files.

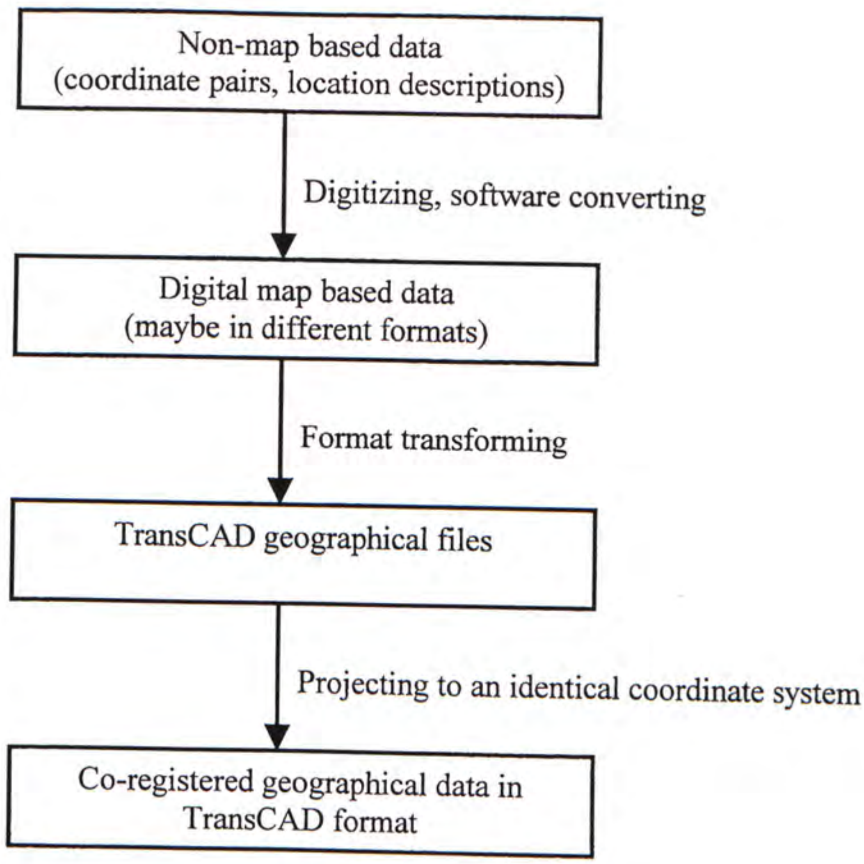


Figure 4.2 Data conversion process of the study area

(1) Converting non-map based data into digital map based data

There are two types non-map based geographical data in the data sources of the study area. One is coordinate pairs based road central line on Hong Kong Island, and the other is location description based public transport service route information. As route information can be input into the computer based on constructed network in TransCAD environment, its input is talked in the later part of this section. In this part, efforts are focused on conversion of road central line.

The data of road central line is given in text-based coordinate pairs (see Figure 4.3). Because digitized by the Land Department of Hong Kong SAR based on paper-based maps, the data of road central line on Hong Kong Island is in more than

100 files as in map sheets instead of a single data file. Each file name is after its relating sheet map serial number. Road central lines are recorded in the file as a sequential coordinate pairs in Hong Kong 1980 Grid System with a line number at its beginning and an 'END' at its end. An extra 'END' at the end of the file to show the finish of a file.

```
15nw10d.txt
        1
        0.844253766109000D+06          0.810146860874000D+06
        0.844267445499000D+06          0.810138827992000D+06
        0.844273184170000D+06          0.810134762570000D+06
        0.844295671753000D+06          0.810114582404000D+06
        0.844308950771000D+06          0.810101798367000D+06
END
        2
        0.844308950771000D+06          0.810101798367000D+06
        0.844274185101000D+06          0.810084165212000D+06
        0.844270515021000D+06          0.810081128391000D+06
        0.844267045127000D+06          0.810076279273000D+06
        0.844252831906000D+06          0.810043315069000D+06
END
        3
        0.844338378142000D+06          0.810020832797000D+06
        0.844345451388000D+06          0.810045617176000D+06
        0.844345718302000D+06          0.810052131647000D+06
        0.844343249339000D+06          0.810060066567000D+06
        0.844339579259000D+06          0.810067707600000D+06
        0.844327034257000D+06          0.810083773364000D+06
        0.844316958219000D+06          0.810094647143000D+06
        0.844308950771000D+06          0.810101798367000D+06
END
        4
              ...                              ...
END
END
```

Figure 4.3 Original data format of road central line

First, all data files of the study area are joined into one file. It is not a simple work of joining files together. An editing job should be done when joining the files. Because each line should have a unique identity number among the study area to differentiate itself from others, original line number is extended with the serial number of its file name, which means the number of map sheet containing the line.

A nine digital number is used to identify each road central line segment. First two digits are the map sheet number in scale of 1:20000, 11 or 15. The third digit is the location in four parts of a 1:20000 map, using 1, 2, 3, and 4 to indicate SE, SW, NE, and NW. The following two digits are number of zone in each part, from 01 to 25. The sixth digit is the number of another quadrifid zone, using 1, 2, 3, and 4 to indicate a, b, c, and d. The last three digits are line number in each file. For example, line number 9 in file nw10d.txt of map sheet 15 is numbered as 153104009. Then each line has a unique identity number, and data can be processed further. Figure 4.4 shows part of the joined data file after necessary editing.

```
          153104001
          0.844253766109000D+06          0.810146860874000D+06
          0.844267445499000D+06          0.810138827992000D+06
          0.844273184170000D+06          0.810134762570000D+06
          0.844295671753000D+06          0.810114582404000D+06
          0.844308950771000D+06          0.810101798367000D+06
END
          153104002
          0.844308950771000D+06          0.810101798367000D+06
          0.844274185101000D+06          0.810084165212000D+06
          0.844270515021000D+06          0.810081128391000D+06
          0.844267045127000D+06          0.810076279273000D+06
          0.844252831906000D+06          0.810043315069000D+06
END
          153104003
          0.844338378142000D+06          0.810020832797000D+06
          0.844345451388000D+06          0.810045617176000D+06
          0.844345718302000D+06          0.810052131647000D+06
          0.844343249339000D+06          0.810060066567000D+06
          0.844339579259000D+06          0.810067707600000D+06
          0.844327034257000D+06          0.810083773364000D+06
          0.844316958219000D+06          0.810094647143000D+06
          0.844308950771000D+06          0.810101798367000D+06
END
          153104004
              ...                              ...
END
END
```

Figure 4.4 Road central line data after processing

This data file contains the coordinate information, so it can be inputted into computer to generate geographic map by GIS software. This data format is recognized by ARC/INFO as *.lin file, and can be used to create a geographic map. After input the data file, a coverage file with an extension E00 is generated. Then it can be imported into another format named by ESRI as *.shp file (see Figure 4.5), which can be opened by ARC/VIEW, another ESRI's product.

(2) Transforming geographical data in other formats into TransCAD files

Base map (1:20000) of Hong Kong Island purchased from the Lands Department of Hong Kong SAR government is in ESRI ARC/INFO *.E00 format. It contains several coverages of Hong Kong Island, including double-line streets, buildings, railways, and hydrological entities. Street layer, building layer, and railway layer are useful in the prototype. These layers can be imported into *.shp files, the same format as the road central line generated for coordinate pairs. TransCAD can successfully converts geographical files in *.shp format into its own geographical file format, *.dbd file.

The total process of file conversion can be described as below:

*.txt → *.lin (Arc/Info) → *.E00 (Arc/Info) →*.shp (Arc/View) →*.dbd (TransCAD).

(3) Co-registering all generated TransCAD geographical files

In order to match different layers together, a uniform coordinate system should be applied to all geographical data of the study area. World coordinate system (longitude and latitude) is adopted in this research. Because the coordinate system of

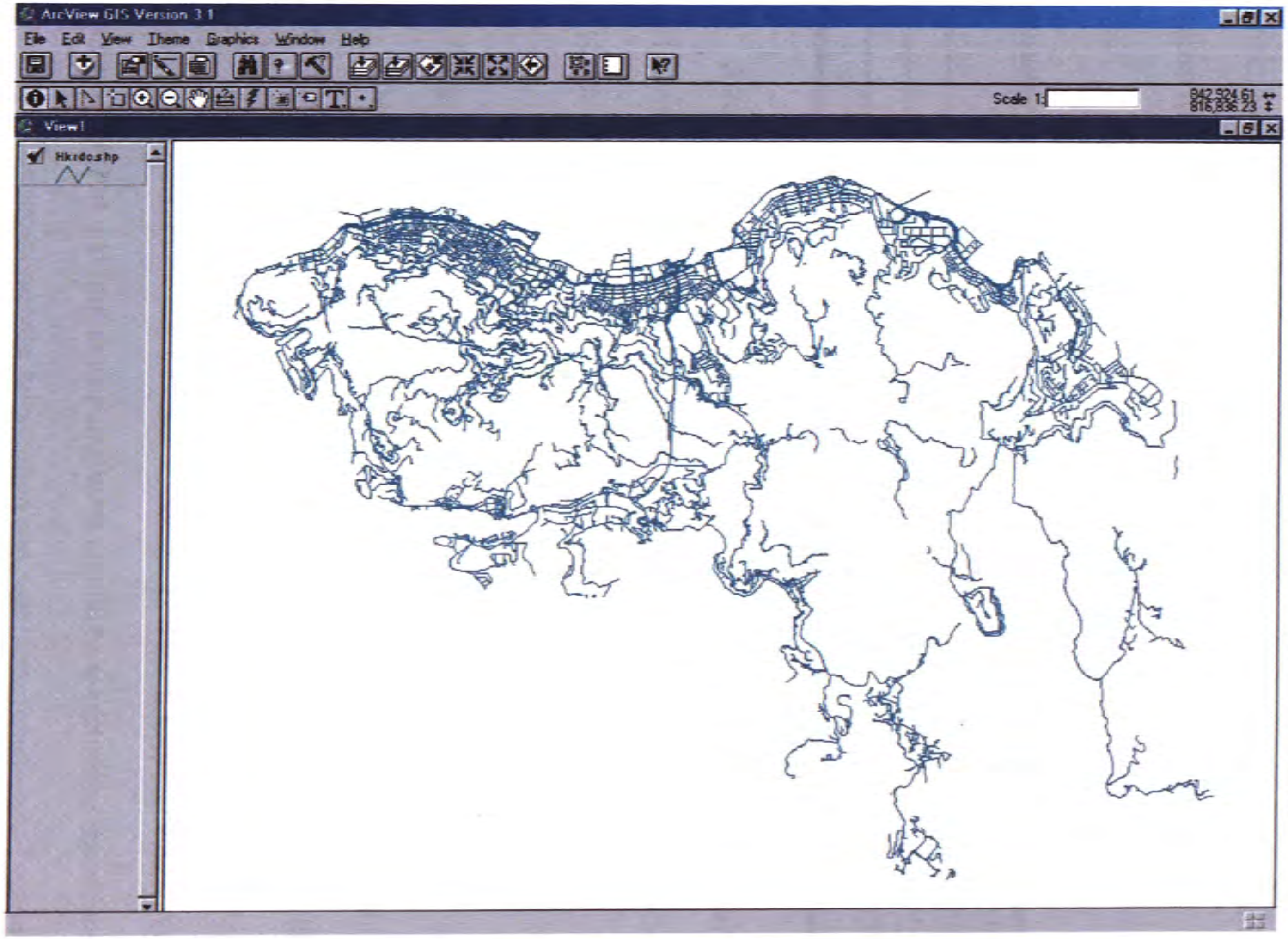


Figure 4.5 Geographical data of road central line on Hong Kong Island in Arc/View *.shp file after converting

road central line is Hong Kong 1980 Grid, it should be transformed into world coordinate system. Parameters are needed for transformation. TransCAD adopts simple linear interpolation method to reach the transformation, so coordinates of three control points in Hong Kong 1980 Grid System and World Coordinates System are given to set up the transformation function. Their corresponding relationship can be drawn from standard Hong Kong Map (see Table 4.3).

Table 4.3 Parameters for projection transformation in TransCAD

	HK 80 Grid System		World Coordinate System	
	x	y	Longitude	Latitude
1	830,000	812,000	114.1161°E	22.2468°N
2	845,000	812,000	114.2616°E	22.2468°N
3	845,000	824,000	114.2616°E	22.3551°N

After transformation, all geographical data are in the same projection system, World Coordinate System, and in the same file format, TransCAD geographical file format. Then, these data are ready for use.

4.4.2 Geographical Data Input

When data input into the system, we may encounter two cases. One is that data is already in digital format. After processing the format transformation, data can be input the system directly, and only few editing work need be done later, such as road central line and basic map of Hong Kong Island. The other is that data is not ready for use. Effort and time consuming work should be overcome to input data into the system, such as route service information and route service network. To deal with this kind of data, we simply input the data under the environment of TransCAD, with the help of information collection form public traffic service companies and maps and directories of Hong Kong.

(1) The basic layer of Hong Kong Island

This layer is only used as a background of other layers over it. It can help users easily find the position with a familiar environment.

This layer contains Hong Kong coastal lines, double-line streets, and buildings on Hong Kong Island. Data of these themes is already in digital format and has been transformed into the format acceptable of TransCAD. They can directly join into the system. Figure 4.6 is the map of the basic layer of Hong Kong Island. The blue part is the sea around Hong Kong Island and the light yellow part is the land of Hong Kong Island. Brown lines in the land part are double-line based streets on the island, and gray blocks are buildings.

(2) Transportation infrastructure network

Transportation infrastructure network is composed of all kinds of physical facilities of different traffic modes, including road central lines, railways, subways, tramlines, and water routes. In the prototype system, we include only road central lines, subways, and tramlines. Data for these entities is already in digital format and transformed, so they can just put together to form an integrate network. Figure 4.7 shows the transportation infrastructure network layer combining multiple modes.

(3) Route system information

In route system layer, spatial information of public traffic service will be recorded, such as locations of service routes and stops. Different traffic modes will run on different physical infrastructures. Subway routes will run on the subway lines, tram routes will operate on tramlines, and bus routes will go on roads. All service

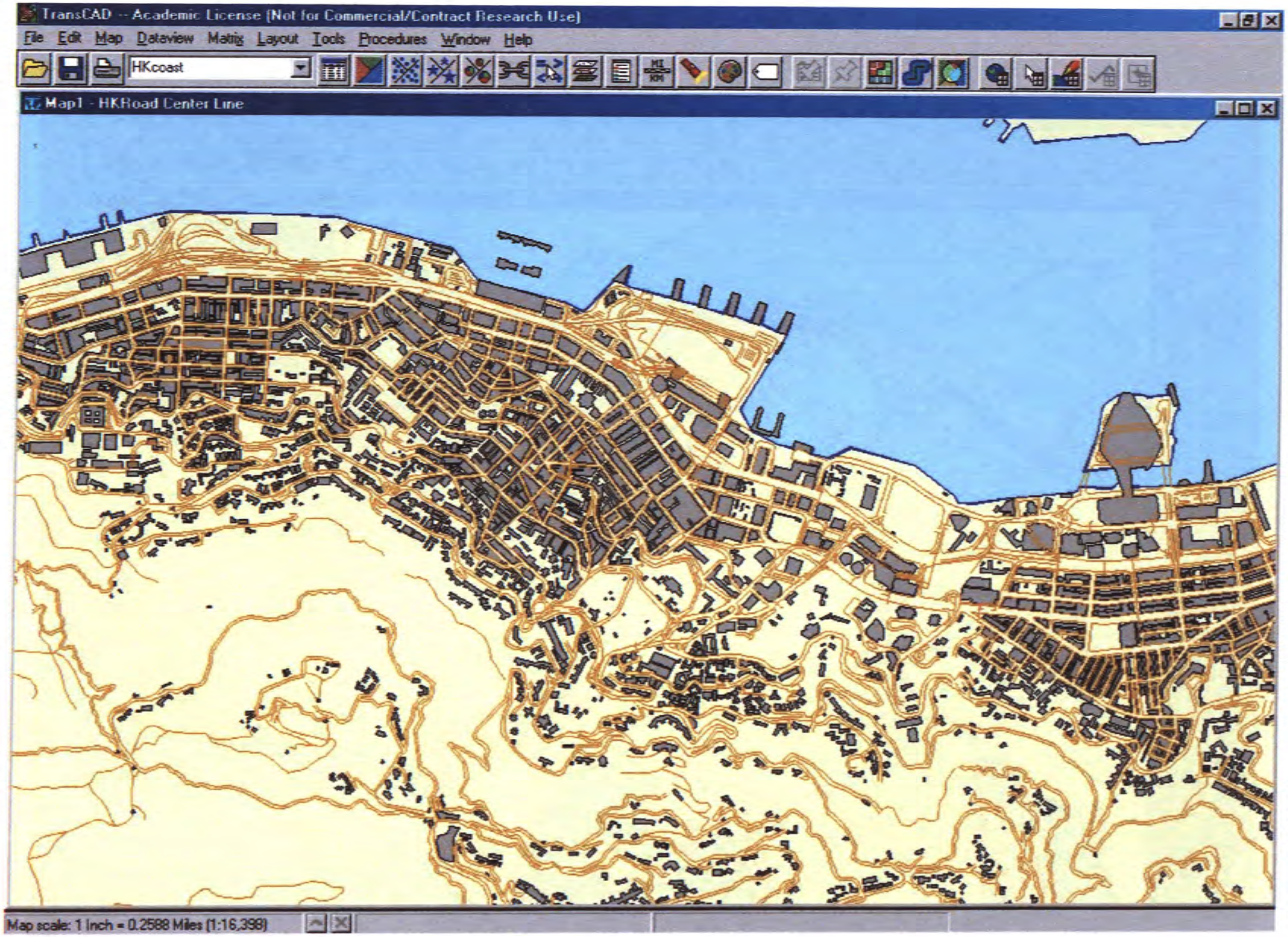


Figure 4.6 Base map of Hong Kong Island with coastal line, streets, and buildings

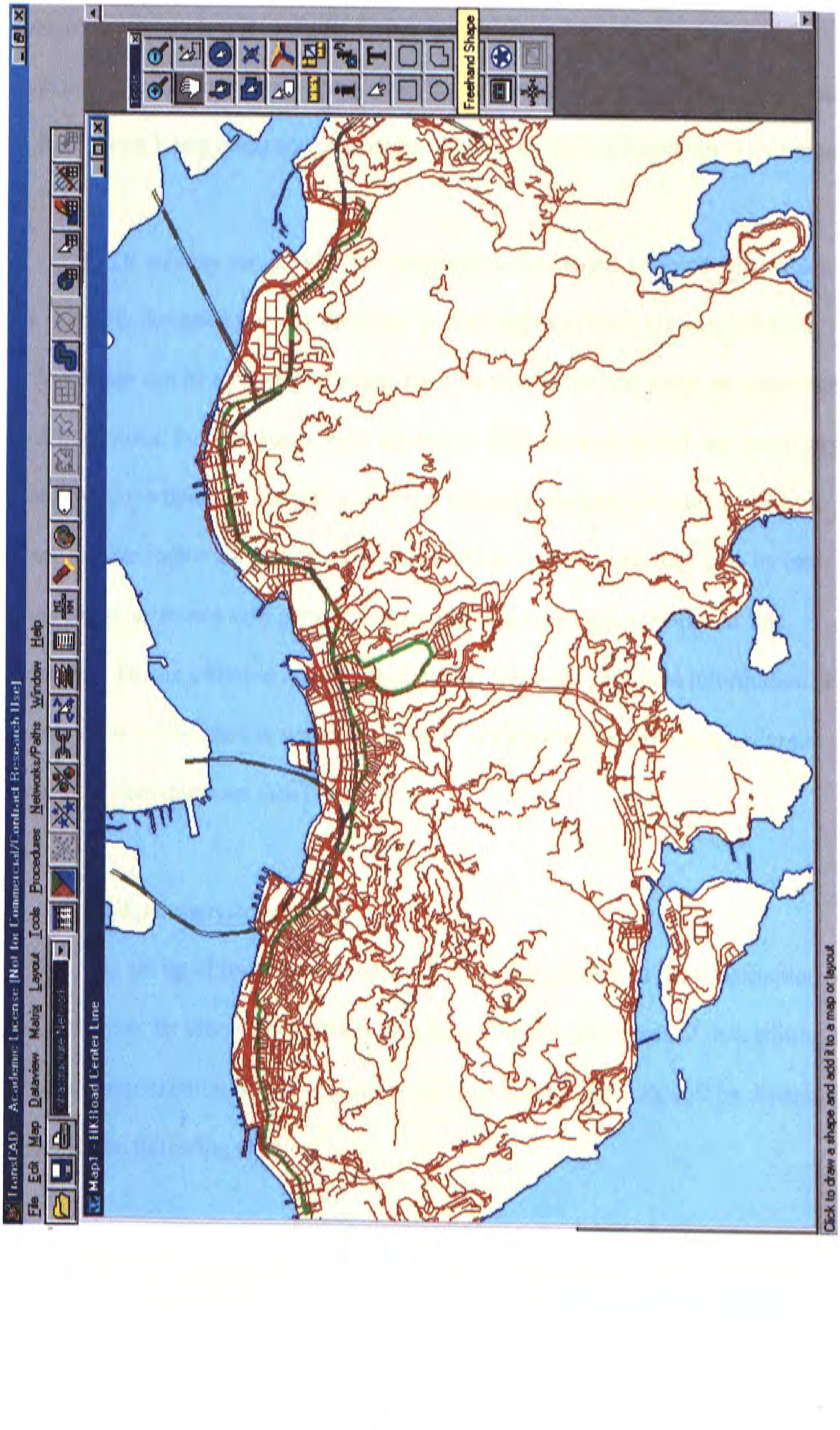


Figure 4.7 Infrastructure layer of Hong Kong Island

routes have to depend on physical infrastructures that already exist. So each service route is a set of line segments in infrastructure layer that are used by it. Unlike basic map, route system is not in digital format ready. The information is collected from each public traffic service company directly, or from their public service homepage, or from Hong Kong maps and directories. Almost all their information is text-based.

MTR subway service and Tramway service are based on fixed rails, which are specially designed for only their use, so their service routes are comparatively less and also can be easily figured out. Their service routes and stops are more stable than bus routes. For bus routes, they depend on road network, which has much larger mobility scope than rail network and is not specially designed for only bus's use. Their service routes are recorded in a series of street names that they pass by (see Figure 4.8), or from a GIS perspective, in a special collection of series of line segments. This is a kind of location description based geographical information. The information can be used to generate the route system map by digitizing under the TransCAD environment (see Figure 4.9).

(4) Route service network

The set up of route service network is the key process of the construction of the prototype. Its setup is not simply data input, but also a process of data editing and structure organization, so the generation of route service network will be discussed in detail in the following chapter.

Bus No.1: Rumsey Street Bus Terminus ↔ Happy Valley (Upper) Bus Terminus

Up Route: Pier Rd → Gilman St → Connaught Rd Central → Harcourt Rd → Tree_ Drive → Queensway → Hennessy Rd → Fleming Rd → Wan_Chai_Rd → Morrison Hill Rd → Sports Rd → Wong Nai Chung Rd → Sing Woo Rd → Blue Pool Rd → Green Lane → Broom Rd.

Down Route: Blue Pool Rd → Sing Woo Rd → King Kwong St → Shan Kwong Rd → Wong Nai Chung Rd → Morrison Hill Rd → Wan Chai Rd → Fleming Rd → Hennessy Rd → Queensway → Des Voeux Rd Central → Wing Wo St → Connaught Rd Central → Rumsey St

Bus No. 3B: Rumsey Street Bus Terminus ↔ Pokfield Road Bus terminus

Up Route: …

Down Route: …

…

Figure 4.8 Text-based bus routes information

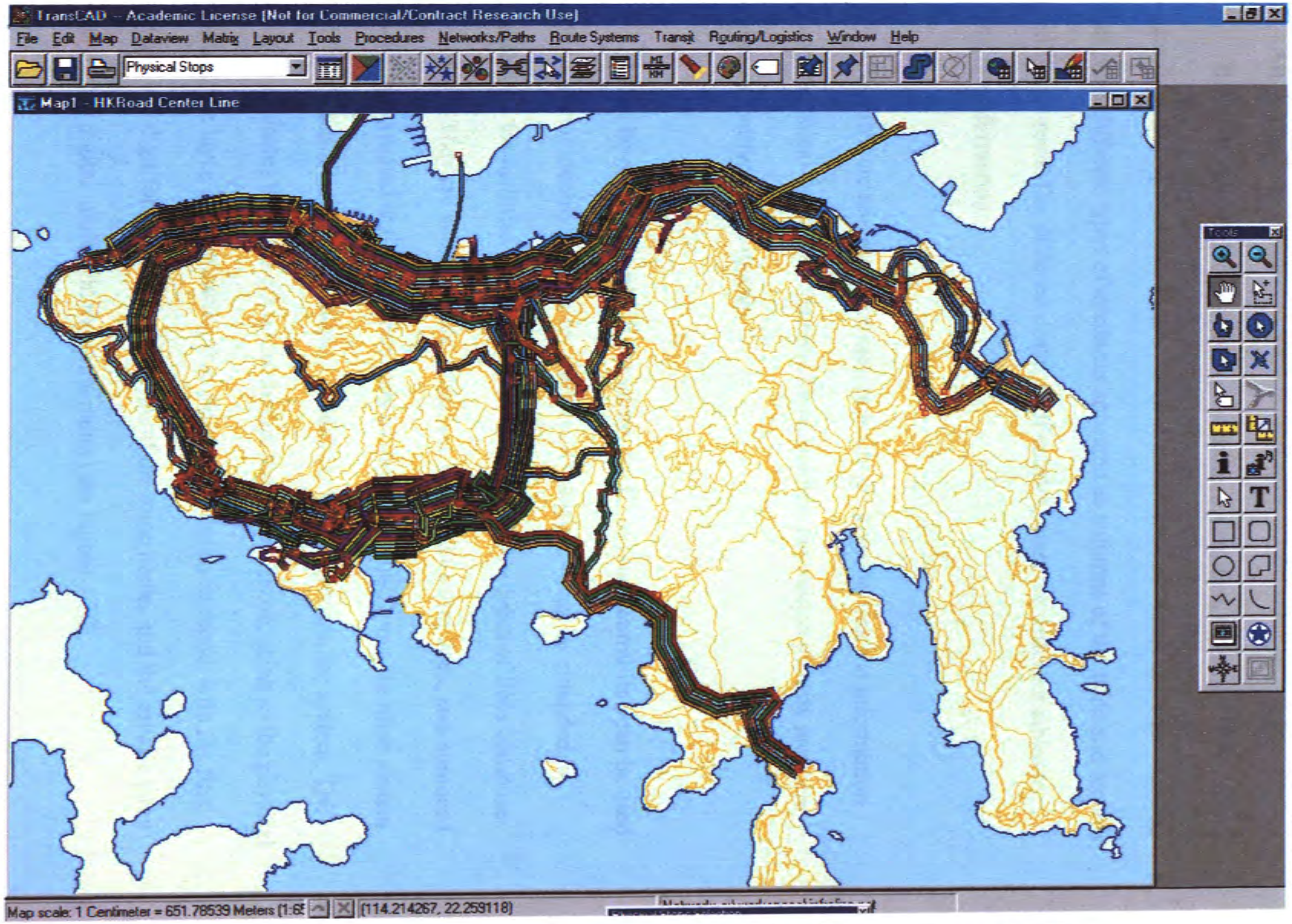


Figure 4.9 Map of route system of the study area including different routes and modes

4.5 Attribute Data Input

Besides the spatial data showing locations for entities, there are attribute data to record the non-spatial characteristics of entities. Attribute data can be recorded in tables, with different types of attributes appeared as columns of the table and records of entities as rows. For different contents of entities, there are different tables to record the information.

For attribute records of entities, pointers are given to link the information with geographical entities on the map. Here, pointers are unique identity numbers assigned to entities in the system.

In the layer of physical infrastructure, the ID of road central line can be used as the universal identity number for features in the layer. It can be extended to include lines for facilities of subways and tramlines. Three types of lines compose the network. They are subway lines, tramlines, and road central lines, and number 1, 2, and 3 are assigned to them respectively as identity of their types. In route system layer, a seven-digit number is adopted as identity for all routes in the system. The first digit indicates the physical infrastructure the route runs on, same as the physical infrastructure layer. The following five digits mean the route name, with the first digit and last digit for pre- and post-capital of the route name, and the middle three digits for the digital number in the route name (see Figure 4.10).

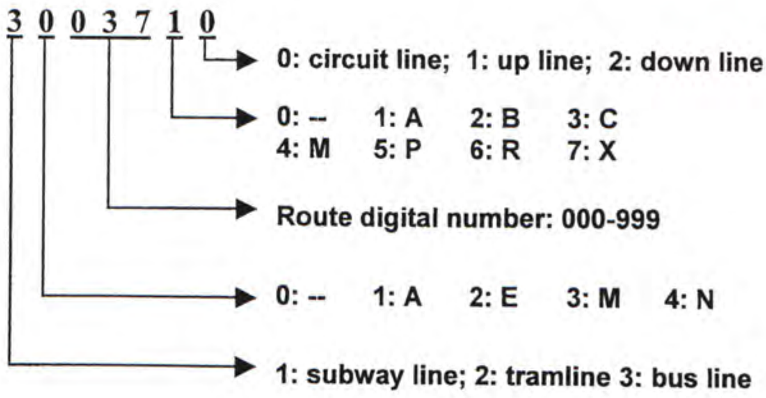


Figure 4.10 Structure of route identity

For example, the above ID means a circuit bus route line of 37A, 3000321 means an up line of bus route 3B, and 1000100 indicates a subway line, that is, Island line.

After routes IDs are given, it is readily to determine the IDs of stops along each service route. Two digits are extended to the route ID to work as the stop ID of the service route. Then a stop ID 300371001 means the first stop of the bus route 37A.

In the table of service route, basic information about the route is recorded, including route ID, origin and terminus, service period, and headway. Stop table contains the stop ID and stop name. All the information attained from the mass transit service companies is stored in the table for later use.

4.6 Summary

Data is the basic element of a GIS. Although data collection and processing are both time and efforts consuming tasks, they are indispensable processes for constructing a workable GIS. Without proper data, a GIS cannot function.

In this chapter, process of data collection is described in detail after a brief introduction to the study area, Hong Kong Island. Various sources can provide data for the study area of the prototype GIS-T. However, as the data are from diverse sources, they are inevitably in different formats. Conversion works should be done to unify the data so that the data can be organized together. In data organization, TransCAD, GIS software specialized to handle transportation problems, is chosen to do the work. Through several ways, both geographical and attribute data for the study area are converted into TransCAD files, and co-registered for further use.

CHAPTER V

IMPLEMENTATION OF THE PROTOTYPE

5.1 Introduction

In Chapter III, data model for routing on the multi-modal public transportation system is discussed in detail, and in Chapter IV, relative data preparations for the study area are finished. Based on the works of former two chapters, implementation of a GIS-T prototype for routing on the multi-modal mass transit system of Hong Kong Island is studied in this chapter. The construction of the route service network involving different modes is the key process of the system implementation. Detailed structures of the route service network, including transfers, attributes setting, are discussed and applied in the starting part of the chapter. Then the traffic service network layer is joined with other layers to form the GIS-T prototype of Hong Kong Island. Functions of the system are introduced after the prototype construction. Handling routing problems on the multi-modal public transportation system, as its most important function, is described with more efforts, and some routing results are illustrated and compared with outcomes by the traditional method.

5.2 Construction of the Route Service Network

Service network layer is the key layer of the system for routing purpose on the multi-modal transportation system. It should contain not only the basic information of the service routes, such as the length or time cost of the route segment, but also the topologic information of the service routes' links and nodes. Moreover, the extra information for transferring on the multi-modal mass transit system is included.

Also the data for service network can be classified into spatial data and attribute data. Accordingly, the generation of service network layer is demonstrated in these two parts.

5.2.1 Generation of the Geographical Network

In the route system layer, a service route is recorded by linkage information to its corresponding line segments and points in the infrastructure layer. For those route segments that pass the same road, the same set of lines in infrastructure layer is recorded for them. It is no problem for representing the service routes in cartographic aspect by this method, but it is quite difficult to construct the topologic relationship between different route segments, and record the distinctive attributes for each pair of links at transfers. So a separate link is used to represent each route segment, even though several route segments pass the same physical infrastructure line (see Figure 5.1).

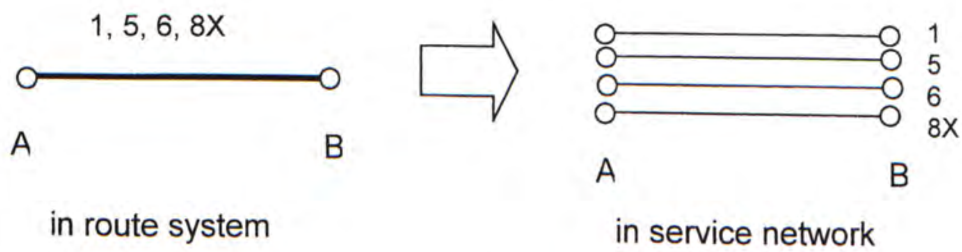


Figure 5.1 Difference on presentation of routes in the route system layer and the service network layer

(1) Generating transfers – merging nodes in service network

Each service route has many stops for passengers boarding or alighting. Some stops of different routes stand at the same location or so close that passengers can alight from one route, transfer from its stop to another one, and wait for taking the new route. In this case, the two different service routes can be joined together at the stops, or, in other words, the stops of the two routes can be converged into one at this location. Then the converged stops become a transfer, at which passengers can change the route they take. In the service network layer, such a process of generating transfers is presented as a series of actions to merge several nearby nodes into one.

For the question that which stops should be converged into transfers, different people may have quite different answers. It depends much on passengers themselves. A basic principle for merging stops in route service network relies on the measurement of distance that passengers prefer to cover in order to transfer from one route to another. Some passengers can bear traveling a long distance to change route, while others like to cover only a short distance. Then the former can have a larger range of stops for considering as transfers than the latter. In this case, transfer can be recognized as a super node representing a set of stops that connects to different routes.

In plain area, we can define 300 meters (about a three or four minutes' walk at a walking speed of 5 km/h) as the threshold of nearby stops to be considered as transfers. In this condition, a central stop (mostly a terminus or large stop) is defined and the stops around it within 300 meters are merged into a transfer. However, on Hong Kong Island, this rule cannot be applied for following reasons:

- Road network is constructed on three-dimensional space and stops are not all on a plan, some are even in underground or on overpass;
- Fences on the road central line interrupt the direct connection of road's two sides;
- The condensed buildings and complicated tunnels and overpasses make the area absolutely out of a plan area.

So the merging of stops on the service network on Hong Kong Island cannot be processed by simple rules. It should be decided according to special conditions on each location. Mainly, experiences are used on estimating the range that passengers travel for three or four minutes on street networks of Hong Kong Island.

By the way of transfer generating in this data model, some characteristics of transfers can be deducted: a) generally, transfers are the same as other nodes in the network, working as connectors of links, although they may connect much more links of different routes than common nodes; b) transfers are dependent features in the network, that is, their existence is conditional on other features. Only when route change detected on the links before and after the nodes, transfers can be considered as transfers on a route. Otherwise, they have no difference from other nodes in the network.

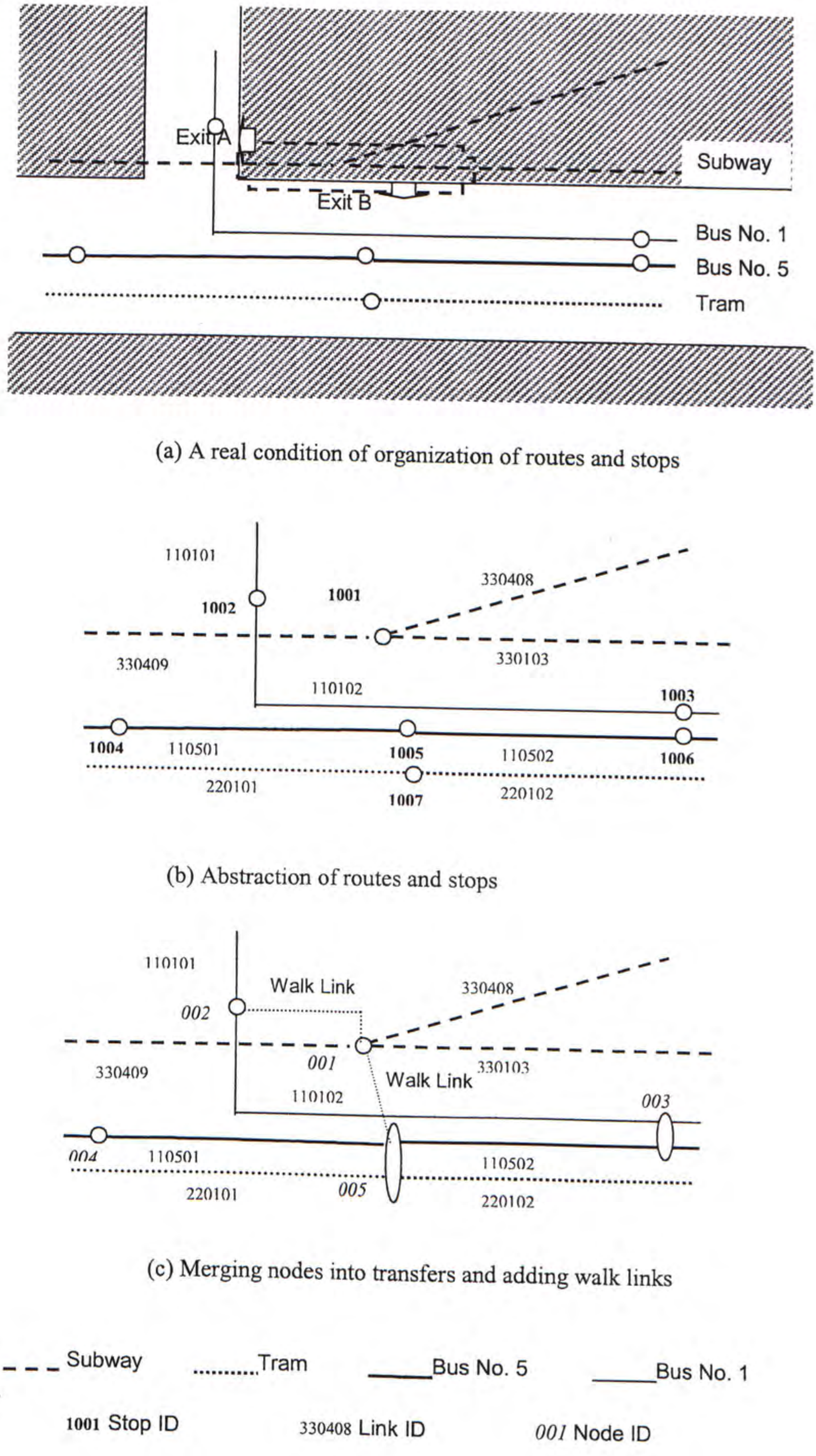
(2) Walk link

A subway station is much larger than a bus stop in scale. On Hong Kong Island, a subway station can cover a large area and many tunnels can lead passengers from underground station to several different locations on the ground. In some way, the subway station has the function of tunnels, which can lead riders directly to the position without being troubled by the obstacles on the ground. Although a subway station covers a large area, it is showed as a node, a zero-dimensional feature, the same as other bus and tramline stops in the network. However, it can be considered as a transfer that can merge stops distributed in a quite broad range, as it can connect a bus stop two-street away on the ground by tunnels. Because of distinctive location change of stops, these stops cannot be simply merged to the subway station. In this case, walk links are generated to connect the underground subway station to ground stops near each station exit by these tunnels. Also, when there are only one stop around the current stop, although the distance may be farther than four minutes' walk, passengers have to travel to the stop to make an interchange because of having no other choices. Then, a walk link is used to connect the stops that have long distance from each other in order to let passengers make a transfer.

In fact, walk links are only additional links in the route service network. They have no corresponding features in the infrastructure layer and route system layer, for people's walk is too freely to be constrained to the road network. They are only used for routing assistant in network analysis. In function, they can be considered as part of a transfer.

(3) A typical case

In Figure 5.2, it shows a common case in public transportation system on Hong Kong Island. Near a subway station, many stops are arranged around the exits



(a) A real condition of organization of routes and stops

(b) Abstraction of routes and stops

(c) Merging nodes into transfers and adding walk links

Figure 5.2 Processing on the service network for a typical case of subway station for passengers' easy transfer. Figure 5.2(a) is the real organization of the routes and stops at the site, with some stops at the same location and others at separate location, but all close to the exits of subway. Figure 5.2(b) shows the result of abstraction on routes and stops in real world. In figure 5.2(c), the stops are re-arranged for easy representation in a GIS system. Near stops are merged into transfers, subway station which covers a larger area is abstracted into only a node as other stops, and walk links are added to connect the subway station to bus or tram stops near each exit.

5.2.2 Setting Attribute Data for the Route Service Network

Attribute data contains the characteristic information of entities, which is also very important for data analysis. Some attribute data are ready for use after collected and input, such as stop names, common information of service route. They need only to be stored with an ID for each record and linked to the corresponding feature, and then they are ready for further analysis. Besides these data, many other attribute data are not ready for direct use. Further processing work are required to determine their value.

(1) Time cost for route segment

Time is one main measurement of travel. In public transportation, time is also an important reference for traffic service efficiency. Generally, time consumption is determined by a function of distance and speed. In this research, various ways to determine time cost for different kind of traffic modes are applied. For railway and subway, vehicles run on fixed routes of rails. Because these routes are designed only for their own use and operated in a rather separated system, vehicles can operate at a stable speed and run on a strict schedule. So, each route segment of railway and subway has a fixed time cost. Much different from railway and subway, buses run on roads together with other vehicles, which means that they are affected by traffic condition greatly, especially in urban area. The distance of each bus service route segment is clear, so only the speed of vehicles is not sure to determine the time cost. In this study, determination of vehicle speed in urban area is not the point, so we simply give a supposed speed to buses running in urban area. We also suppose that buses run at an even speed along their routes. Thus, the time cost for each route segment can be reached simply by dividing the distance of the segment by the average speed. For tramline, because vehicles also run on the ground, although they are on rails, they are unavoidably affected by the traffic conditions as buses. So the time cost for their route segments are decided the same way as buses. In this study, the average speed of bus and tram is pre-determined at 12km/hour for all bus and tram routes, except for Aberdeen Tunnel and Island Eastern Corridor, on which bus can run at a speed of 30km/hour for their special design for fast speed. Figure 5.3 shows part of the contents in the link attribute table of service network layer.

(2) Time cost for transfer

As mentioned in the previous part, time cost of traveling on the multi-modal public transportation system happens not only on each route segment, but also at transfers for walking from a route to another and waiting for a vehicle coming (Chapter III). Time delay is an attribute of transfers. For the two parts of time delay of travel in a mass transit system, different methods are used to set the time cost.

ID	Length	Dir	Name	Type	Time
2	125.31	1	"1<"	3000102	0.60
4	269.07	1	"3B<"	3000322	1.30
5	466.09	1	"5>"	3000501	2.30
6	235.87	1	"5<"	3000502	1.20
9	319.67	1	"7>"	3000701	1.60
10	288.61	1	"7<"	3000702	1.40
11	631.23	1	"8X>"	3000871	3.20
12	100.48	1	"8X<"	3000872	0.50
13	214.41	1	"10>"	3001001	1.00
14	232.05	1	"10<"	3001002	1.20
17	298.07	1	"25A"	3002510	1.50
18	296.31	1	"37A"	3003710	1.50
19	292.61	1	"40>"	3004001	1.50
20	443.83	1	"40<"	3004002	2.20
21	395.12	1	"41A>"	3004111	2.00
22	211.38	1	"41A<"	3004112	1.10
23	290.32	1	"47A>"	3004711	1.50
…	…	…	…	…	…
1459	2636.610		"KwunT L"	1000300	4.00
1460	790.66	0	"TsuenW L"	1000200	2.00
1461	2254.550		"TsuenW L"	1000200	3.00
1462	413.48	0	"Tram1"	2000100	2.10
1463	290.77	0	"Tram1"	2000100	1.50
…	…	…	…	…	…

Figure 5.3 Contents in the link table of the service network layer

For walking between stops, walk links have been generated to represent them, so the time cost for walking can be considered as an attribute of walk links. Because these walk links are simplified symbols of passengers' walks in the three-dimension space, including tunnels, overbridges, stairs, and ground roads, it is difficult to determine the real length of the walk, and further to get the time cost. So the time cost of walk links is determined by practical experience.

Time of waiting for a vehicle can be calculated by the following method. Public traffic services in Hong Kong mostly run at their own schedules. Here the waiting time is calculated in a simplest case. We suppose that vehicles of each mass transit service start out at a same regular time slot (T) and passengers arrive at the stop with an equal chance during the time slot. Then the waiting time for a vehicle coming can be determined as:

$$EXP(T) = \int_0^T p(t) * f(t)dt \qquad (5)$$

where p (t) is the probability distribution of a passenger arriving at the stop at time t, f(t) is the waiting time for the next vehicle at time t.

As supposed, passengers arrive at the stop with an equal chance during the time slot T, then

$$p(t) = \frac{1}{T} \qquad (6)$$

and the waiting time for passengers arriving at time t is

$$f(t) = T - t \; (0 \le t \le T) \tag{7}$$

then

$$EXP(T) = \int_0^T p(t) * f(t)dt = \frac{1}{2}T \tag{8}$$

The waiting time is half of the vehicle headway.

This part of time delay depends only on the route on which passengers will aboard, and it has nothing to do with the previous route that passengers have taken. In transfer table, the waiting time is recorded together with the route number. It is used to all links in the network. When doing a route finding, comparison will be kept making on the route name of previous link and following link at each node. If a difference is found, the waiting time for the following route is added to the total travel time. Figure 5.4 shows the table of waiting time for each route when transferring to that service route.

(3) Fare

Fare of public transportation services on Hong Kong Island, mostly, is not simply determined by a linear function of distance. Some route services have only one fare for all passengers, in spite of stops at which they board and get off. Some have different fares for different segments at which passengers board. Also, some have different fares for different route segments that passengers travel. For all these fare types, matrices can be used to store the fare for each stop pair in a service route, with the value in the *i*th row and the *j*th column indicating the fare for boarding at the *i*th stop and getting off at the *j*th stop (see Figure 5.5).

ROUTE_ID	HEADWAY	WAIT_TIME
3000101	15.00	7.50
3000102	15.00	7.50
3000321	10.00	5.00
3000322	10.00	5.00
3000501	13.00	6.50
3000502	13.00	6.50
3000601	20.00	10.00
3000602	20.00	10.00
3000701	13.00	6.50
3000702	13.00	6.50
3000871	13.00	6.50
3000872	13.00	6.50
3001001	8.00	4.00
3001002	8.00	4.00
3001100	11.00	5.50
3001200	12.00	6.00
3002510	12.00	6.00
3003710	9.00	4.50
3004001	11.00	5.50
3004002	11.00	5.50
3004111	13.00	6.50
3004112	13.00	6.50
3004711	13.00	6.50
...	...	...

Figure 5.4 Waiting time for service routes

Matrix5 - Fares for Subway:70 (Matrix 1)

	1413	1414	1415	1416	1417	1418	1419	1420	1421	1422	1423	1424	1425	1426	1427	1428	1429	1430
1413	0.00	9.00	4.00	0.00	4.00	4.00	5.00	5.00	5.00	6.00	6.00	6.00	7.50	7.50	7.50	7.50	13.00	9.00
1414	9.00	0.00	9.00	9.00	9.00	9.00	11.00	11.00	11.00	11.00	11.00	13.00	13.00	13.00	13.00	13.00	7.50	4.00
1415	4.00	9.00	0.00	4.00	4.00	5.00	5.00	5.00	6.00	6.00	6.00	7.50	7.50	7.50	7.50	7.50	13.00	9.00
1416	0.00	9.00	4.00	0.00	4.00	4.00	5.00	5.00	5.00	6.00	6.00	6.00	7.50	7.50	7.50	7.50	13.00	9.00
1417	4.00	9.00	4.00	4.00	0.00	4.00	4.00	5.00	5.00	6.00	6.00	6.00	7.50	7.50	7.50	7.50	13.00	9.00
1418	4.00	9.00	5.00	4.00	4.00	0.00	4.00	4.00	5.00	5.00	6.00	6.00	7.50	7.50	7.50	7.50	11.00	9.00
1419	5.00	11.00	5.00	5.00	4.00	4.00	0.00	4.00	4.00	5.00	5.00	6.00	6.00	7.50	7.50	7.50	11.00	11.00
1420	5.00	11.00	5.00	5.00	5.00	4.00	4.00	0.00	4.00	4.00	5.00	5.00	6.00	6.00	7.50	7.50	11.00	11.00
1421	5.00	11.00	6.00	5.00	5.00	5.00	4.00	4.00	0.00	4.00	4.00	5.00	5.00	6.00	6.00	6.00	9.00	11.00
1422	6.00	11.00	6.00	6.00	6.00	5.00	5.00	4.00	4.00	0.00	4.00	4.00	5.00	5.00	6.00	6.00	9.00	11.00
1423	6.00	11.00	6.00	6.00	6.00	6.00	5.00	5.00	4.00	4.00	0.00	4.00	4.00	5.00	5.00	6.00	9.00	11.00
1424	6.00	13.00	7.50	6.00	6.00	6.00	6.00	5.00	5.00	4.00	4.00	0.00	4.00	4.00	5.00	5.00	9.00	13.00
1425	7.50	13.00	7.50	7.50	7.50	7.50	6.00	6.00	5.00	5.00	4.00	4.00	0.00	4.00	4.00	4.00	9.00	13.00
1426	7.50	13.00	7.50	7.50	7.50	7.50	7.50	6.00	6.00	5.00	5.00	4.00	4.00	0.00	4.00	4.00	11.00	13.00
1427	7.50	13.00	7.50	7.50	7.50	7.50	7.50	7.50	6.00	6.00	5.00	5.00	4.00	4.00	0.00	4.00	11.00	13.00
1428	7.50	13.00	7.50	7.50	7.50	7.50	7.50	7.50	6.00	6.00	6.00	5.00	4.00	4.00	4.00	0.00	11.00	13.00
1429	13.00	7.50	13.00	13.00	13.00	11.00	11.00	11.00	9.00	9.00	9.00	9.00	9.00	11.00	11.00	11.00	0.00	7.50
1430	9.00	4.00	9.00	9.00	9.00	9.00	11.00	11.00	11.00	11.00	11.00	13.00	13.00	13.00	13.00	13.00	7.50	0.00

Figure 5.5 Fares of a service route stored in a matrix

(4) Changes

Like waiting time, change of service route happens only when passenger transfers from a service route to a new one. So it only relates to the route, not to the route segment. We handle it the same as the waiting time for each service route, giving a tag for each route. Here '1' is given to each route as the value of field 'change', in order to count the times of route change during a trip.

5.3 A GIS-T Prototype for the Study Area

After the construction of the service network, a GIS-T prototype for routing on the multi-modal public transportation system of Hong Kong Island can be set up together with other layers under TransCAD environment. The framework of the prototype for the study area is shown in Figure 5.6.

Grouped as layers appeared in the data model, all geographical and attribute data are organized in TransCAD environment with an extended relational database management system. Attribute data are connected to relevant map data by IDs. As the route system is generated from the infrastructure layer and the service network is created from the route system layer, different layers have close relationships. They can share information by common fields, and, moreover, keep data consistency among different layers.

Several functions are provided by the prototype, such as information retrieve, map display, data query, and routing. Information retrieve, display, and data query are common functions of a GIS. These functions can be used on either layer to get the information or map from geographical data and relating attribute data in the

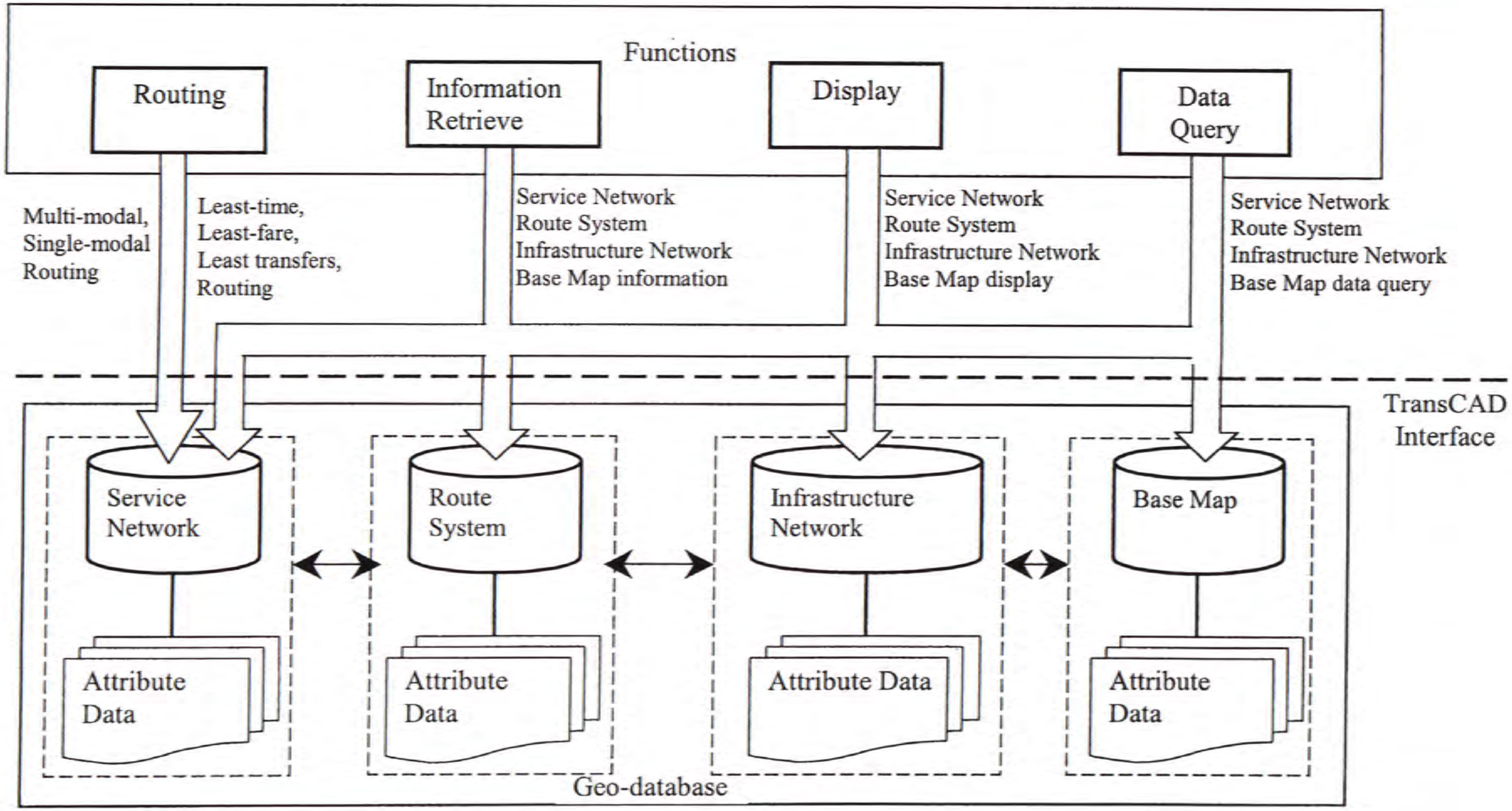


Figure 5.6 Framework of the prototype for the multi-modal public transportation system

database. For example, to retrieving a route's information, user can select the interested route on the map of route system. Then its attribute data will be retrieved from attribute table through entity ID and displayed in front of user, such as the route's name, schedule, and terminals. Routing is the main topic of this prototype. In order to implement the routing function on the multi-modal public transportation system on Hong Kong Island, some programming works are done with the programming tools provided by TransCAD. When routing, user can select multi-modal network or single-mode network, and routing criterion. Then, the system will chose the right network by mode and pick out the right attribute data (time, or fare, or change) for analysis. A result for the shortest path analysis is given at the end of operation, presented in both map and text to give an illustration of the path.

5.4 General GIS Functions of the Prototype

This prototype is a GIS first, so it has the common functions as other GIS. As GIS is a computer system that can help us collect, store, operate, and display spatial data, the prototype can execute the following functions on spatial data and attribute data.

5.4.1 Information Retrieve

As a GIS, the prototype can easily link attribute data with their spatial data, or their locations. Information stored in various attribute tables, such as road central line table, route information table, and stop table, is not simply data in a two-demisional table, but characteristics of special positions. By simply choosing the transportation feature to be queried, users can see its information clearly. For example, if users want to query the route information of a service route, they can choose the route system layer and selection the route that they are interested in, then the corresponding information about the route is shown beside the route, including the route number, route ID, terminus, service time, and headway (see Figure 5.7).

5.4.2 Display

In GIS, display becomes easier and more clear, because users can select contents and the scale of the map for display. Users can choose the information that they need and delete the extra information that they do not care at the moment. Then the map will not be full of all kinds of notes and features and can be viewed clearly (see Figure 5.8). Also, with the function of changing map scale freely, users can view the total area as clearly as the detail stucture of routes at a transfer.

5.4.3 Data Query

Thanks to DBMS, users can query data of the system stored in database by simple logic operation. For example, if users want to find the location of a stop, they can make a query in the stop table with the stop's name. Then the system will check the field containing stop name in the table, return the matched results, and show the locations on the map.

5.5 Routing in the Prototype

Route finding is the main function of the prototype. As the purpose of the system design, it is used to solve the route finding problems for single source and destination on a network combined with traffic routes served by multiple modes. Embodied into a real world, it can be used in the following dialy life case. A passenger wants to go to place B from his/her current location A by the mass transit

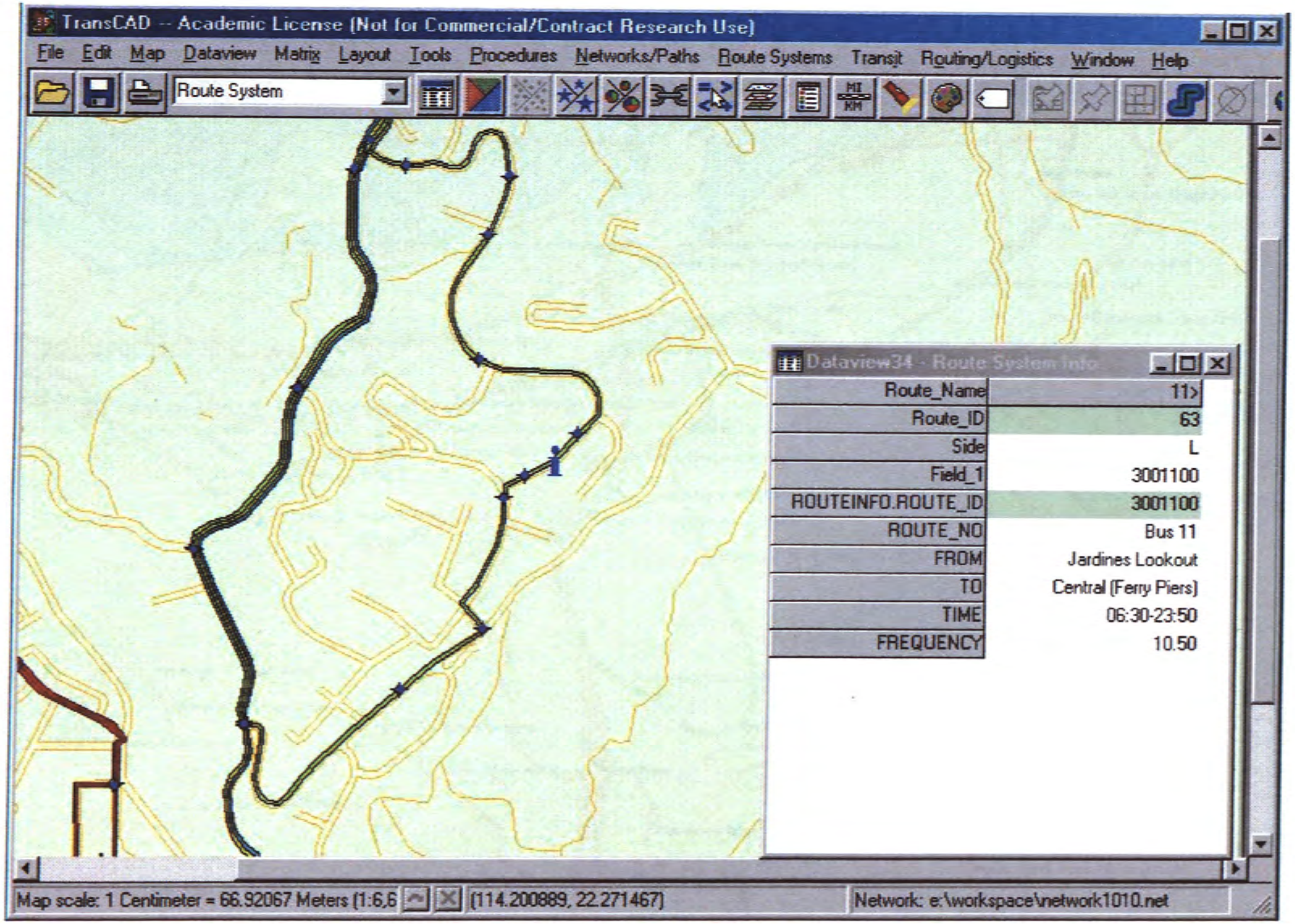


Figure 5.7 Information retrieve in the prototype

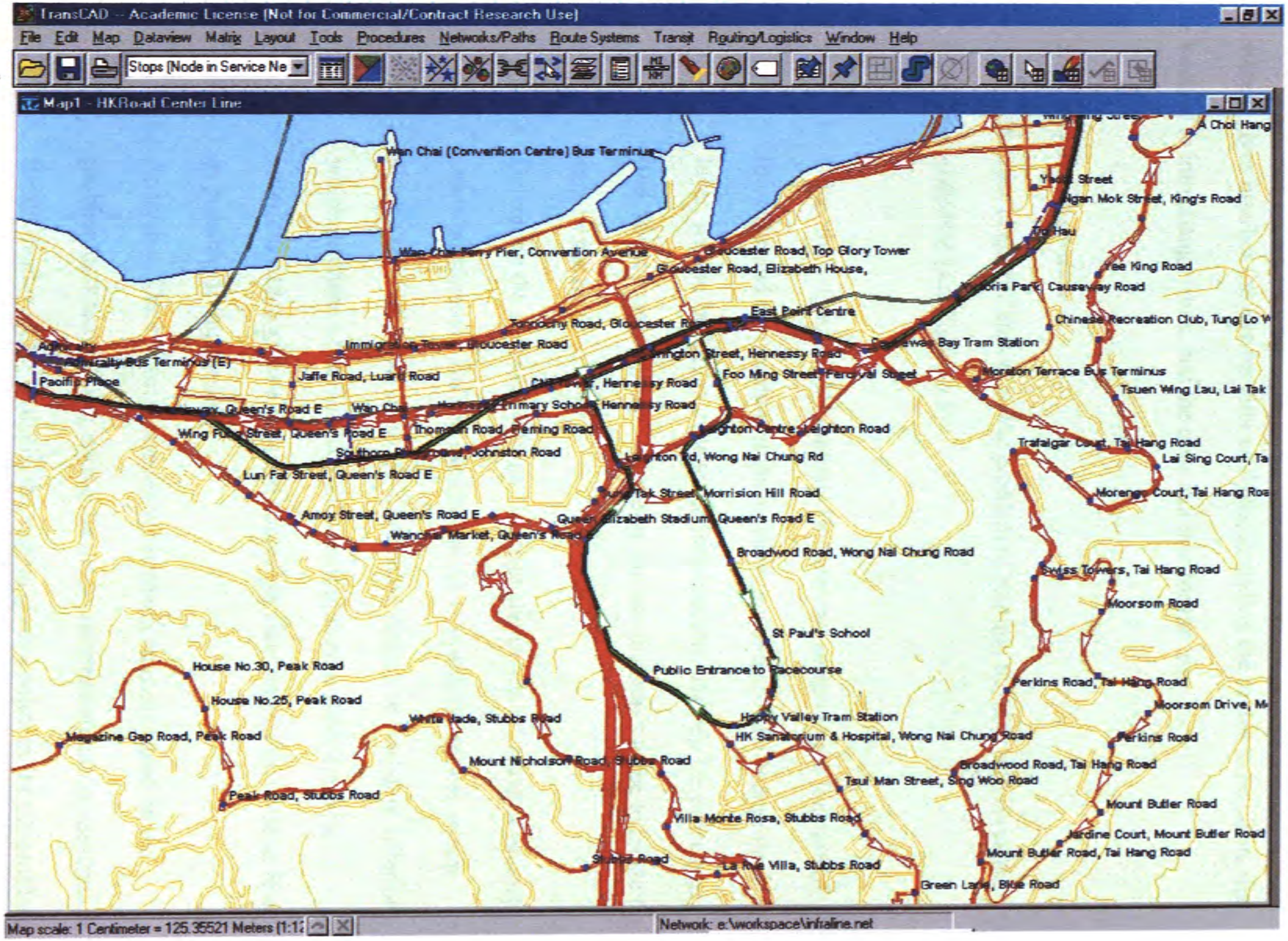


Figure 5.8 Annotations on the map of the prototype

system, but he/she does not know which route to take and how he/she can get there early. Then the passenger can use the system to find the solution to the problem. The system gives him/her the answer after analysis, including the routes to be taken, the transfer to intrechange route, and the time and fare for the trip.

5.5.1 Routing Procedure

In order to get the answer to the problem of routing, the user will do as the following prodedure (see Figure 5.9):

1. Select the origin and destination. The user can selection the location of the orign and destionation stops by click on the map. The background layer, such as buildings, roads, and intersections can help the passenger find the stops more easily. Also, user can use the stop's name to locate the stop on the map.
2. Determine the routing criterion. User can choose the criterion of routing as his/her demand. He/She can choose the least-time criterion, which gives a result that can get to the destination fastest, or least-fare criterion, which provides a path that costs the least money, or least-transfer criterion, which gives a way that passenger changes service route as few as possible during the trip.
3. Analysing. The system processes the network analysis based on the problem user has defined, taking the mode information into consideration.
4. Result display. After analysis, the system gives a solution for the problem based on combined service routes. The path is shown on the map with different colors for different routes and postitions of transfers, together

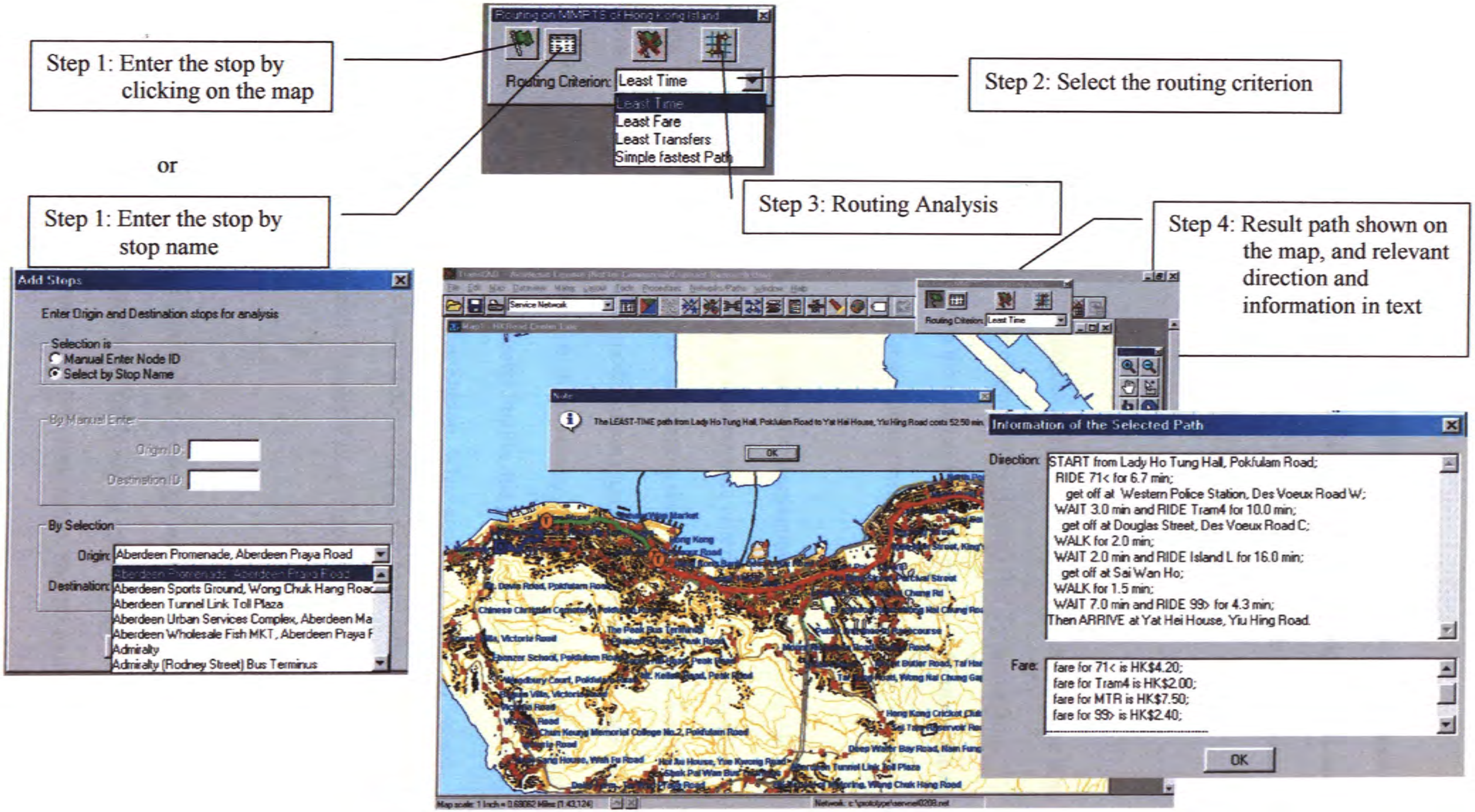


Figure 5.9 Routing procedure of the prototype

with the total cost for the selected criterion. Further more, a text-based instruction is provided to tell the user how to finish the trip in detail, such as the service route to be taken, the time and fare for each service route, and the location to make a change of service route.

5.5.2 Examples and Results

In this part, some routing examples and results are shown in detail. Here is an example. A passenger wants to go to Happy Valley (Upper) Bus Terminus from Tsim Sha Tsui. How can he/she gets the destination on the multi-modal mass transit system of Hong Kong Island by different routing criteria?

At first, the passenger wants to get to the destination as soon as possible. Then this is a routing problem based on shortest time criterion. After entering the origin and destination, choosing least-time routing, the passenger gets the result shown in Figure 5.10. In the result, mode information is taken into cosideration for route finding. Following the guidance, the passenger starts at Tsim Sha Tsui, taking subway of Tuen Wan Line. At Admiralty Station, the passenger transfers to Island Line of subway and rides to Wan Chai Station. When arrives at Wan Chai Station, the passenger walks out of the subway station and transfers to up route of bus No. 1, and takes the bus to the destination – Happy Valley (Upper) Bus Terminus. The total time cost is 30.4 minutes.

How about the cheapest route? If the passenger wants to reach the destination with the least money, he/she can chooses the least-fare criterion. The result is shown in Figure 5.11. It is the same route as the least time result. For this route, the

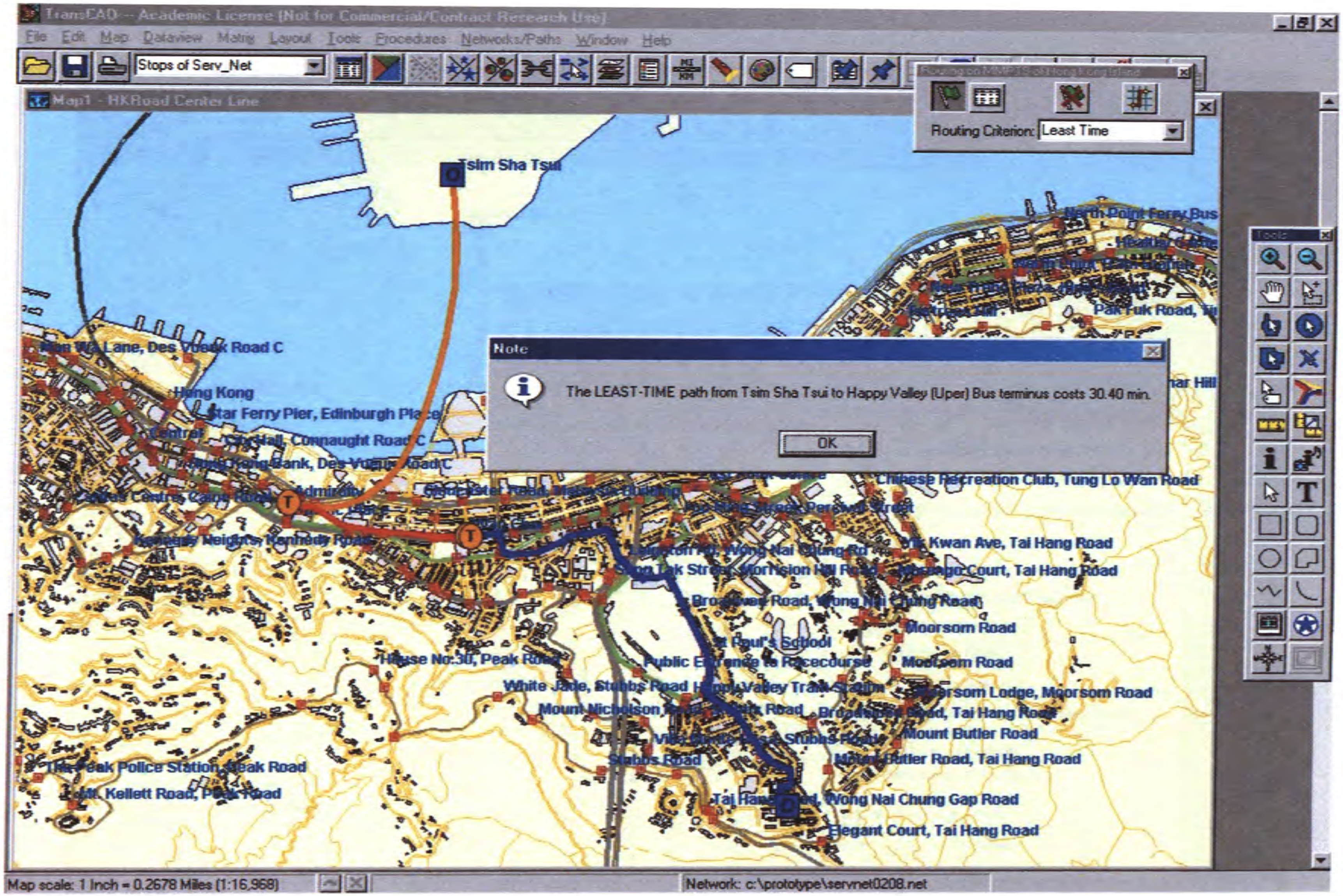


Figure 5.10 Least-time routing result from Tsim Sha Tsui to Happy Valley (Upper) Bus Terminus given by the prototype

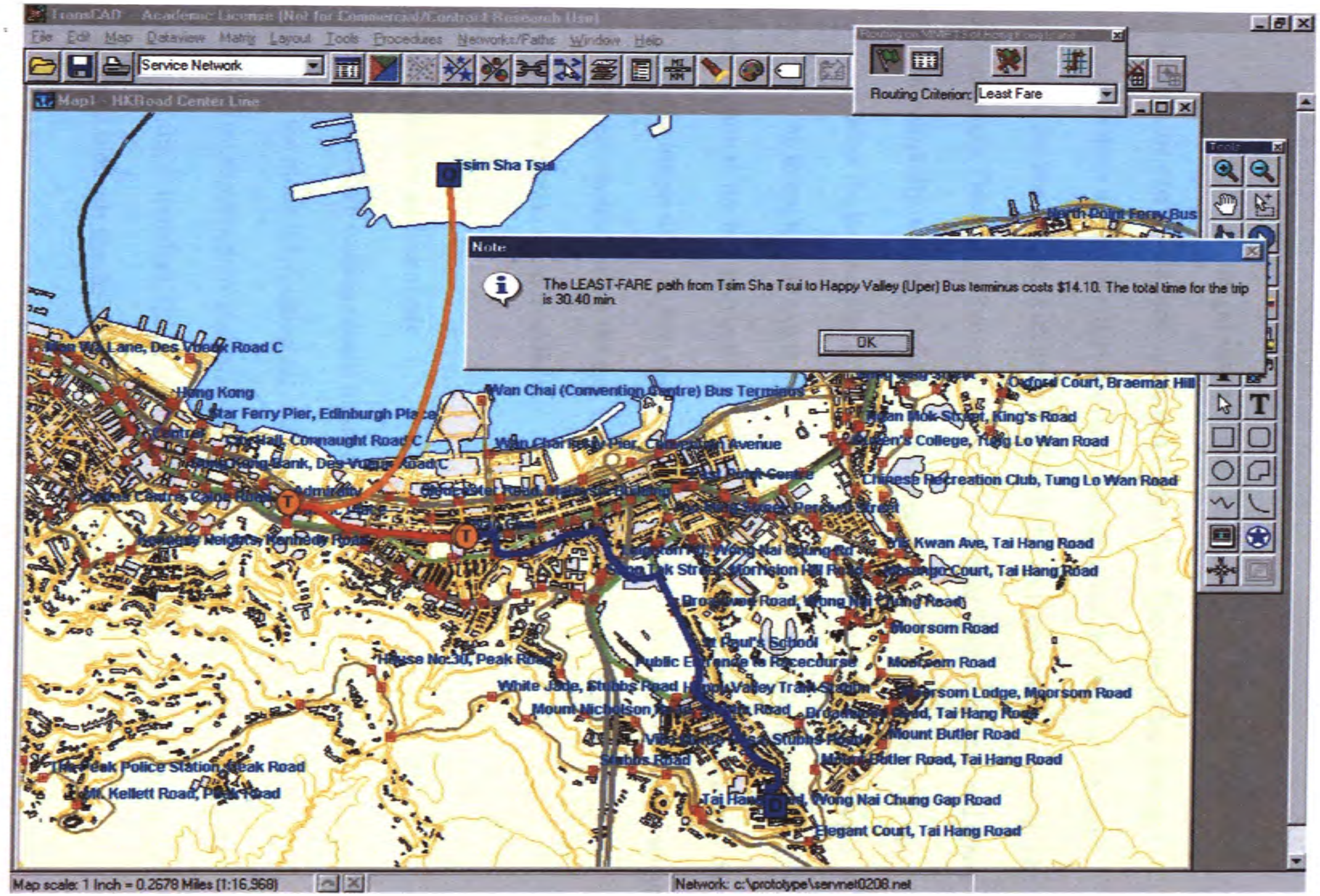


Figure 5.11 Least-fare routing result from Tsim Sha Tsui to Happy Valley (Upper) Bus Terminus given by the prototype

passenger pays HK$9.00 for subway route and HK$5.10 for up route of Bus No. 1. The total fare for the trip is HK$14.10.

This time, the passenger wants to meet least transfers during the trip considering the energy and time consumed at transfers. Then the route finding procedure is done under the criterion of least transfers. For the same origin and destination, the result route is displayed in Figure 5.12 of least-transfer routing. The passenger takes Tsuen Wan Subway Line to Admiralty at Tsim Sha Tsui, and when arrives at Admiralty, walks out of the subway station to the stop of Bus No. 1 up route, then takes the bus directly to the destination – Happy Valley (Upper) Bus Terminus. The totoal travel time is 32.4 minutes, including 3 minutes' walk from subway station to the bus stop and 7.5 minutes for waiting at bus stop. Although this path is a little longer than the first result in time, which is 30.4 minutes, the passenger meets only one transfer during the trip, less than the first result and saving the passenger's energy on route transfering.

5.5.3 Comparison and Analysis

The above are routing results based on the data model discussed in this paper, considering the mode information for route analysis. However, most current applications on shortest path analysis only count the weight of links, ignoring the costs happening at transfers. Using least time as routing criterion, resutls from the two different methods can be compared.

For the example above, if mode information and time delay at transfers are omitted, a different result is coming out as shown in Figure 5.13. The passenger

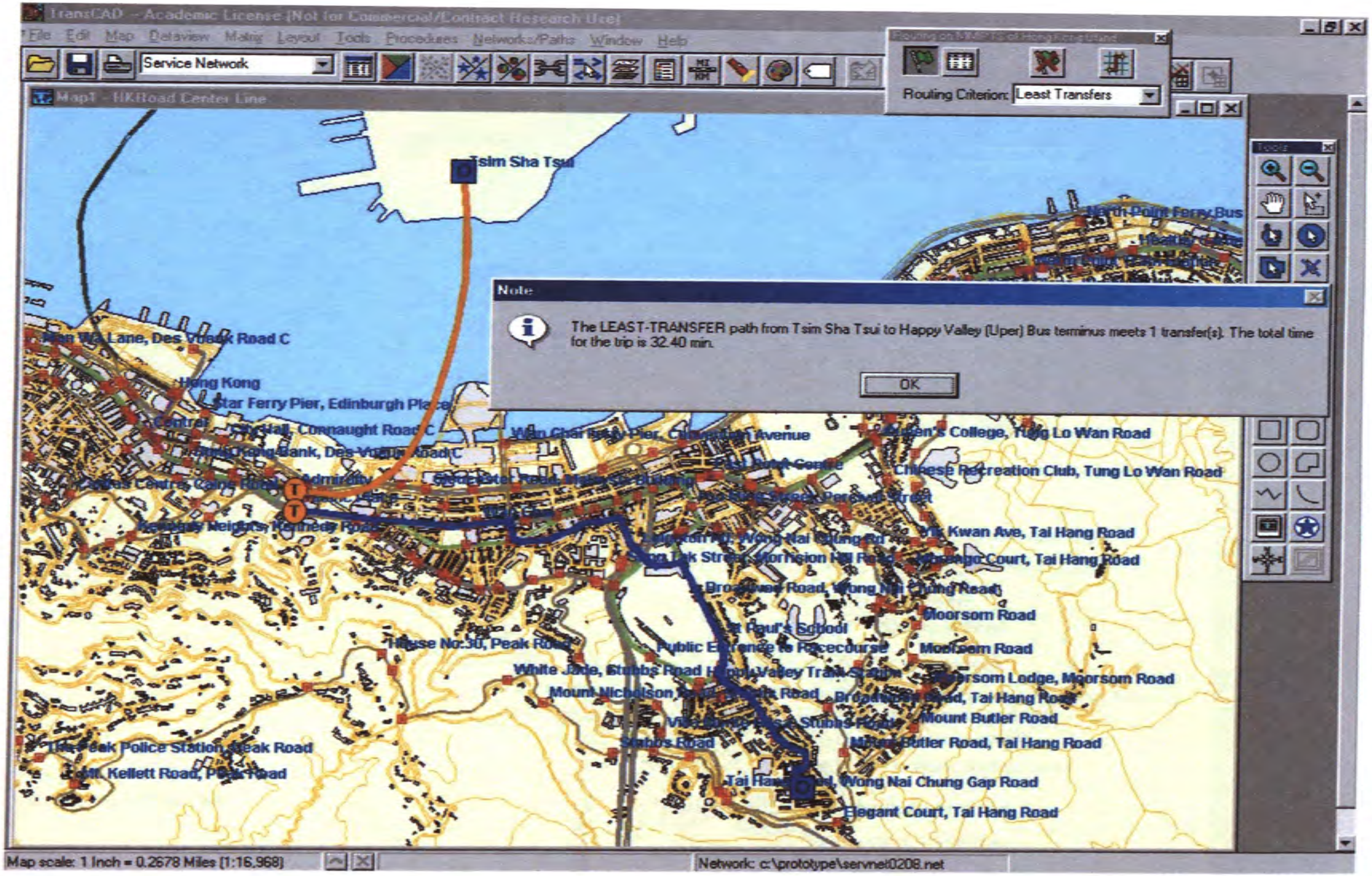


Figure 5.12 Least transfers routing result from Tsim Sha Tsui to Happy Valley (Upper) Bus Terminus given by the prototype

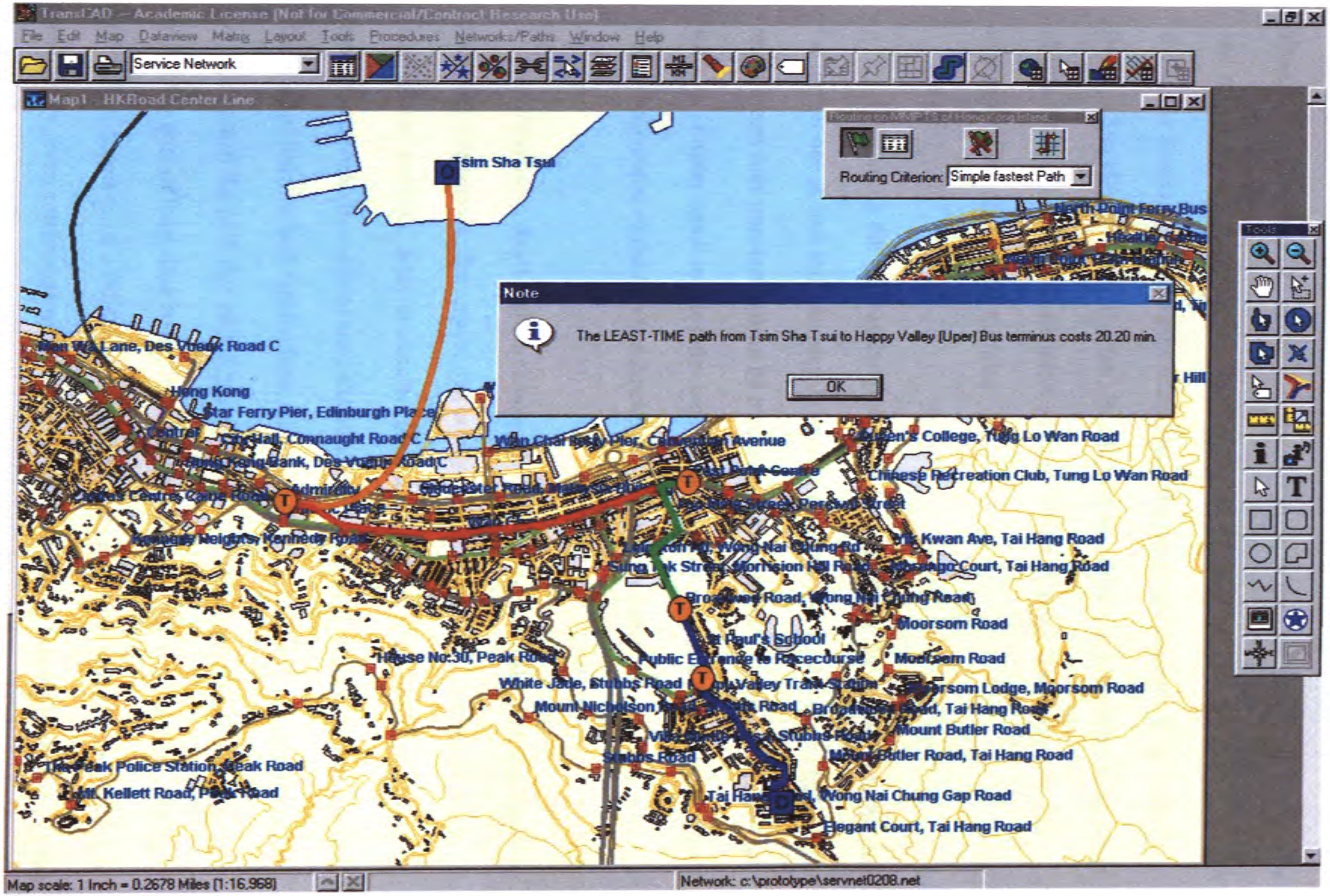


Figure 5.13 Least-time routing result from Tsim Sha Tsui to Happy Valley (Upper) Bus Terminus without considering extra costs at transfers

starts from Tsim Sha Tsui by Tsuen Wan Line of subway to Admiralty. At Admiralty station, the passenger changes to Island Line of subway to Causeway Bay station. Then, the passenger walks out of the subway station to the near tram stop, takes tram line No.2, which runs from Shau Kei Wan to Happy Valley. When the tram arrives at Broadway Road on Wong Ngai Chung Road, the passenger changes to up route of Bus No. 5 to Happy Valley (Lower) Bus Terminus, and at there, transfers to up route of Bus No. 1 to reach the destination – Happy Valley (Upper) Bus Terminus. The time cost of this trip is 20.2 minutes.

Comparing the two results, passengers may think the latter route is better than the former one at first look, by simply reading the numbers. However, the latter result meets four transfers during its trip, and the total fare for the path is HK$19.80, while the former result meets only two transfers and its total fare is HK$14.10. The detail comparison of the two results can been seen from Table 5.1.

Is the latter result really a reasonable path and does it really cost less time? From the comparison, the answer can be clearly reached. In the latter result, mode information and time delay at transfers are not considered. Only calculating time cost of each link (in vehicle time), the traditional method is prone to choose the path (a series of links) which has the least total time. So the result will not care the route type, and then the path can switch among different service routes freely in order to reach the goal of least time cost. The path changes route type for four times during the trip. It seems to be a ridiculous route, because passengers have to change lines so frequently, even sometimes need to change route when just boarding the line. For the result got based on the data model of this paper, it seems to be a more reasonable

Table 5.1 Comparison of routing results by two different methods

	Result by the prototype	Result by the traditional method
Principle	Considering extra costs at transfers for routing	**Not** considering extra costs at transfers for routing, only care about the weight of links.
Path	Start from **Tsim Sha Tsui**; ride *Tsuen Wan Line* of subway for 3.0 min, get off at Admiralty; wait 2.0 min and ride *Island Line* of subway for 2.0 min; get off at Wan Chai; walk for 1.5 min; wait 7.5 min and ride *up route of bus No. 1* for 14.4 min; Then arrive at **Happy Valley (Uper) Bus terminus.**	Start from **Tsim Sha Tsui**; ride *Tsuen Wan Line* of subway for 3.0 min; get off at Admiralty; wait 2.0 min and ride *Island Line* of subway for 4.0 min; get off at Causeway Bay; walk for 1.5 min; wait 3.0 min and ride *Tram2* for 4.7 min; get off at Broadwod Road, Wong Nai Chung Road; wait 6.5 min and ride *up route of bus No. 5* for 2.0 min; get off at Happy valley (Lower) Bus Terminus, Wong Nai Chung; wait 7.5 min and ride *up route of bus No. 1* for 5.0 min; Then arrive at **Happy Valley (Uper) Bus terminus**.
Total time	30.4 min	20.2 min
Fare	**MTR:** HK$9.00; **Up route of bus No.1:** HK$5.10; **TOTAL FARE:** HK$14.10	**MTR:** HK$11.00; **Tram2:** HK$2.00; **Up route of bus No. 5:** HK$3.40; **Up route of bus No. 1:** HK$3.40; **TOTAL FARE:** HK$19.80

path. Passengers need to change route for only twice to get to the destination. In the total 30.4 minutes, it includes 2 minutes waiting for train of Island Line at Admiralty station, 7.5 minutes waiting for a vehicle of Bus No. 1 at Wan Chai, 1.5 minutes' walk from subway station to the bus stop at Wan Chai, and other 19.4 minutes in-vehicle travel time. If the time consuming at transfers is added for the latter route, 2 minutes for waiting for a train of Island Line at Admiralty, 3 minutes for Tram Line 2 at Wan Chai, 6.5 minutes for Bus No. 5 at Broadway Road, and 7.5 minutes for Bus No. 1 at Happy Valley (Lower) Bus Terminus, the revised total time of the result will be 39.2 minutes, more than that of the former route.

Comparisons of other four pairs of routing results are given in Figure 5.14. From the comparison, we can find out that the least time routing results without considering mode information and time delay are prone to change route frequently, and if the extra time cost at transfers is added to the results, the pathes will cost more time than the results got from the prototype. So, the routing results by the prototype are more reasonable and better than the results by the tranditional method.

5.6 Summary

This chapter focuses on the implementation of a GIS-T prototype for processing multi-modal routing on the mass transit system on Hong Kong Island. For the generation of the service network, because it is a network for multi-modal routing, some special works are needed to construct the network and store the multi-modal information, such as duplicating links for each route, generating transfers by merging nodes, and setting attribute data for transfers. After the completion of the service network, the prototype is implemented under TransCAD environment.

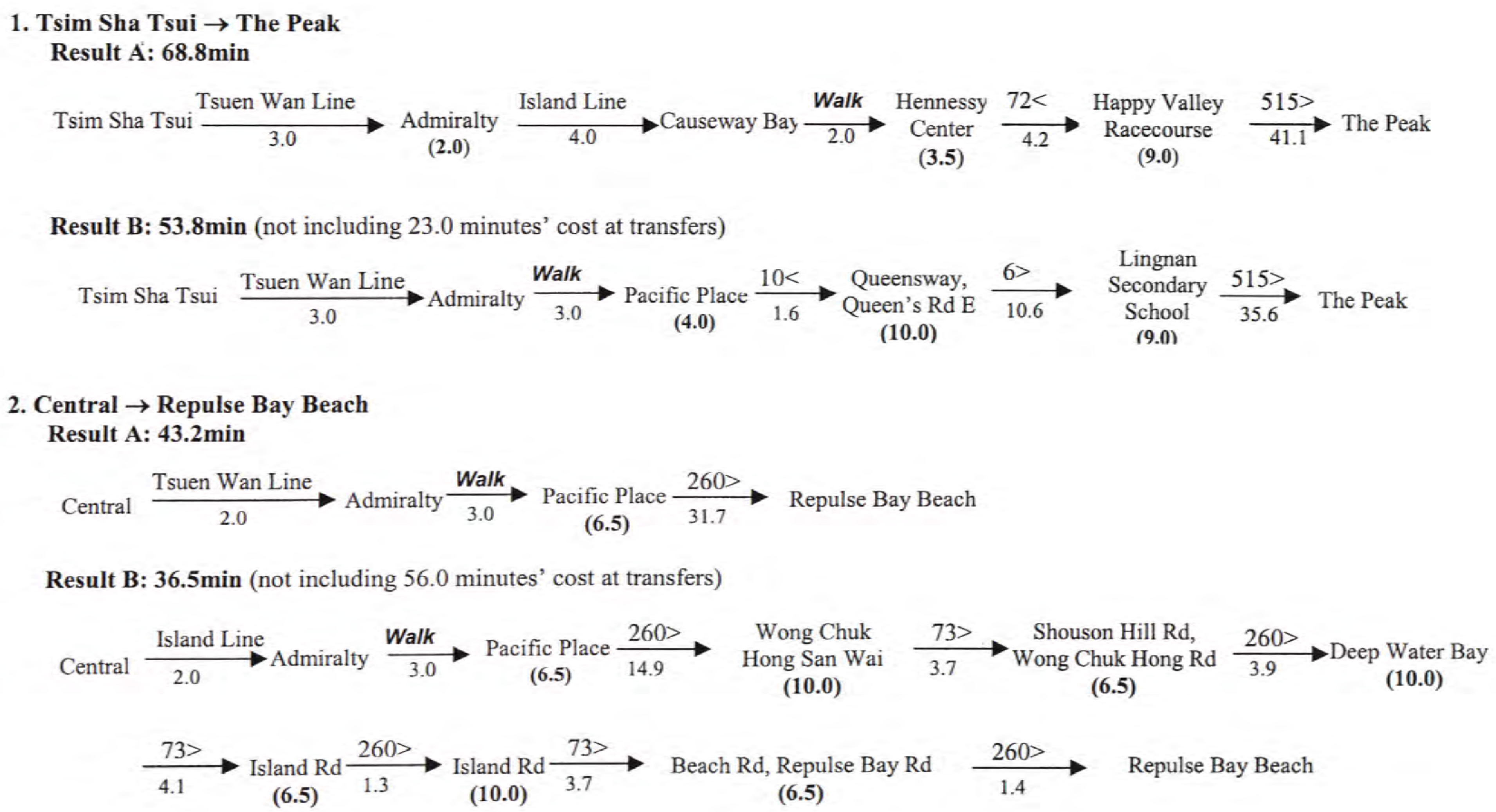


Figure 5.14 Comparison of routing results from the prototype and from the traditional method

3. North Point Ferry → Lei Tung Estate

Result A: 46.3min

North Point Ferry —10> (17.5)→ Happy Valley Racecourse **(6.0)** —96> (21.9)→ Lei Tung Estate

Result B: 37.2min (not including 61.5 minutes' cost at transfers)

North Point Ferry —10> (1.0)→ Kam Hong St, King's Rd **(9.0)** —515> (1.2)→ Metropole Building **(4.0)** —10> (1.8)→ Winner House, King's Rd **(6.5)** —8X> (1.6)→ Fortress Hill MTR **(9.0)**

—515> (1.4)→ Ching Fung St Flyover **(7.0)** —99< (13.7)→ Aberdeen Tunnel Link Toll Plaza **(7.5)** —72< (3.5)→ Aberdeen Sport Ground **(6.0)** —96< (2.9)→

Nam Long Shan Rd, Wong Chuk Hong Rd **(7.5)** —N72< (1.9)→ E On Industrial Building **(6.0)** —96< (8.2)→ Lei Tung Estate

Figure 5.14 Comparison of routing results from the prototype and from the traditional method (cont'd)

4. Wah Fu (North) → Victoria Park

Result A: 46.3min

Wah Fu (North) —73> (10.7)→ Tin Wan St, Shek Pain Wan Rd **(3.5)** —72> (26.2)→ East Point Center —***Walk*** (0.5)→ East Point Center **(2.0)** —Tram1 (3.4)→ Victoria Park

Result B: 39.1min (not including 72.5 minutes' cost at transfers)

Wah Fu (North) —48> (1.5)→ Wah Song House **(10.0)** —73> (9.2)→ Tin Wan St, Shek Pai Wan Rd **(3.5)** —72> (3.2)→ Aberdeen Bus Terminus **(4.5)** —37A (1.6)→ Yin Yee Mansion, Aberdeen Main Rd **(5.0)** —48> (2.9)→

E On Industrial Building **(5.5)** —70< (0.8)→ Vita Tower **(7.0)** —99> (2.1)→ Maxim's Factory **(7.5)** —N72> (5.4)→ Aberdeen Tunnel Link Toll Plaza **(6.0)** —96> (5.6)→ Sung Tak St, Morrison Hill Rd **(6.5)** —5< (1.9)→

Leighton Center **(6.5)** —8X< (0.9)→ Bonaventure House **(4.0)** —10< (1.6)→ Pennington St **(6.5)** —8X (2.4)→ Victoria Park

***Note*:** —route name / time cost in min→ East Point Center **(waiting time in min)** —route name / time cost in min→

Figure 5.14 Comparison of routing results from the prototype and from the traditional method (cont'd)

Functions of the prototype for a general GIS, information retrieving, displaying and data querying, are introduced briefly. Then, routing function is described in detail. Several routing examples based on different routing criteria reached by the prototype are shown and illustrated. For least-time routing, the results are compared with the outcomes by the traditional method in which mode information and time delay at transfers are not considered. Based on the comparison, the differences of results from two methods are pointed out and the reasons are given. The results from the prototype are indicated to be more reasonable outcomes for passengers than those from the traditional method.

CHAPTER VI

CONCLUSION

6.1 Research Findings

In this paper, in order to help passengers find reasonable paths on the multi-modal mass transit network in Hong Kong, a data model for representing and routing on such a network is designed. Then, setting Hong Kong Island as the study area, based on the relevant public transportation data collected, and following the data model, a GIS-T prototype is constructed and some useful results are given by the system. By now, two purposes of this research mentioned at the beginning of this thesis are generally reached. It is the time to make a summary on the work of this research, in order to give constructive suggestions for further studies. Research findings from the conceptual data model for the multi-modal mass transit system and the GIS-T prototype of the study area are described in the following part.

Node/link based data model, which is a simple and widely used model for network representing, can still work for the multi-modal public transportation system by generating service network and defining transfers. The service network is created from the route system layer, which is originally generated on the transportation infrastructure network. As these layers have been co-registered, they can share information of different types through the linkages between layers. Then service network contains not only the topology information of service routes, but also the information of the physical transportation infrastructures. Different routes that pass the same infrastructure segment are treated as several separated features in service network instead of a single feature. This helps constructing topologic relationship among different routes conveniently. Defining of transfer in service network is important to execute routing on the multi-modal public transportation system. They are special nodes in the network, which connect links of different routes. Extra cost happens at transfers, such as time for waiting, more fare to reach the destination. The information of extra costs for traveling is attached as attributes to the node that may works as a transfer. Then, the information is used for shortest path analysis and can greatly affect the routing result.

During the process of route finding, transfers in the service network of the multi-modal public transportation system are only a kind of transitory and conditional features. That is, in shortest path analysis, a node works as a transfer only when route change detected on the incoming link and the out link at the node. Otherwise, it is the same as other nodes in service network, working as a connector of links.

Dijkstra's algorithm for single-source shortest path problems, after slightly revised, can be used for the single-source shortest path analysis on the multi-modal public transportation network. For shortest time routing, origin Dijkstra's algorithm only calculates the costs for links, which are considered as in-vehicle travel time in public transport. However, out-vehicle travel time, such as time of waiting vehicles and walking between transfers, cannot be ignored in most route decisions for public transport. After revised, besides the weight of each link, extra costs brought out at transfers are taken into consideration, also. With the revised algorithm applied on the data model, a more reasonable result is given by the prototype.

With the data model designed in this thesis and the routing model based on Dijkstra's algorithm adopted, the GIS-T prototype of Hong Kong Island can organize the multi-modal mass transit data and help passengers choose a reasonable path on the public transit network to a certain extent. Although only part of the mass transit routes on Hong Kong Island are included in the prototype, it has no harm to represent the generality and characteristics of the system. Organized in GIS-T with the data model, the mass transit information of Hong Kong Island can be easily accessed and clearly presented. Drawing geographical data in map with diverse map scales and various map symbols, showing attribute data in tables by only a simple click on relevant features on the map, displaying required information while getting rid of unwanted data, all these functions give a more convenient and clear presentation of public transport information than text-based information and traditional maps. More over, with the help of the routing model based on Dijkstra's algorithm, public transport information stored in GIS-T can be used for finding fairly reasonable path for passengers in the prototype. Then, information of the mass transit is not only read by passengers, but it is organized under GIS-T to give passengers suggestions on route choice for a certain pair of origin and destination. This is much different from traditional ways for the mass transit information organization in Hong Kong, which usually organize the information in text or text and figure mixed format, and is difficult to give a solution for route choice. Furthermore, the prototype gives the routing result as a map and a text-based guidance. All these features show that, with the data model, the GIS-T prototype can provide a much better organization and presentation for the mass transit information. The prototype is useful and feasible to help passengers in Hong Kong to get a comprehensive understanding on and take full advantages of the public transportation system.

6.2 Research Limitations

As no beauideal exists in the world, there are also several constraints in this research that are worth examining.

Data redundancy exists in the service network layer. Although separated representation of links for different routes passing the same transportation infrastructure segment can bring about easy constructing of topologic relationship among links and fast analyzing on the network, it unavoidably leads to data redundancy in the database. For example, if four routes pass the same road segment, a link for each route is recorded with the road central line information. Then, three more duplicated links are stored in the database with different link IDs. If the database is not very large and duplication is not very often, the situation of redundancy can be ignored. But, if duplication appears very frequently in a large database, the situation may become serious. New solution is desired to maintain the convenience for route link representation and efficiency in routing on the one hand, and decrease the data redundancy in the database on the other hand.

Geographical information update can be an arduous work. Layer-cake model gives a clear way for data organization of different layers. The relationship of corresponding features in different layers is maintained by common fields in attribute tables. As database for GIS is not pure relational database, especially for geographical data, normal forms used for normalization of relational database cannot be totally applied on GIS database. Then, when geographical data update work happens in one layer, corresponding update work in other layers should be completed manually. Otherwise, the relationship among different layers is likely to be destroyed.

Representation of transfers needs further improvement. Stops and stations are abstracted and represented as zero-dimensional features – nodes in the service network, because they all work as connectors of links. Such a way of representation is suitable for bus stops, which usually are poles with route signs in the real world. For representation of subway stations, it is rather limited. As subway stations usually occupy large areas, they are more suitable to be abstracted as two-dimensional features instead of zero-dimensional nodes. When working as transfers, subway stations have much lager scope than bus stops for route transfer. Although solutions are given in the thesis to deal with this problem, some characteristics and connectedness information of subway station transfers are inevitable lost.

The prototype can provide only one result, the minimum one, for each pair of origin and destination and a given criterion. As Dijkstra's algorithm is adopted as the routing algorithm, only one result is given, the result of the shortest path in terms of weight of links. Then, even though the second choice has no different from the first choice to passengers or it is also useful, it is excluded from the result and its information is hidden in the sea of data.

Reliability of the result needs further examining. Routing result reached by the prototype includes the extra cost happening at transfers, and it is better and more reasonable than the result only including in-vehicle costs for consideration. However, as the situations in the real world are much more complicated than that people can assume, the result from the prototype can never exactly match the real situation. For example, the determination of time consumption for each route link is a difficult task. As the traffic condition of a road can greatly affect the speed of vehicles and, further on, their travel time on the road, the routing result may change greatly under different traffic conditions. If the information of real-time traffic conditions can input the system, the result will be much more accurate. But the data collection and input of real traffic conditions are still barriers to be overcome. So this research is trying to get more reliable result with the data currently available.

6.3 Direction of Further Studies

This research is only a beginning of study on GIS-T for the multi-modal public transportation system. Many works can be done based on it. The following are several possible directions for future studies.

First of all, the data model for the multi-modal public transportation system can be improved in further research. As mentioned in research limitations, representation of transportation features and organization of data are required to be under further considerations. For example, two-dimensional polygons can be treated as node features serving as connectors in the network, in order to keep their shape and maintain node's characteristics together. When real-time data collection and input become possible, the data model can be extended to deal with the real-time transportation data (Etches, Claramunt, Bargiela, & Kosonen, 1999), such as the real travel speed on a road, in order to give more in time and accurate results.

Secondly, routing criteria can be studied in detail for future research. In this thesis, only three criteria are assumed to be accepted by passengers for route choice. In fact, result routes reached by those three criteria are seldom adopted by passengers in real life, due to the extreme 'perfect' of the result. Generally, passengers prefer to an optimal route rather than a best route. An optimal route is usually a compromised result by several travel factors, such as a faster but not expensive route. Routing models will be studied to deal with these new requirements. Under such models, more than one result routes may be provided as optimal routes for passengers' choice.

As the development of web-based GIS, techniques allow GIS functions practiced on the Internet (Gittings, 1999; Plewe, 1997). Also, the prototype can be further developed in detail, such as including all the mass transit information of Hong Kong, and distributed on the Internet in the future. Then, the public can access the system through the Web. When passengers want to go out by public transport, before they start out, they can log on the web page for route selection, input the origin and destination, and get the recommended routes described both in map and in text. Passengers can make their decision on the provided recommendations. Such a service will not only benefit local passengers on taking full advantages of the public transportation system, but also help tourists and new comers move around the city easily.

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