A MULTIMODAL MULTI-CRITERIA DYNAMIC ROUTE CHOICE MODEL USING GIS AND MICROSCOPIC TRAFFIC SIMULATION

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NATIONAL UNIVERSITY OF SINGAPORE
2004
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A THESIS SUBMITTED
FOR THE DEGREE OF MASTER OF ENGINEERING
DEPARTMENT OF CIVIL ENGINEERING
NATIONAL UNIVERSITY OF SINGAPORE
2004
ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to my supervisors, Dr. Huang Bo and Dr. Lee Der-Horng for their invaluable guidance, advice and encouragement throughout the course of this study. Appreciation is also extended to Prof. Cheu Ruey Long, the ITVS Laboratory supervisor, for his support and encouragement.

Sincere thanks are due to the lab technicians Mr. C. K. Foo, Mr. S. H. Ooh, Ms. Chong Wei Leng and other administrative staff, for their assistance in providing excellent laboratory equipment and a conducive research environment.

I would like to thank Liu Qun, Wang Hao and Liu Daizong, for their continuing help on my study and research.

I am also pleased to thank Huang Wei, Brandon, Wu Lan, Yao Li, Zheng Weizhong, Pan Xianhong and all other ITVS Laboratory members, for their care and encouragement.

Special acknowledgements are accorded to the National University of Singapore, who provided the financial support for this study in the form of a research scholarship, without which I would not have been able to complete my studies here.

Last but not least, I am grateful to my parents and relatives, for their love, endless support and understanding throughout the entire course of my work.
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SUMMARY

Multimodal transportation, comprising trips consisting of two or more vehicular modes, is a common travel phenomenon in Singapore. With an increasing population and traffic congestion, multimodal transportation has become a more attractive and important alternative for travelers. However, due to the special features of topography and physiognomy in Singapore, travelers are often confused by thousands of facility stations, twisted routes and complicated transfers, whenever they are routing. Under these circumstances, the development of Advanced Traveler Information Systems (ATIS) has great potential in Singapore. However, so far these systems are mainly based on printed or digital maps and text descriptions. These route maps and facility assistants are not very convenient for travelers to refer to. With the rapid development of Geographic Information Systems (GIS) and their growing impact on transportation, GIS applications for Transportation (GIS-T) is considered as a significant approach for managing and solving the multimodal transportation problems.

This study proposed a Multimodal, Multi-criteria Dynamic Route Choice (MMDRC) model. The main goal of this model is to provide route choices for travelers across different transportation modes, based on multiple criteria. The three main transportation modes in Singapore include cars, buses and the Mass Rapid Transit (MRT). The multiple criteria are travel distance, travel time, fare and reliability. Given an origin and destination, under certain constraints, an optimal route can be obtained by the MMDRC.
GIS techniques and a traffic simulation method were adopted for developing this model. MapObjects and PARAMICS were chosen for building GIS and simulation models, respectively. GIS was used to organize the multimodal networks and derive the optimal path in terms of various criteria posed by users. A traffic simulation system was used to simulate the traffic conditions and generate real-time traffic data. To provide travelers with a multi-criteria routing environment, the Analytical Hierarchy Process (AHP) was adopted to determine the weights of each criterion for calculating a generalized link cost. A dynamic, least-cost path-finding algorithm and a switching delay model were also formulated and applied in this model.

An integrated prototype fulfilling the above aspects was developed to implement the proposed model using Singapore’s multimodal transportation network data. From the Graphic User Interface (GUI), which was developed for this study, travelers could obtain the optimal routes through map displays and text illustrations. The prototype developed exhibited a great potential for providing real-time route guidance service to the public. It also holds the potential to become a personalized travel planner to assist travelers in planning an itinerary for multiple visits, depending on individual preferences.

Key Words: GIS, Route choice, Multimodal, Multi-Criteria, Microscopic Traffic Simulation
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CHAPTER 1

INTRODUCTION

1.1 RESEARCH BACKGROUND

With the realization that this could improve efficiency, safety and flexibility, the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) and the Transportation Equity Act of the 21st Century (TEA-21) were enacted and presented a shift in the traditional transportation policy of promoting individual modes to a multimodal system approach. Multimodalism offers the promise of lowering overall transportation costs by allowing each mode to be used for the portion of the trip to which it is best suited, thereby reducing both congestion and the burden on overstressed infrastructure components. While multimodal transportation benefits our daily lives, few studies have been contributed towards this topic, especially on multimodal network construction and multimodal route choice (Ziliaskopoulos, 2000). This is due to the fact that multimodal networks are characterized by dynamically changing conditions and multiple modes of transportation operating simultaneously on them. Route choice in land transportation is a major component of many Intelligent Transportation Systems (ITS) and a major area of study in the field of transportation research. However, route choice in urban transportation is made complicated by the existence of multiple transportation modes, planned schedules and multiple fare structures. In addition to these factors, when it comes to considering the dynamic traffic information and multimodal routing criteria, most traditional route choice
systems become impractical and inefficient. This study aims to propose a model which allows for route choice across different transport modes in terms of multiple criteria which are based on the transportation environment of Singapore.

Singapore operates a world-class land transport system. Within its territory of 647.5 km$^2$, there are three main transport modes: the car, the bus and the rail (see Table 1.1). Currently, the total length of her arterial road exceeds 3,000 km and of this, the express way is about 140 km. The total length of the railway exceeds 80km. However, the road capacity still faces a challenge resulting from the rapid increase in the number of private vehicles and in the population. Today, Singapore’s population of 3.8 million makes 7 million passenger trips per day, of which 63% are made on public transport. By the year 2030, the population is expected to exceed 4.1 million, and the projected number of daily trips will grow to 10 million, 75% of which is estimated to be made on public transport. Therefore, continuous efforts are being made in Singapore to improve and expand the public transport system and services. Hence, constructing a smart and convenient route advisory system is very important and necessary for commuters.

To tackle the complex multimodal problem calls logically and strongly for the introduction of advanced information technologies. Geographic Information System (GIS) has rapidly risen to become one of the top technology choices for ITS developments since 1997. This technology has been widely used in many areas and has been applied successfully in the transportation community and is known as “GIS-T”.
Chapter 1 - Introduction

GIS-T applications cover much of the broad scope in transportation issues such as infrastructure management, fleet and logistics management, and transit management. However, few efforts have been made to advance multimodal modeling in GIS-T, though this could be essential in multimodal routing (Goodchild, 1999).

Table 1.1 Main Transportation Modes in Singapore

<table>
<thead>
<tr>
<th>Traffic mode</th>
<th>Operator</th>
<th>Service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>Private Car</td>
<td>Land Transport Authority</td>
</tr>
<tr>
<td></td>
<td>Taxi</td>
<td>Comfort Group &amp; CityCab</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TIBS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yellow-Top Cab</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,000</td>
</tr>
<tr>
<td>Bus</td>
<td>Singapore Bus Service Transit Ltd. (SBS)</td>
<td>Total 200 routes: 2,500 buses; 3,000 bus stops;</td>
</tr>
<tr>
<td></td>
<td>Trans-Island Bus Services Ltd. (TIBS)</td>
<td>Total 53 routes: 600 buses</td>
</tr>
<tr>
<td>Rail</td>
<td>Singapore Mass Rapid Transit Pte Ltd (SMRT)</td>
<td>Total track length: 249km</td>
</tr>
<tr>
<td></td>
<td>Singapore Light Rapid Transit Pte Ltd. (SLRT)</td>
<td>About 10.3 km</td>
</tr>
</tbody>
</table>

Data source: Land Transport Authority of Singapore

Microscopic traffic simulation, another booming, state-of-the-art technique has been widely adopted in transportation studies recently, owing to its capabilities, such as accurate representation of the realistic traffic conditions and for providing real-time traffic data. Furthermore, simulation becomes the best alternative because of its relatively low costs and easy controllability of the variables involved. On the basis of well-developed traffic theories, traffic simulation models have served as acceptable
tools for meeting the requirements of traffic studies in both on-line operation of control strategies, and in off-line design and evaluation.

From the GIS-T perspective one of the most important challenges for GIS currently, is to generate a corporate resource whose full potential will be achieved by making the integrated systems accessible to a large set of end-users (Fletcher, 2000). By combining the advantages of the GIS and the traffic simulation, it is possible that a powerful system could be built up. It is with this in mind that a dynamic multimodal route choice model which combines GIS and traffic simulation, and is based on multiple criteria, is developed and tested in this thesis.

1.2 Objectives

The objectives of this thesis are:

1) To build a synergism multimodal, multi-criteria route choice model;

2) To develop a suitable dynamic routing algorithm in a multimodal traffic environment;

3) To build a multimodal network and geo-database in a GIS environment which can perform routing;

4) To construct a transfer delay model for presenting the switching delay between modes;

5) To create a multi-criteria evaluation system for satisfying the variable routing;

6) To test the proposed model using the current Singapore road network.
1.3 SCOPE OF RESEARCH AND APPROACH

This study aims at creating a multimodal, multi-criteria, dynamic route choice model with the synergy of the GIS and the microscopic traffic simulation, which could be applicable under all kinds of urban traffic conditions. The inherent complexities of the multimodal transportation model include the representation of multiple road networks, the dynamically-changing conditions and multiple transportation modes. Conventional techniques cannot make much use of spatial or locational attributes of transportation entities, other than serve as reference details for them. Therefore, advanced information technologies should be employed. A sophisticated technology, i.e., GIS, is introduced to conduct the complex multimodal problem. GIS has developed at a rapid pace in the past three decades. The integration of various application models into the GIS enables users to go beyond the data inventory and management stage to conduct complicated modeling, analysis and visualization for spatial decision-making.

However, most GIS tools are based on a static view of networks. Due to the lack of compatibility with real-time traffic data, GIS seems insufficient in coping with network dynamics (Huang, 2002). The advent of microscopic traffic simulation, however, shows potential in overcoming such problems. Microscopic traffic simulation has become a popular tool for examining the feasibility of an ITS project and assessing its impact on transportation systems (Jayakrishnan, 2001). This is not only due to its ability to capture the full dynamics of time-dependent traffic phenomena, but also to its
capability of dealing with behavioral models accounting for drivers’ reactions. Hence, there are compelling reasons for integrating the GIS and traffic simulation into a system to manage and control the multimodal transportation models, since their strengths complement each other (You, 2000). In this study, the simulation tool (PARAMICS 4.0) is used to produce real-time traffic data for dynamic routing.

In addition to the two techniques mentioned above, a transfer model and a dynamic path-finding algorithm are proposed and implemented. The transfer model is formulated for presenting the switching between each transportation mode. It is of the utmost importance in a multimodal problem, but little research has been devoted to this problem. Although previous studies have extensively investigated the shortest path algorithm, few of them have focused on multi-modal path finding and these few studies are mainly limited to static transit networks for planning application (Chabini, 1999, Ahuja, 2002). This is due to the inherent complexities arising from this problem, such as time-dependent networks, multi-modal transportation and time constraints. The dynamic path-finding algorithm proposed in this thesis is generated mainly for the multimodal system which is based on the classic Dijkstra’s algorithm.

To build a comprehensive route choice system, different routing criteria should be taken into account. Travel distance, time, costs and safety are selected as the routing criteria. At the same time, a generalized cost, synthetically considering all the factors, is also considered as an important factor. The Analytical Hierarchy Process (AHP) is
adopted for determining the weights of each routing criteria.

The entire model and a friendly Graphic User Interface (GUI) is also devised by the GIS tool-MapObjects 2.0. Finally, a prototype fulfilling the above contents was implemented on multimodal transportation networks in the Central Business District (CBD) of Singapore.

1.4 THESIS OUTLINE

This thesis is organized into seven chapters. Chapter 2 presents a review on the related methodologies and techniques. The studies conducted on the multimodal network modeling are introduced at the beginning. This is followed by the multi-criteria optimization applied on the shortest-path problem and a description of the Analytical Hierarchy Process (AHP) methodology. In the next section, the integration of transportation models with GIS is described.

Chapter 3 presents the modeling approach for multimodal transportation systems. Firstly, the application domain of the proposed model is given. In the next section, a detailed description of the architecture of the system is presented, followed by the procedures of the multimodal network construction in a GIS environment. The dynamic switching delay model is presented in the last section.

Chapter 4 contains a detailed description of proposed multi-criteria evaluation
model, which based on the transportation environment of Singapore. Travel distance, travel time, travel costs and safety are selected as the basic and necessary factors. The generalized cost is the combination of the travel time, travel costs and safety which using AHP methodology.

Chapter 5 is entirely devoted to the dynamic path finding algorithm for multimodal routing problem. The chapter begins with a review on the traditional path-finding algorithm, then it is specified to the multimodal routing algorithm. Finally, the proposed dynamic path finding algorithm is presented.

Chapter 6 is a case study. It begins with the implementation procedure, and case study network modeling and the building of a GUI. The next section describes the implementation of the simulation model. It is followed by a description of the implementation of the simulation tool. Given the results analysis which gained from implantation. The general functions provided by the system are presented next. The chapter ends with analysis of the results obtained from the implementation of the proposed model.

Finally, Chapter 7 presents the conclusions of this thesis and provides suggestions for future research.
CHAPTER 2
LITERATURE REVIEW

This chapter presents a literature review on multimodal network modeling, the optimization of multi-criteria and the integration of transportation models with the GIS. Another aspect which is discussed is the dynamic routing algorithm, for consistent representation of the proposed algorithm in Chapter 5.

2.1 MULTIMODAL NETWORK MODELING

2.1.1 The Significance of the GIS in Transportation Models.

GIS-T is a main branch of GIS applications and dates from the very earliest studies on GIS in the 1960s (Goodchild, 1999a). A fairly complete 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.

According to Goodchild’s study (1999b), evolutions of GIS-T can be reviewed from three perspectives: the map view, the navigational view, and the behavioral view. All these three perspectives of GIS-T represent different application aspects. The map view is a static representation of a transportation system. The navigational view aims to transform the dynamic nature into a static geometry transportation network. The
behavioral view usually uses discrete objects on or off the linear network in mobile characteristics (Shaw, 1999).

A GIS is a spatial representation or model of the data used to depict a portion of the surface of the earth. In the transportation context, three classes of GIS models are relevant (Goodchild, 1998):

- **Field models** (Represent continuous variations of a space object which used in terrain elevation);
- **Discrete models** (Represent discrete entities, such as points, lines or polygons. These models usually used in expressway rest areas, toll stations, and urbanized areas);
- **Network models** (Represent linear entities, such as roads, rail lines, or airlines. These models are fixed in the continuous reference surface.

The above three models are important in GIS fields. However, from the point of view in transportation, the basic networks built by nodes and links still are most prominent, even considering single mode or multi modes transportation networks. Actually, most transportation networks only need the network can represent both geometric objectives and the data associated with.

Examples of such applications include:

- Pavement and other facility management systems;
• Real-time and online routing applications, including emergency vehicle
dispatching and traffic assignment in the four-step urban transportation planning
process;
• Web-based traffic information systems and trip planning engines;
• Vehicle navigation systems; and
• Real-time congestion management and accident detection.

At present, one of the most important challenges from the GIS-T perspective for
the GIS is to generate a corporate resource, the full potential of corporate resource will
be obtained by integrating the systems accessible to a large set of end-users (Goodchild,
2000).

2.1.2 GIS Data Models for Multimodal Route Choices

➢ Early GIS Models for Multimodal Transportation
Most of GIS-T models are suitable of a single traffic mode (Goodchild, 1999b), and
are too limited to represent and handle the complicated cases of the real world. In the
real world, a transportation network consists of various traffic modes: different
categories roads, railways, water routes, and airways. Besides, one single journey
usually consists different traffic modes. In fact transportation network is a complicated
multi-mode network with different characteristics and rules applied 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 GIS framework.
Several attempts and practices have been made by researchers. Grayson in 1993, for accessibility analysis on a public transit system, proposed a comprehensive framework of three levels of networks to represent a multimodal public transportation system by linking GIS with Relational Database Management System (RDBMS). The three networks are road network, transit network dedicated for bus routes and stops, and a super network for the abstraction of transit routes facilitating network analysis (Koncz et al., 1995). This prototype constructed only for bus routes but not consider the walking between bus stops to nearby locations.

In order to develop a GIS-based simultaneous transportation equilibrium model on a multi-modal network, Miller et al. (1995) constructed a multimodal transportation network using topological relationship. This network is a GIS-based simultaneous transportation equilibrium model. It includes route classes (transit routes and streets) which abstracted from a basic topologic network. This approach separates the multimodal network from the physical network for mode-specific attributes, and contributes to a better data consistency.

In the designing of a GIS-based automatic trip planning system (ATPS), Peng (1996) modeled the transit network by another approach. By decomposing the physical transport network into segments, Peng set up a form of pattern, composed of one or several segments, and later, used these patterns to build up mass transits. Studies at the Center for Spatial Information Science in the University of Tokyo, which is conducting
spatial analysis on inhomogeneous networks, may provide a more general outline for dealing with the multimodal problem.

Zhou et al. (1999) attempted the representation of Miller’s virtual network using an object-oriented approach. All these efforts have been made to construct an integrated network which can record the topologic relationships among different traffic modes or transit routes.

Cohn et al. (1996) described a model to predict and analyze mode competition between rail and other transport modes, where access and the egress level of service directly affect the attractiveness of the main modes. The assignments, however, are completely unimodal. Nielsen (2000) gave a description of the application of error component models to route choice in transit assignment models that successfully dealt with route overlap and incorporated differences associated with travel preferences. The model reported in (Florian, Wu and He, 2000) is a large-scale application of a multi-class, multi-mode traffic model in Santiago, which computed the equilibrium between travel demand, mode choice and route choice, where interaction between modes such as buses and cars is explicitly accounted for. In that model, multimodal trips (e.g. car and the metro) are represented as a distinct mode. However, Benjamins et al. (2002) pointed out that what these modeling approaches had in common was that the analyst had to predefine all available modes. When such models deal with multimodal trips, they could show practical drawbacks concerning choice set
constraints, transfer penalties and interaction between modes.

➢ The Development of Multimodal Transportation in GIS-T

Responding to the developing trends towards GIS software, a data consortium called UNETRANS (Unified Network for TRANSportation), led by Environment Systems Research Institute (ESRI) staff and researchers at the University of California at Santa Barbara (UCSB), and 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 project, which ended at the end of 2001, was to generate a conceptual object model of transportation features incorporating multiple traffic modes and accommodating multiple scales. As a result, more than 30 points were listed as problems that the data model should or must deal with regarding modeling multimodal, transit, and travel demand forecasting (Kratzschmar, 2000). Their attempts at constructing a GIS framework were based on the basic data structures provided by ArcGIS 8. It was a tough task to meet all the requestments. However, a rough conceptual model is taking shape. A more recent model, the Transims micro-simulation package is a good example of multimodal trips which can assign travelers to multimodal routes with minimum generalized costs (Los Angeles National Laboratory, 2001).

While the scholars in the University of California, Santa Barbara, were working
on a state-of-the-art of data model for application on a multimodal transportation system, some other researchers were working on providing data sources for a multimodal 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 multimodal network. The results of this effort include both a combined multimodal 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 a CFS multimodal network, incorporating highways, rail lines, and water ways, along with a set of intermodal terminals and a terminal model to connect them. As the multimodal network is considered to be composed of several single-mode networks, each occupying a horizontal plane, and with intermodal terminals connecting two modes at the transfer, the researchers used 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 not only for vehicle routing and scheduling, but is also used in other studies on geographically-based highway networks (Center for Transportation Analysis, 1996). Similarly, updated databases for railway networks, waterway networks, and intermodal terminals in the United States are created by CTA (Bureau of Transportation Statistics, 2000).
The Application of Multimodal Modeling using GIS-T

Southworth (2000) developed an integrated digital multimodal freight transportation network with the aid of GIS technologies. The construction of this model was based on the United States Commodity Flow Survey in 1997. The main function of this model is to simulate the freight routing on this transcontinental network by combining truck, rail and water transport. The key to this modeling is a properly constructed and multimodal digital representation of the freight-supporting transportation infrastructure.

The construction of the network was established through merging individual mode-specific transportation network databases into a single, integrated multimodal network that allowed both single and intermodal traffic routing. This was done by linking them through a series of intermodal truck-rail, truck-water and water-rail transfer terminals. The network was a logical network with resulting virtual links ranging from sections of real highway pavement to broad ocean lanes and national rail networks extending to main rail lines in neighboring countries.

Routing procedures were applied specifically to multimodal freight transfers, i.e., from trucks on highways, to trains on rail networks and then to ships on trans-oceanic or “deep sea” networks. The networks were linked via terminal access connectors which were absent from the original databases. A logical network (unlike a spatial data structure) called for routing analyses to be performed outside a GIS package, and the
results thus obtained were then transferred onto a GIS model for presentation.

Figure 2.3 illustrates that “irrelevant” portions of the individual networks were “switched off” during the routing process by applying infinite impedance to those links. Depending on the desired origin and destination, a suitable shortest-path algorithm is applied to perform the routing on the final network which consists of essential mode specific links. The essential transfer costs across different modes are incorporated in the terminal Access/Egress links and the Within-Terminal Transfer links as shown in the above diagram.

The main drawback of this method is the representation of the multimodal network as a “logical” network which means that the routing procedure is performed outside a GIS package. Currently, it is therefore more efficient to analyze and represent two-dimensional Cartesian coordinate system networks entirely in an integrated GIS.
spatial data environment. This is in view of the availability of digital geometric or geographic data through relatively cheap advanced remote sensing techniques like satellite imaging. It is also easier to implement and maintain a complex network using GIS as compared to a conventional logical node-link network data structure.

➢ The Supernet Approach for Route Choice

Benjamins et al. (2002) and Carlier et al. (2003) in Transportation Research Board (TRB) presented a supernet approach to handle multimodal transport modeling. Actually, the first supernet approach was proposed by Sheffi (1985). The main idea of the supernet is to combine all modes into a single multimodal network that includes access, egress, transfer, and waiting links. In this approach mode choice follows from the route choice through the network. Sheffi also formulated the route choice using a utility function. The supernet approach was used by Benjamins et al. to study an area in the Netherlands from the point of view of computational feasibility, and the results were positive. The level of service between each pair of public transport stops was represented by explicitly coding a link between each pair of public transport stops on the network. The same idea was used by Carlier et al. But the difference was at the operational and complicated levels of the approach. The improved approach reduced the network complexity at the expense of a modest increase in the processing needed to reconstruct point-to-point levels of service for transit services.
2.2  THE OPTIMIZATION OF MULTI-CRITERIA

2.2.1  The Multi-criteria Analysis of the Shortest-Path Problem

Traditionally, the problem of finding the shortest path from a specified origin node to another node has been considered in the framework of a single objective optimization. More specifically, it is assumed that some value is associated to each arc (for example, the length or the travel time), and the goal is to determine the most suitable path for which either the total distance or the total travel time is minimized.

In many real applications it is often found that a single objective function is not sufficient to adequately characterize the problem. For instance, in the routing of hazardous materials, it is important to consider not only the total distance from a source to a destination, but also the number of people brought into contact with the hazardous materials along a route. In transportation networks, a typical situation that can be adequately represented by only considering more objectives, is related to highway construction, where time, costs, and ecological factors must be taken into account at the same time. In 1996, Fujimura presented the use of multiple objectives, such as safety, time and energy consumption to optimize the mobile robot navigation system.

In the context of multi-criteria optimization, the concept of Pareto-optimality, nondominance or efficient solutions, plays a crucial role since it is usually assumed that the criteria are in conflict, and thus, general speaking, it is not possible to find a
single optimal solution, but rather a set of Pareto-optimal solutions. In this case, it is necessary to choose from the Pareto-optimal solution set a reasonable solution, i.e., not the best solution for all criteria, but the most satisfactory.

In this thesis, a multi-criteria method was employed as constraints when routing on the multimodal network. Obviously, routing on the multimodal transportation network is restricted by many factors, such as travel distance, travel time, transfer times and so on. Therefore, a single criterion cannot perform well for these kinds of routing. It is when there is a need to find a route which considers several criteria together, that multi-criteria optimization is most important and practical.

2.2.2 The AHP Methodology

The Analytic Hierarchy Process (AHP) was pioneered by Saaty (1980). It employs a complete and hierarchical set of attributes for evaluating alternatives. In this technique, the problem is decomposed into a hierarchy to include all attributes. The underlying principle is to make a pairwise comparison on a nine-point scale.

This process requires the decision-maker to provide judgments about the relative importance of each of the criteria, and then to specify a preference for each decision alternative that is relative to each criterion. The output of the AHP is a prioritized ranking, indicating the overall preference for each of the decision alternatives (Ling, 1998).
In eliciting weights, pairwise comparisons of attributes are made on the nine-point scale. After all the values have been entered, the maximum eigen-value and its associated normalized eigen-vector are calculated. The eigen-vector represents the best weighting for the attributes. The normalized weights of all hierarchical levels are combined to determine the unique, normalized weights corresponding to the last level.

In rating the alternatives, the decision-maker makes pairwise comparisons of the alternatives on each attribute, on a nine-point scale. The pairwise comparisons are manipulated through eigen-vector calculations to create a ratio value scale on each attribute that is normalized to sum to 1.0.

The overall score for each alternative is then calculated by aggregation. The largest eigen-value of the pair-value of the pairwise comparison matrix is computed, and its associated eigen-vector represents the selection priority or ranking of candidates. A linear model is then derived and used to rank the alternatives.

The AHP employs an underlying scale with values from 1 to 9, to score the relative preferences for two items. Table 2 records the numerical scores recommended for the verbal preferences expressed by the decision-maker. Research and experience has confirmed the nine-unit scale as a reasonable basis for discriminating between the preferences for two items.
Table 2.1. The numerical rating criteria for the judgment factors

<table>
<thead>
<tr>
<th>Verbal Judgment of Preference</th>
<th>Numerical Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely preferred</td>
<td>9</td>
</tr>
<tr>
<td>Very strongly to extremely preferred</td>
<td>7</td>
</tr>
<tr>
<td>Very strongly preferred</td>
<td>8</td>
</tr>
<tr>
<td>Strongly to very strongly preferred</td>
<td>6</td>
</tr>
<tr>
<td>Strongly preferred</td>
<td>5</td>
</tr>
<tr>
<td>Moderately to strongly preferred</td>
<td>4</td>
</tr>
<tr>
<td>Moderately to preferred</td>
<td>3</td>
</tr>
<tr>
<td>Equally to moderately preferred</td>
<td>2</td>
</tr>
<tr>
<td>Equally preferred</td>
<td>1</td>
</tr>
</tbody>
</table>

In 1992, Brad suggested several advantages of the AHP. The method is more acceptable to decision makers. It is useful for a large number of attributes with outcomes measured on a subjective scale. It makes use of a decision maker’s intuitive judgments, knowledge and experience. It is also more accessible and more conductive for consensus building. Decision makers have no difficulty furnishing the necessary data and discussing results (Ling, 1998). In 1994, Maas found that pairwise comparisons can be used to detect intransitivity. It is also able to cope with problems that are difficult or impossible to structure using other techniques. Another advantage of the AHP raised by Schoemaker and Waid is that measurement scales can be used in areas that are too fuzzy, too unstructured, or too political for traditional techniques.

Despite having many advantages, the AHP also has its disadvantages. One of its limitations is the rapid explosion in the number of pairwise comparisons. In order for comparisons to be kept within a reasonable limit, the number of alternatives or attributes to be compared has to be limited. The number of pairwise comparisons,
which is the basis of this technique, is governed by the formula \( \frac{n(n-1)}{2} \), where \( n \) is the number of attributes.

### 2.3 Integration of Transportation Models with GIS

#### 2.3.1 The Main Types of Hybrid Models

Currently, there are three distinctive models that have been developed in close conjunction with GIS (You, 2000). As shown in Figure 2.3, they are:

- Type 1, the transportation model including GIS;
- Type 2, the transportation model connected to GIS; and
- Type 3, the transportation model within the GIS.

![Figure 2.3: Three types of hybrid models integrating with the GIS](image)

**FIG. 2.2.** Three types of hybrid models integrating with the GIS

Type 1 and Type 3 represent an inclusive relationship between transportation and GIS models. It is generally believed to be difficult to build customized programs for GIS due to the complicated mechanisms of GIS data. One possible solution is to use current object-oriented GIS function libraries and ActiveX controls which are offered by GIS vendors. MapObjects, NetEngine, GISDK and MapX are some examples of
this category. Their object libraries and controls allow users to perform spatial and attribute-based queries, communicate with external applications and build custom application interfaces in conjunction with object-oriented development environments such as Visual Basic, Visual C++ and Delphi. As a result, Type 1 applications could be more efficient than other methods, although they would be difficult to implement.

Type 3, in contrast with Type 1, emphasizes the GIS function. The inherent functions in GIS can implement many transportation studies such as those on transportation planning, traffic assignment and traffic data analysis. For developing a transportation model within GIS, built-in macro languages should be used, including Arc Macro Language (AML) in ARC/INFO, Avenue in Arc-View GIS, and GISDK in TransCAD. Nevertheless, it is understood that these macro languages are less effective in comparison to object-oriented development environments.

By integrating GIS and transportation, Type 2 could be the most efficient of the three models and was therefore adopted in this study. Using a customized software interface a bridge was built over the GIS and transportation models. On the one hand, GIS has an excellent capability for database management and display; while on the other hand, most current transportation modeling software packages interface with ESRI’s coverage and shape file to access GIS data formats. This makes it comparatively convenient for researchers to develop the overlap between GIS and transportation. In this study, PARAMICS version 4.0, an advanced suite of software
tools for microscopic simulation was employed to provide transportation data for the proposed system.

2.3.2  **Microscopic Traffic Simulation**

In traditional transportation studies, field experiments are necessary but need large investment, human efforts and time. Therefore, field experiments are often acceptable for large projects. Even field experiments impact the daily traffic flow, the collected data is often not suitable for microscopic analysis. People since start think an alternative method to collect and examine traffic data and theories.

Along with the development of computer and software, researchers tried to examine mathematical models through computer applications. This method is so called simulation and applied to transportation fields about thirty years ago. Through traffic simulation, a virtual transportation network can be constructed. Traffic signal, road constraints, varies vehicle types and even traveler behaviors can be simulated. Particularly, the traffic data is able to be collected through simulation. The development of simulation relieve the conventional engineering design and examine which need large investment, long duration and huge manpower.

So far, simulation has become the best alternative to field experiments in traffic studies because of its relatively low costs and easy controllability of the variables involved. On the basis of well-developed traffic theories and computer technologies,
traffic simulation models have served as mature tools for meeting the requests of traffic studies for off-line design and evaluation, as well as for online operation of control strategies. Several renowned traffic simulation tools, such as NETSIM (Federal Highway Administration, 1980), INTEGRATION and so on, have been developed and implemented in transportation research for decades. In this study, PARAMICS version 4.0, an advanced suite of software tools for microscopic simulation is employed to generate the link travel time at regular time intervals. Microscopic simulation models differ from traditional computational models in that they have significantly random components and attempt to represent the dynamic nature of traffic systems by simulating the interactions of individual vehicles. They model numerous components of traffic flow and their influences, and therefore provide more accurate traffic flow information, which is necessary for the analyzing of congested road networks. Microsimulation models also differ in that vehicles move in the system in real-time and are modeled according to the behavior of vehicle drivers. Researchers have indicated that vehicle drivers perform according to their aggression and awareness. In traffic engineering terms this can be accounted for in terms of simple rules of car-following, gap acceptance and vehicle kinematics. The detailed implementation of microsimulation models and PARAMICS are found in Chapter 6.
2.4 Summary

Based on the above literature review, GIS-T is suitable for representation of transportation features due to its well-developed data models and techniques for handling spatial data. The link/node based network model is a proper target domain for abstracting and representing a transportation network in the real world. Furthermore, it is convenient to apply a routing algorithm based on graph theory, onto the network model for shortest-path analysis. However, networks created in most GIS-T systems are focused on no more than one traffic mode. Under normal conditions, several different traffic modes are often integrated to serve public demand. Goodchild (1999) indicated that few efforts have been made to create databases that combine various modes, but these would be essential for multi-modal route choices. Although universal network connectivity is becoming a reality, no universally accepted data structures, formats, syntax, terminology, or quality standards exist at present (Fletcher, 2000). Problems related to representation of multi-modal transportation systems are receiving increasing attention from GIS-T specialists, transportation sectors and other traffic facility users. Consortiums are being organized to work on general data models for transportation, with the handling of multi-mode-based travel as one of their priorities.

AHP Methodology is adopted in this study for combining the different factors which would affect the results of route choice. With the aid of AHP, the coefficient of each decision element can be fixed. The application of AHP is presented in detail in
Simulation plays a very important role in the current development of ITS. In this study, simulation is employed as the corporate resource to provide specified traffic information to the GIS-T model.

As was mentioned in Chapter 1, the main public transportation modes in Singapore are a combination of car, bus and rail. Without a hybrid network that combines different traffic modes, GIS-T can hardly offer an adequate optimal route analysis. A proper approach for dealing with a multi-modal public transportation service is required. It is with this in mind that a method using the existing GIS-T principles, combined with a developed shortest-path algorithm and simulation technologies to handle the route choice in a multimodal transportation environment is proposed and implemented. The proposed model is discussed in detail in the following chapters.
CHAPTER 3

MODELING THE MULTIMODAL TRANSPORTATION SYSTEM

A detailed description of the multimodal transportation system modeling will be given in this chapter. It begins with a description and analysis of the application domain of this study. Based on the analysis of the application domain, the architecture of the proposed multimodal route choice model is formed. This is followed by the representation of the multimodal network construction in a GIS environment. At the end of this chapter, the dynamic switching delay model is formulated and explained.

3.1 APPLICATION DOMAIN: THE MULTIMODAL TRANSPORTATION SYSTEM

3.1.1 A Description of the Proposed Multimodal Transportation System

Travelers are likely to encounter a scenario on an urban transportation network, where one may select driving a car, riding a transit line, riding a bicycle, or walking to approach a destination. Before the rush hour, the route choices may consist of driving to a parking lot close to the destination and then walking to the ultimate destination, while later, during the rush hour, the choices may consist of driving to a park-and-ride facility, riding a bus or a train to a transit stop close to the destination, and walking from there to the ultimate destination.
Chapter 3 - Modeling the Multimodal Transportation System

However, finding the optimal transfer point and to decide upon the optimal transit service is fairly difficult. One may say that the existing car navigation products are well developed for route guidance. However, it is very different from navigation for a single car routing on a multimodal network. In navigation for a car, a driver faces the network of transportation infrastructures, mostly the roads, as well as the regulations applying on them. The route choices that face the traveler include a multimodal transport system, different traffic modes, twisted transit services and numerous stops. It is almost impossible for a traveler to collect all the dynamic information and make the optimal routing decision at once. The essential and comprehensive information for multimodal routing is vast and also exiguous. Such a scenario is just a simple example of routing for a multimodal trip. It can indicate that the multimodal transportation system is a very complicated system, covering a large variety of modal combinations with an even larger diversity of trip characteristics.

Multimodal networks are characterized by dynamically changing conditions and multiple modes of transportation operating simultaneously on them. They indicate the modes, routes, stops and transfer choice decisions on the part of the travelers (Benjamins, 2002). A possible advantage of multimodal transportation is the reduction in the number of long distance car trips by the offering of better access to long-distance public transportation and improving accessibility to city centers.
To visualize the concept of the multimodal transportation system, each modal network (e.g. rail and highway) can be imagined as occupying a horizontal plane, while multimodal terminals connecting two modes lie between the planes and are attached above and below by vertical access links. In Figure 3.1., the car, the bus and the MRT respectively occupy parallel planes of networks. The vertical access links represent switching delays occurring while accessing from one mode to another. These delays include parking time, waiting time at bus stops or MRT stations, the MRT-to-bus transfer which involves traveling from the MRT station to a nearby bus stop, or the car-to-MRT transfer which involves parking the car and traveling to the MRT station, etc. When routing on a multimodal network, it is implied that a traveler sets off at a certain time, and from a certain origin to various destinations. During the travel period, he will dynamically select and change proper transportation modes throughout the trip.

FIG.3.1. The conceptual model of a multimodal network

The construction of a multimodal system that provides the optimum path should take into account the existence of multiple modes of transportation, including travel in
private cars, buses, the MRT, and so on. With multiple transportation modes, the system also has to incorporate transfers between modes. Examples include the MRT-to-bus transfer which involves traveling from the MRT station to a nearby bus stop, or the car-to-MRT transfer which involves parking the car and traveling to the MRT station. Even within a single transportation mode, it may be needed to model time delay factors like delays at intersections or parking delays. Subsequently, the system must incorporate multiple objective functions (or multi-criteria) to offer commuters a variety of criteria for route guidance, such as the route with the minimum number of mode transfers, shortest travel time, or minimum total travel costs. Each of these criteria may be of the utmost importance to a commuter at a given time, and so the system should provide the option for the commuter of choosing from one of these. The fixed schedules of all available transit lines, and the time-dependent nature of the link travel times should be taken into account as well.

In general, the major difficulties associated with the building of a system for a multimodal transportation environment and providing paths on the multimodal include:

(1) The presentation of modes which consist of highways, transit and rail lines, with each line essentially operating on a different network, and this means that each line has to be treated as a different mode.

(2) The need to account for delays at switching points (e.g., at park-and-ride or multimodal facilities).
(3) The need to employ a proper algorithm for dynamic route planning on a multimodal network.

3.1.2 Objectives of the Modeling Work

Faced with different traffic modes, complicated transfers, numerous transit services, and in particular, dynamic traffic information, a traveler can hardly make a reasonable decision which satisfies his needs, which include traveling in the least time, with the least fare, and so on. However, by allowing GIS-T to predominate the single mode traffic network, it is reasonable to explore its potential capability for handling the multimodal network. This study attempts to construct such a multimodal network model which can effectively solve all the problems mentioned above.

3.2 Architecture of the Multimodal Transportation Model

Based on the description of the research domain, a multimodal, multi-criteria dynamic route choice model is proposed. The architecture of this model consists of three modules: the GIS module, the simulation module and the dynamic routing module.

FIGURE 3.2 shows that the GIS module includes the multimodal network and related topology information. The simulation model acts as a data resource for providing the necessary and real-time traffic data. The system functions are carried out through the GUI. The dynamic routing module resides with the GIS and can access the data generated by the traffic simulation module, which consists of a dynamic routing
algorithm, and this will be introduced in Chapter 5. The following section describes the GIS module and the traffic simulation module.

![Diagram showing the architecture of the proposed multimodal, multi-criteria dynamic route choice model](image)

**FIG.3.2** The architecture of the proposed multimodal, multi-criteria dynamic route choice model

### 3.2.1 Modeling the GIS Module

The GIS module is the core part of the proposed model and consists of three parts (layers), i.e., the private car, bus and MRT layers. Each layer is presented according to its respective inherent attributes. Generally, the topological information includes the coordinates of the nodes and the start-end of links. In addition to the general information, each layer has its own attributes. The MRT layer should embed in the rail network information, the train schedule, the fares charged, the travel times between two stations, and so on. The bus layer should embed in the bus schedule, the bus stop information and fare stages. The private car layer should be embedded in the link
travel times, the road distances, the intersection layers and so on. Different layers have close relationships with interconnecting entity IDs and so they can share information through common fields and maintain data consistency. The link attribute, in particular, should be pointed out as each link is associated with a set of attributes (link travel time, fare stage, etc.). This technique will be discussed again later in this study for the purpose of realizing dynamic path findings.

Among the three layers, the switching delay is also set as a layer containing every transfer link which connects all the transfer points. Although this layer has no virtual entity, it is the most significant layer in the GIS module, as it is through the switching delay layer that all the other layers can connect and construct the multimodal system. Other than operating the connections, the switching delay also implicates the transfer delays at every transfer point.

Actually, the GIS module is a geo-database which incorporates the basic road network geographic information with related attributes. The transport modes defined by developers are conceptual layers. The GIS database is characteristically a geographic description of the surface of the Earth. Each entity record is a geographic event in the sense that it is tied to a unique location defined in a given referencing framework. With the spatial referencing of objects, the topology of the data can be defined, which in turn enables a host of spatial query operations on objects and sets of objects (Thill, J-C. 2000).
The dynamic shortest-path finding algorithm is also embedded in the geo-database. Display of the geo-entities and route choices are displayed through the GUI. The system functions provided by the proposed model are established in terms of MapObjects, the current popular GIS software. In addition to the basic functions, like Information Retrieve and Map Display, Dynamic Routing is the main function. Details related to the routing algorithm and GUI will be presented in the following sections.

3.2.2 Modeling the Simulation Module

It was mentioned in Chapter 2, that because GIS serves static networks, it is thus insufficient for handling a network with dynamic information. However, the microscopic simulation tool can perform well in simulating traffic and generating real-time traffic data. To generate a simulation corporate resource with the ability to mimic dynamic traffic conditions, and providing dynamic traffic information, is an approach worth further exploration to make up for the drawbacks of a static GIS and to resolve the challenges mentioned by Goodchild (2000).

In Figure 3.2, it was shown that the simulation module serves as a dynamic data information source to provide real-time traffic data for GIS use. In this thesis, the simulation tool is specified as PARAMICS. Through the modeling and writing of the Application Programming Interface (API) in PARAMICS, the traffic data can be obtained after the simulation run. This data will be fed into the GIS module. With the aid of the simulation tool, the static geo-database will then be updated in a specified
time interval in order to achieve the goal of solving dynamic problems in a GIS environment. In this study, the dynamic data is used to update the link attribute table. The changing of the attribute data will affect the results of the dynamic path-finding algorithm so that real-time route choices are produced.

3.3 **MODELING THE MULTIMODAL NETWORK**

After clarifying the research domain expressed above, the next stage is to focus on the modeling of the proposed multimodal network. Three dominant transport modes are selected to construct this multimodal network. The three main components of this network will be described individually in the following sections.

3.3.1 *Construction of the Multimodal Network*

**The Car Layer**

The car layer belongs to the transportation infrastructure layer, and covers almost all the roads displayed on a map. Other transport networks are usually built on the car layer. The main components in the car layer are: Points, Line strings and Transportation features.

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

- **Line string**: a line unit. Usually, it is a segment of road.

- **Transportation feature**: a road, a highway, an expressway, etc., which are formed by points and line strings.


**The Bus Layer**

The bus layer can be regarded as a subset of the car layer. It is normally constructed by the arteries and sub-arteries crossing the urban network. The main components are *Bus stops, Route segments* and *Routes*.

- **Bus stop**: stop is sequential point feature along a route, serving as boarding or alighting point for passengers.

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

- **Route**: a service line in a bus layer.

**The Train Layer**

The train layer is a comparatively independent layer among all the transport modes. Although the train layer covers the whole city, the planning of the train route is independent of the existing road networks because the light-rail and subway systems can approach their destinations without any limitations. Other than these considerations, the travel speed, schedule and distance make the train a very special transportation mode. The main components in the train layer are: *Train station, Rail segment* and *Rail*.

- **Train station**: a station is a sequential point feature along a rail line, serving as a boarding or alighting place for passengers.

- **Rail segment**: part of a service line. Mostly, it is the segment between two sequential stops along a rail line.

- **Rail**: a service rail line in the train layer.
The Switching Layer

The switching layer is a virtual layer in the real world. As the switching between modes is the behavior of travelers, but not vehicles, it is therefore very difficult to define such human behavior in a general theory. In this study, it is considered that there is a virtual layer which records all the transfers between modes. This virtual layer is the switching layer. Taking into account different people, transfer times and locations, the switching results can be very different. However, the main components in this layer can be confirmed as:

- Switching location: the location of the switching. Generally these is transit stop, car park or other public facility.
- Switching link: the route segment that connects two switching locations.
- Switching mode: switching from car to bus, bus to train, and so on.

3.3.2 Representation of the Switching Delay

In urban transportation system, the intersections and streets can be translated into nodes and links, respectively. Based on the traditional representation of networks, the urban and transit networks can be elaborately presented, and can be found in Figure 3.3 (a). It is a typical presentation of an urban network. The circle nodes represent the road network. The intersections in the road network, are usually replaced by four extended nodes for specific elaboration of the turning restrictions and impedances. The diamond nodes represent the transit network. The transit link is represented by a linear network in which the transit stations are represented by nodes and the line haul portion
by links. The transit stations are replaced by two nodes for expressing transfer behaviors (Sheffi, 1985). The triangle node represents both a source and a destination for trips. This node is connected to both transit and car lines. It represents a set of trip origins and destinations which are located in the vicinity of the transfer station. The real network can best be represented by these methods.

FIG. 3.3. Simplified network representing a multimodal transportation

The traditional representation method is however usually employed in microcosmic analysis of traffic engineering. Along with an increase in the whole network, the number of nodes and links would increase rapidly and the origin network would be heavily extended. Almost every node is replaced by two to four dummy nodes. Therefore, the space for storing the geo-database behind the network would
expand inconceivably. It is impractical and also unnecessary to carry out this kind of representation method.

In this study, the multimodal network representation is simplified. It can be seen in Figure 3.3 (b), that the urban and transit networks maintain their original formats so that no redundant nodes will be added to the map. Taking advantage of data attribute storage methods in geo-database, the traffic impedance information is stored in the database instead of being expressed on the map. Such as the one-way and two-way links can be stored by their start and end nodes. The direction can be represented by the order of the OD pairs. Then the transfer links and loading links are unified to switching links as they all express switching delays. The switching links in this study are the mode transfer links. This representation is beneficial for reducing redundant data, and allows for clear presentation of maps.

3.4 THE DYNAMIC SWITCHING DELAY MODEL

Although previous studies have proposed some concepts for multimodal trips, few of them have mentioned a formulation for switching delays. It is interesting to note that these unsolicited studies focused mainly on static formulations, but were heavily dependent on the local transportation situations and accounted for time-dependency (Fletcher, 2000). This study, bearing in mind the transportation situation in Singapore, mainly considers the following as elements of switching delays, i.e. the parking time at car parks, the waiting time at bus stops and MRT stations, the walking time between transportation facilities and the age of the travelers. Below is the model for switching
delay:

\[ SD_{ij} = \frac{WD_{ij}}{74} \times \text{Age} + \frac{T_{\text{MRT}_{ij}} + T_{\text{Bus}_{ij}}}{2} + PT_{ij} \]  

(1)

In which

- \( ij \): The link from \( i^{th} \) to \( j^{th} \) transfer node \( \forall i \in N \) (\( N \) is the transfer node number)
- \( SD_{ij} \): the switching delay on link (i-j).
- \( WD_{ij} \): the walking distance between transfer nodes \( i \) to \( j \). \( 74 \text{m/min} \) is the average walking speed. Where \( \text{Age} \) is an indicator. \( \text{Age}=1 \) when \( 15 \leq \text{age} \leq 55 \); \( \text{Age}=1.3 \) otherwise (Menson, 2000).
- \( T_{\text{MRT}_{ij}} \): the frequency of MRT link \( i \) to \( j \)
- \( T_{\text{Bus}_{ij}} \): the frequency of Bus link \( i \) to \( j \)
- \( PT_{ij} \): the car parking time on transfer link \( i \) to \( j \).

This formulation is a general model. All the switching delays are listed into this formulation. However, when apply it into a real case the none-related items should be deleted. For example, supposing the traveler would transfer from MRT to bus, equation (1) will be

\[ SD_{ij} = \frac{WD_{ij}}{74} \times \text{Age} + \frac{T_{\text{Bus}_{ij}}}{2} \] in which \( \frac{T_{\text{MRT}_{ij}}}{2} \) and \( PT_{ij} \) are not applicable.

The \( WD \) and \( PT \) are arbitrary parameters. They can be obtained from surveys or field studies. It should be noted that almost every transfer node has a different \( WD \) and \( PT \).

There is also the difficulty of formulating the transfer costs. In this study, it is assumed that the \( WD_{ij} \) and \( PT_{ij} \) equal constants are 200m and 10min, respectively.

The waiting time at the transit can be calculated by its frequency. Assuming that if each public vehicle starts out at the same regular time frequency \( T \), and passengers have an equal chance of arriving at the stop during the time slot, then the waiting time for a vehicle to arrive can be determined as:

\[ EXP(T) = \int_0^T p(t) \times f(t) dt \]  

(2)
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 \( t \). It is assumed that if passengers arrive at the stop with an equal chance during the time frequency \( T \), then

\[
p(t) = \frac{1}{T} \tag{3}
\]

and the waiting time for passengers to arrive at time \( t \) is

\[
f(t) = T - t (0 \leq t \leq T) \quad \text{then} \quad \text{EXP}(t) = \int_0^T p(t) \times f(t) \, dt = \frac{1}{2} T \tag{5}
\]

Hence, the waiting time at transit stations is found to be half of the line frequency (Dial, 1979) and the bus and MRT delays are expressed as \( T_{\text{MRTij}} \) and \( T_{\text{Busij}} \).

The inherent attribute of dynamics in switching delay should also be considered in this formulation. It can be noted, for example, that when transferring from one bus line to another at a bus stop, there is a waiting time caused by waiting for the next bus. Another example is that of an MRT-to-bus transfer that involves alighting from an MRT station, and walking from the MRT station to a nearby bus stop with the appropriate bus line, and waiting for the next bus to arrive. This waiting time is dynamic in the sense that it depends on the time that the commuter arrives at the stop/station as well as the schedule of the line.

Based on the proposed formulation of the switching delay, the delay time of every transfer node can be calculated. Table 3.1 lists the delay times used in this study. To simplify calculations, the walking distance is assumed to be constant 200. The age is assumed among 15 to 55 so that the age indicator is 1. The parking time is not
considered into this calculation for transferring between car to other mode does not occur occasionally. The frequencies of the MRT lines and Buses were obtained from the Singapore Bus Services (SBS) and Singapore MRT (SMRT). The frequencies were divided into two categories, i.e., weekdays and Sundays, based on the real situation of Singapore’s transportation services. These parameters will be used in Chapter 6 for dynamic routing.

Table 3.1 Calculation of the switching delay

<table>
<thead>
<tr>
<th></th>
<th>WD&lt;sub&gt;ij&lt;/sub&gt; (m)</th>
<th>Age</th>
<th>T&lt;sub&gt;MRTij&lt;/sub&gt; (min)</th>
<th>T&lt;sub&gt;Busij&lt;/sub&gt; (min)</th>
<th>PT&lt;sub&gt;ij&lt;/sub&gt; (min)</th>
<th>SD&lt;sub&gt;ij&lt;/sub&gt; (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weekdays</td>
<td>200</td>
<td>1</td>
<td>3</td>
<td>6</td>
<td>NA</td>
<td>7.2</td>
</tr>
<tr>
<td>Sundays</td>
<td>200</td>
<td>1</td>
<td>6</td>
<td>12</td>
<td>NA</td>
<td>16.2</td>
</tr>
</tbody>
</table>

Calculate by $SD_{ij} = \frac{WD_{ij}}{\tau} \times Age + \frac{T_{MRT_{ij}} + T_{Bus_{ij}}}{2} + PT_{ij}$

3.5 SUMMARY

Multimodal networks are characterized by dynamically changing conditions and multiple modes of transportation operating simultaneously on them. A well constructed network was the backbone of a complex multimodal transportation. In this chapter, the application domain of this study was first presented. Then the framework of the proposed model for multimodal routing was illustrated. Two main modules: the GIS model and the simulation module were explored separately. The next section focused on the modeling of the proposed multimodal network. Based on the traditional network representation method, a new proposed method was adopted to represent the proposed multimodal network in a GIS environment. Finally, the dynamic switching delay was formulated.
CHAPTER 4
THE MULTI-CRITERIA EVALUATION MODEL

This chapter discusses the proposed multi-criteria evaluation model for providing the rules during a route choice procedure. It is quite complicated and even stochastic of the decision-making involved when a traveler pre-processes his trip. Such decisions are heavily dependent on the local transportation environment, the habits of travelers, the departure times, and so on. Fortunately, many behavioral studies have been dedicated to this field (Hickman & Wilson, 1995). Based on analyses of traveler behavior these studies show that route choice can be determined by some general routing criteria. The travel distance, travel time, travel fare and reliability are considered as the most critical factors which affect traveler behavior and evaluation of route choice (Tate-Glass, Bostrum, & Witt, 2000). In addition to the above factors, that are usually considered in route choice on a multimodal transportation system, a general cost method is proposed which is able to enable travelers to combine any of the factors in the permutations. The AHP methodology is used in this thesis for determining the coefficient of every factor. The multi-criteria evaluation model is constructed by these factors and they will be presented in detail.

4.1 ROUTING OF TRAVEL DISTANCE

Travel distance has been one of the most fundamental evaluation factors in the routing
field. It is an intuitionistic and obvious criterion used in routing processes. In the field of aviation, logistics and land transportation, distance is the ultimate guideline for referencing. However, when considering microcosmic transport phenomena, the distance alone cannot influence the details. This is due to the effect of transportation impediments and delays at every intersection. In the three-dimension real world, time should be factored to assist in two-dimensioned evaluation.

4.2 **Routing of Travel Time**

Time is one of the most accepted factors for measuring travel efficiency (Tate-Glass et al., 2000). While finding a least-time route on a network, time costs at nodes are often ignored and only time consumption at links are included in least-time routing, especially in the case of the car layer. Among all feasible routes that connect the origin and the destination, the route that has the minimum total time costs for its links is considered as the routing result. This can be presented as follows:

\[
C = \min \left( \sum_{j} T_{ij} \right) \quad i = 1, 2, 3, 4, \ldots, m; \; j = 1, 2, 3, 4, \ldots, n_i
\]  

in which, \( m \) is the number of feasible paths, \( n_i \) is the number of links in the \( i^{th} \) feasible path, and \( T_{ij} \) is the time cost for the \( j^{th} \) link of the \( i^{th} \) path.

However, the costs at nodes (usually intersections) can hardly be ignored in most cases, such as the bus layer and MRT layer. Particularly when routing on a small scale, time costs on intersections can account for a fair portion of the total travel time, should
be included in the travel time. Delays caused by intersection movements are considered in calculating shortest paths by using the following functional equation (Kirby & Potts, 1969):

\[ C = \min_i \left( \sum_j T_{ij} + d_i \right) \quad i = 1, 2, 3, 4, \ldots, m; j = 1, 2, 3, 4, \ldots, n_i \] (4-2)

in which the additional term \( d_i \) is the delay associated with the \( i^{th} \) path. Although the delay time can be easily incorporated into the formulation, it is, in practice, difficult to calculate. Fortunately, the simulation tool employed in this study is appropriate for solving this problem. The travel time obtained from the simulation is the result of simulated travel time in reality, and includes every delay at every intersection. Thus, the routing based on equation (4-1) can be directly presented.

### 4.3 Routing of Travel Fare

The travel fare is the fare charged by each travel mode. For a transit system, this fare is in the form of tickets charged by the public transportation system. At the car level, this fare comes from the toll road, toll stations, and petrol consumption. In this study, the car fare is the fare charged by a taxi. This is because the taxi is a special vehicle which can connect both transit and private transportation and is suitable for a multimodal transport system.

Fares for different public traffic services, such as the bus and rail services, can be
obtained from the service fare charge table. The taxi fare is generally determined by the travel distance. The value of a fare can be broken down into several segments in terms of the boarding and alighting stations, and is thus encoded into the link segments. The sum of all the fares of different routes is the total cost of the travel. The path that has the least cost is the routing result.

4.4 Routing of Safety

In urban transportation, besides travel distance and travel time, safety is another vital factor that should not be ignored. Safety is here dependent upon functioning or non-functioning links within the network, and may be defined as the degree of stability of the quality of service which a system normally offers. It can be mainly defined as the probability of involving in vehicle crashes. Various factors can contribute to crashes, including human factors, meteorological conditions, environmental factors, and the mechanical failure of vehicles. Additionally, the location and functional class of the roadway can contribute to driver error, making certain types of crashes more likely to occur. In this study, it is decided the method used by Transportation Research Board (TRB) (National Cooperative Highway Research Program, 1997) to confirm the safety rank for every link. The final safety rank can be estimated as a semi-log regression model:

\[
Safety \text{ Rank} = 0.517(0.972^{PSR})(1.068^{TOPCURV})(1.179^{PASSES})(1.214^{ADTLANE})
\]

\[
(0.974^{RIGHTSH})(0.933^{LANES})(1.051^{TOPGRAD})
\]  

(4-3)
Where: the dependent variable is Natural log of number of incidents per million vehicle miles traveled (VMT).

- **PSR**: present serviceability rating, ranging from 0 (poor) to 5 (excellent), is a measure of the general surface quality of a road segment.

- **TOPCURV**: the number of degrees of arc subtended by a 100-foot length for the sharpest curve on the segment. Scaling of the variable is as follows: 0=no curve, 1=0.1-1.4, 2=1.2-2.4, … , 12=28.0 degrees or more.

- **PASSRES**: a dummy variable coded 1 if a passing restriction exists anywhere on the road segment and 0 if no passing restriction exists.

- **ADTLANE**: average daily traffic in thousands per lane.

- **RIGHTSH**: width of the right shoulder in feet.

- **LANES**: a dummy variable coded 1 if the road has 4 lanes and coded 0 for 2 lanes.

- **TOPGRAD**: the change in elevation, as a percentage of the horizontal distance traversed for the greatest slope in the segment. Scaling of the variable is as follows: 0= no grade, 1=1.0-1.9 percent, 2=2.0-2.9 percent, … , and 12=15.0 percent or more.

Eventually, the estimated incident rates of all links can be obtained from equation (4-3). Fortunately, the results calculated by Chee (2002) and we also apply the same results in this research.
4.5 Routing of General Cost

The previous three kinds of routing criteria, namely, distance, travel time and reliability, meet the general requirements of routing. They can sufficiently satisfy single mode routing. However, in a multimodal environment, single criterion routing is inadequate when it is necessary to evaluate a route choice comprehensively. From a practical viewpoint, the route choice which considers the routing constraints as much as possible is needed. In other words, it is necessary to consider the travel mode, distance, travel time, transfer times, reliability, weather, departure time, and other factors as the relevant aspects for determining route choice. The reason that the general cost routing is proposed in this study, is that such generalized cost routing enables the combining of any of the factors in any permutation, and will yield a result that satisfies all the desired criteria.

Although the generalized cost of traveling is only a rough estimation conceptually, it can be viewed as an extension of the multi-criteria optimization method since it assigns weights to each factor and combines the weighted factors into a single objective function.

The general cost is the cost which considers all the possible routing constraints. In this study, three factors, namely, travel time, fare and reliability, have been identified to perform the general costs as given in equation (4-4):
\[ C_{ij} = w_1 \text{TIME}_{ij} + w_2 \text{FARE}_{ij} + w_3 \text{SAFETY}_{ij} \] (4-4)

Where:

- \( C_{ij} \) is the cost of traveling on the link between node \( i \) to node \( j \);
- \( \text{TIME}_{ij} \) is the in-vehicle travel time between node \( i \) and node \( j \);
- \( \text{FARE}_{ij} \) is the fare charged between node \( i \) and node \( j \);
- \( \text{SAFETY}_{ij} \) is the reliability on a specified link \( i \) to \( j \);
- \( w_1, w_2, w_3 \) are weights attached to each element and such that
  \[ \sum_{i=1,2,3} w_i = 1.0 \]

It can be seen at this point that the proposed generalized cost is not dimensionally correct. Consider that \( \text{TIME} \) is measured in minutes, \( \text{FARE} \) is measured in dollars and \( \text{REL} \) is a series of integer. Obviously, it is not correct to simply add these factors together. One proposed method of solving problem was not to define each individual factor by its own measurements, but to actually give a ranking to each measurement of the factor. This means that for each factor, the total range of the data for the factor will be broken down into specified groups.

If, for example, the range of the value for travel time is \([T_{\text{Min}}, T_{\text{Max}}]\), then let these values be grouped into 5 levels, with the lowest in the range being assigned a ranking of 1. The range will be \( R = (T_{\text{Max}} - T_{\text{Min}}) / 5 \), in which \( R \) is range. Thus group 1 within the range \([T_{\text{Min}}, T_{\text{Min}} + R] \) will be given a ranking value of 1; group 2 within the range \([T_{\text{Min}} + R, T_{\text{Min}} + 2R] \) will be given a ranking value of 2, and so on. Hence, each different
factor of each different measuring unit will be normalized into a fixed ranking “measurement”, and the generalized traveling cost will yield equation (4-5):

\[ C_y = w_1 T_{IMER} + w_2 T_{ARER} + w_3 S_{AFETY} \quad \text{with} \quad \sum_{i=1,2,3} w_i = 1.0 \]  

in which every factor suffixes \( R \) to present the normalized ranking.

The next step is to determine the weight of every factor. In multi-criteria optimization, the weight-sum approach is used to obtain a compromise solution. The weights illustrate how important this factor is to the traveler compared to other factors. For instance, if \( \{w_1, w_2, w_3\} = \{0.7, 0.2, 0.1\} \), it means he considers the first factor to be much more important than the others. As can be seen, there are many infinite combinations of the weights that will affect the outcome of the general costs. In fact, in many situations, the traveler may not be able to easily assign weights to the different decision factors, and it will become a rather irrational process if weights were to be assigned at random. Therefore, to find a technique that will allow a more rational estimation of the weights is very important.

A better approach was proposed by Professor Saaty from the University of Pittsburgh and it is the Analytical Hierarchy Process (AHP) (Saaty, 1980). This weights-assigning procedure has the ability to imitate the user’s rational decision-making process and in general involves pair-wise comparisons between the various factors. The AHP involves assumptions about what people are observed to do with their biological equipment, and is especially useful when making intuitive
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decisions (i.e. from a user’s perspective). This process is also useful for trying to obtain a meaningful result when mixing different quantities of different scales (e.g. dollars, distance, hours, etc) directly. The theory behind the AHP is best explained thus:

**Step 1:**

The first step is to make pair-wise comparisons between all factors and present a scale of measurement from 1 to 9, as defined by Table 2.1. The question to ask the traveler is:

Between factor $i$ (row) and $j$ (column), how much more important is attribute $i$ as compared to attribute $j$? The results of the decisions can be summarized in a matrix given below in Table 4.1.

<table>
<thead>
<tr>
<th>Factor $i/j$</th>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor 1</td>
<td>1</td>
<td>$a$</td>
<td>$b$</td>
</tr>
<tr>
<td>Factor 2</td>
<td>$\frac{1}{a}$</td>
<td>1</td>
<td>$c$</td>
</tr>
<tr>
<td>Factor 3</td>
<td>$\frac{1}{b}$</td>
<td>$\frac{1}{c}$</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>$1+\frac{1}{a}+\frac{1}{b}=T_1$</td>
<td>$a+1+\frac{1}{c}=T_2$</td>
<td>$b+c+1=T_3$</td>
</tr>
</tbody>
</table>

The diagonal entries are fixed values of 1, where each factor is compared to itself. The entry $ij$ is the reciprocal value to entry $ji$ as defined by the theory of reciprocity, which is assumed when adopting the AHP process.

**Step 2:**

The next step is to normalize the values in the matrix, thus resulting in the following matrix as shown in Table 4.2.
### Table 4.2 The matrix normalized from Table 4.1.

<table>
<thead>
<tr>
<th>Factor i/j</th>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>(w_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor 1</td>
<td>(1 \times \frac{1}{T_1})</td>
<td>(a \times \frac{1}{T_2})</td>
<td>(b \times \frac{1}{T_3})</td>
<td>(\sum_{j=1}^{3} 1j/3)</td>
</tr>
<tr>
<td>Factor 2</td>
<td>(\frac{1}{a} \times \frac{1}{T_1})</td>
<td>(1 \times \frac{1}{T_2})</td>
<td>(c \times \frac{1}{T_3})</td>
<td>(\sum_{j=1}^{3} 2j/3)</td>
</tr>
<tr>
<td>Factor 3</td>
<td>(\frac{1}{b} \times \frac{1}{T_1})</td>
<td>(\frac{1}{c} \times \frac{1}{T_2})</td>
<td>(1 \times \frac{1}{T_3})</td>
<td>(\sum_{j=1}^{3} 3j/3)</td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

### Step 3:

Note that the summation of the arithmetic mean \(w_i\) gives a value of 3, and hence it is necessary to divide the entries by 3 throughout to give a total summation value of 1.0. As a result, the weights that should be applied in the generalized cost will be made known. These weights are given in Table 4.3.

### Table 4.3 Final weights given to each factor by the AHP

<table>
<thead>
<tr>
<th>Result</th>
<th>Weight (w_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor 1</td>
<td>((1 \times \frac{1}{T_1} + a \times \frac{1}{T_2} + b \times \frac{1}{T_3}) / 3)</td>
</tr>
<tr>
<td>Factor 2</td>
<td>((\frac{1}{a} \times \frac{1}{T_1} + 1 \times \frac{1}{T_2} + c \times \frac{1}{T_3}) / 3)</td>
</tr>
<tr>
<td>Factor 3</td>
<td>((\frac{1}{b} \times \frac{1}{T_1} + \frac{1}{c} \times \frac{1}{T_2} + 1 \times \frac{1}{T_3}) / 3)</td>
</tr>
</tbody>
</table>

Finally, the generalized cost of traveling is:

\[
C = \sum_{k=1}^{q} w_k f_k(x), \quad \sum_{k=1}^{q} w_k = 1.0
\]  

(4-6)
where $C$ is the cost of traveling on the links between destination, $f_i(x)$ is the objective function, and $w_k$ represents the weights given to each objective function.

Table 4.4 Calculation of General Costs

<table>
<thead>
<tr>
<th>Rank Stage</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel Time(min)</td>
<td>0.52-2.92</td>
<td>2.92-5.32</td>
<td>5.32-7.72</td>
<td>7.72-10.12</td>
<td>10.12-12.54</td>
</tr>
<tr>
<td>Fare(cent)</td>
<td>0-30</td>
<td>30-60</td>
<td>60-90</td>
<td>90-120</td>
<td>120-150</td>
</tr>
<tr>
<td>Safety</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Pairwise comparison matrix in AHP

<table>
<thead>
<tr>
<th></th>
<th>Travel Time ($T$)</th>
<th>Fare ($F$)</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel Time</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Fare</td>
<td>1/2</td>
<td>1</td>
<td>1/3</td>
</tr>
<tr>
<td>Safety</td>
<td>1/5</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Normalized matrix in AHP

\[
\begin{pmatrix}
0.5882 & 0.3333 & 0.7895 \\
0.2941 & 0.1667 & 0.0530 \\
0.1176 & 0.5000 & 0.1579 \\
\end{pmatrix}
\]

\[w_i = \begin{bmatrix} 0.5703 & 0.1713 & 0.2585 \end{bmatrix}^T\]

General Cost is then calculated by equation 4-5 for each link.

Table 4.4 shows the calculation procedures of the general costs in this study. The travel time ranges from 0.52min to 12.54min is link travel time obtained from the results of simulation. The fare values are the current transit charges which can be looked up through the transit guides. Calculated by AHP, the weights can be obtained as: 0.5703, 0.1713 and 0.2585 for the *Time*, *Fare* and *Safety* respectively. Based on the integration of the above proposed evaluation model with a dynamic routing algorithm, travelers can realize multi-criteria routing on the multimodal network.
4.6 SUMMARY

In this chapter, the proposed multi-criteria evaluation model was described in detail, and included four aspects: travel distance, travel time, reliability and general costs. As a result of introducing the simulation tool, the travel time could be obtained more accurately and easily. Then, emphasis was put on the construction of the general costs. The ranking method was used to normalize every factor so that different evaluation items could be combined. In addition, the AHP algorithm was used to determine the weights. This method can imitate a user’s rational decision-making process and finally allocate a reasonable weight for the user.
CHAPTER 5

DYNAMIC PATH FINDING ALGORITHM FOR MULTIMODAL ROUTING

When traveling on the transportation network, a traveler is most likely to consider how to reach the destination and, more importantly, how to complete each trip with the least costs. Hence, finding the shortest path (in terms of travelers’ preference) 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). The routing algorithm has been transformed from a static to a dynamic form. While multimodal operations are on the increase, researchers have paid much attention to multimodal shortest-path analysis. As the key part of the proposed model is a procedure or algorithm for conducting analyses and solving route choice problems within a multimodal network. This chapter focuses on a dynamic path finding algorithm for multimodal routing. Beginning with a detailed review of the development and trends of routing algorithms, it is followed by the presentation of the proposed algorithm in the proposed model.

5.1 REVIEWS OF DYNAMIC PATH FINDING ALGORITHM

5.1.1 An Overview of Path Finding Algorithms

Euler’s famous “Königsberg bridge” question, dating back since 1736, normally is
seen as the origin of modern path finding problem. The solution he proposed formed the basis of the graph theory, which in turn paved the way for path-finding algorithms (Husdal, 2000).

Since the end of the 1950s, transportation network analysis has become one of the main research areas in which shortest path finding is the fundamental problem. A large number of studies have focused and published on this topic.

Path finding problems in transportation fields have many different categories need to be solved. These include classical problems, such as determining shortest paths under various criteria (e.g., length, cost and so on), between some given origin/destination pairs in a certain area. Another category includes non-standard criteria, such as finding shortest paths either under additional constraints or on particular structural graphs. Although the popularity of the conventional static routing replaced by dynamic path finding gradually, the substantial is to converting dynamic network into static in term of time interval. One way of dealing with dynamic networks is by splitting continuous time into discrete time intervals with fixed travel costs, as did Chabini (1997). Thus, understanding shortest path algorithms in static networks becomes fundamental to working with dynamic networks.

5.1.2 The Static Routing Algorithms
Since the establishment of graph theory in 1960s, a large amount of routing algorithms had been developed and wide spread. As transportation network can be abstracted into
points and links with or without direction, routing problem on transportation network is finally represented as path finding problems on a graph (Yu, 2001).

These algorithms include the Dijkstra’s algorithm, the Bellman-Ford algorithm and the Floyd-Warshall algorithm. Of these algorithms, algorithms for single-source shortest path problems attract more interest due to many other problems can be transformed into single-source shortest-path problems and be solved by such algorithms (Cormen, Leiserson, & Rivest, 1990). It is also the reason why it has been possible to study and develop Dijkstra’s algorithm even today.

The Dijkstra’s algorithm is a graph searching algorithm. It can solve single-source shortest path finding with nonnegative path costs. Thus the lowest cost of path is investigated step by step, node by node, based on the directions of paths. An extension of Dijkstra’s algorithm is A* algorithm which achieves better performance by using heuristics. This avoids considering directions with non-favorable results and reduces computation time.

Generally speaking, the A* algorithm, in conjunction with Dijkstra’s-based algorithms, is preferred in most of researchers. It should be noted that Dijkstra’s algorithm has prevailed to the present date, proving its universal validity. (Husdal, 2000)
5.1.3 The Dynamic Routing Algorithms

Since 1990s, due to fast development of communication industry and information technology the computation speed is great faster than before. The ITS technologies are booming as well. Various traffic data collection technologies have been adopted world widely. The usage of real time data in transportation fields has been paid more attention than before, i.e., link costs that generally depend on the entry time of a link. Thus results a new family of shortest-paths problems known as Dynamic or (time-dependent) Shortest Path Problems (Chabini, 1997).

Chabini (1997) listed the following types of dynamic shortest-path problems depending on:

1. Time representation (Discrete or continuous);
2. Path finding criteria (minimum cost or minimum time);
3. Transportation network representation (FIFO or non-FIFO);
4. Nodes attribution (especially regards whether the waiting is allowed);
5. Link attribution values (real value or integer number);
6. Path finding modes (one to all or all to one).

Chabini (1997) extended path finding algorithms to discrete and continuous network. For designing dynamic routing algorithm, although the static routing algorithm can be adopted by using time-space expansion representation, it has to appropriate formulating because of the difference between real transportation network and theoretical assumption network.
Horn (1999) examined some variant Dijkstra’s algorithms which under his assumption which most traffic conditions can be estimated due to real transportation environment. Especially, an algorithm was proposed to find shortest path with minimum travel time which independent of any particular navigation between nodes. As reviewed by Husdal (2000), when study dynamic path finding algorithm, it is worth to note an experienced driver more likely to estimate the travel time rather than to follow the theoretical shortest path.

5.1.4 The Multimodal Routing Algorithms

As multimodal (intermodal) operations become daily transportation mode, the need for complex routing algorithms have arisen from the development of intelligent transportation systems and intermodal freight systems.

Ziliaskopoulos (2000) proposed an intermodal routing algorithm with dynamic link travel time and switching delay. He summarized when designing multimodal routing algorithm, the importance is to identify the existence of all available transit lines, the determined schedules, the waiting time, the delays at switching points and the time-dependent nature of the link travel times. He listed the major difficulties in multimodal transportation network path finding algorithm:

1) Discontinuities transit schedule;
2) The same links may consist different transit modes;
3) The construction of switching points and calculation of switching time;

4) Links do not follow First-In-First-Out (FIFO).

Static transportation network representation is still the main stream in most research works. As mentioned above, it is due to the most dynamic network can be represented by static network through time interval limitation. Crainic and Rousseau (1986) successfully solved path finding on one normal freight network which embedded certain multimodal freight layer. The key solution is to represent and increase the designed network with terminal delays. The result was proved efficient and feasible.

It is noteworthy that most transportation multimodal networks are concerned with transit network. Thus the multimodal network representation in transportation usually connects closely with transit schedule, bus waiting time and transit switching points.

A transit network was expanded by increasing links to reflect waiting, switching and walking time in Spiess and Florian (1989). They proposed least time path finding algorithm on such expanded network in which waiting time was stochastic and transit schedule was fixed. The proposed algorithm was implemented and well performed as a transit assignment tool in real project.

A heuristic path finding method was recommended by Battista et al. (1995) on a network with two modals. The innovation point is this method introduced and considered users preference when selecting paths.
Nguyen et al. (1995) proposed a user assignment path finding algorithm with taking into consideration of travel times in terms of time slots. They also expanded the transit network by adding additional links represented waiting time, switching time and especially travel time. However, the routing computation is still a static approach. Therefore this method would result sub optimal paths and cycling when FIFO can not be complied. Although dynamic transit assignment is functional solved, it can not suitable for normal multimodal networks.

5.2 THE PROPOSED DYNAMIC PATH FINDING ALGORITHM

As the proposed algorithm is based on Dijskstra’s algorithm, Dijskstra’s algorithm is first introduced in this section and then details of the proposed algorithm are provided.

5.2.1 Dijkstra’s Algorithm

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

Dijkstra’s algorithm is base on graph searching algorithm and limited by single-source and nonnegative link costs. The assumption is partially optimal searching will result to entirely optimization. It will search successive nodes step by step till reach the destination. Cormen et al. (1990) introduced Dijkstra’s algorithm and presented as follow:

The basic graph network is $G = (V, E)$, in which the nodes are $V$ and links are $E$. It is a nonnegative and directed network and the link weight is $w(u, v) \geq 0$, $u$ and $v$ are nodes belong to $V$. Dijkstra’s algorithm includes a set $S$ of nodes which their final shortest path weights from the start point $s$ have already been fixed. Therefore for all nodes $v \in S$ there $d[v] = \delta(s, v)$. This algorithm will then repeat to select the node $u \in V - S$ based on minimum link weights. During this finding procedure algorithm will not search all the links, this will increase the computation time. Till the destination node $n$ is in $S$, or $n$ is not included in set $Q$, the result will appears and the process will terminate. This procedure can be shown as below Cormen et al. (1990):

**DIJKSTRA** $(G, w, s)$

1. **INITIALIZE SINGLE SOURCE** $(G, s)$
2. $S \leftarrow \emptyset$
3. Initialize priority queue: $Q \leftarrow V[G]$

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4. while $Q \neq \emptyset$

5. do $u \leftarrow \text{EXTRACT MIN}(Q)$ //Pull out new node

6. $S \leftarrow S \cup \{u\}$ // Perform relaxation for each node $v$ adjacent to $u$

7. for each node $v \in \text{Adjacent}[u]$

8. RELAX $(u, v, w)$

5.2.2 The proposed Dynamic Routing Algorithm

In Chapter 3, it was mentioned that when constructing the proposed multimodal network, the multiple layers were integrated into a single layer. The essential part of this integration is integrating the databases of these different layers and coding them into the routing algorithm. In Chapter 4, it was mentioned that the multi-criteria evaluation method, ensures that the routing process is on a nonnegative link cost network. Hence, the situation of route finding between the specified origin and destination on a multimodal transportation network with reference to the selected factors (e.g., time, fare, transfer or general costs) can be abstracted as the single-source, shortest-path problem on the nonnegative directed graph, which falls right in the scope of Dijkstra’s algorithm. Therefore, multi-layer routing can be transformed into single-layer routing.

After transforming the multiple layers into single layer, the factor “time” should be taken into consideration during routing. In this study, it shall be assumed that the time variable $t$ can vary in the discrete set $T=\{t_1, t_2, ..., t_q\}$. Hence, the network can be divided into $q$ stages so that each time stage $t$ owns a instantaneous network the traffic
conditions are at time $t$. Using this concept, the *Space-Time Network* $R=(N,L)$ can be introduced. A key property of the discrete set is that it is possible to solve almost all the dynamic routing problems by working implicitly on $R$ by means of a topological visit, since $R$ is acyclic.

By combining the single-source, label-setting method of Dijkstra’s algorithm and the concept of the Space-Time network, the proposed dynamic routing algorithm can be realized. The proposed algorithm maintains the basic elements of the label-setting method, while the labeled link list is defined as $L_i: (l_1, l_2, \ldots, l_n)$. When the time factor is introduced, a space-time network can be established. Associated with each time stage is a set of link cost-time networks such that the link list $L_i$ is reformed as $L_{ij}(l_{i1}, l_{i2}, \ldots, l_{ij})$, in which $L_{ij}$ means the link $L_i$ at timer interval $j$. Then the $q$ discrete time stages can be treated as $q$ discrete routing according to Dijkstra’s algorithm.

Based on the travel time routing, namely the link cost is link travel time, we state the algorithm as follow.
Mathematical representation of the proposed algorithm:

The pseudo code is shown below:

procedure (R (N,L,T), v);
{
    var: double integer;
    for each u in N do \{C(v,u,t)\}= \infty ; C(v,v,t)=0; path (v,u):= null\}

input to, update the [L] at time series to,

frontierSet := [v]; exploredSet := \emptyset ;

while not_empty (frontierSet) do
{
    Select w from (w.adjacencyList) with minimum C(v,w,	i) at time 	i;
    for each <u, C(w,u,	i)> in w.adjacencyList at time 	i
    {
        if C(v,u,	i)> C(v,w,	i)+C(w,u,	i)

        and then re-fetch w, otherwise
        {
            C(v,u,	i) = C(v,w,	i)+C(w,u,	i);
        path (v,u,	i):=path (v,w,	i)+(w,u,	i);

        if u \in frontierSet \cup exploredSet then
        {
            frontierSet := frontierSet+[u]; }

        if C(v,w,	i)< \sum \Delta t then,

            frontierSet := frontierSet-[w]; exploredSet := exploredSet+[w];

        if C(v,w,	i)>\sum \Delta t, then update L at time (int [C(v,w,	i)/\Delta t ]+1)

        and return to select w\}

    if (u=w) then terminate
in which,

\( R \): the time-space network.
\( N \): the set of nodes.
\( L \): the set of links
\( T \): the set of discrete time series
\( t_i \): the time series start from \( t_0 \) to \( t_n \)
\( v \): the input \( v \) in the procedure is the source node.
\( u \): the specified node as destination.
\( w \): the selected node \( w \) during the routing process.
\( td \): the specified departure time.
\( \Delta t \): the specified interval
\( C(v,w,t_i) \): the travel time on link \((v,w)\) on time \( t_i \)

The main procedures are enumerated as follows:

**Step 1.** Initialize the network:

\( R \) (\( N, L, T \)), the cost \( C(v,v,td) \) is set to zero. All other costs are set to infinity: \( C(v,u,td) = \) infinity. The path \((u,v,td)\) is set to null. \( td \) is specified departure time. The \( \text{frontierSet} \) is set to be equal to the source node \( v \). The \( \text{exploreSet} \) is initialized to the empty set.

**Step 2.** If the \( \text{frontierSet} \) is empty, go to **Step 4**; otherwise, the following computations are carried out. A node \( w \) is selected from the \( \text{frontierSet} \), which has the shortest path from the source node \( v \). In the first iteration, the source node is selected because the cost \( C(v,v,td) \) is zero while all other costs are at infinity. The selected node \( w \) is removed from the \( \text{frontierSet} \) and added to the \( \text{exploreSet} \). The adjacent list of \( w \) is
retrieved from the secondary storage if it is not already in the main memory buffer.

For each element \( <u, C(w,u,t_i)> \) in the adjacent list satisfying the condition, calculate the following:

For all time intervals \( t_i \in T \), do the following:

\[
C(v,u,t_i) > C(v,w,t_i) + C(w,u,t_i)
\]

(i.e., there exists a shortest path from \( v \) to \( u \) via \( w \)), the accumulative cost of the path is updated. Then the cost of the path from the source node \( v \) to \( u \) is updated as:

\[
C(v,u,t_i) = C(v,w,t_i) + C(w,u,t_i)
\]

and the path \((v,u,t_i) := path(v,w,t_i)+(w,u,t_i)\). The node \( u \) is added to the \textit{frontierSet} if it is not in the \textit{frontierSet} or the \textit{exploreSet}.

**Step 3.** Go to **Step 2.**

**Step 4.** Terminate the algorithm.

Some constraints are underlying the performing of the proposed algorithm. Firstly, the network is a First-In-First-Out (FIFO) network. It implies that every link in the network satisfies the FIFO property: if for each pair \( t_0, t_i \) of times with \( t_0 < t_i \),

\[
C_y(t_0) + t_0 \leq C_y(t_i) + t_i.
\]

Secondly, the flow of the computation is forward only. This implies that after selected a node \( i \) at time \( t_i \), at the next time interval \( (t_i + \Delta t) \), the algorithm is only allowed to search paths from node \( i \) to forward nodes. Actually, it is also a reasonable constraint. It is impossible for a person to return the passed link even if the travel time of the link is less in the next time interval.
The proposed algorithm was tested on a set of random networks with 9, 50, and 208 nodes. The network contains 208 nodes is the real network for implementation which is the CBD of Singapore. The interval was set as 5min, 10min, and 20min respectively. Randomly selected OD on these network, the computation time is all under 0.2 second. The configuration of the test computer is: 1.6Ghz Intel Pentium 4 processor and 512M memory. However, this study is not concerned with a run-time analysis of the algorithm. One reason is that the focus was mainly on the multimodal multi-criteria routing system; and not the routing algorithm. This is because that measuring the time requirements of an algorithm is not as straightforward as it might initially appear. It is not possible to provide a definitive answer by simply coding the algorithm, executing it on a computer, and measuring the execution time for problems of different sizes. The actual execution time can be affected by many factors. These can include the computer language, the skill of the programmer in translating the algorithm to the computer language, the computer’s hardware configurations, and operating system. They can also depend on whether the computer was networked, what else was going on in the computer system and network when the codes were executed, and so on. Therefore, a run-time analysis does not provide definitive results, unless performed within very carefully controlled experimental settings (Miller, 2000).
5.3 SUMMARY

In this chapter, a detailed literature review on the shortest-path algorithm is first presented, and followed by the development of a routing algorithm, these algorithms were subdivided into three aspects: static routing algorithms, dynamic routing algorithms and multimodal routing algorithms. The proposed dynamic shortest path algorithm was presented in the next section. As the proposed dynamic multimodal routing is based on a modification of Dijkstra’s algorithm, a brief introduction to Dijkstra’s algorithm was given. Finally, a mathematical representation was presented to explain the proposed algorithm.


Chapter 6

Implementation of the Proposed Model and Analysis of Results

In the preceding chapters, the framework of the proposed model was introduced and this model was divided into the GIS Module, the Simulation Module, the Multi-criteria Evaluation Model and the Dynamic Shortest-path Algorithm in Chapters 3, 4 and 5. In this chapter, a case study for implementing the proposed integrated model is established by developing the structure of the framework that presents the GIS module and then the simulation module. Following this the test network used in this study is described and includes the developed graphic user interface (GUI). The simulation module is implemented in the next section. Finally, alternative route choices are generated by this model and every example is illustrated and analyzed.

6.1 Implementation of the GIS Module

6.1.1 Implementation Procedures

To implement the proposed model is the final step of this study. Before elaborating on the details, the main procedures should first be made clear. Figure 6.1 illustrates the implementation scheme. The first step is the collecting of data, which includes the study network information, multi-mode information, and so on. Generally, the original
data needs to be modified into the required format. After modification, the data is transferred into the GIS and simulation database separately. During the simulation we can obtain the measures of effectiveness (MOE) can be obtained, in this study if the MOE is specified as the link speed. Thus the link speed will then be transformed into link travel time and used to update the geo-database at a specified time interval. Both the dynamic shortest-path algorithm and multi-criteria evaluation are encoded in the geo-database. Finally, the optimal route choice will be obtained by the geo-database and displayed by the developed GUI.

Having established the implementation procedures, the each process will be elaborated on individually in the following sections.

![FIG. 6.1. Framework of the implementation process](image)

6.1.2 Multimodal Network Modeling

**Multi-modal Transport**

The multimodal forms of transportation in Singapore include three main modes: buses,
MRT and car. It is of the utmost importance that the information on the three modes is systematically organized in the geo-database.

➢ The Buses

In Singapore, there are 2 major bus operators: Singapore Bus Services (SBS) and Trans-Island Bus Services Ltd. (TIBS). Both service over 3,000 bus stops and 300 bus lines island-wide. Generally, each service line is identified by a name (e.g. Bus 97, Bus 133), a source station and a destination station. Each service line consists of a sequence of stops along a prescribed route, with the first stop being the source station, and the last stop being the destination station. The stops along the service route serve as the passenger pick-up and alighting points. Different service lines and transport modes may share the same stop.

For a given service line, there is an arrival schedule that shows the first arrival time and the frequency of arrival for the given service line for each stop along the route. For instance, the schedule may indicate a frequency of 1 bus every 6 to 12 minutes. In general, the frequency may vary during the day, with a typically higher frequency during peak hours, and a lower one during off-peak hours.

In Singapore the fare structures of every bus operators are the same. The fare for each trip is not determined by the total number of stops traveled, but based rather on the concept of fare stages along the bus route. The fare stage of a given bus line starts
from 1 at the source station and increases along the bus route. Table 6.1 and 6.2 show
the detailed schedules and fare charges of bus lines 97 and 133 (Mighty Mind, 2003).
However, due to the bus fare is non-additive, we should model the fare for bus system.
We can find that the fare stages are increased by 3 or 4 bus stops. Base on this
character, it is easy to find the fare on each bus link. Here, we assume the increasing
stage is 3 so that we can divide the fare stage by 3 separately. And finally, attach this
new fare stage in every bus link. Through this transformation, the fare routing can be
implemented.

Table 6.1 Schedule and Fare Stage of Bus Line 97

<table>
<thead>
<tr>
<th>Bus Line 97</th>
<th>Weekdays</th>
<th>Saturdays</th>
<th>Sundays &amp; Public Holidays</th>
</tr>
</thead>
<tbody>
<tr>
<td>From:</td>
<td>First Bus</td>
<td>Last Bus</td>
<td>First Bus</td>
</tr>
<tr>
<td>Direction 1</td>
<td>05:45</td>
<td>23:45</td>
<td>05:45</td>
</tr>
<tr>
<td>Direction 2</td>
<td>05:30</td>
<td>23:45</td>
<td>05:30</td>
</tr>
</tbody>
</table>

Service Frequency

<table>
<thead>
<tr>
<th>Period (hours)</th>
<th>06:30-09:00</th>
<th>09:01-16:20</th>
<th>16:30-19:00</th>
<th>After 19:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction 1</td>
<td>4-6</td>
<td>4-6</td>
<td>5-10</td>
<td>12-15</td>
</tr>
<tr>
<td>Direction 2</td>
<td>3-6</td>
<td>3-13</td>
<td>5-13</td>
<td>10-15</td>
</tr>
</tbody>
</table>

Fare Stage

| Bus Stop | B02 | B10 | B08 | ... | B06 | B21 | B19 | ... | B01 | ... | B03 |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Fare Stage | 1  | 1.5 | 1.5 | ... | 6   | 7   | 7.5 | ... | 28  | ... | 31  |
| Fare (cents) | 60  | 60 | 60 | ... | 80  | 80  | 80 | ... | 140  | ... | 140 |

Table 6.2 Schedule and Fare Stage of Bus Line 133

<table>
<thead>
<tr>
<th>Bus Line 133</th>
<th>Weekdays</th>
<th>Saturdays</th>
<th>Sundays &amp; Public Holidays</th>
</tr>
</thead>
<tbody>
<tr>
<td>From:</td>
<td>First Bus</td>
<td>Last Bus</td>
<td>First Bus</td>
</tr>
<tr>
<td>Loop Service</td>
<td>05:30</td>
<td>23:30</td>
<td>05:30</td>
</tr>
</tbody>
</table>

Service Frequency
<table>
<thead>
<tr>
<th>Period (hours)</th>
<th>06:30-09:00</th>
<th>09:01-16:20</th>
<th>16:30-19:00</th>
<th>After 19:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Range (mins)</td>
<td>2-10</td>
<td>2-10</td>
<td>1-15</td>
<td>4-13</td>
</tr>
<tr>
<td>Loop Service</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fare Stage</th>
<th>B08</th>
<th>B18A</th>
<th>B02</th>
<th>…</th>
<th>B10A</th>
<th>B09</th>
<th>B07</th>
<th>…</th>
<th>B10</th>
<th>…</th>
<th>B08</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fare Stage</td>
<td>1</td>
<td>1.5</td>
<td>1.5</td>
<td>…</td>
<td>6</td>
<td>7</td>
<td>7.5</td>
<td>…</td>
<td>28</td>
<td>…</td>
<td>31</td>
</tr>
<tr>
<td>Fare (cents)</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>…</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>…</td>
<td>140</td>
<td>…</td>
<td>140</td>
</tr>
</tbody>
</table>

**The MRT**

Singapore Mass Rapid Transit (SMRT), the main operator of public transport in Singapore, services 63 stations and four MRT lines covering over 80km of rail lines over almost the whole island. According to the SMRT’s Annual Report by the Land Transport Authority of Singapore (LTA), an average of 94% of trains arrive/depart within 2 minutes of the schedule, with no more than 1 failure for every 1,500 station stops for the train signaling system over the past few years. From the SMRT website, the fare charges for the MRT depend only on the source and destination stations, i.e. it does not depend on the route taken. Hence, fare charge calculation is computed by simply referring to a lookup table. Table 6.3 shows the detailed information on travel times and fare charges of the MRT.

**The Cars**

Based on the policy advocated by the Singapore Government, the use of private cars is not encouraged, and the prices of cars are generally very expensive in comparison with other countries. However, the taxi is a relatively cheap and popular mode of transport.
Its fares can be measured by travel time and distance. In this study, such information can be obtained through traffic simulation.

<table>
<thead>
<tr>
<th>Travel Time</th>
<th>EW20</th>
<th>EW19</th>
<th>EW18</th>
<th>EW17</th>
<th>EW16</th>
<th>EW15</th>
<th>EW14/NS26</th>
<th>EW13/NS25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fare (cents)</td>
<td>0</td>
<td>2min</td>
<td>6min</td>
<td>9min</td>
<td>11min</td>
<td>13min</td>
<td>15min</td>
<td>...</td>
</tr>
<tr>
<td>EW20 (Commonwealth)</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>...</td>
</tr>
<tr>
<td>EW19 (Queenstown)</td>
<td>2min</td>
<td>2min</td>
<td>4min</td>
<td>7min</td>
<td>9min</td>
<td>9min</td>
<td>9min</td>
<td>...</td>
</tr>
<tr>
<td>EW18 (Redhill)</td>
<td>2min</td>
<td>0</td>
<td>2min</td>
<td>4min</td>
<td>6min</td>
<td>8min</td>
<td>11min</td>
<td>1.04</td>
</tr>
<tr>
<td>EW17 (Tiong Bahru)</td>
<td>6min</td>
<td>4min</td>
<td>2min</td>
<td>4min</td>
<td>6min</td>
<td>6min</td>
<td>9min</td>
<td>...</td>
</tr>
<tr>
<td>EW16 (Outram Park)</td>
<td>9min</td>
<td>7min</td>
<td>4min</td>
<td>2min</td>
<td>0</td>
<td>2min</td>
<td>4min</td>
<td>6min</td>
</tr>
<tr>
<td>EW15 (Tanjong Pagar)</td>
<td>11min</td>
<td>9min</td>
<td>6min</td>
<td>4min</td>
<td>2min</td>
<td>0</td>
<td>2min</td>
<td>4min</td>
</tr>
<tr>
<td>EW14/NS26 (Raffles Place)</td>
<td>13min</td>
<td>11min</td>
<td>8min</td>
<td>4min</td>
<td>2min</td>
<td>0</td>
<td>2min</td>
<td>...</td>
</tr>
<tr>
<td>EW13/NS25 (City Hall)</td>
<td>15min</td>
<td>13min</td>
<td>11min</td>
<td>9min</td>
<td>6min</td>
<td>4min</td>
<td>0</td>
<td>...</td>
</tr>
<tr>
<td>EW12 (Bugis)</td>
<td>17min</td>
<td>13min</td>
<td>11min</td>
<td>8min</td>
<td>6min</td>
<td>4min</td>
<td>2min</td>
<td>...</td>
</tr>
</tbody>
</table>

### Multimodal Network Representation

The multimodal network modeling method was presented in Chapter 3, and in this chapter the real network will be implemented. The selected study network covers the whole Central Business District (CBD) of Singapore. Figure 6.2a shows the entire Singapore network with the area marked out indicating the study area, while Figure
6.2b is the magnified map of the study area. The study area is approximately 7.1 km by 5.9 km which covers 12 MRT stations and more than 50 bus lines (Singapore Street Directory, 2003). It is chosen because of its high density of roads and the heavy traffic. Many alternative transfer facilities exist in this area as connectors to other transportation modes such as cars, buses and the MRT. Thus, various route choices can be better examined by using this urban network.
After selecting the study area, the multi-mode networks should be classified individually. The separating layer method in the GIS is used for creating the multiple layers because the original data is a one-layer graphic. Based on the current Singapore road map, the bus and train networks are abstracted from the original network. As shown in Figure 6.3, the one-layer network is divided into a three-layer network. It is worth noting that the process of dividing a network into layer is merely an operation on the graphic. The inherent attributes and coordinate system of the graphic still maintains their original format.

**FIG. 6.3** Layers of transportation modes

**Representation of the Multimodal Network**

In Chapter 3 a switching delay model was mentioned. When the three layers were planned, the switching delay layer is added as a new layer which represented all the switching behaviors. It should be noted that this layer is a nonobjective layer in the real world, but substantially exists for research purposes.
To begin the representation, a new layer named the *Transfer layer* was created. Dashes were used to present these dummy links. The transfer links represented the waiting time at stations, parking time between urban facilities and the walking trip from the alighting point to the destination. Through the method shown in Figure 3.3, the modified network could be established (see Figure 6.4). Figure 6.4a shows the original network clipped from the layer-divided CBD network. Three modes of the networks (i.e. cars, buses and the MRT) were presented using different line types with no transfer links. In Figure 6.4b, the bus and MRT layers were replaced slightly so that they could be displayed distinctly. This is because many links overlapped over two or three modes, and the car park points, bus stops and MRT stations had to share the same nodes. The dashes marked out the transfer links. Bus stops, MRT stations, Park-and-Ride facilities were selected as transfer nodes. Transfer links were constructed through these nodes. Like other types of links (e.g. road links), the switching link attribute tables store the information for procedures like link start and end, link length, travel time, and so on.
A well-designed GUI is the fundamental part of the functional software. In the Advanced Traveler Information Systems (ATIS) a friendly user interface is very important. The GUI in ATIS needs to be easily understood and mastered by the user so that the end results can be clearly displayed.

In this study, MapObjects 2.0 (MO) is employed for developing the GUI. MO is the mapping component software created by the Environmental Systems Research Institute, Inc. (ESRI) for providing a flexible programming environment in GIS. By making full use of the 46 ActiveX controls in MO, almost all the functions in GIS can be realized (ESRI MapObjects, 1999).

There are 3 main functions which can be provided by the developed GUI. They are: Map display, and Data query and Route choice analysis (see Figure 6.5). Map
display is the basic function which provides the intuitionistic maps for the users. It provides zooming, pan, draw basic shape and other functions. The **Data query** function enables users to look up the information on graphic entities by selecting these entities. The dynamic link libraries will find the related information by tracing out the attributes of every entity. Route choice analysis is the core function provided in the proposed system. The dynamic routing algorithm is coded in and through it the optimal route choices can be obtained. All the functions are realized by making use of the MO ActiveX controls and Visual Basic programs.

![Map Display](image)

**FIG. 6.5** GUI and the main functions of the system

### 6.2 IMPLEMENTATION OF THE SIMULATION MODULE

#### 6.2.1 Overview of the Simulation Tool

Since 1992, a succession of microscopic traffic simulation research and
development projects have been performed by Quadstone Ltd under the Europe DRIVE initiative. As a result of seven years of effort, PARAMICS has been developed in version 4.0, which possesses five software modules: Modeler, Processor, Analyzer, Programmer and Monitor.

PARAMICS is applicable to commonly used major computer systems without any limitations of network size. In addition to the inclusion of a detailed physical description of the road network, the movements and behavior of individual vehicles are modeled in detail for the duration of the entire trip, providing accurate and dynamic information about traffic flow, travel time and congestion. Features such as bus operations, traffic signal settings, driver’s behavioral characteristics and vehicle kinematics are represented (PARAMICS Modeller, 2002).

PARAMICS can simulate the traffic impact of signals, ramp meters, loop detectors linked to variable-speed signs, VMS signing strategies, in-vehicle network state display devices, and in-vehicle messages advising of network problems and re-routing suggestions.

One notable characteristic of PARAMICS is that many features of the underlying simulation model can be customized. Access is gained through a functional interface or Application Programming Interface (API), which allows additional functionality by adding external modeling routines (PARAMICS Programmer, 2002).
6.2.2 Obtaining Traffic Data from Simulation

Figure 6.6 shows the study network coded in PARAMICS. It describes the same study area as the GIS network, i.e., the CBD area of Singapore. There are 894 nodes (inclusive of 113 signalized intersections), 2558 directional links and 108 traffic zones. The details of the geometry and physical layout of the roads were collected via field surveys, and included information such as the number of lanes, turning restrictions, post speed limits, and so on. The data on signal timing and phasing, origin-destination (OD) statistics and information on the demarcation of zones in the CBD were collected from related transportation authorities. The traffic composition comprises cars (about 78%), light-goods vehicles (about 12%) and ordinary vehicles (about 10%). Public transportation, consisting of 7 bus services were coded in this network. Bearing in mind, the peak hours and non-peak hours, 3 groups of OD demands were designed. The dynamic feedback assignment method was used during the simulation ensured that the simulated environment approached the reality maximally. The simulation period was set as 24 hours. During the simulation, the travel time of the specified links could be recorded through the APIs at the simulated time intervals of 5 minutes, and finally transferred for dynamic routing.

Table 6.4 indicates the output data of PARAMICS. The output format can be managed by API programming. The units of link speed and travel time that are used are m/s and second, respectively. The APIs recorded the traffic data during the simulation runs. After the data was obtained, the links IDs in the simulation module
were matched with the GIS module. This is a full manual process and can be improved upon in further studies.

FIG. 6.6  CBD network of Singapore in PARAMICS

Table 6.4 Output data of PARAMICS

<table>
<thead>
<tr>
<th>INTERVAL</th>
<th>ID</th>
<th>LinkName:</th>
<th>LinkSpeed:</th>
<th>TravelTime:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>3333:3381</td>
<td>11.724809</td>
<td>8.528924</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>49:47</td>
<td>11.354095</td>
<td>192.657843</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>38:2735</td>
<td>12.628947</td>
<td>22.018487</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>2977:2981</td>
<td>13.981731</td>
<td>82.560145</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>548:312</td>
<td>10.472632</td>
<td>521.235648</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>3333:3381</td>
<td>11.354095</td>
<td>8.495621</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>49:47</td>
<td>11.425687</td>
<td>180.564974</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
6.3 DISCUSSION AND ANALYSIS

In this section, three groups of route choices used by the developed model were generated. The three scenarios were selected from the typical locations and used different travel modes and different routing criteria.

➤ Scenario 1 - Route Choices in terms of Distance and Different Start Times

This scenario considered the route choice between the same OD, but with different criteria (e.g. least distance with different departure times) and assumed that the traveler is a car user. The selected ODs were the Alexandra and Kallang River. The results are illustrated in Figure 6.7, 6.8 and Table 6.5. Path 1 is the route with the least distance. The travel time of Path 1 was calculated at the average speed of 52km/h. Paths 2-4 showed the dynamic routing generated by least travel time, but resulting in different departure times. The travel times of Path 2 and Path 4 were longer than that of Path 1 because the driving times were during the peak hours in morning and afternoon. Comparing these 4 paths, it is apparent that the travel distance and travel time of Paths 2-4 are shorter than those of Path 1. It is because dynamic routing considers real-time traffic information. This routing method is especially reliable in Path 2 when the Centre Express Way (CTE) is chosen.
FIG. 6.7 Scenario 1-Route choices in terms of distance and different start time

Table 6.5 Scenario 1-Route choices in terms of distance and different start time

<table>
<thead>
<tr>
<th>Solutions</th>
<th>Path 1</th>
<th>Path 2</th>
<th>Path 3</th>
<th>Path 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criterion</td>
<td>Least Distance</td>
<td>Least Travel Time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start Time</td>
<td>-</td>
<td>8:00am</td>
<td>1:30pm</td>
<td>6:40pm</td>
</tr>
<tr>
<td>Mode</td>
<td>Car Only</td>
<td>Car Only</td>
<td>Car Only</td>
<td>Car Only</td>
</tr>
<tr>
<td>Distance(m)</td>
<td>5412.79</td>
<td>5880.57</td>
<td>5496.19</td>
<td>5716.65</td>
</tr>
<tr>
<td>Travel Time(min)</td>
<td>6.25 (average)</td>
<td>15.80</td>
<td>13.16</td>
<td>20.53</td>
</tr>
<tr>
<td>Fare (S$)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Transfer Times</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Switching</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Delay(min)</td>
<td>13</td>
<td>11</td>
<td>13</td>
<td>14</td>
</tr>
</tbody>
</table>
Scenario 2 – Route Choices in terms of a Combination of Different Modes

In scenario 2, the route choice combining different modes is examined. As shown in Figure 6.8 and Table 6.6, the selected ODs were AIA Tower and Stamford Pr. School. Three routes are found with the same departure time (9:00am) and OD, but with different mode combinations. Paths 1 and 2 illustrate the common combinations: MRT & bus, and bus & bus. By comparing the results, it was found that Path 1 was much faster than Path 2, and that the fare of Path 1 was slightly higher than that of Path 2. It indicates that taking the MRT is the most effective method without compromising expense very much.

Path 3 illustrated a special combination which employed 3 modes (i.e. car, MRT and bus). It was assumed that a parent set off from Opp AIA Tower to his/her office at City Hall and the parent could only take the child to City Hall rather than to the child’s school, which was Stamford Pr. School. Path 3 provided a strategy for the child to use
public transport after he left parent’s car at City Hall. In other words, after alighted car, the child transferred to the MRT, and alighted at Bugis station and transferred to Bus 133, which took him to the bus stop Stamford Pr. School. This example is a good illustration of how a multi-modal routing strategy is conducted.

![Diagram of transport routes]

**FIG. 6.9** Scenario 2-Route choices in terms of a combination of different modes

Based on the results of Scenario 2, Fig 6.10 shows that between the same OD and departure time, taking the bus is usually the most economic choice, but means that the total travel time would increase drastically. Generally, combining the MRT and bus travel is the most economical and time-saving choice. Path 3 is a special case that would seldom occur, but it can still be seen that combining the 3 traffic modes is not the best choice at least in this case. Actually, switching between 3 different modes within the urban area will result in a waste of time spent on switching and incur greater travel costs, without much saving of the travel time.
Table 6.6 Scenario 2-Route choices in terms of a combination of different modes

<table>
<thead>
<tr>
<th>Solutions</th>
<th>Path 1</th>
<th>Path 2</th>
<th>Path 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criterion</td>
<td>Least Travel Time</td>
<td>Least Travel Time</td>
<td>Least Travel Time</td>
</tr>
<tr>
<td>Start Time</td>
<td>7:00am</td>
<td>7:00am</td>
<td>7:00am</td>
</tr>
<tr>
<td>Mode</td>
<td>MRT &amp; Bus</td>
<td>Bus 97 &amp; Bus 133</td>
<td>Car, MRT &amp; Bus</td>
</tr>
<tr>
<td>Travel Distance (m)</td>
<td>MRT 1897.00, Bus 845.43</td>
<td>Bus 97 1509.81, Bus 133 1418.79</td>
<td>Car 1648.91, MRT 879.62, Bus 407.19</td>
</tr>
<tr>
<td></td>
<td>2742.43</td>
<td>2928.60</td>
<td>2935.72</td>
</tr>
<tr>
<td>Travel Time (min)</td>
<td>MRT 19.2, Bus 4 30.4, SD 10.2</td>
<td>Bus 97 7.2, Bus 133 9.4, SD 13.8</td>
<td>Car 3.2, MRT 2, Bus 3, SD 12.5</td>
</tr>
<tr>
<td></td>
<td>2742.43</td>
<td>2928.60</td>
<td>2935.72</td>
</tr>
<tr>
<td>Fare (S$)</td>
<td>MRT 0.64, Bus 1.20</td>
<td>Bus 97 0.60, Bus 133 0.60</td>
<td>Car 5.2 (taxi), MRT 0.64, Bus 0.60</td>
</tr>
<tr>
<td></td>
<td>1.84</td>
<td>1.20</td>
<td>6.44</td>
</tr>
<tr>
<td>Transfer Times</td>
<td>4</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Details</td>
<td>2 MRT station and 2 bus stops Via Raffles Place, City Hall, and Bugis MRT station</td>
<td>8 bus stops Via City Hall interchange</td>
<td>1 MRT station and 1 bus stop Via City Hall interchange</td>
</tr>
</tbody>
</table>

FIG. 6.10. Routing results under Scenario 2
Scenario 3 – Route Choices in terms of Different General Costs

The last scenario focused on the multi-criteria route choice with different sets of weights. This is because the pair-wise comparison matrix in the AHP is defined subjectively by different users. This indicates that individual commuters may have their different preferences. As shown in Figure 6.9 and Table 6.7, the selected ODs were Orchard MRT Station and Suntec City Mall. The selection of Path 1 was based on the generalized cost as calculated in Table 4.4. As the combination of MRT and bus is very common, the result can be assumed to be logically grounded. Path 2 privileges the travel time factor, and therefore the car mode is the only optimal choice (i.e. users taking a taxi). Path 3 privileges the least fare, hence only the MRT was selected as the optimal mode. As the walk from the City Hall MRT station to the destination took less than 10 minutes, the obvious choice for the rest of the route was to walk.

FIG. 6.11. Scenario 3-Route choices obtained in terms of different general costs
Table 6.7. Scenario 3-Route choices obtained in terms of different general costs

<table>
<thead>
<tr>
<th>Solutions</th>
<th>Path 1</th>
<th>Path 2</th>
<th>Path 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start Time</td>
<td>8:30pm</td>
<td>8:30pm</td>
<td>8:30pm</td>
</tr>
<tr>
<td>Mode</td>
<td>MRT &amp; Bus</td>
<td>Car</td>
<td>MRT &amp; Walk</td>
</tr>
<tr>
<td>Criterion</td>
<td>General cost</td>
<td>Least time</td>
<td>Least Fare</td>
</tr>
<tr>
<td>Travel Distance(m)</td>
<td>MRT</td>
<td>Bus</td>
<td>Car</td>
</tr>
<tr>
<td></td>
<td>2512.19</td>
<td>1486.20</td>
<td>3785.66</td>
</tr>
<tr>
<td></td>
<td>3998.39</td>
<td>3785.66</td>
<td></td>
</tr>
<tr>
<td>Travel Time(min)</td>
<td>MRT</td>
<td>Bus</td>
<td>SD</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>8</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>22.2</td>
<td>17.8</td>
<td></td>
</tr>
<tr>
<td>Fare (S$)</td>
<td>MRT</td>
<td>Bus</td>
<td>Car</td>
</tr>
<tr>
<td></td>
<td>0.64</td>
<td>0.60</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>1.24</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>Transfer Times</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Details</td>
<td>3 MRT station and 4 bus stops</td>
<td>Via Raffles Place, City Hall, and Bugis MRT station</td>
<td>9 intersections</td>
</tr>
</tbody>
</table>

FIG. 6.12. Routing results under Scenario 3

Fig 6.12 shows the resulting curves based on data from Scenario 3. It can be seen that the general costs calculated in Chapter 4 had resulted in a compromised route choice. The value of travel time and cost was between the least time and cost routing.
of Paths 2 and 3. Therefore, the route choice obtained by calculating the general costs can generally satisfy the traveler’s requirements. Compared with the results of Scenario 2, it can be seen that in the urban traffic environment of Singapore, combining MRT and bus travel is the optimal choice.

6.4 SUMMARY

This chapter focuses mainly on the implementation of the proposed model. Based on the procedure introduced in Chapter 3, the implementation processes were divided into the GIS and the simulation module. The same study area, i.e., the CBD network of Singapore was used in these two systems because this area, contains many alternative transfer facilities and various route choices which can be better examined by using this urban network. As a component of data preparation, three main transportation modes were also presented. The processes of multimodal network modeling, switching delay presentation and simulation were presented in detail.

In the last part of this chapter, three scenarios presented by the developed system were discussed and analyzed. The three scenarios covered all the typical route choice situations: the same OD but with different departure times, different combinations of transportation modes, and different routing criteria. The results obtained by the proposed model indicated that it is more reasonable and practical for travelers, compared with the traditional models.
CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This study proposed a multimodal multi-criteria dynamic route choice model which attempted to manage multimodal transportation using a GIS environment. Within the GIS module, a dynamic path-finding algorithm was proposed to handle the routing on a multimodal network. With the help of the AHP, a multi-criteria evaluation model was also realized. The simulation tool used in this study supplied a dynamic data source for the GIS module to realize the dynamic routing. A switching delay model was also formulated in this study for representing the delay time resulting from mode transferring.

The proposed model was implemented using the current CBD network in Singapore. The same network was coded in both the GIS and simulation modules. A GUI was developed with GIS software. Using this developed system, three scenarios were carried out to demonstrate that the proposed approach provided travelers with an effective alternative to facilitate the making of more comprehensive and preferable route choices.


7.1 Conclusions

In this thesis, an integrated model for representing multimodal transportation was established. The main objective of this model is to provide route choices for travelers. To obtain the optimal routes and better exhibit the capabilities of the GIS and ITS, a dynamic routing algorithm, a transfer delay model and a multi-criteria evaluation model were proposed and implemented. It was demonstrated that the proposed approach could provide an effective alternative for travelers to facilitate the making of more comprehensive and preferable route choices.

The framework of this model was illustrated in Figure 3.2. It has three main modules: GIS module, simulation module and system function. The task of the interface was to connect these three modules and display the final results in the form of graphics and text. The routing algorithm and multi-criteria evaluation model were built-in components which were processed during routing.

The software made available by GIS are mapping, map display, topology analysis, and so on. They can be used to manage multimodal transportation and display routing results. Therefore, the modeling of the multimodal networks and building of GUI were realized by the GIS. MapObjects was selected to construct the GUI used in this study.

Much research has been concentrated on dynamic routing in recent years. The main difficulties associated with researching this area are the obtaining of real-time
data and the employing of a dynamic routing algorithm. In this study, microscopic simulation, an advanced technology in ITS, was used for generating real-time traffic data for the proposed model. The results show that this method is both feasible and performs well.

A classic routing algorithm based on Dijkstra’s algorithm and incorporating AHP methodology was employed in this study. Dijkstra’s algorithm was employed for developing a dynamic routing algorithm for multimodal routing in the proposed model. The AHP methodology was used for obtaining the weights of every factor in the proposed multi-criteria evaluation model.

In addition, a transfer delay model was formulated to represent the transfer behaviors of travelers. In this model, factors like the waiting time at the transit stations, the walking time between these stations, and the ages of travelers were considered.

Finally, the proposed model was implemented using the current CBD network of Singapore. Figures 6.5, 6.7, 6.8, 6.9 illustrate the developed system. The overall performance demonstrates the feasibility and capability of the proposed model. Although making a route choice on a multimodal transportation system is difficult, it was found that the proposed model can still provide travelers with optimal route choices in terms of their criteria.
The contributions of this thesis are identified as follows:

- A multimodal network was constructed in the proposed model using the GIS approach.

- The combination of GIS and the simulation system was realized and this coupling demonstrates that it is a powerful and promising method devoted by using the complementary functions of two systems in ITS.

- A dynamic shortest path algorithm was proposed and implemented for this proposed multimodal routing.

- A multi-criteria evaluation system has been established for routing, in which AHP methodology has been successfully applied for determining the weights of all factors.

- A transfer delay model was formulated for representation of travelers’ behaviors.

- A simulation platform for simulating the test network was constructed for realizing the transferring of real-time traffic information,

- Using the ActiveX control that the GIS vendor provided, a GIS-based GUI which connected all the components in this proposed model, was designed and constructed.

### 7.2 Recommendations for Future Research

This section suggests a number of recommendations for future research to further investigate and improve on the performance of the proposed multimodal, multi-criteria,
route choice model.

The proposed approach of using a simulation tool to provide dynamic traffic information is a promising method for the development of AITS. Further research should be conducted on database management in multimodal networks and on the integrating of simulation tools. A well-matched method can reduce the amount of redundant work and improve on the transfer of data between the GIS and the simulation system.

The network area used in this research is a relatively small one for studying multimodal transportation. Future studies could be extended to continent-size networks and the traffic modes to be accordingly increased to include air and marine transport.

With the development of a web-based GIS, techniques can be developed which will enable real-time data sharing on the Internet. Thus, multimodal routing can be globalized. Well-organized geo-databases can be explored by the online user to perform the routing needed to find the optimal route at any point in the world.
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