國　立　交　通　大　學
運　輸　與　物　流　管　理　學　系

博 士 論 文

考量移動性之複合路網綠色運輸策略

Green Transportation Strategies in Multimodal Networks while Preserving Mobility

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中　華　民　國　一 〇 四　年　五　月

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ABSTRACT

This dissertation aims to investigate green transportation strategies in multimodal networks while preserving mobility and to assess corresponding travel efficiency from a network point of view. Green transportation is advocated worldwide to reduce the environmental impact caused by transportation sector. However, the promotion of green transportation fails easily without considering mobility. This dissertation focuses on green transportation in urban multimodal networks. Various transport modes are usually involved and trips can be accomplished with more than one pattern. The first part of this dissertation develops a green index to evaluate the sustainability of different paths of origin-destination (OD) pairs in urban transportation networks. The study proposes a new idea to increase the accessibility of MRT stations in Taipei City by using convenience stores as transfer points. Convenience stores are densely distributed in Taipei City, and connect activity and transportation networks. They are important delivery points in Taipei. Furthermore, this dissertation proposes green feeder alternatives to carry travelers from convenience stores to MRT stations. A Monte Carlo simulation of thousands of OD pairs in Taipei City is conducted to examine proposed strategies. The second part of this dissertation applies small-world theory to investigate the proposed networks, which are current multimodal networks incorporating green transfer nodes. The green transportation connectivity efficiency and mobility in global and local scales are explored.

A series of case studies in Taipei City are performed to demonstrate the applications of this dissertation. The results indicate that for short trips, commuters can directly use electric motorcycles by renting and returning those at convenience stores of origins and destinations. For medium and long trips, commuters can take green transport modes at convenience stores to access MRT stations. Electric

motorcycles are effective green feeder modes, and electric feeder buses can be an alternative of green feeder modes for long trips. The results also show that the global mobility and local mobility of the proposed networks are more than 55%. It implies that travelers can travel from any district to any other districts with green transportation in a rather efficient way. In addition, the results show that Wan-hua is the district where the first trial of incorporating convenience stores in transportation networks should be conducted. In the proposed network, the local mobility of Wan-hua and Xin-yi districts is more than 66%, which indicates that travelers in Wan-hua and Xin-yi districts can reach any important destinations more efficiently than those in other districts.

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Chapter 1

Introduction

The general field of interest in this dissertation is to propose green transportation strategies while accommodating transportation basic functions and to explore the green transportation connectivity efficiency in multimodal networks. This chapter presents an overview of the motivation, problem statement, research objectives, methodology, and framework of this dissertation.

1.1 Motivations and background

According to Intergovernmental Panel on Climate Change fourth assessment report, the transport sector plays a crucial role not only in world energy use but emissions of greenhouse gases (GHG). Besides, road transport accounted for 93% of GHG from transport (European Environment Agency, 2004). Sustainable transport, including environmental, social, and economic aspects, has become a prominent issue. This dissertation focuses on the environmental aspect and aims at proposing green transportation strategies so that a more efficient urban transit system with less environmental impact is available for individuals. The results can be a reference for the public transportation department. Green transportation includes walking, bicycling, and public transportation. This study focuses on public transportation with given networks. Many studies strive for the reduction of emission and energy consumption in the transportation sector (e.g., Ross Morrow et al., 2010; Weigel, 2014). However, the performance of transportation in terms of basic functions, mobility and accessibility, has rarely been discussed in the prior published literature.

In urban transportation, trips can be accomplished not only by a single mode but by multiple modes in urban transportation networks. Different transport modes have their respective influences on the environment. For instance, electric trolley buses and the automated rapid transit SkyTrain are much more energy efficient than conventional private vehicles (Poudenx and Merida, 2007). On the other hand, travelers usually prefer private vehicles to transit based on considerations of travel time. It is difficult for travelers to lessen their environmental impact while traveling at the expense of their convenience. Poudenx (2008) indicates that policies aiming to curb private vehicle use are failing because they do not incorporate human propensities for accessibility and comfort.

Generally, if a trip requires more than two transfers, it is assumed that the user will switch to another means of transportation (Guihaire and Hao, 2008). Therefore, it is important to enhance transportation sustainability while preserving transportation basic functions, mobility and accessibility. Feng et al. (2010) studied how to reduce emission while simultaneously accommodating mobility by maximizing the level of car ownership and number of trips by private and public modes subject to environmental capacity constraints. Nevertheless, the study did not address how to proactively establish a green transportation environment for travelers. This dissertation focuses on Mass Rapid Transit and shared electric motorcycles.

Methods to assess transportation sustainability have addressed by several studies in the past. Amekudzi et al. (2009) presented a sustainability footprint framework and model that may be used in analyzing the impacts of a transportation system. Browne et al. (2008) compared the ecological footprint for travel-commuting patterns with different transport policy scenarios related to automobiles. However, the transportation sustainability has not been assessed from a multimodal network point of view. Studies on multimodal transport networks have focused on finding the shortest path with user preferences or its trait of catering to the needs of a variety of demand-responsive transports (e.g., Modesti and Sciomachen, 1998; Bielli et al., 2006). Lozano and Storchi (2001) developed the shortest (in travel time) viable path algorithm in the multimodal networks. Poudenx and Merida (2007) used emission per vehicle–kilometer (vkm) and emission efficiency to compare different transport modes. However, it didn't address the emission expelled along a path in the multimodal networks of an OD pair. From the planning aspect, emission produced by the transportation sector is a concern of sustainable urban living. Delucchi and Kurani (2014) developed an urban-settlement and transportation-infrastructure scheme to support sustainable transportation. It is more appropriate to consider emission expelled along a route in urban networks from a comprehensive perspective. In this dissertation, the sustainability of a path in the multimodal networks is assessed based on the amount of emission that a passenger produced along a path when taking the mode or the modes.

In the late 1990's, Watts and Strogatz (1998) found that the topology of some networks lay somewhere between completely regular or completely random. They can be highly clustered, like regular lattices, yet have small characteristic path lengths, like random graphs. They called them 'small-world' networks. Latora and Marchiori (2001, 2002) proposed global and local efficiency models so that the small-network model of Watts and Strogatz (1998) can also be applied to transportation systems. Hsu and Shih (2008) used travel time as a determinant to formulate the mobility and accessibility models in air transportation networks, which can more precisely measure transportation system performance. However, small-world network models have not been applied to examine the green connectivity efficiency of multimodal transportation networks.

Past studies have explored how to alleviate transportation impacts on the environment, developed measurements of transportation sustainability, and proposed policies for sustainable travel. However, the performance of transportation in terms of basic functions, mobility and accessibility, has rarely been discussed in the prior published literature. This dissertation will focus on promoting green transportation while preserving mobility and accessibility. In regards to literature related to multimodal networks, it was focused on finding the shortest path. Few studies have examined the sustainability of different paths in urban multimodal networks. In addition, these studies rarely investigated the green connectivity efficiency and mobility of a multimodal network and combined the activity network to increase transit accessibility. As to small-world related issues, there is study applying small-world theory to analyze transpiration network efficiency. However, the sustainability of paths in multimodal network of OD pairs has not been explored with small-world network theory. In addition, these small-world related studies have rarely investigated the green connectivity efficiency of multimodal networks in the urban area.

To sum up, the performance of the transportation basic functions, mobility and accessibility, has rarely been discussed when mitigating the transportation impact on the environment in the prior literature. This dissertation begins with providing green transportation strategies with consideration of trip characteristics while maintaining mobility and accessibility in urban multimodal networks. Next, the study explores the green transportation connectivity efficiency in multimodal networks with small-world network theory.

1.2 Research objectives

The overall goal of this dissertation is to enhance transportation sustainability while preserving the transportation basic function, and to validate the corresponding green transportation connectivity efficiency in multimodal networks. Specifically, the purpose of this dissertation is to investigate green transportation strategies in consideration of mobility and accessibility and to validate the improvement of green transportation connectivity efficiency with the proposed strategies in multimodal networks. According to the issues of significance, there are two distinct parts in this dissertation, which can be addressed as green transportation strategies while preserving mobility and accessibility, and small-world network theory in the study of green transportation connectivity efficiency in multimodal networks. These two parts can be illustrated as follows.

In the first part of this dissertation, this study explores green transportation strategies while giving consideration to mobility and accessibility. A green index associated with the transportation mode is developed to investigate the sustainability of crucial viable paths of an origin-destination (OD) pair, which is derived by the algorithm proposed in Lozano and Storchi (2001). Then, the travel time of the current most sustainable path is analyzed and effective methods are provided to increase its mobility and accessibility. Kim and Ulfarsson (2008) suggested short trips were mainly made by automobiles and rarely by bus and bike. Therefore, trip length is an important travel attribute for environmental sustainability. Finally, this study uses Monte Carlo simulation to sample thousands of OD pairs and analyzes the travel time of single mode and multiple modes of each pair. Mobility difference between these two transport patterns at various travel distances is examined. Then, the study provides strategies for green transportation for different trip lengths.

In the second part of this dissertation, the study attempts to apply small-world network theory to explore the green transportation connectivity efficiency in the multimodal networks. According to the green transportation strategies derived from the first part of the dissertation, green transfer nodes and green extended arcs are introduced to the current multimodal networks. The functions of the introduced green extended arcs are identified and are related to the shortcuts in the small-world networks. Green connectivity efficiency model and mobility model are developed to assess representative OD pairs in the multimodal networks of the studied city. The global and local Green connectivity efficiency and mobility are presented and the corresponding implications are discussed.

Specifically, the objectives and contributions of each part of this dissertation are discussed respectively as follows.

(1) The study develops a green index associated with the transportation mode to investigate the sustainability of crucial viable paths of an OD pair. Then, this study analyses the travel time of the current most sustainable path and provides effective methods to increase its mobility and accessibility. In addition, Monte Carlo simulation is applied to demonstrate the mobility difference between single mode and multiple modes of each sampled OD pair at various trip lengths. Finally, this study provides green transportation strategies for different trip lengths.

(2) This study explores green transportation connectivity efficiency in multimodal networks with small-world network theory. The functions of the green extended arcs introduced in this study are identified and are related to the shortcuts in the small-world networks. Green connectivity efficiency model and mobility model

are developed both in global and local scales. Then, this study examines the representative OD pairs in multimodal networks of the studied city and the implication of the results is discussed.

1.3 Research scope and approaches

This dissertation aims at exploring important issues with respect to sustainable transport accommodating mobility in multimodal transportation networks. The sustainable transport in the study focuses on the environmental aspect. Transportation impact on the environment can be evaluated from different aspects: energy, emission, noise, and so on. In this dissertation, emission is adopted and green transportation is defined as a form of transportation where greenhouse gas is discharged no more than 0.053 kilograms per vehicle kilometer when travelers are in-vehicle. The figure is based on Skytrain's emission shown in Poudenx and Merida (2007). The greenhouse gas refers to the combination of CO_2, CH_4, N_2O and it is represented with eCO_2 according to Poudenx and Merida (2007). The first topic of this dissertation aims to investigate strategies for green transportation in multimodal networks. The multimodal transportation networks include private and transit networks. It is assumed that the Mass Rapid Transit (MRT) network and the bus network in the studied city are given. The mobility of an OD pair is defined as a ratio of benchmark travel time of the OD pair to travel time of modes that travelers use, because travel time of an OD pair in the multimodal network varies with the path (i.e. the transport modes). The accessibility in this study focuses on access to MRT station from the origin. It can be reflected in the relationship between access time to MRT and total travel time. This study uses travel time as the key measure of transportation basic functions, mobility and accessibility, because it is a significant measure in mobility and accessibility formulations (Levinson, 2003).

In this dissertation, representative OD pairs of home-based work trips in Taipei City are investigated; the origin is home and the destination is the workplace. The set of modes considered in this study include automobiles, motorcycles, buses, and MRT. The single mode represents automobiles (motorcycles) used for the whole trip. Though the multiple modes may represent different patterns of more than one mode used in a trip, they mainly represent buses followed by MRT in this study. The access of MRT stations, including the first mile from home to bus stops, is examined. It is assumed that most of the important workplaces and landmarks can be reached within walking distance from an MRT station. Therefore, the strategy of improving egress of MRT stations, the last mile, is not discussed.

This dissertation adopts the shortest (in travel time) viable path algorithm in the multimodal networks developed by Lozano and Storchi (2001). Their approach is appropriate to explore this issue because it is for home-based work trips, which is especially useful for rush hours (Lozano and Storchi, 2001). This algorithm doesn't consider the first and last mile of public transport, but it helps identify the travel time bottleneck of using buses followed by MRT for a trip. Representative OD pairs are scrutinized in the first place. The walking time of the first mile (i.e. from home to transit stations) and the last mile (i.e. from transit stations to the workplace) of these OD pairs is within one minute respectively so that the algorithm is still applicable. In addition to finding the shortest travel time viable path, this dissertation modifies the arc cost with emission to find the least emission path in the multimodal networks.

This dissertation proposes strategies to make green transportation more accessible to travelers to save time so that they are more inclined to take the least emission producing path. Enhancing MRT utilization is a practical approach toward green transportation. However, its accessibility is limited compared with that of private vehicles. This study proses a new idea to increase the accessibility of MRT stations by using convenience stores as transfer points. Convenience stores are densely distributed in Taipei City. There is a very high density of convenience stores, almost five per square kilometer. For home-based trips, travelers usually can arrive at their nearby convenience stores within a five-minute walk, which indicates good accessibility. Convenience stores connect activity networks and transportation networks, and they are important delivery points in Taipei. In fact, Internet shoppers picking up their goods at the convenience store has become the second-largest logistics mode in Taiwan (EC Consultant, 2014). Therefore, a set of convenience stores by the important origins and destinations in Taipei are proposed to be the green transportation transfer points.

This dissertation further proposes green feeder alternatives (i.e., electric motorcycle rentals, bicycle rentals, hybrid taxi pool, and feeder transit service with hybrid or electric buses) to shorten the travel time between the convenience stores and MRT stations, thereby yielding the environmental path with the lowest impact. The proposed alternatives are feasible to fit within the transportation systems in Taipei City. Motorcycles are popular modes in Taipei City, and electric motorcycles are promoted by the government. There are regular motorcycle parking spaces alongside convenience stores. It is feasible to locate rental electric motorcycles or bicycles there because the location of regular motorcycle parking space is flexible enough to be changed in order to promote green transportation. For instance, Taipei City Parking Management and Development Office cancelled 2600 regular motorcycle parking spaces around the recently opened MRT lines and set up bicycle rental facilities

(Taipei City Government, 2014).

Convenience stores have been providing taxi calling service since 2009. In hybrid taxing pooling, travelers can get to the nearest MRT station in a short amount of time and share the cost. Even though the workplaces of these travelers are different, it is still a viable strategy because travelers enter the MRT system efficiently. Regarding the current status related to feeder transit service, there are citizen mini bus routes to complement the current bus networks. However, it is too circuitous for travelers who want to access MRT stations. The feeder transit service at the convenience store can eliminate travelers' concern of the least direct route. Finally, the Monte Carlo simulation is applied to examine proposed strategies for different trip lengths. The approach in the first part of this dissertation involves both transport network and mode perspectives and provides a more comprehensive view to enhance green transportation in Taipei City.

The second part of this dissertation explores the green transportation connectivity efficiency in the multimodal networks. This study incorporates green transfer point, convenience stores, into the transport networks as green transfer nodes. In addition, the arc between the green transfer node and the MRT node is defined as green extended arcs. Small-world network theory proposed by Watts and Strogatz (1998) is applied to explore the green transportation connectivity efficiency among important OD pairs in the multimodal networks. Shortcuts in a small-world network not only enhance the connectivity of nodes located at different regions but increase the overall interaction of the network. This dissertation supposes that green extended arcs are similar to the shortcuts of a small-world network. The functions of shortcuts in a small-world network are to provide opportunities to reduce the steps and the time required for transmitting any kind of communication among nodes, to enhance the connectivity of those nodes located at different regions, and to increase the overall interaction of the network (Hsu and Shih, 2008). The functions of green extended arcs are to shorten the access time to MRT stations, to increase green transportation connectivity efficiency of different OD pairs, and to enhance network interaction without environmental impacts. Therefore, it is suitable to adopt small-world network theory to investigate green transportation connectivity efficiency in multimodal networks.

1.4 Dissertation framework

The framework and organization of this dissertation is shown as Figure 1.1, which depicts the content and key factors of each part of this dissertation, and shows the relationships among them. Chapter 1 illustrates the overview of this dissertation in terms of motivations and background, objectives, spectrum of the framework. Chapter 2 reviews literature in the relevant topics and distinguishes the study from past studies. The contribution of each part of this dissertation is also emphasized.

Chapter 3 investigates green transportation strategies for different trip lengths in multimodal networks. First, this study defines the nods and arcs of the multimodal networks. Then, the multimodal shortest viable path algorithm is applied to obtain two different kinds of path: the shortest travel time path and the least emission path. Next, these paths are assessed with mobility and green level this study develops. Alternatives are proposed to improve the path either of high green level with low mobility or of high mobility with low green level. Finally, this study applies Monte Carlo simulation to examine the proposed green transportation strategies for different trip lengths. A comprehensive green transportation strategy, from network and mode perspectives, is proposed in this chapter.

Chapter 4 explores green transportation connectivity efficiency in multimodal networks with small-world theory. The green transfer nodes and green extended arcs are first introduced to the original multimodal networks. Then, this study identifies the functions of green extended arcs and relates them to the shortcuts in the networks. Next, small-world theory is applied to explore the networks. Green connectivity efficiency and mobility models are presented in global and local scales. The original and proposed multimodal networks are evaluated and the results can be a reference for the authorities. Finally, Chapter 5 summarizes the important findings as well as some conclusions and management implications with respect to each part of this dissertation.

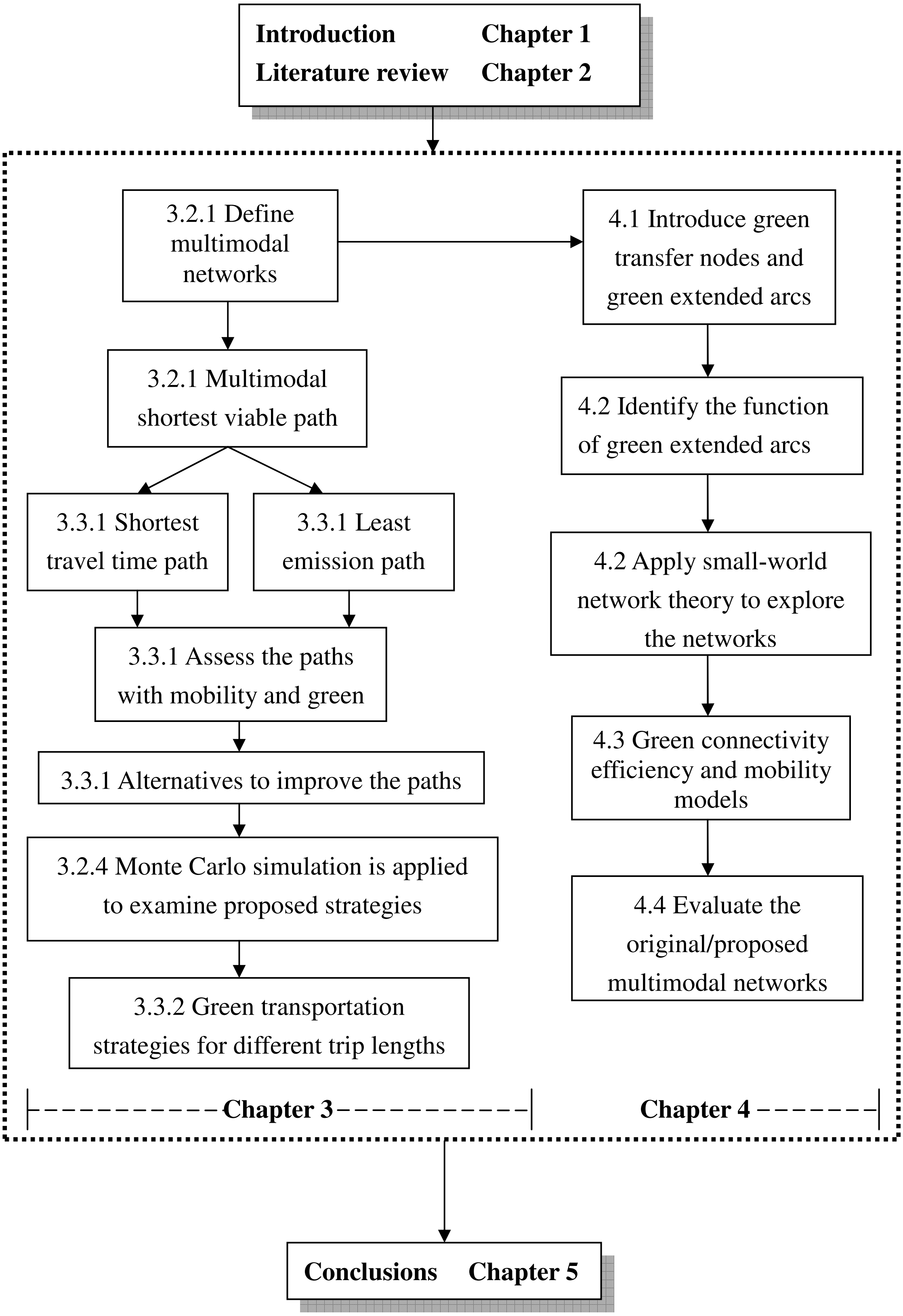


Figure 1.1 Research framework

The research processes and steps can be expressed in detail as follows.

1. Definition of research problems

According to the motivation and backgrounds, the research problems, issues, scope and objectives are first identified.

2. Literature review

To better understand the problems, this dissertation comprehensively reviews the existing literature in the relevant topics, such as transportation impacts on environment, multimodal networks, sustainability assessment and so on. By doing so, this dissertation can clarify and illuminate the contributions of this research, as well as can take into account the key factors when formulating models and designing green transportation strategies.

3. Multimodal networks

This dissertation defines the nodes and arcs of the networks, including different layers of transportation network, such as private networks and different transit networks, and the connection arcs among them. Then transportation impact of multimodal viable paths of each OD pair on the environment and mobility of those paths can be assessed.

4. Sustainability and mobility of important OD pairs

The study develops the green level to assess the sustainability of viable paths of important OD pairs in the multimodal networks. Mobility of the same OD pair may vary as different viable path associated with different transport modes. For the current most sustainable path with low mobility and least sustainable path with high mobility, the corresponding solutions are discussed.

5. Green transportation strategies

Several green transportation strategies are proposed to improve the crucial viable path of important OD pairs in the multimodal networks. These strategies are feasible because the status quo of the studied city is taken into consideration. The strategies incorporate using the green single mode and increasing the green transit accessibility. The sustainability and mobility of the path with the proposed strategy of each OD pair are examined.

6. Small-world network theory and methodology

The small-world network theory and methodology are investigated thoroughly. The proposed green transportation strategies in Step 5 can be further regarded as introducing green transfer nodes and green extended arcs to the current multimodal networks. The functions of the green extended arcs are similar to those of shortcuts in the small-world networks. Therefore, small-world network theory is applied to examine the green transportation connectivity efficiency in the multimodal networks.

7. Green connectivity efficiency and mobility models

This dissertation formulates green connectivity efficiency model and mobility model based on the small-world network theory to evaluate the sustainability and the ease of movement for travelers in multimodal networks. The proposed strategies in Step 5 will be examined with these models.

8. Case studies

Case studies are provided in each parts of this dissertation to illustrate the application of the models and to demonstrate the proposed strategies' effectiveness.

9. Conclusions and suggestions

Finally, the summary, conclusions and the future studies of this dissertation are presented.

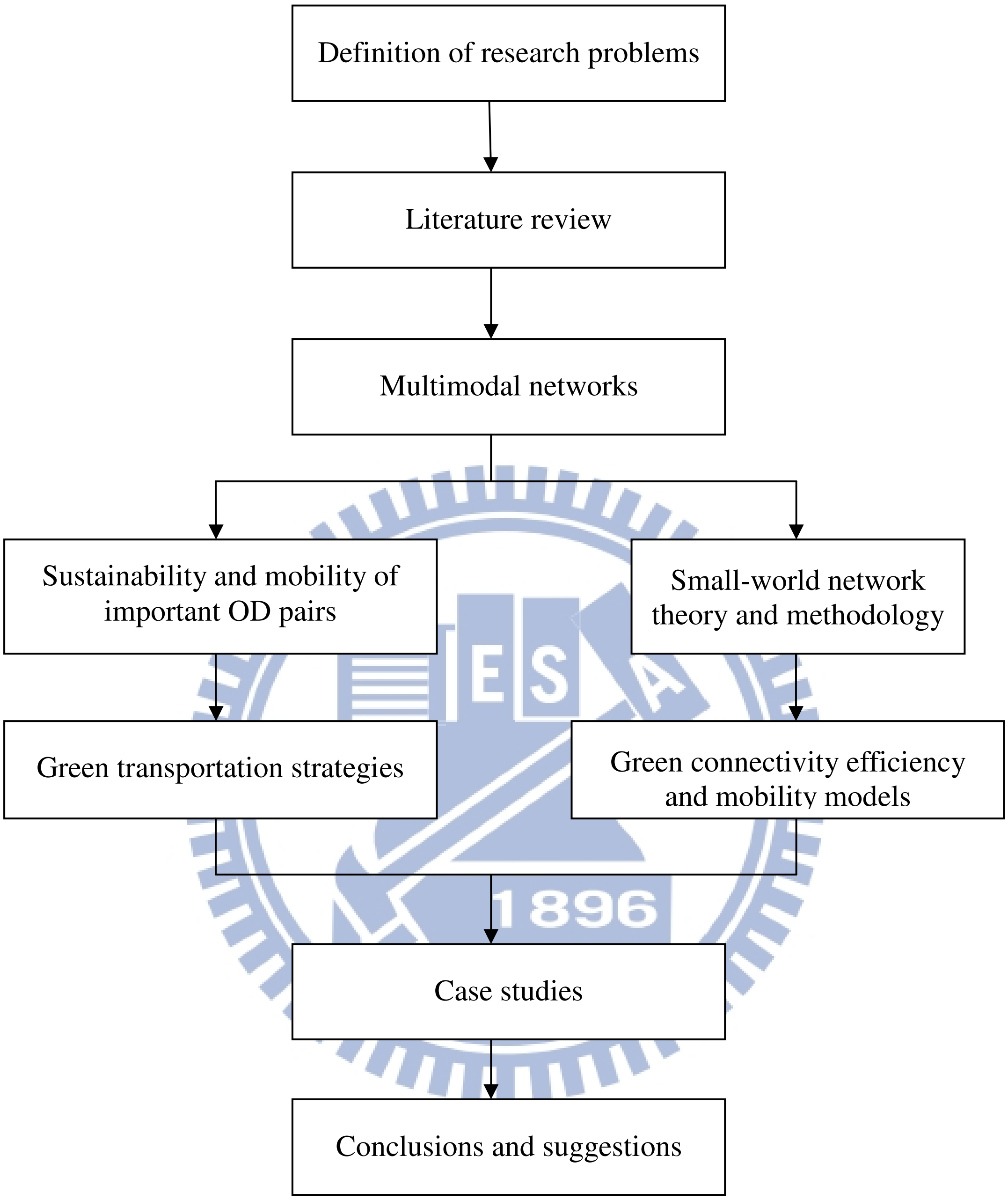


Figure 1.2 Research process

Chapter 2

Literature Review

This chapter reviews the literature on related areas including: 2.1 Green transportation; 2.2 Multimodal transportation networks; 2.3 Small-world related issues. 2.4. The research issues, theoretical methods and contributions of the relevant studies are discussed and summarized. Furthermore, the contributions of the study are also clarified in 2.4 Summary.

2.1 Green transportation

Green transportation is advocated worldwide. Many studies strive for the reduction of emissions and energy consumption in the transportation sector (e.g., Ülengin et al., 2010; Abrell, 2010; Ross Morrow et al., 2010; Brand et al., 2013). Trips can be accomplished not only by a single mode but by multiple modes in urban transportation networks. Different transport modes have their respective influences on the environment. For instance, electric trolley buses and the automated rapid transit SkyTrain are much more energy efficient than conventional private vehicles (Poudenx and Merida, 2007). On the other hand, travelers usually prefer private vehicles to transit based on considerations of travel time. It is difficult for travelers to lessen their environmental impact while traveling at the expense of their convenience. Poudenx (2008) indicates that policies aiming to curb private vehicle use are failing because they do not incorporate human propensities for accessibility and comfort. In addition, some studies reveal that residential density and trip lengths will have different degrees of impact on the environment. Brownstone and Golob (2009) indicated that the residential density has an impact on vehicle usage and energy consumption. Kim and Ulfarsson (2008) suggested short trips were mainly made by automobiles and rarely by bus and bike.

Some studies investigate measurement of transportation sustainability and policies for sustainable travel. Mihyeon Jeon and Amekudzi (2005) characterized the emergent thinking on what constitutes transportation sustainability and how to measure it. Frameworks based on important causal relationships between infrastructure and the broader environment, infrastructure impacts on the economy, environment, and social well-being; and the relative influence of agencies over causal factors, are largely being used to develop and determine indicator systems for measuring sustainability in transportation systems.

Amekudzi et al. (2009) presented a sustainability footprint framework and model that may be used in analyzing the impacts of transportation and other infrastructure systems on regional sustainable development. A specific application of the framework is in the quality of life contributions that transportation systems may make to communities as a function of their impacts on natural assets that contribute inputs and absorb the byproducts of development. The value of this framework and model lie in introducing both spatial and temporal flexibility that may enable stakeholders with widely different priorities to reach consensus on interim goals for sustainable development to ultimately attain sustainability.

Browne et al. (2008) compared the ecological footprint for travel-commuting patterns for the residents of an Irish city-region. Scenario building, based on ecological footprint analysis, is used to estimate the impact of different policy choices for 2010. The optimal policy mix for sustainable travel is proposed and consists of a mix of reduced demand through travel demand measures, better spatial planning and technological improvements in fuel economy.

Table 2.1 Main issues, features and results in literature on green transportation

Authors	Main issues and features	Important results
Mihyeon Jeon and Amekudzi (2005)	Characterize the emergent thinking on what constitutes transportation sustainability and how to measure it	Infrastructure impacts on the economy, environment, and social well-being are largely being used to develop indicator systems for measuring sustainability in transportation systems
Poudenx and Merida (2007)	Analyze the energy consumption and greenhouse gas emissions of all private and transit vehicles	Electric trolley buses and the automated rapid transit SkyTrain were eight times as energy efficient as private vehicles
Browne et al. (2008)	Compare the ecological footprint for travel-commuting patterns for the residents	A mix of reduced demand through travel demand measures, better spatial planning and technological improvements in fuel economy is optimal policy for sustainable travel
Poudenx (2008)	Offer a brief journey through twelve major cities with various policies in place to curb private vehicle use and assess their success in term of energy consumption and greenhouse gas emission.	Policies aimed at reducing private vehicles use are failing because they do not incorporate the reality of human propensities for accessibility and comfort
Kim and Ulfarsson (2008)	Analyze transportation mode choice for short home-based trips	Influencing people's choice of transport mode on short trips should be an important part of efforts encouraging the use of non-automobile alternatives

Table 2.1 (continued)

Authors	Main issues and features	Important results
Amekudzi et al. (2009)	Propose a sustainability footprint framework and model that may be used in analyzing the impacts of transportation	Introducing both spatial and temporal flexibility that may enable stakeholders to reach consensus on interim goals for sustainable development
Brownstone and Golob (2009)	Specify and estimate a joint model of residential density, vehicle use, and fuel consumption	There is an direct effect of density through lower fleet fuel economy of 20 gallons per year, a result of vehicle type choice
Ülengin et al. (2010)	Propose a methodology for analyzing the effects of transportation policies on environment, society, economy, and energy	The extent of the relationships between transportation and the environment must be considered to achieve a sustainable transportation system
Abrell (2010)	Analyze the use of market-based emission regulation instruments to address the carbon dioxide emissions of transportation	Including transportation into the European emission trading system is superior to a closed emission trading system for transportation or a tax-based approach
Ross Morrow et al. (2010)	Examine different sector-specific policy scenarios for reducing GHG emissions and oil consumption under economy-wide CO2 prices.	The largest reductions in GHG emissions result from increasing the cost of driving
Brand et al. (2013)	Accelerate the transformation to a low carbon passenger transport system	Governments should focus on designing incentive schemes with strong up-front price signals that reward ‘low carbon’ and penalize ‘high carbon’

Summary:

Past studies have explored how to alleviate transportation impacts on the environment, developed measurements of transportation sustainability, and proposed policies for sustainable travel. However, the performance of transportation in terms of basic functions, mobility and accessibility, has rarely been discussed in the prior published literature. This study will focus on promoting green transportation while preserving mobility and accessibility.

2.2 Multimodal networks

Studies on multimodal transport networks have focused on finding the shortest path with user preferences or its trait of catering to the needs of a variety of demand-responsive transports (e.g., Modesti and Sciomachen, 1998; Bielli et al., 2006). Lozano and Storchi (2001) proposed a modified Chronological Algorithm to solve the multimodal shortest viable path problem (MSVPP) with label-correcting techniques.

Hoogendoorn-Lanser and Van Nes (2004) revealed the insight into the structure and complexity of multimodal trips. An individual embarking on a multimodal trip faces a number of choice dimensions, such as access and egress mode or modes, origin and destination railway stations, train service types, and transfer stations. For each of these choice dimensions, multiple alternatives are available. It is concluded that many alternatives are available to travelers, whereas only a limited subset of those alternatives is actually perceived. Even fewer alternatives are actually considered in the choice process.

Li et al. (2007) investigated park-and-ride (P&R) services developed by local authorities of large Asian cities. P&R services encourage commuters to reach the cities' central areas by transferring from private cars to metro at stations. It is assumed that commuters can complete their journeys by three options: auto mode, walk-metro mode, and P&R mode. The proposed model simultaneously considered commuters' travel choices on travel mode, route-path, and transfer point, as well as their parking choice behavior. The effects of elastic travel demand, together with passengers' discomfort in metro vehicles, were explicitly incorporated. The results show that the introduction of P&R schemes could bring a positive, neutral, or even negative social welfare increment, and its efficiency depends greatly on the parking charging level and the number of parking spaces supplied at the P&R site and in the urban central area, as well as the metro dispatching frequency and fare.

Table 2.2 Main issues, features and results in literature on multimodal networks

Authors	Main issues and features	Important results
Modesti and Sciomachen (1998)	Find OD shortest paths in urban multimodal transportation networks incorporating users' propensities	Propose a utility measure for finding multiobjective shortest paths in urban multimodal transportation networks
Lozano and Storchi (2001)	Propose a modified Chronological Algorithm (Pallottino and Scutellá, 1997) to solve the multimodal shortest viable path problem with label-correcting techniques	Show the resulting paths of an application on a network for different number of modal transfers
Hoogendoorn-Lanser and Van Nes (2004)	Reveal the insight into the structure and complexity of multimodal trips	Many alternatives are available to travelers, whereas only a limited subset of those alternatives is actually perceived

Table 2.2 (continued)

Authors	Main issues and features	Important results
Bielli et al. (2006)	The network object modeling and multimodal shortest path algorithm	Provide a tool for detecting the facilities of using different travel modes through a transportation network
Li et al. (2007)	Investigate Park and Ride services and proposed a model simultaneously considered commuters' travel choices and elastic travel demand	P&R schemes could bring a positive, neutral, or even negative social welfare increment, and its efficiency depends greatly on the parking charging level and the number of parking spaces, as well as the metro dispatching frequency and fare.

Summary:

The literature related to multimodal networks focused on the shortest path algorithm, the structure and complexity of multimodal trips, and effectiveness of park-and-ride service to transfer commuters from private cars to metro at stations. Few studies have examined the sustainability of different paths in urban multimodal networks. In addition, these studies rarely investigated the green connectivity efficiency and mobility of a multimodal network and combined the activity network to increase transit accessibility.

2.3 Small-world related issues

Watts and Strogatz (1998) indicated that the connection topology was ordinarily assumed to be either completely regular or completely random, but many biological, technological and social networks lay somewhere between these two extremes. They explore simple models of networks that can be tuned through this middle ground:

regular networks ‘rewired’ to introduce increasing amounts of disorder. They found that these networks can be highly clustered, like regular lattices, yet have small characteristic path lengths, like random graphs. They called them ‘small-world’ networks. To interpolate between regular and random networks, they considered the following random rewiring procedure. They started from a ring lattice with n vertices and k edges per vertex, and then rewired each edge at random with probability p. This construction allowed them to ‘tune’ the graph between regularity (p=0) and disorder (p=1), and thereby to probe the intermediate region $0<p<1$, about which little was known. They further quantified the structural properties of these graphs by their characteristic path length $L(p)$ and clustering coefficient $C(p)$. $L(p)$ was defined as the number of edges in the shortest path between two vertices, averaged over all pairs of vertices. And $C(p)$ was defined as follows. Suppose that a vertex v has k_v neighbors, then at most $k_v(k_v-1)/2$ edges can exist between them (this occurs when every neighbor of v is connected to every other neighbor of v). Let C_v denote the fraction of these allowable edges that actually exist. Define $C(p)$ as the average of C_v over all v. For friendship networks, these statistics had intuitive meanings: $L(p)$ was the average number of friendships in the shortest chain connecting two people; C_v reflected the extent to which friends of v are also friends of each other; and thus $C(p)$ measured the cliquishness of a typical friendship circle. In other words, $L(p)$ measured the typical separation between two vertices in the graph (a global property), whereas $C(p)$ measured the cliquishness of a typical neighborhood (a local property).

Following Watts and Strogatz (1998), some studies were proposed to investigate whether specific real-world networks reveal small-world properties or not. In particular, Latora and Marchiori (2001, 2002) pointed out that the mathematical formalism of

Watts and Strogatz (1998) suffered from severe limitations: (1) it applied only to some cases, whereas in general the two quantities L and C were ill-defined; (2) it worked only in the topological abstraction, where the only information retained was about the existence or the absence of a link, and nothing was known about the physical length of the link. Therefore, Latora and Marchiori (2001, 2002) proposed global and local efficiency models to overcome the restriction. They defined the shortest path length d_{ij} between two generic nodes i and j as the smallest sum of the physical distances throughout all the possible paths in the graph from i to j. The efficiency ε_{ij} in the communication between nodes i and j was then defined to be inversely proportional to the shortest distance between them, i.e. $\varepsilon_{ij} = 1/d_{ij}$. When there was no path in the graph between nodes i and j, $d_{ij} = +\infty$ and, consistently, $\varepsilon_{ij} = 0$. The global efficiency of a generic weighted (and possibly even disconnected) graph $\overline{\mathbf{G}}$, is formulated as $E_{glob}(\overline{\mathbf{G}}) = \sum_{i \neq j \in \overline{\mathbf{G}}} \frac{1}{d_{ij}} \Big/ (\|\mathbf{N}\|(\|\mathbf{N}\|-1))$, where $\|\mathbf{N}\|$ is the total number of nodes in $\overline{\mathbf{G}}$ .The local efficiency of $\overline{\mathbf{G}}$ is formulated as $E_{loc}(\overline{\mathbf{G}}) = \frac{1}{\|\mathbf{N}\|} \sum_{i \in \mathbf{G}} \left(\sum_{l \neq m \in \mathbf{G}_i} \frac{1}{d_{lm}} \Big/ (V_i(V_i - 1)) \right)$, where V_i is the number of nodes that connect to node i, and $\overline{\mathbf{G}}_i$ is the subgraph of node i. Latora and Marchiori (2001, 2002) confirmed that a small-world network is a network with both high global and high local efficiency. They also showed that if the Boston subway transportation system (MBTA) is combined with its bus system, then this extended system is a small-world network.

Hsu and Shih (2008) investigated the network connectivity and efficiency of international airline alliances, and conceptually applied the shortcuts of small-world networks to analyze alliance routes. Based on travel time, mobility and accessibility models are formulated to evaluate the effects of alliance on network connectivity. The results show that the connectivity of the alliance network is better than before, and the alliance effectively improves accessibility from high–medium traffic airports to low traffic airports. After the alliance, the shortest paths between origin–destination pairs will involve more transfers but less travel time. In addition, Hsu and Shih (2010) explored the effects of air travel activities on an influenza pandemic in a small-world network. These activities of air travel include passengers' consolidation, conveyance and distribution in airports and flights. Dynamic transmission models were developed to assess the expected burdens of the pandemic, with and without control measures. This study also investigated how the small-world properties of an air transportation network facilitate the spread of influenza around the globe. The results show that, as soon as the influenza is spread to the top 50 global airports, the transmission is greatly accelerated. Under the constraint of limited resources, a strategy that first applies control measures to the top 50 airports after day 13 and then soon afterwards to all other airports may result in remarkable containment effectiveness. As the infectiousness of the disease increases, it will expand the scale of the pandemic, and move the start time of the pandemic ahead.

Hsu et al. (2013) used an integrated model utilizing a small-world network and choice-based conjoint adoption model to examine the dynamics of consumer choice and diffusion in the hybrid electric vehicles market. It specifically compares the effectiveness of hybrid diffusion through the traditional word of mouth and via social media. The results show that without the advantage of increased gasoline prices, the growth of the hybrid vehicles market is insignificant, and that the Internet has a significant influence on the word of mouth effect in the purchasing process. Hybrid electric vehicles market shares decrease dramatically as a result of negative word of mouth communication via social media. The use of a higher fuel taxes is more effective than providing a subsidy for disposing of old vehicles and purchasing a hybrid.

Derrible and Kennedy (2010) adapted network science methodologies to the transportation literature, and offers one application to the robustness of metros; here, metro refers to urban rail transit with exclusive right-of-way. The study found that most metros are indeed scale-free and small-worlds; they show atypical behaviors, however, with increasing size. In particular, the presence of transfer-hubs (stations hosting more than three lines) results in relatively large scaling factors. The analysis provides insights/recommendations for increasing the robustness of metro networks. Smaller networks should focus on creating transfer stations, thus generating cycles to offer alternative routes. For larger networks, few stations seem to detain a certain monopole on transferring, it is therefore important to create additional transfers, possibly at the periphery of city centers; the Tokyo system seems to remarkably incorporate these properties. Sheikh Mohammad Zadeh and Rajabi (2013) proposed a new specialized centrality measure to quantify the importance and the contribution amount of each street in an urban transportation network. Contrary to the previous general centrality measures (e.g., degree, betweenness, and closeness), this measure considers three important vehicular traffic characteristics: street capacity restrictions, the dominant pattern of travel demands, and the traffic-flow equilibrium. Applying the developed centrality measure to simulated networks shows that traffic flows more efficiently in urban networks with "small-world" configurations, where a certain number of shortcut links and locally clustered streets are allowed. However, with regular grid networks, the application of the proposed measure shows little efficiency.

This outcome suggests that the regular grid is not suitable as a base structure in urban planning.

Table 2.3 Main issues, features and results on small-world related literature

Authors	Main issues and features	Important results
Watts and Strogatz (1998)	First propose the small-world network theory	Clustering coefficient and characteristic path length can measure the distinctive properties of small-world networks
Latora and Marchiori (2001, 2002)	Propose the global and local efficiency models	The proposed models can drop all restrictions of previous models, and an extended transportation system embracing the MBTA is a small-world network, with both high global and high local efficiency
Hsu and Shih (2008)	Apply small-world network theory to explore the connectivity and efficiency of airline alliance networks based on travel time	The alliance effectively improves accessibility from high–medium traffic airports to low traffic airports
Hsu and Shih (2010)	The effects of air travel activities on an influenza pandemic in a small-world network	As soon as the influenza is spread to the top 50 global airports, the transmission is greatly accelerated
Hsu et al. (2013)	Integrate small-world network and choice-based conjoint adoption model to examine the dynamics of consumer choice and diffusion in the hybrid electric vehicles market	Without the advantage of increased gasoline prices, the growth of the hybrid vehicles market is insignificant, and that the Internet has a significant influence on the word of mouth effect in the purchasing process

Table 2.3 (continued)

Authors	Main issues and features	Important results
Derrible and Kennedy (2010)	Adapt network science methodologies to the transportation literature and offer one application to the robustness of metros	Most metros are indeed scale-free and small-worlds. Smaller networks should focus on creating transfer stations; larger networks should create additional transfers
Sheikh Mohammad Zadeh and Rajabi (2013)	Propose a new specialized centrality measure to quantify the importance of each street in an urban transportation network.	Traffic flows more efficiently in urban networks with "small-world" configurations, where a certain number of shortcut links and locally clustered streets are allowed

Summary:

There are studies exploring the small-world properties of specific real-world networks, such as complementary international airline alliances networks, word-of-mouth social network, metro networks, and street networks. However, few studies evaluate sustainability and connectivity efficiency in multimodal network with small-world network theory. In addition, these small-world related studies have rarely investigated the green connectivity efficiency of multimodal networks in the urban area.

2.4 Summary

Past studies have explored how to alleviate transportation impacts on the environment, developed measurements of transportation sustainability, and proposed policies for sustainable travel. However, the performance of transportation in terms of basic functions, mobility and accessibility, which is prominent for travelers, has rarely been discussed. The literature related to multimodal networks focused on the shortest path algorithm, the structure and complexity of multimodal trips, and effectiveness of park-and-ride service to transfer commuters from private cars to metro at stations. Few studies have examined the sustainability of different paths in urban multimodal networks. There are studies exploring the small-world properties of specific real-world networks, such as complementary international airline alliances networks, word-of-mouth social network, metro networks, and street networks. However, few studies evaluated sustainability and connectivity efficiency in multimodal network with small-world network theory.

This dissertation will focus on crucial issues that have not been addressed in the prior literature. Strategies for green transportation in multimodal networks are proposed while preserving the transportation basic function, which is prominent but seldom taken into consideration in past studies. Moreover, a green index is developed to assess the sustainability of a path in a multimodal network. Whether it is a single mode path or multiple-modes path, it can be evaluated. Furthermore, small-world theory is applied to investigate green transportation connectivity of nodes located at different regions and the overall interaction of the multimodal network.

Chapter 3

Strategies for Green Transportation While Preserving Mobility

This chapter attempts to provide green transportation strategies while giving the consideration of mobility in multimodal networks. Particularly, the study develops a green index to evaluate the sustainability of different paths in urban transportation networks of an origin-destination pair. Mobility and accessibility are also defined to assess different OD pairs. Green transportation strategies for different trip lengths are proposed to improve the crucial paths of OD pairs in the multimodal network. Monte Carlo simulation is applied to examine the proposed strategies.

3.1 Introduction to the problem

The performance of transportation in terms of basic functions, mobility and accessibility, has rarely been discussed in the transportation emission-related literature. However, it is crucial to lessen the environmental impact while considering transportation basic functions. This study focused on promoting green transportation while preserving mobility and accessibility. Trips can be accomplished not only by a single mode but by multiple modes in urban transportation networks. Multiple modes refer to the different modes an individual may use in travel from a trip origin to a trip destination. Different transport modes have their respective influences on the environment. Fig. 3.1 is a diagram of different mode networks of an OD pair and the connections among them. The detail definition of nodes and arcs would be explained in section 3.2.1. There are many possible paths that travelers may take from the origin to the destination. For instance, path 0-3-2-5-6-7-8 means travelers first drive cars to the MRT stations, then take MRT, and finally ride the bus. Before providing strategies

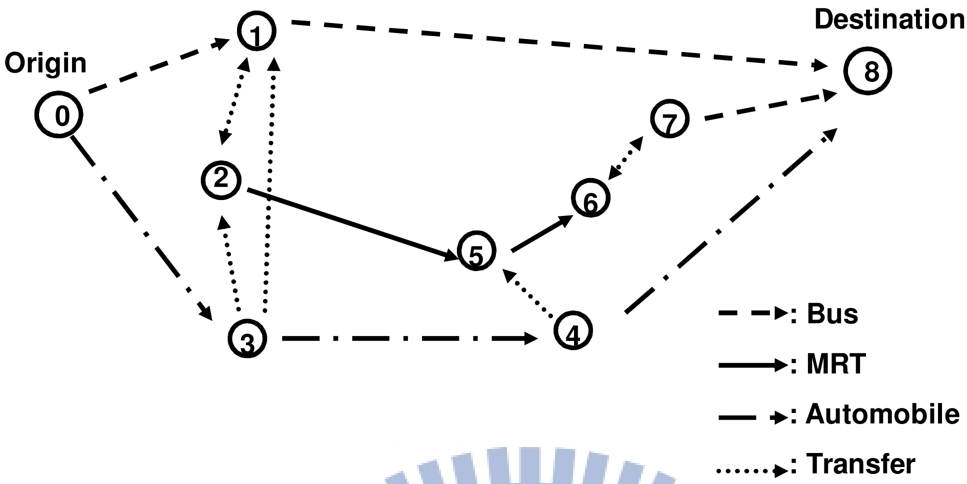


Figure 3.1 Multimodal networks

for the studied city to shift smoothly to green transportation, the first thing is to identify the prominent path in the multimodal networks and its sustainability can be assessed.

This study develops a green index associated with the transportation mode to investigate the sustainability of crucial viable paths of an origin-destination (OD) pair, which is derived by the algorithm proposed in Lozano and Storchi (2001). Then, the travel time of the current most sustainable path is analyzed and effective methods are provided to increase its mobility and accessibility. Kim and Ulfarsson (2008) suggested short trips were mainly made by automobiles and rarely by bus and bike. It is suggested that trip length is an important travel attribute for environmental sustainability. Finally, this study uses Monte Carlo simulation to sample thousands of OD pairs and analyzes the travel time of the single mode and multiple modes of each pair. Mobility difference between these two transport patterns at various travel distances is examined. Then, we provide strategies for green transportation in Taipei City for different trip lengths.

3.2 Model formulation

In this section, a summary of the multimodal shortest viable path algorithm in Lozano and Storchi (2001) is provided and the meaning of mobility and accessibility in this study is defined and explained. This study also develops a green index for each mode and assesses the environmental impact of a multimodal viable path. Moreover, the travel cost of single and multiple transportation modes are evaluated. Finally, the study explains how to apply Monte Carlo simulation to examine thousands of OD pairs with the developed index.

3.2.1 Algorithm of multimodal shortest viable path

Lozano and Storchi (2001) proposed a modified Chronological Algorithm (Pallottino and Scutellá, 1997) to solve the multimodal shortest viable path problem (MSVPP) with label-correcting techniques. Their approach is adopted to find the MSVPP solution for home-based work trips, which is especially useful for rush hours (Lozano and Storchi, 2001). A node is a place where travelers have to determine to either continue with the current mode or change it. An arc connects two nodes with one type of mode. The multimodal network consists of different travel mode networks, and the arc connecting between the nodes in the same travel mode network is the travel arc, weighted by travel time. The connection between nodes in different travel mode networks is the modal transfer arc, weighted by walking/waiting time. The mode associated with the modal transfer arc is the mode transfer, which is in the form of walking or waiting. When travelers determine to change the mode in the middle of the trip, they will undergo the transfer before entering another mode network. Therefore, the set of modes, V, in the multimodal network includes private vehicles (automobiles or motorcycles), mass rapid transit (MRT), buses, and mode transfers. Let $G(N, A)$ be the multimodal network of the urban area, where N and A are the set of nodes and the set of arcs, respectively. The sets of nodes and arcs forming each one of the travel mode networks are respectively denoted by N_v and A_v, where v ($v \in V$) stands for a mode. If v indicates mode transfers, N_v is empty and A_v includes all transfer arcs. In the multimodal network, each arc is associated with only one mode, as is each node except the origin/destination nodes.

Travelers may use different modes from an origin to a destination. The multimodal viable path is defined as the path with reasonable sequences of used modes. There are different layers of mode networks in the metropolitan area, including private vehicle networks, mass rapid transit (MRT) networks, and bus networks. They are connected by modal transfer arcs. Travelers may travel with more than one transportation mode without undertaking too many modal transfers, usually less than three (Guihaire and Hao, 2008). However, the sequence of multiple modes that travelers use has some constraints in the real world. For example, if travelers making a home-to-work trip use bus/MRT first, they cannot choose private vehicles afterwards because private vehicles will have been left at home. Another example is if travelers use the private mode at the origin and change from the private mode to another mode in the middle of the trip, it can't be used again afterwards. In addition, different MRT lines are connected and the transfer among lines is made easier for travelers. Thus, if travelers take the MRT, they will ride it as long as possible in their path. It is illogical to have the following sequence of mode choices for travelers, MRT − another mode − MRT in multimodal networks. In other words, if travelers use the MRT in a multimodal viable path, it will only appear once in the sequence of used modes. Therefore, the restriction of private mode and MRT usage should be addressed.

Lozano and Storchi (2001) developed an attribute, state, to indicate the specific concatenation of the modes on each viable path and a state transition mechanism to assure that no illogical paths occurred. According to Lozano and Storchi (2001), this study finds multimodal viable paths in this paper, which are listed as follows: origin − bus − MRT − destination, origin − private mode − MRT − destination, origin − private mode − bus − destination. The generalized costs of a viable path are calculated based on the arcs used in the path, which is the summation of the cost associated with those arcs.

According to Lozano and Storchi (2001), the node-state pair $[i, s]$ represents the path from the origin to node *i* with state *s*, and five labels are associated with each pair, including the current shortest path cost (C_i^s), the number of transfers (w_i^s), the predecessor node to node *i* (N_i^s), the state of the current shortest viable path up to node N_i^s (S_i^s) and the cost of the last shortest viable path with less than w_i^s transfers (L_i^s). The algorithm first determines the shortest viable path without modal transfers. Then, the mechanism of state transitions for multimodal viable paths is applied, and only the path whose cost is improved by one more transfer is considered by the algorithm. The iteration stops when the number of transfers is more than the maximum number that travelers are disposed to execute. Let *Qnow* and *Qnext* be the sets used by the algorithm to contain the labeled node-state pairs that indicate a viable path from the origin to node *i* with *h* and *h*+1 model transfers, respectively. The procedure of the algorithm based on the pseudo code in Lozano and Storchi (2001) is shown as follows.

Step 1: While *Qnow* is not empty, take one node-state pair $[i, s]$ out of *Qnow* and delete it from *Qnow*.

Step 2: Examine C_i^s of node-state pair $[i, s]$. If C_i^s is smaller than L_i^s, renew L_i^s with the value of C_i^s. For each arc from node *i* to its forward node *j*, apply the state transition mechanism based on the current state *s* and the mode associated with the arc (*i, j*) to obtain the state, s_y, which is the state of the path from the origin to node *j* via its predecessor node *i.*

Step 3: Calculate the cost from the origin to node *j* , which is the current shortest path cost from the origin to node *i* plus the cost of arc (*i, j*), denoted by $C_i^s + c_{ij}$. If

$C_i^s + c_{ij}$ is smaller than the current cost of the shortest path from the origin to node *j* with state s_y, go to Step 4.

Step 4: Compare $C_i^s + c_{ij}$ with $C_j^{s_f}$. $C_j^{s_f}$ is the current lowest cost of the shortest path from the origin to node *j* and s_f is its associated state. If $C_i^s + c_{ij}$ is smaller than $C_j^{s_f}$, renew the following labels of the node-state pair $[j, s_y]$, $C_j^{s_y}$, $w_j^{s_y}$, $N_j^{s_y}$, $S_j^{s_y}$. If arc (*i, j*) is a travel arc and $[j, s_y]$ is not in *Qnow*, let *Qnow* include $[j, s_y]$. If arc (*i, j*) is a transfer arc and $[j, s_y]$. is not in *Qnext*, let *Qnext* include $[j, s_y]$.

Step 5: Go to Step 1 until *Qnow* is empty. Renew *Qnow*, which is moving all the node-state pairs in *Qnext* to *Qnow*, and empty *Qnext*. The number of transfer is added by one for the next iteration.

Step 6: The iteration stops either the number of transfers is more than the predefined maximum number or *Qnow* is empty after renewing.

For the detail procedure of the algorithm, please refer to Lozano and Storchi (2001).

This study applies this algorithm to attain not only the path with the shortest travel time but also the path with the least emission of an OD pair in the multimodal networks. In the case of attaining the most sustainable (i.e. the least emission) path, this study redefines the cost of each arc from the environmental perspective. Instead of time, travel and transfer arcs are weighted by emission which reflects the impact caused by transport. Since each arc is associated with one mode, the emission of the arc is related to its mode characteristics and travel distance. The detailed calculation of the arc emission would be introduced right after the illustration of green level this study develops.

3.2.2 Mobility and green level

This study uses travel time as the key measure of mobility and accessibility because commuters usually choose their modes and routes based on the least travel time, and it is a significant measure in mobility and accessibility formulations (Levinson, 2003). The travel time of an OD pair varies with the transport mode used by the commuter. The mobility of an OD pair r with mode v, M_r^v, is defined as follows:

$$M_r^v = t_r^a / t_r^v,\ r \in R \tag{3.1}$$

where t_r^a is the automobile travel time of OD pair r, R is the set of origin-destination pairs within Taipei City, and t_r^v is mode v travel time of the same OD pair. Mode v can be either single mode or multiple modes. When v refers to multiple modes, t_r^v also includes walking time and transfer time occurred in the trip of OD pair r. The route of automobiles is more direct than that of transit to the destination. Besides, no waiting time for other passenger getting on/off the transit occurs when travelers use automobiles. Therefore, t_r^a in a smooth traffic flow is set to be the benchmark because it usually can be regarded as the ideal travel time of an OD pair among all types of transport modes.

Enhancing MRT utilization is a practical approach toward green transportation. However, its accessibility is limited compared with that of private vehicles. It is thus necessary to provide seamless green transportation options for travelers. Improving the accessibility of MRT stations can attract travelers to use this public green mode. In this paper, a new idea to increase the accessibility of MRT stations by using convenience stores as transfer points is provided. Convenience stores connect activity and transportation networks in Taipei. Moreover, this study proposes green feeder alternatives (i.e., electric motorcycle rentals, bicycle rentals, hybrid taxi pool, and feeder transit service with hybrid or electric buses) to further shorten the travel time between the convenience stores and MRT stations, thereby yielding the environmental path with the lowest impact.

This study proposes to use convenience stores as transfer points of green transportation because convenience stores are densely distributed. There is a very high density of convenience stores in Taipei, almost five per square kilometer. For home-based trips, travelers usually can arrive at their nearby convenience stores within a five-minute walk, which indicates good accessibility. Convenience stores are important delivery points in Taipei. In fact, Internet shoppers picking up their goods at the convenience store has become the second-largest logistics mode in Taiwan (EC Consultant, 2014). Taipei City Government plans to allow convenience stores to facilitate green transportation promotion. The Department of Environmental Protection will negotiate with convenience stores to set up charging stations for electric motorcycles (Department of Environmental Protection, 2012).

The proposed alternatives are feasible to fit within the transportation systems in Taipei City. Motorcycles are popular modes in Taipei City, and electric motorcycles are promoted by the government. Travelers who possess driver’s licenses of motorcycles or automobiles can ride electric motorcycles. More than half of the residents in Taipei City hold motorcycle licenses. Therefore, this study considers providing electric motorcycle rentals or bicycle rentals at the convenience store to increase individual's mobility to access MRT stations. There are regular motorcycle parking spaces alongside convenience stores. It is feasible to locate rental electric motorcycles or bicycles there because the location of regular motorcycle parking space is flexible enough to be changed in order to promote green transportation. For instance, Taipei City Parking Management and Development Office cancelled 2600 regular motorcycle parking spaces around the recently opened MRT lines and set up bicycle rental facilities (Taipei City Government, 2014). It only reserved some parking spaces on surrounding roads, lanes, and alleys because travelers are encouraged to use green transportation (Taipei City Government, 2014). Moreover, travelers are familiar with the payment system of existing bicycle rentals at several locations in Taipei City and MRT stations. This study proposes to use the same payment system for electric motorcycle rentals or bicycle rentals at convenience stores.

Convenience stores have been providing taxi calling service since 2009. In hybrid taxing pooling, travelers can get to the nearest MRT station in a short amount of time and share the cost. Even though the workplaces of these travelers are different, it is still a viable strategy because they enter the MRT system efficiently. Regarding the current status related to feeder transit service, there are citizen mini bus routes to complement the current bus networks. However, it is too circuitous for travelers who want to access MRT stations. The feeder transit service at the convenience store can eliminate travelers' concern of the least direct route.

Current MRT stations in Taipei City are connected to bus networks to increase the transit service area. The travelers who live in the area beyond walking distance of MRT stations usually have to take a bus before entering the MRT system. Current multimodal transport is defined as the pattern of origin – bus – MRT – destination. Walking is both an access/egress mode of public transit, and the transfer mode from bus stops to MRT stations. However, walking time to the bus stop, bus waiting time, and bus riding time along a circuitous route to the MRT station are associated with a decrease in travelers' willingness to take the MRT. In addition, some buses frequently pull over to pick up passengers at the bus stop on the way to the MRT station. Therefore, this study suggests that travelers walk to the convenience store closest to their place of origin, and take the proposed green feeder alternatives to the nearest MRT station directly. The green feeder waiting time varies with different alternatives, and it is generally shorter than current bus waiting time. Thus, the access time of the MRT system can be reduced by introducing convenience stores as MRT transfer points and the accessibility of MRT stations is increased.

This study proposes an inter-connectivity ratio to assess the accessibility of the MRT from the origin for an OD pair r. The inter-connectivity ratio for r with multimodal m, which includes MRT, C_r^m, is shown as follows:

$$C_r^m = \frac{t_r^m}{(\alpha+\delta)+t_r^m},\ r \in R \tag{3.2}$$

where α is the access time to MRT stations, and δ is the waiting time of the access mode. t_r^m is the total multimodal travel time of OD pair r. It is assumed that the given MRT system is efficient, which means travelers can arrive at any MRT stations nearest to their destinations efficiently once they enter the MRT system. Therefore, α and δ only relate to the origins, not the OD pair r. In addition, α and δ are in the denominator instead of the numerator in order to have C_r^m present accessibility intuitively and directly. High inter-connectivity ratio means high accessibility, and vice versa. The accessibility comparison among different OD pairs is straightforward. The value of the inter-connectivity ratio is between 0.5 and 1. Travelers are more likely to choose MRT if it is close to 1, which means that there is less access and waiting time involved (i.e. seamless multimodal transportation). On the other hand, when it is close to 0.5, the access time of MRT stations dominates multimodal total travel time. The strategies proposed in this study can decrease the value of α and δ so that the value of C_r^m can be increased. That is, C_r^m can reflect the improvement in MRT accessibility.

In this study, green transportation is defined as a form of transportation where greenhouse gas is discharged no more than 0.053 kilograms per vehicle kilometer when travelers are in-vehicle. The figure is based on Skytrain's emission, relatively low compared to those of automobiles, motorcycles, and diesel buses as shown in Poudenx and Merida (2007). The main transport modes in Taipei urban networks are private vehicles, buses, and MRT. This study develops a green index to access the environmental impacts of different modes based on their emission per kilometer and corresponding average occupancy. In this study, the greenhouse gas refers to the combination of CO_2, CH_4, N_2O and it is represented with eCO_2 according to Poudenx and Merida (2007). A limitation of the study is that it only considers emission per vehicle-kilometer, which constitutes an important part of the environmental impact in the travel process. However, environmental and driving conditions, emission expelled during vehicle waiting, and the emission control system of the vehicle can be incorporated in future studies. Besides, to have an overall emission calculation, future studies should include the emission led by the variation of combustion engine states such as cold starts and hot soaks in the algorithm.

The figures shown in Table 3.1 are based on Poudenx and Merida (2007), Taipei City Department of Transportation, and Institute of Transportation in Taiwan. The emission efficiency demonstrates the amount of emission expelled for a passenger traveling one kilometer. According to the data in Table 1, the emission efficiency of each mode can be derived, which is emission per vehicle-kilometer (vkm) divided by the average vehicle occupancy (number of persons per vehicle), and the values of automobiles, motorcycles and diesel buses are 0.275, 0.112, and 0.0689 kilograms per passenger-kilometer (pkm), respectively. The emission efficiency of MRT is extremely small relative to other modes, so this study regards it as zero when calculating the green level of an OD pair.

The green index is a new method to evaluate the sustainability of a path of an OD pair in multimodal networks. The sustainability of a path is determined by the emission efficiency of modes used in the path and the travel distance in accordance with the mode. The way to calculate emission efficiency of each mode is based on Poudenx and Merida (2007). Latora and Marchiori (2001) used the reciprocal of the shortest distance between two vertices to represent the efficiency in the communication. In this study, this study uses the reciprocal of emission expelled along a path to present green level G_p. The green level of a path, *p*, G_p, is defined as follows:

$$G_p = 1/\left[(\sum_{k \in p} e_k d_k) + 1 \right] \tag{3.3}$$

where e_k and d_k are the emission efficiency and travel distance in kilometers of mode *k* used on path *p*. The unit of “1” in the denominator of Eq. (3.3) is the kilogram per passenger. The “+1” in the denominator is designed to set the maximum value of G_p, 1, when there is zero emission along path p. Otherwise, G_p goes to infinity and fails to compare the sustainability among different paths. $1/\left[(\sum_{k\in p} e_k d_k)+1\right]$ is a decreasing function with non-negative $e_k d_k$, which can efficiently extract the sustainability variation related to the travel mode and distances. In addition, if only one type of mode is used on path *p*, then G_p can be regarded as the green level of the single mode.

The most sustainable path, which is the path with the least emission, is calculated by the multimodal shortest viable path algorithm. However, this study replaces time with emission for the cost of all arcs in the multimodal networks. Each arc is weighted by emission expelled from its associated mode. The emission of the travel arc is the product of its mode emission efficiency and the travel distance accordingly; that is, the travel arc cost is redefined as the amount of emission that a passenger produced when taking the mode. Transfer arcs only involve walking and waiting so emission of those is zero.

Table 3.1 Emission efficiency of automobiles, motorcycles, and diesel buses

Attributes	Automobile	Motorcycle	Diesel bus
Emission per vkm[a] (kg)	0.286	0.112	1.752
Average vehicle occupancy[b] (number of persons per vehicle)	1.04	1	25.43
Emission efficiency (kg/pkm)	0.275	0.112	0.0689

[a] Poudenx and Merida, 2007

[b] Taipei City Department of Transportation, and Institute of Transportation in Taiwan

3.2.3 Travel cost of single and multimodal transport

This study evaluates current travel costs of single mode and multiple modes from a traveler's point of view. The single mode includes regular cars and motorcycles. In addition to conventional vehicles, green vehicles available in Taipei City are also taken into consideration, such as hybrid cars and electric motorcycles. For single mode travel costs, this study considers the travel time and the variable cost associated with the mode. Kim and Ulfarsson (2008) suggested that parking cost could be an important factor in mode choice for short trips, especially in the central business district. Thus, parking costs and the time to find a parking space, often overlooked yet cumbersome for travelers, are also taken into consideration. The travel cost of a single mode, Y_r, of an OD pair r is calculated as follows:

$$\mathrm{Y}_r = \tau b + l + \varepsilon d + \tau'(g + o),\ r \in R \tag{3.4}$$

where τ is the value of a unit in-vehicle travel time, b is the in-vehicle travel time indicating the driving/riding time of the single mode, l is the parking cost at destinations, ε is the unit distance variable cost of the mode (e.g., fuel, vehicle depreciation, and maintenance), d is the actual travel distance, τ' is the value of a unit out-of-vehicle time, g is the average time of finding parking spaces and o is the average walking time from the parking lot to the destination. For multimodal travel costs, Krygsman et al. (2004) indicated that access and egress are the weakest links in a public transport chain. Thus, in addition to in-vehicle time and transit fares, this study also considers the access and egress time of the transit system. The travel cost of multiple modes, Q_r, of an OD pair r is expressed as follows:

$$Q_r = \tau \sum_{u \in p} t_u + \sum_{u \in p} f_u + \tau'(\theta + \pi),\ r \in R \tag{3.5}$$

where t_u is the in-vehicle travel time when mode u is used in multimodal path p, f_u is the transit fare of mode u, θ is the sum of the access and egress walking time of the transit system, and π is the total transfer waiting time accumulated during the trip.

3.2.4 Monte Carlo simulation

This study applies Monte Carlo simulation to efficiently capture the effectiveness of proposed green transportation strategies instead of identifying the specific multimodal networks for each of thousands OD pairs. With this method, this study can investigate thousands of OD pairs in various trip lengths without complicated traffic zone division. Monte Carlo simulation is widely used for methodological investigations whenever the uncertainty is expressed in probability distributions. Multimodal travel time of OD pairs with the same trip length is uncertain because of vital uncertain parameters such as access time to bus stops and transit waiting time. Usually, the uncertain parameters are given in the form of specific probability distributions. (Mavrotas et al., 2010). In this study, the input for an iteration of the simulation includes the Euclidean distance of an OD pair, parameters associated with the original multimodal path, and parameters related to the proposed strategies as explained later. The outputs are mobility and green level of the original multimodal path and of the improved multimodal path respectively. In the simulation, though this study uses Euclidean distance between an OD pair as an input, it is converted to the real travel distance to estimate the travel time of different paths. The proposed strategies of green transportation in this study are for improving the path of current multimodal real travel time rather than with the shortest travel time path. The shortest travel time path between an OD pair usually merely refers to the private mode path. However, improving the multimodal transport path by fully utilizing the existing MRT system is also considered. From the trip length perspective, more feasible and practical strategies of green transportation to fit within urban networks can be provided.

This study first investigated 30 representative OD pairs with various trip lengths, selected from the official trip distribution survey conducted by the Department of Transportation (Chung et al., 2010), to observe the travel time of single mode and multiple modes. The results of the simulation depict the current travel time of single mode and multiple modes of each OD pair. For automobiles, the travel time can be calculated by the total travel distance divided by its average speed in the urban area. The average speed of automobiles is from the real data, which is the result of an equilibration process between supply and demand. The equilibration process of automobile travel time is beyond the scope of the simulation. Besides, the travel time of motorcycles is calculated in the same way as automobiles with the average speed of motorcycles. The total travel distance of trips with automobiles can be estimated by adding approximately 20% to the Euclidean distances (Newell, 1980). In the simulation, this study randomly generates various Euclidean distances to represent different OD pairs in Taipei City, which is similar to randomly selecting set of points in an urban environment. In this condition, Newell (1980) indicated that network distance is about 1.2 times the Euclidean distance. Besides, Ballou et al. (2002) investigated the circuity factor of United States, and the average value is also 1.2. Therefore, .It is proper to estimate the travel distance of automobiles with this factor.

In the simulation of multimodal travel time, the transfer time is considered in terms of walking and waiting. The fundamental components of multimodal travel time include bus stop access time, bus waiting time, bus riding time, MRT transfer time, and MRT riding time. However, this study focuses on the process of accessing MRT stations, and bus waiting time is a prominent parameter in the simulation.

This study simulates the multimodal travel time of an OD pair mainly based on the automobile travel time of the same OD pair. The total multimodal travel time is estimated by the product (λt_r^a) of automobile travel time (t_r^a) and a random multiplier (λ) plus random bus waiting time (φ). The random multiplier (λ) and bus waiting time (φ) are generated from the probability distributions of 30 observed OD pairs respectively. Bus waiting time is a separated parameter because its dramatic variation will increase the range of λ. In this study, this study proposes strategies to reduce the access time to MRT stations. In order to examine the access time to MRT stations, this study separates λt_r^a into two components. One is bus related time ($\beta(\lambda t_r^a)$) and the other is time involved with MRT (z). $\beta(\lambda t_r^a)$ represents the sum of bus stop access time and bus riding time. This study uses a ratio, β, to estimate the percentage of bus stop access time and bus riding time in λt_r^a. Therefore, the travel time of multiple modes, t_r^m, of an OD pair r can be shown as follows:

$$t_r^m = \lambda t_r^a + \varphi = \beta(\lambda t_r^a) + z + \varphi,\ r \in R \tag{3.6}$$

where λ is a random multiplier, t_r^a is automobile travel time of OD pair r, φ is bus waiting time, β is the ratio of bus stop access time and bus riding time to multimodal travel time which excludes bus waiting time, and z is transfer time and riding time related to MRT. This study simulates the fundamental parameters shown in Eq. (3.6), including λ, φ, and β.

Most of the important destinations and landmarks can be reached within walking distance from an MRT station. The proposed strategies focus on the access to MRT stations and the egress time remains unchanged after adopting the strategies. The egress time is a constant in the last term of multimodal travel time of an OD pair and it doesn't affect the amount of time reduced in accessing MRT stations with the proposed strategies. The time saving by the proposed strategy is based on the 30 investigated OD pairs. For each OD pair, this study calculated the current access time to MRT stations and the access time to MRT stations through a transfer point of the nearest convenience store. The difference between the current access time and the access time via the convenience store is the time saving. In the simulation, this study uses the time saving ratio, which is the time saving divided by the original access time to the MRT station, to calculate the time saving by the proposed strategy. It is illogical to have the time saving more than the original access time. Therefore, this study uses the time saving ratio to assure that the time saved by the proposed strategy is not more than the original access time to MRT stations. The travel time of multiple modes accommodating proposed strategies, $t_r^{m'}$, of an OD pair r is expressed as follows:

$$t_r^{m'} = t_r^m - \Delta + x, \quad r \in R \tag{3.7}$$

where t_r^m is original travel time of multiple modes, Δ is the time saved by the proposed strategy, and x is the walking time from home to its nearest convenience store.

As to model validation, this study samples another 30 important OD pairs in Taipei City on Google Map and acquires the corresponding multimodal travel time. In addition, we input the Euclidean distance of those OD pairs and simulate their multimodal travel time. The estimated values by simulations are very close to real data of multimodal travel time, and the mean error is 2.78 minutes. The percentage error is 6.7% of 30 OD pairs for validation. In the case study, this study simulates five thousand OD pairs; thus the percentage error would be much less. There are many variables which affect multimodal travel time. Deak et al. (2008) indicated that given the complexity of the simulation, percent difference within 20% are considered as a good approximation of the real situation. Therefore, the simulation model has been verified to provide a fairly accurate result.

For each replication in the simulation, a set of parameters is randomly generated from their respective distributions as a specific instance to calculate mobility and green level. The simulation is conducted to attain a set of outputs in two different multimodal paths. One is the original path, and the other is the improved one. This study further compares two sets of outputs to shed light on effectiveness of adopting proposed green transportation strategies.

3.3 Case study

In this section, this study proposes feasible green transportation strategies so that the current transportation pattern in Taipei can smoothly shift to a more sustainable pattern. The strategies are tailored for the current transportation system in Taipei City, and the approaches involve both transport networks and mode perspectives. Taipei is the capital of Taiwan and has integrated transportation networks, which include mass rapid transit, exclusive bus lanes, and roadways. The trip length distribution is shown in Table 3.2. More than 90% of trip lengths are less than 10 kilometers in Euclidean distance. The travel distance of trips within Taipei is relatively short when compared to other global cities such as New York. The population density of Taipei City is close to that of New York City but with almost one-fifth of its area.

Table 3.2 Current statistical data for Taipei City

Trip length distribution in Euclidean distance [a] (km)	Percentage (%)	Modal split [b]	Percentage (%)
0-5	53.99	Private mode	42
5-10	40.68	Motorcycle	25.5
10-15	4.55	Automobile	15.7
15-20	0.78	Other [d]	0.7
Residents hold licenses [c]		Public transport	38
Motorcycle	56.76	Non-motorized mode	20
Automobile	69.37		

[a] Estimated based on the OD distribution survey conducted by the Taipei City Government
[b] Ministry of Transportation and Communications (MOTC), 2013a
[c] MOTC, 2011
[d] Private trucks and private buses

The modal split in Taipei City among private modes, public transport, and non-motorized modes is 42%, 38%, and 20%, respectively, as shown in Table 3.2. In the private mode sector, motorcycle use represents 25.5%, whereas automobile use is 15.7%. The motorcycle is a prevailing transport mode because of its high maneuverability and compact characteristics. Table 3.2 also shows the percentage of residents in Taipei City holding motorcycle and automobile licenses. In total, 56.76% of residents hold motorcycle licenses. Some green single modes, including hybrid vehicles and electric motorcycles, are available in Taipei City. Though the electric motorcycle is promoted by the government with subsidies, its usage rate among motorcycle users is only 0.27% (Industrial Development Bureau, 2012). People perceive that the price of electric motorcycles is still too high. Moreover, charging facilities are not as common as gas stations. Therefore, travelers are not willing to use privately own electric motorcycles. Electric cars are excluded because of their unavailability in the Taiwanese automotive market.

The current MRT system stretches out to all the twelve districts in Taipei City, and there are 11 lines in operation with 109 stations (Metro Taipei, 2014). Most buses operated throughout the city are diesel buses, with hybrid buses being approximately 2.75% of the total (Environmental Protection Administration, 2012). In addition, Taipei City Government is currently attempting to promote electric buses (Department of Environmental Protection, 2013). In 2013, there are domestically developed 11 medium-sized electric buses that are being operated in other cities in Taiwan (Department of Transportation, 2013).

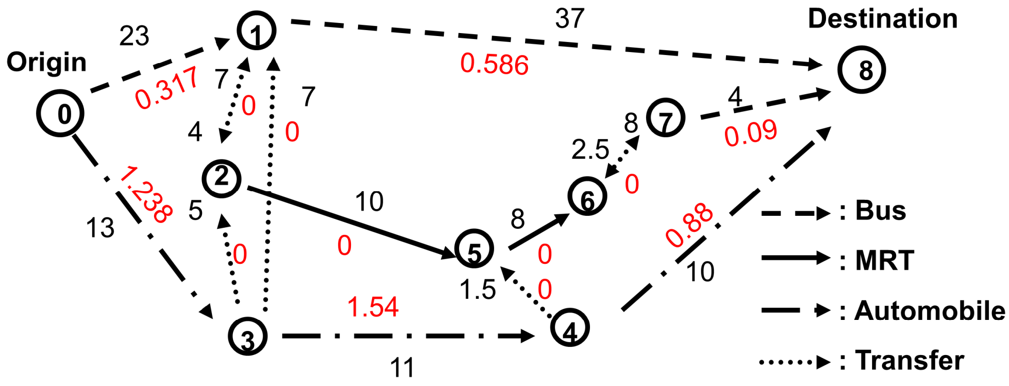
Thirty representative OD pairs of home-based work trips in Taipei were investigated using Google Maps as based on the official trip distribution survey conducted by the Department of Transportation (Chung et al., 2010). Most of the Euclidean distances of these OD pairs in Taipei are within 20 kilometers. In the case study, some prominent OD pairs to analyze their viable paths in multimodal networks are examined with respect to mobility and green level. Secondly, this study simulates thousands of OD pairs to verify the proposed green transportation strategies in terms of mobility and green level.

3.3.1 Prominent OD pairs analysis

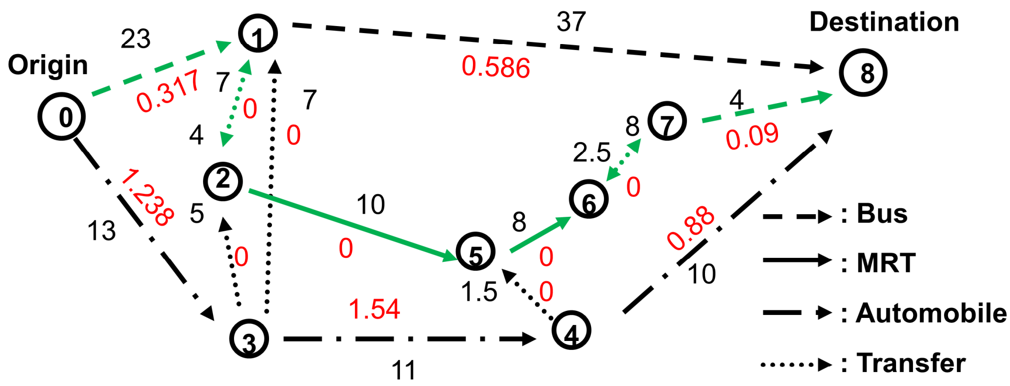
In this section, this study determines the optimal paths of OD pairs with two different objectives: minimizing travel time and maximizing green level. In addition, the mobility, green level, and number of transfers of the corresponding optimal paths are presented, respectively. Furthermore, this study provides several strategies in accordance to the problem in the optimal path of specific OD pairs while maximizing green level and enhancing mobility.

The alternative modes in Taipei City are automobiles, motorcycles, buses, and MRT. However, automobiles and motorcycles are mutually incompatible choices in a multimodal viable path because they are both private modes. Therefore, for each multimodal network, only one type of private vehicle is available.

This study selects a representative and prominent OD pair to study. This pair is from a home in the high-density residential District, Shih-lin, to a Taipei City landmark, Taipei 101, and the travel distance is about 14 kilometers. The multimodal network of this OD pair is shown in Fig. 3.2(a). The arc cost in black is time (minute), and the one in red is emission (kilogram). First, this study illustrates the arc cost in black when minimizing travel time. The values associated with travel arcs are travel time. Waiting time is different for opposite directions on a transfer arc because of the different headways of the successive modes. The transfer time from the automobile to other transit modes includes the walking time from a nearby parking lot to the MRT station or bus stop plus the average waiting time. When maximizing green level in the multimodal networks, the arcs are examined from environmental aspect. The travel distance of each arc is identified to attain the arc cost, i.e. emission, as shown in red. The travel time and distance of the automobile and bus arcs are estimated using Google Maps, and the travel time of the MRT arcs are assumed to be approximately two minutes between adjacent stations. The distance between MRT stations in Taipei is mostly around 1 kilometer, and the assumed travel time between MRT stations is based on the estimation according to Metro Taipei (2013). In addition, this study also analyzes the scenario of travelers choosing motorcycles instead of automobiles. The travel time of motorcycle arcs are derived from UrMap, which provides trip planning for motorcycles. The travel distance between the two private modes may be different because certain express ways are only available for automobiles.



(a) Arc costs weighted by different aspects



(b) The most sustainable path

Figure 3.2 Multimodal networks from a residential home in Shih-lin to Taipei 101

The results are shown in Table 3.3. The table shows that the optimal path of minimizing travel time involves a single private mode. The mobility of the optimal path with motorcycles is 0.7727, which is lower than that with automobiles. However, the motorcycle green level, 0.3715, is better than that of automobiles, 0.2147, which implies that the low occupancy rate of automobiles may lead to this outcome. If travelers replace conventional motorcycles with electric ones, the optimal path of minimizing travel time also simultaneously becomes completely green. In such a way, the mobility, accessibility, and sustainability of the path are simultaneously preserved by merely changing the private vehicle type, which is in accordance with the future trends of transportation: individual transport with high mobility, accessibility, and low environmental impact.

Table 3.3 also shows that the mobility of the optimal path while maximizing the green level with two transfers is quite low, 0.5965. To improve the mobility, this study first identifies the travel arc bottleneck of this path (i.e., path 0-1-2-5-6-7-8) as shown in Fig. 3.2(b). The bottleneck is defined as the travel arc with the longest travel time per unit distance. Then strategies to improve it are provided. Prior studies have explored the issue of reducing the waiting time of transfer arcs (e.g., Hsu, 2010; Shafahi and Khani, 2010). In this paper, this study focuses on tackling the travel arc bottleneck. The bottleneck occurred at the travel arc 0-1, which can be regarded as the access time to the MRT. It takes 5.1 minutes to travel one kilometer. The transport mode is the diesel bus, which serves as many as 12 bus stops along the route. To shorten the access time from homes around the home in Shih-lin to the MRT station, this study shifts the origin node from the home to its nearby convenience store. The accessibility of the convenience store is extremely high such that each traveler can arrive at the nearest convenience store from home within a five-minute walk.

Convenience stores have become parts of people's lives in Taipei City. They provide all types of services from calling a taxi to paying all sorts of bills. In addition, people can pay with the Easycard, which is used for MRT and buses. The idea of turning a convenience store into an origin node is to facilitate travelers being more willing to choose a greener path with the existing MRT facilities. Therefore, this study provides several alternatives to carry travelers from the convenience store to the MRT station with sustainable vehicles: electric motorcycle rentals, bicycle rentals, hybrid taxi pool, and feeder transit service with hybrid or electric buses.

Table 3.3 Results of different objectives on selected OD pairs

OD pair	Objective	Mobility	Transfer	Green level
Shih-lin to Taipei 101	Minimum travel time [a]	1	0	0.2147
	Minimum travel time [b]	0.7727	0	0.3715
	Maximum green level [c]	0.5667	0	0.5255
		0.5965	2	0.7107
Da-an to Chung-shan	Minimum travel time [a]	1	0	0.4824
	Minimum travel time [b]	1.0327	0	0.6863
	Maximum green level [c]	0.4615	0	0.7686
		0.6486	1	0.9141

[a] Travelers use automobiles as private modes
[b] Travelers use motorcycles as private modes
[c] In the objective of maximizing green level, the result is the same for different private vehicles

For electric motorcycle rentals or bicycle rentals, travelers have no waiting time as they can hire one by placing the Easycard near the sensor area at the convenience store and return the mode following use to an MRT station. Electric motorcycles can be charged either at convenience stores or MRT stations. Most travelers in Taipei have at least one Easycard, as its volume of circulation in 2013 is approximately 2955081 (Taipei City Department of Transportation, 2013). There are a large number of idle taxis in Taipei City because of MRT. This study suggests that every four travelers can call a hybrid taxi at the convenience store so that its capacity is fully utilized. The maximum seating capacity of a taxi is four. Four travelers who want to take a hybrid taxi at the convenience store to its nearest MRT station can share the cost; otherwise using a hybrid taxi as a green feeder mode is not as competitive as other alternatives. This study uses the lower bound cost of hybrid taxi pool so that it is compatible with others. Even though the workplaces of these four travelers are different, they can quickly arrive at their distinct destinations once they efficiently enter the MRT system using the same origin station. The waiting time is approximately 4 minutes based on the on-call taxi services currently provided by the convenience stores. The waiting time of the feeder bus service is determined by the feeder bus frequency, which depends on demand density at the convenience store. The operation costs per passenger-kilometer of these alternatives are estimated using data from the Institute of Transportation in Taiwan with adjustment reflecting different fuel efficiencies of hybrid or electric vehicles. The depreciation rates of different vehicles in the alternatives are also taken into consideration. The mobility and green level of the path improved by the alternatives are shown in Table 3.4.

The electric motorcycle rental has the highest mobility of 0.7234 but relatively low cost of 4.24 New Taiwan Dollar (NTD) per passenger-kilometer. The mobility of the path improved by bicycles is quite low as the distance from the convenience store to the MRT station is rather long, 4.56 kilometers. For the feeder transit service, the cost of electric buses is slightly lower than that of hybrid buses. The maintenance and fuel costs of electric buses are one-tenth of diesel buses. In addition, the green level of electric buses is much higher. In regards to the hybrid taxi pool, the green level of the path is slightly lower than that by feeder transit of hybrid buses. However, its operating cost is lower by 2.88 NTD per passenger-kilometer.

Table 3.4 Path comparisons with different alternatives

OD pair	Evaluation item	Do nothing (Diesel bus)	Hybrid taxi pool	Feeder transit bus		Electric motor-cycle	Bi-cycle
				Hybrid	Electric		
Shih-lin to Taipei 101	Mobility	0.5965	0.6667	0.7083	0.7083	0.7234	0.6538
	Green level	0.7107	0.7643	0.7690	0.9178	0.9178	0.9178
	Cost(NTD/pkm)	0	5.31	8.19	8.06	4.24	3.83
Da-an to Chung-shan	Mobility	0.6486	0.6486	0.75	0.75	0.8276	0.7362
	Green level	0.9141	0.9329	0.9352	1	1	1
	Cost(NTD/pkm)	0	1.75	2.69	2.65	1.44	1.30

Another OD pair this study scrutinizes is from an apartment in Da-an District, where most residents live, to the Taiwan Life Financial Building in Chung-shan District. The analyzed results are shown in Table 3.3. The total travel distance is approximately 4 kilometers. Given the objective of minimizing travel time, the green level of the optimal path with motorcycle is still better than that with an automobile. In addition, the motorcycle mobility is even slightly better, which is possible in a short travel distance as travelers can ride a motorcycle down the lanes and alleys, which are too narrow to drive automobiles. The path with one transfer has the maximum green level. Its mobility of 0.6486 is relatively low compared with that of the optimal path in minimizing travel time. The path consists of three arcs: the diesel bus arc, transfer arc, and MRT arc. A bottleneck occurs in the first one, taking 5.8 minutes per kilometer, which also can be regarded as the access time to the MRT. Table 3.4 shows the results of the paths with different alternatives. The path is totally green with three feeder alternatives: electric feeder buses, electric motorcycle rental, and bicycle rental. Most of the alternatives also improve the mobility except the hybrid taxi pool. The mobility of the path improved by the hybrid taxi pool is exactly the same as that of the original path, 0.6486. The values are the same because the waiting time involving calling a taxi is too long to shorten the transport time from the convenience store to the MRT station.

This study further evaluates the travel cost of single and multimodal transport for each OD pair from a traveler's perspective. Several types of single modes are included: regular cars, motorcycles, hybrid cars, and electric motorcycles. The travel cost comparison of different transport modes is shown in Fig. 3.3. The travel cost of hybrid cars is higher than that of regular ones because of their high depreciation cost.

It is suggested that the fuel cost saving of hybrid cars cannot fully compensate for their current market price in Taipei. Interestingly, this study finds that at the same OD Euclidean distance, the travel cost for a regular car without parking costs is lower than that of multimodal transport. We may infer that travelers choosing regular cars hardly consider parking costs when selecting transport modes. Furthermore, regular motorcycles are preferable to travelers because of low costs and agility. These results also demonstrate the reason why 30% of commuters in Taipei ride a motorcycle to work (Ministry of Transportation and Communications, 2010).

Fig. 3.3 shows that the electric motorcycle has the lowest cost among all transport modes. Its cost is lower than that of a regular motorcycle mainly because the Taipei City Government provides exclusive parking spaces for electric motorcycles to promote their usage. Green single mode usage and fully utilized multimodal networks can both be strategies for green transportation. For multimodal transport, it is prominent to enhance the accessibility to MRT stations for commuters, which was suggested by our previous analysis.

This study further applies the cost effectiveness analysis to evaluate proposed alternatives for the two OD pairs discussed previously. The cost effectiveness is measured in terms of the cost of increasing 1% of the mobility/green level on the path by the proposed alternatives as compared to the case of do-nothing shown in Table 3.4. Table 3.5 shows the cost effectiveness of different alternatives in mobility and green level. The alternatives are listed based on the cost effectiveness of mobility improvement from the lowest to the highest.

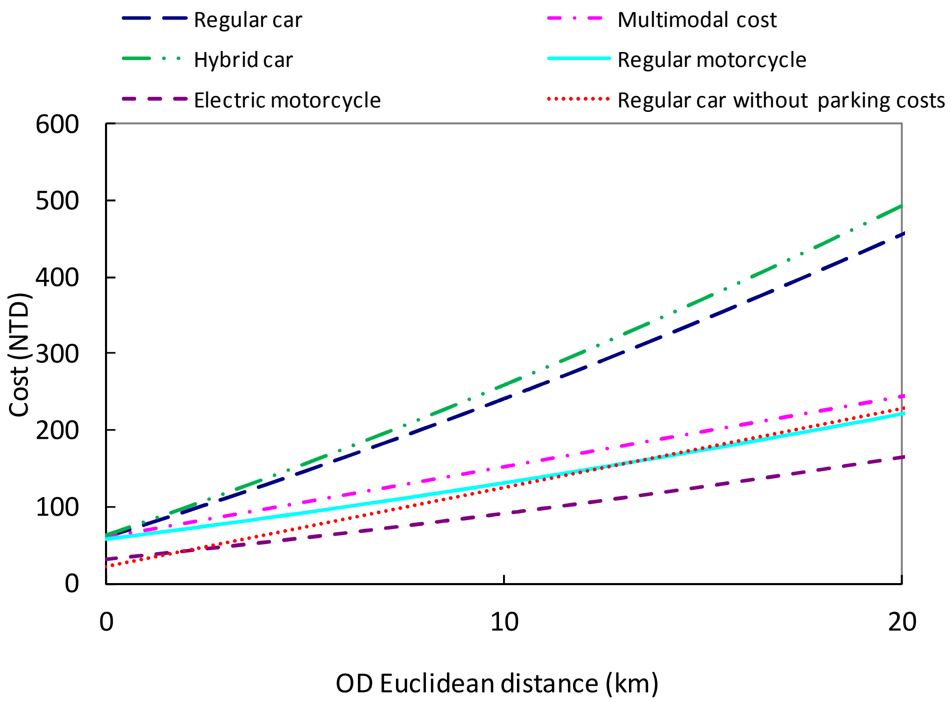


Figure 3.3 Travel cost comparison of different transport modes

Table 3.5 Alternatives evaluation with cost effectiveness

Alternatives	Cost effectiveness (NTD/percentage)		Cost (NTD/pkm)	OD pairs
	Mobility	Green level		
Electric motorcycle	19.93	14.55	4.24	Shih-lin to Taipei 101
Bicycle	39.87	13.14	3.83	
Electric feeder bus	43.00	27.66	8.06	
Hybrid feeder bus	43.70	99.84	8.19	
Hybrid taxi pool	45.12	70.41	5.31	
Electric motorcycle	5.22	15.32	1.44	Da-an to Chung-shan
Bicycle	9.64	13.86	1.30	
Electric feeder bus	16.95	28.20	2.65	
Hybrid feeder bus	17.21	116.54	2.69	
Hybrid taxi pool	n/a	85.09	1.75	

For the OD pair, Shih-lin to Taipei 101, the cost of improving 1% of mobility is varied from 19.93 NTD to 45.12 NTD with different alternatives as shown in Table 3.5. The electric motorcycle costing 19.93 NTD significantly outperforms the other alternatives. In addition, it costs 14.55 NTD to improve 1% of green level, which is slightly higher than that of the bicycle, 13.14 NTD. To consider simultaneously the cost of improving mobility and green level, the electric motorcycle is the most favorable among all alternatives. The electric feeder bus and the hybrid feeder bus have close cost effectiveness of mobility improvement, but have distinct cost effectiveness of green level improvement. The electric feeder bus is much better than the hybrid feeder bus. The hybrid taxi pool ranks last as it has the highest cost of improving 1% of mobility.

For the other OD pair, Da-an to Chung-shan as shown in Table 3.5, the cost effectiveness in mobility of all alternatives except the hybrid taxi pool is better than that of Shih-lin to Taipei 101. It is suggested that the trip length may have an influence on the cost of mobility improvement. The hybrid taxi pool is not applicable for the cost effectiveness in mobility because its mobility is the same as the case of do nothing as shown in Table 3.4. The cost of improving 1% of mobility is still the lowest with the electric motorcycle, which is 5.22 NTD as shown in Table 3.5. Its cost of 1% green level improvement is 15.32 NTD, the second best. Though the bicycle costs 13.86 NTD to improve 1% of green level, it costs 9.64 NTD, almost twice as much as the cost with the electric motorcycle, in mobility improvement. Therefore, the electric motorcycle is still the best alternative considering the cost effectiveness in mobility and green level simultaneously. In short, the electric motorcycle is the most suitable mode to access MRT stations. Travelers are willing to take the electric motorcycle since motorcycles are the prevailing transport modes in Taipei City.

Next, this study simulates thousands of OD pairs in Taipei City to verify the proposed green transportation strategy for current commuting trips by mobility and green level.

3.3.2 Green transportation strategies for different trip lengths

This study uses Monte Carlo simulation to examine the mobility differences between automobiles and multimodal transport with increasing trip lengths (Fig. 3.4). The trip length in Euclidean distance started at 0.4 kilometers because it is the maximum acceptable walking distance in general (Atash, 1994). The difference between automobiles and multimodal transport in short trips is so large that commuters hardly consider multimodal transport until lengths of 2.5 kilometers. Therefore, increasing multimodal transport utilization for green transportation for trips less than 2.5 kilometers is infeasible. In addition, the mobility difference decreasing rate became insignificant after 12.5 kilometers. Therefore, this study categorizes the Euclidean distance of OD pairs into three ranges: short (0.4 km-2.5 km), medium (2.5 km-12.5 km), and long distance (12.5 km-20 km). The trip lengths of important OD pairs in Taipei mostly pertain to short and medium distances. The variation of MRT accessibility at origins and different detour ratios of trips lead to the fluctuation of multimodal mobility in the same trip length.

For short trips, commuters are especially reluctant to use multimodal transport because of its extremely low mobility compared with single mode transport. To promote green vehicles such as hybrid/electric ones in this sector is more viable for green transportation. Many residential condominiums and office buildings have good access to their nearby convenience stores. This study proposed that convenience stores provide electric motorcycle rentals. Commuters can rent an electric motorcycle with Easycards at the convenience store near their homes, ride it directly toward their work place and return it to a convenience store near the destination. Electric motorcycles are charged at the convenience stores. It is feasible for convenience stores in Taipei to provide electric motorcycle rentals. The electric motorcycle parking space is available, and the payment system of Easycards is familiar to travelers. Basically, it is a self-service electric motorcycle rental at the convenience store. Kondo et al. (2013) examined the mobility improved by rental bicycles and rental electric motorcycles in the central area of Tokushima City. The results showed that the strategy has an effect on expansion of the movable field of people and the increase in the availability of urban facilities, such as convenience stores, post offices, hospitals and so on.

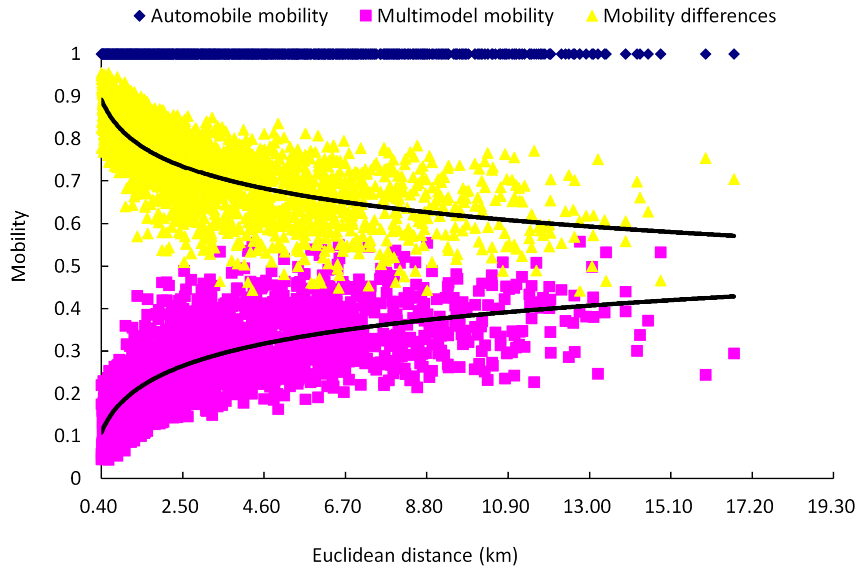


Figure 3.4 Mobility of automobiles and multimodal for different trip lengths

Fig. 3.5 shows the mobility and green level of privately owned regular motorcycles and electric motorcycles rented at the convenience store. Though the mobility of private owned regular motorcycles is higher than that of rental electric motorcycles by 0.6 for a trip length of 0.4 kilometers, the travel time difference between the two is only approximately 4.5 minutes. However, with the same travel time difference, the mobility difference is reduced to 0.27 for a trip length of 2.5 kilometers. These results imply that commuters with short trips are more sensitive to travel time. In addition, the mobility variation of rental electric motorcycles is caused by different walking time from commuter residences to convenience stores. The green level of the regular motorcycles decreased to 0.75 at 2.5 kilometers. In contrast, the rental electric motorcycle green level is 1 for any trip length because of the production of zero emission during the entire trip.

For medium and long trips, this study focuses on improving MRT utilization. Rental electric motorcycles at convenience stores are proposed to be the access mode to MRT stations. With electric motorcycle rental, people will not be uneasy about the scarcity of charging facilities as there is abundant supply at convenience stores. Some convenience stores in Taiwan have launched electric motorcycle charging stations (Lo, 2011). There are some travelers who have the experience of charging their electric motorcycle at the convenience store. They may also shop for need items at the store while their electric motorcycles are charging. The charging station is compact and alongside the store. The convenience store provides charging service in addition to its primary business.

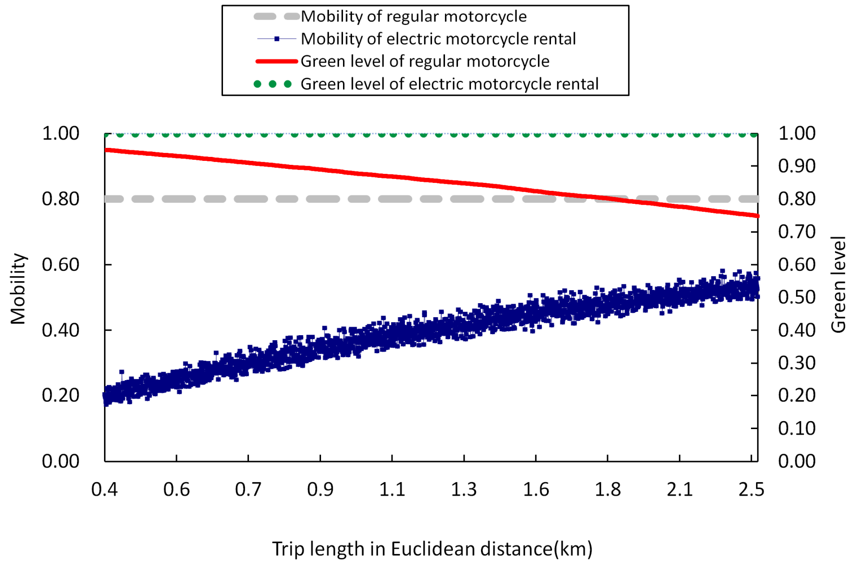
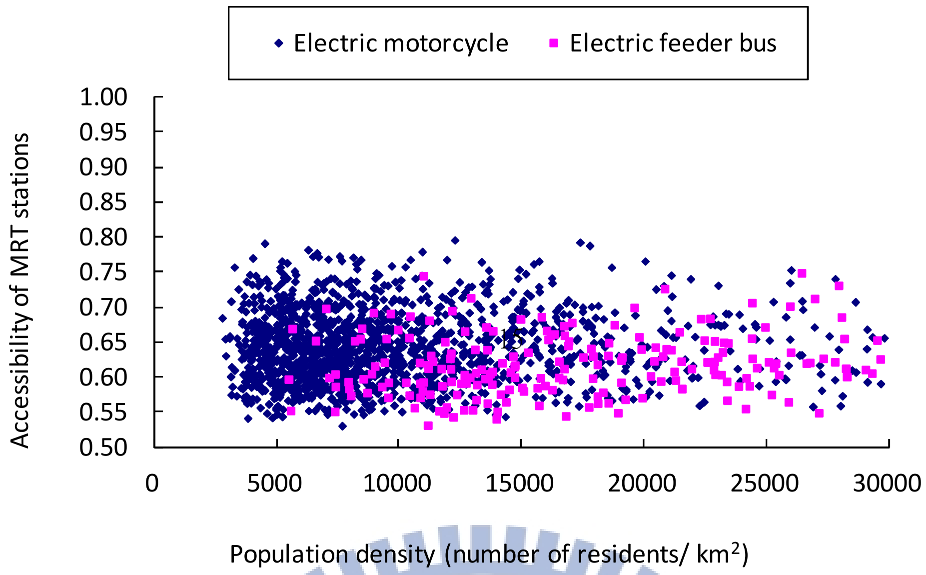
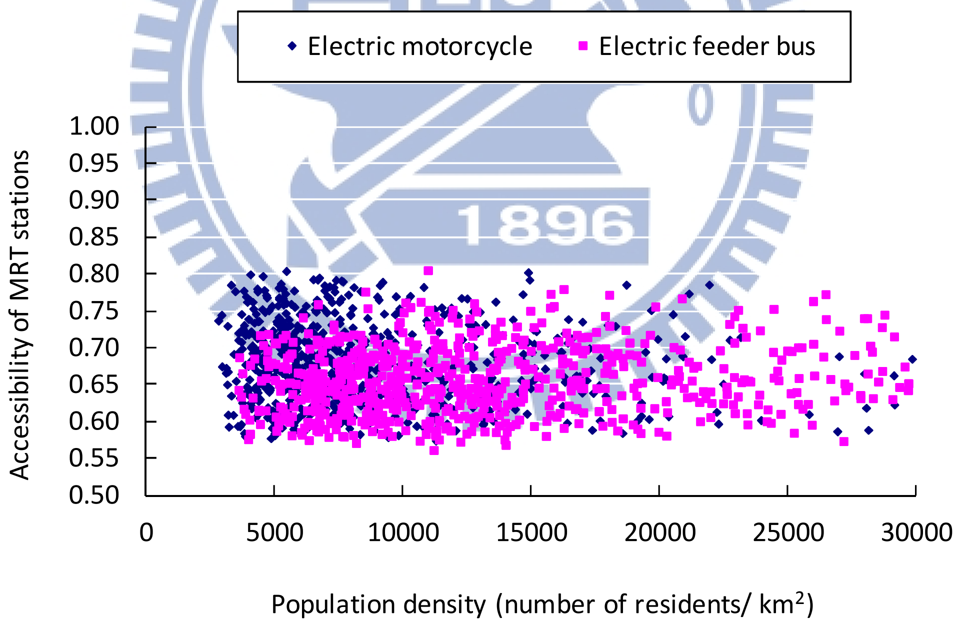


Figure 3.5 Mobility and green level of different single modes for short trips

Another alternative for medium and long trips is that commuters can wait for electric feeder buses at convenience stores depending on the current population density at origins and accessibility to MRT stations. Medium-sized electric buses available in the market can be applied to feeder modes. This study compares the mobility improvement ratio of these two alternatives, and the results are shown in Fig. 3.6. In the medium trip length shown in Fig. 3.6(a), commuters should adopt the electric rental service provided at the convenience store if they live in an area with a population density of approximately 5000 people per square kilometer. In addition, if the current MRT accessibility at origins is relatively high, which is close to 0.8, the electric motorcycle is also a better option. When the population density at origins increases, the electric feeder bus is more competitive in regards to mobility because of waiting time reduction. Fig. 3.6(b) shows that commuters can adopt either alternative for long trip lengths even if population density is low at origins. The distance from the origins to the MRT stations is usually longer than that in medium trip. The electric feeder bus has an advantage on the expressway because motorcycles are not allowed. Therefore, this advantage compensates for the electric feeder bus convenience store waiting time.



(a) Medium trip length

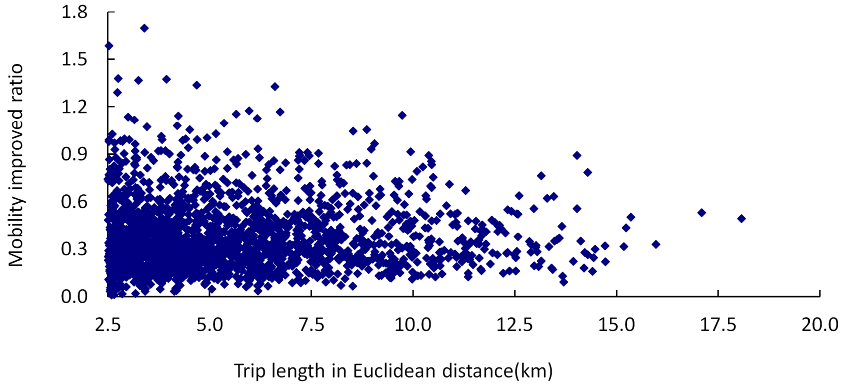


(b) Long trip length

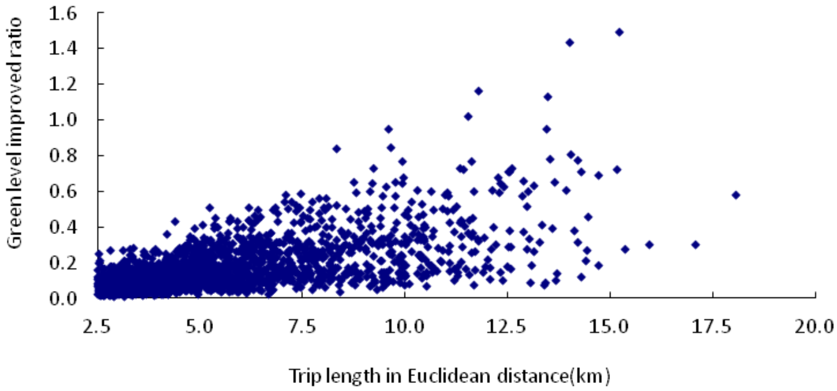
Figure 3.6 Suitable access mode corresponding to population density and MRT accessibility at origins for different trip lengths

This study compares the mobility and green level improved by the proposed strategy with those of original multimodal transport for medium and long trips. The mobility improved ratio is defined as the amount of improved mobility divided by the original multimodal mobility of an OD pair, and the same method is applied to green level improved ratio. Fig. 3.7(a) shows the mobility improved ratio for medium and long trips. The variation of mobility improved ratios is tremendous for the same trip length. This variation is caused by different population density at origins and their accessibility to MRT stations. Moreover, low mobility improved ratios of some OD pairs may indicate that the original multimodal transport pattern is closer to seamless transportation.

As shown in Fig. 3.7(b), there is a tendency for the green level improved ratio to increase with trip lengths. The green level of the proposed strategies is 1 because only electric motorcycles and MRT are involved during the whole trip. Therefore, the green level improved ratio reflects the corresponding green level of the original multimodal transport. When the green level improved ratio is small, the green level of original multimodal transport is high, and vice versa. Based on the simulation results, this study infers that the green level of the original multimodal transport decreases with increasing trip lengths. These consequences may be caused by the longer access time involved with taking diesel buses to MRT stations when trip lengths increase. As shown in Fig. 3.7, the proposed strategy for green transportation for medium and long trip lengths is obviously effective.



(a) Mobility improvement



(b) Green level improvement

Figure 3.7 Mobility and green level improvement for medium and long trips

In summary, this study suggests that commuters rent an electric motorcycle with the Easycard and return it to the convenience store near their work places for short trips. People with automobile licenses can ride light motorcycles (Ministry of Transportation and Communications, 2013b). Thus, at least 69.37% of residents in Taipei City can ride electric motorcycles if only the residents with automobile licenses are considered. More than 50% of trips are less than 5 kilometers in Taipei City and thus can be handled using this green transportation strategy. For medium trips, commuters can likewise rent an electric motorcycle as an MRT station access mode. According to the trip length distribution this study estimated in Table 3.2, the strategy may have an influence on more than 40% of the trips. Regarding long trip lengths, commuters can either take an electric feeder bus or rent an electric motorcycle at a convenience store as access modes to an MRT station.

The mobility of current green transportation in Taipei City is not good enough. By shortening multimodal travel time, more travelers will choose green transportation. Frank et al. (2008) suggested that home based work mode choice tour elasticity of transit in-vehicle time is -0.39, which means reducing transit travel time by 10% is associated with increases in demand for transit by 3.9%. The simulation results of the case study show that the average mobility improved ratio of medium and long trip lengths is 0.38. The average mobility improved ratio can be transformed into the percentage of travel time reduction. According to the mobility definition in this paper, the travel time reduction is 27.5%. Therefore, this study can infer an increase in green transportation usage to approximate 10.53% based on Frank et al. (2008).

3.4 Summary

This study developed a green index to assess the environmental impacts of transportation in multimodal networks. This study made use of high-density convenience stores, which are parts of people's lives in Taipei City, as green feeder mode transfer points. This study connected activity and transportation networks to increase MRT accessibility. Several green feeder modes were evaluated, and the results indicate that electric motorcycles are preferred.

This study simulates thousands of representative OD pairs in Taipei City to observe the mobility difference between automobiles and multimodal transport. The results indicate that automobile mobility for short trips (0.4 km-2.5 km in Euclidean distance) is much higher than that of multimodal transport. These results imply that travelers hardly use multimodal transportation for short trips because of the relatively long travel time. Therefore, green single mode transport is a more viable strategy for sustainable transport. This study suggests commuters rent electric motorcycles with the Easycard at a nearby convenience store at their trip origin and return the vehicles to another store near their work places. More than 50% of trips are less than 5 kilometers in Taipei City and thus can be handled using this green transportation strategy. For medium and long trips (2.5 km-20 km in Euclidean distance), this study focused on increasing MRT accessibility for commuters. Electric motorcycles are effective green feeder modes from convenience stores to MRT stations. The proposed strategy leads to the multimodal pattern, origin – electric motorcycle – MRT – destination, with improvement in both mobility and sustainability compared to the current multimodal transport pattern, origin – bus – MRT – destination. It is because travelers riding electric motorcycles can arrive at the MRT stations more efficiently with no emission discharged along the routes. Commuters living in an area with relatively low population density, 5000 people per square kilometer in Taipei City, should adopt the electric rental service at the convenience store. Besides, if the current MRT accessibility at origins is relatively high, around 0.8 in Taipei City, the electric motorcycle is also a better option. Electric feeder buses can be an alternative of green feeder modes for long trips. In addition, when the population density at origins increases, the electric feeder bus is more competitive.

The simulation results of the case study show that the average mobility improved ratio of medium and long trip lengths is 0.38, which is 27.5% in terms of the travel time reduction. According to home based work mode choice tour elasticity of transit in-vehicle time investigated by Frank et al. (2008), this study can infer an increase in green transportation usage to approximate 10.53%.

Chapter 4
Small-world Network Theory in the Study of Green Transportation Connectivity Efficiency in Multimodal Networks

This chapter attempts to explore green transportation connectivity efficiency in multimodal networks with small-world network theory. The functions of the green extended arcs introduced in this study are identified and are related to the shortcuts in the small-world networks. Green connectivity efficiency model and mobility model are developed both in global and local scale. Then, this study examines the representative OD pairs in multimodal networks of the studied city.

4.1 Introduction to the problem

According to the study results of Chapter 3, the green transportation strategy to enhance MRT accessibility in multimodal networks is to use the convenience store as a transfer point to access its nearby MRT station. This study examines whether green transportation connectivity efficiency will improve in the multimodal networks when adopting the strategy. The green transfer node, which is the convenience store, and the green extended arc, which connects the green transfer node and MRT node, are introduced in this study. Small-world network theory proposed by Watts and Strogatz (1998) is applied to explore the green transportation connectivity efficiency of important OD pairs in the multimodal networks. Shortcuts in a small-world network not only enhance the connectivity of nodes located at different regions but increase the overall interaction of the network. This study supposes that green extended arcs are similar to the shortcuts of a small-world network. In addition, both sustainability and the easiness of travel from origins to destinations in multimodal networks are scrutinized.

This study incorporate green transfer nodes and green extended arcs into the current multimodal networks. The functions of the green extended arcs are identified and are related to the shortcuts in the small-world networks. Green connectivity efficiency model and mobility model are developed. Then, this study examines the representative OD pairs in multimodal networks of the studied city with the models and the corresponding implications are discussed.

4.2 Network component definitions and shortcut application

The multimodal networks consist of various layers of mode networks including private and transit networks. For travelers living at a distance from MRT stations, this study proposes to introduce green transfer nodes, convenience stores, so that they can efficiently access MRT system in Taipei City. Travelers with home-based trip can reach a nearby convenience store within 5-minute walk. Besides, convenience stores are also regarded as green vehicle transfer locations as illustrated in Charter 3. The study defines two types of nodes. One is the origin node and the other is the transport node. Transport nodes are associated with their corresponding modes including private modes, bus, MRT, and green feeder modes such as electric motorcycles. Therefore, green transfer node is a transport node. The destination node is assumed to be on the MRT transport node as most important working places can be reached within the walking distance from MRT. In addition, the study also defines two types of arcs, travel arcs, transfer arcs. Green extended arcs are travel arcs associated with electric motorcycles. Green extended arcs link between green transfer nodes and MRT nodes. Travel arcs and green extended arcs are weighted by travel time, and transfer arcs are weighted by walking time and waiting time. Let **G(N, A)** be the multimodal network of the urban area, where **N** and **A** are the set of nodes and the set of arcs, respectively. $\mathbf{N}^s$ is the set of origin nodes and $\mathbf{N}^t$ is the set of transport nodes. Therefore, $\mathbf{N}^s \cup \mathbf{N}^t = \mathbf{N}$. The set of all origin-destination (OD) pairs is denoted as $\mathbf{J}$, and the total number of OD pairs is denoted as $\|\mathbf{J}\|$. Each arc is associated with one mode, as is each node except $\mathbf{N}^s$. Let $\mathbf{G'}$ be the current multimodal networks; the nodes and arcs are the same as $\mathbf{G}$ excluding green transfer nodes and green extended arcs.

The study focuses on the effect of Chapter 3 proposed strategies on green transportation connectivity in multimodal networks. The activity networks and transportation networks are connected by convenience stores. The key feature of the networks is the green extended arc, between the convenience store and the MRT station. Figure 4.1 shows the green extended arcs in the multimodal networks. The green extended arc makes travelers move from the origin to the MRT station faster and easier instead of taking an indirect bus route to the MRT station. In Figure 4.1, it will take 27 minutes for travelers to MRT station (node number 2) from the origin. If the origin is shifted to the nearby convenience store (O'), the time can be reduced to 13 minutes. Besides, green extended arcs are associated with green feeder modes. The proposed strategy not only improves MRT station accessibility but mitigates the environmental impact. In addition, it shortens the total travel time due to replacing an indirect bus route to access the MRT station.

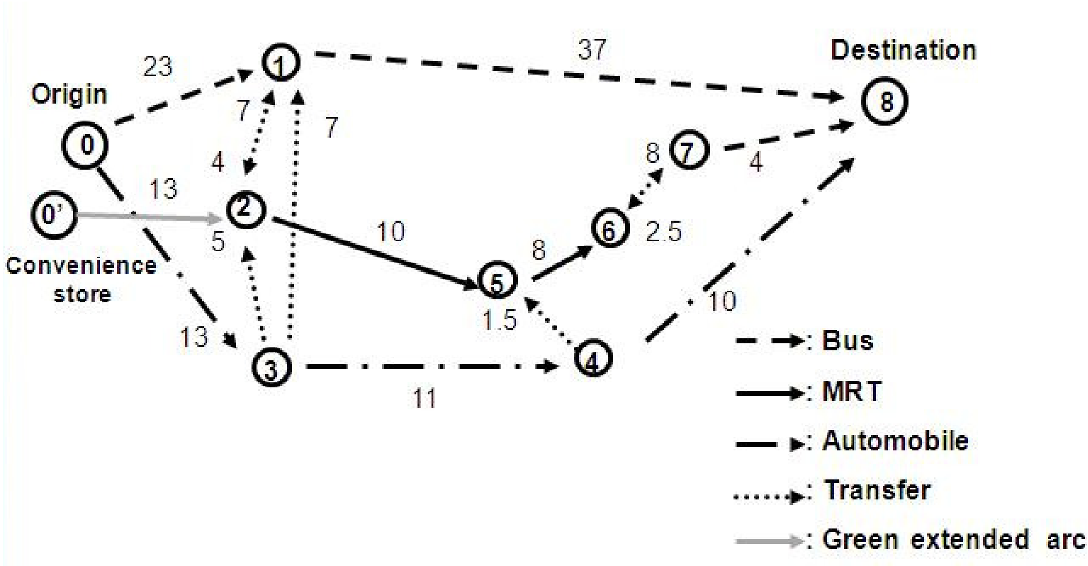


Figure 4.1 MRT shortcuts in multimodal network

This study supposes that green extended arcs are similar to the shortcuts of a small-world network. The functions of shortcuts in a small-world network are to provide opportunities to reduce the steps and the time required for transmitting any kind of communication among nodes, to enhance the connectivity of those nodes located at different regions, and to increase the overall interaction of the network (Hsu and Shih, 2008). This study analyzes the functions of green extended arcs using the concepts of shortcuts of the small-world network. The functions can be described as follows.

(1) Increase green transportation connectivity efficiency. Shortcuts can increase the connectivity efficiency among nodes in a small-world network. By using the convenience stores as green transfer nodes, the green extended arcs connecting to MRT stations can provide this function. With highly accessible convenience stores, travelers can enter the MRT system by green modes more easily.

(2) Reduce steps and time. In a small-world network, shortcuts can reduce the steps and the time required for any kind of communication between nodes. Green extended arcs provide similar advantages because it shortens the access time to MRT stations. Travelers living at a distance from MRT stations don't have to take a bus with several stops before entering the MRT system. As a result, travelers can directly go to MRT stations via the green extended arc and it reduces unnecessary stops of the bus route.

(3) Enhance network interaction. In a small-world network, the interaction of the whole network can be enhanced by the introduction of a few shortcuts. By analogy, travelers can access MRT stations more easily by introducing a few green extended arcs in the multimodal network. As the service coverage of the MRT station increases, it enables more travelers to use sustainable transportation

from their origins to different destinations. The green extended arcs improve the efficiency of green transportation in the multimodal network, and enable the network to enhance its interaction without environmental impacts.

4.3 Green connectivity efficiency and mobility models

This study considers emission along the trip and travel time as determinants, respectively, to formulate models for analyzing the green connectivity efficiency and mobility of important OD pairs in urban multimodal networks. The green connectivity efficiency model and mobility model are formulated in global and local scales based on the efficiency model proposed in the literature. The model is then used to analyze the difference between the green connectivity efficiency of the current situation and the situation of implementing proposed strategies in Chapter 3

4.3.1 Green connectivity efficiency model

In this study, green transportation is defined as a form of transportation where little greenhouse gas is discharged when travelers are in-vehicle. A path's green level of an OD pair in the multimodal networks is closely related to total emission discharged by the modes used along the path, shown as Eq. (4.1)

$$G_p = \frac{1}{(\sum_{k \in p} e_k \times d_k) + 1} \tag{4.1}$$

where e_k and d_k are the emission efficiency and travel distance in kilometers of mode k used on path p, and the green level value is between 0 and 1. In addition, if only one type of mode is used, path p, G_p can be regarded as the green level of the single mode. When MRT is the only transport mode used in the path, then $e_k = 0$, and accordingly $G_p = 1$, which yields the maximum green level between OD pairs. The green connectivity efficiency model further uses the green level to analyze transportation sustainability from a network point of view. Eq. (4.2) shows global green connectivity efficiency model.

$$S_{glob}[\mathbf{G}(\mathbf{J})] = \frac{1}{\|\mathbf{J}\|} \sum_{q \in \mathbf{G}(\mathbf{J})} G_{mq} \tag{4.2}$$

G_{mq} is the green level of the path m which MRT is involved of the OD pair q. $\mathbf{G}(\mathbf{J})$ is the set of all OD pairs $\mathbf{J}$ in the multimodal networks $\mathbf{G}$, and $\|\mathbf{J}\|$ is the total number of those. $S_{glob}[\mathbf{G}(\mathbf{J})]$ is the overall green level between OD pairs.

For the purpose of a consistent analysis, the value of $S_{glob}[\mathbf{G}(\mathbf{J})]$ can be normalized to be in the interval [0, 1] by factor $S_{glob}[\mathbf{G}(\mathbf{J})_{ideal}]$, which is the global green connectivity efficiency of the ideal case. In the ideal case of $\mathbf{G}(\mathbf{J})$, $S_{glob}[\mathbf{G}(\mathbf{J})_{ideal}]$, electric automobile path is adopted for each OD pair, i.e. travelers can move from the origin to the destination in the most sustainable and efficient way. Consequently, $S_{glob}[\mathbf{G}(\mathbf{J})_{ideal}]$ is the maximum value of $S_{glob}[\mathbf{G}(\mathbf{J})]$, and the normalized green connectivity efficiency of $\mathbf{G}(\mathbf{J})$, $S^N_{glob}[\mathbf{G}(\mathbf{J})]$, can be shown as Eq. (4.3):

$$S^N_{glob}[\mathbf{G}(\mathbf{J})] = \frac{S_{glob}[\mathbf{G}(\mathbf{J})]}{S_{glob}[\mathbf{G}(\mathbf{J})_{\mathbf{ideal}}]} \tag{4.3}$$

By normalization in Eq. (4.3), the value of $S^N_{glob}[\mathbf{G}(\mathbf{J})]$ is a nonnegative real number with the maximum value of 1. Eq. (4.3) can easily be used to compare global green connectivity efficiency under various conditions, and can provide information about the difference of network performance between real and ideal cases.

The global green connectivity efficiency of proposed multimodal networks with express access to MRT system will be higher than that of current situation by introducing several green extended arcs from the origin to its nearest convenience store. This is shown as follows. The important OD pairs in current multimodal networks, denoted as set $\mathbf{J}$, when a traveler living at a distance from MRT station and having no private vehicles wants to take MRT, he/she must take the bus before entering to MRT. However, such process usually results in a less convenient experience and more unnecessary stops due to indirect rout to MRT stations. In contrast, by introducing green extended arcs, travelers can efficiently move to MRT stations in a more sustainable way. Besides, other OD pairs will also change their original most sustainable paths in the multimodal networks if the green extended arcs shorten the MRT access time and increase the green level, causing them to shift their original paths to those paths involving green extended arcs; otherwise, they hold their original sustainable paths, and their green level does not change. Let those OD pairs using the green extended arcs be denoted as $\mathbf{R}$, then the difference of global green connectivity efficiency between proposed multimodal networks ($S_{glob}[\mathbf{G}(\mathbf{J})]$) and current multimodal networks ($S_{glob}[\mathbf{G}'(\mathbf{J})]$)can be shown as Eq. (4.4):

$$\begin{aligned} & S_{glob}[\mathbf{G}(\mathbf{J})] - S_{glob}[\mathbf{G}'(\mathbf{J})] \\ & = \frac{1}{\|\mathbf{J}\|} \sum_{q \in \mathbf{R}} (G_{mq} - G'_{mq}) > 0 \end{aligned} \tag{4.4}$$

In Eq. (4.4), the OD pairs whose green level of the path which MRT is involved in proposed multimodal networks is the same as those in current multimodal networks are eliminated, and only those OD pairs belonging to $\mathbf{R}$, which changed their most sustainable paths in the proposed multimodal networks, are left. Furthermore, for each OD pair $q \in \mathbf{R}$, the green level of the path which MRT is involved in proposed multimodal networks, G_{mq}, will be larger than that in the current multimodal networks, G'_{mq}, thereby increasing the global green connectivity efficiency of proposed multimodal networks over that of current multimodal networks.

This study then formulates the local green connectivity efficiency model so as to analyze local features, including the sustainability among neighbor-nodes of destinations. This study defines those destination nodes that are accessible from node i as the neighbor-nodes of node i, and y denotes the OD pair from node i to its neighbor-node. The subgraph of node i, $\mathbf{G}_i$ is composed of node i, its neighbor-nodes, and their corresponding multimodal networks. The OD pair set $\mathbf{J}_i$ denotes all OD pairs from node i to its neighbor-nodes. The local property of $\mathbf{G}_i(\mathbf{J}_i)$ can be characterized by the local green connectivity efficiency model, which is formulated as follows:

$$S_{loc}[\mathbf{G}_i(\mathbf{J}_i)] = \frac{1}{\|\mathbf{J}_i\|} \sum_{y \in \mathbf{G}_i(\mathbf{J}_i)} G_{my} \tag{4.5a}$$

$$S_{loc}[\mathbf{G}(\mathbf{J})] = \frac{1}{\|\mathbf{X}\|} \sum_{i \in \mathbf{X}} S_{loc}[\mathbf{G}_i(\mathbf{J}_i)] \tag{4.5b}$$

In Eq. (4.5a), G_{my} is the green level of the path m which MRT is involved of OD pair y, which is from node i to its neighbor-node; $\|\mathbf{J}_i\|$ is the number of those OD pairs. The local green connectivity efficiency of $\mathbf{G}_i(\mathbf{J}_i)$, $S_{loc}[\mathbf{G}_i(\mathbf{J}_i)]$, is calculated by averaging the green level of the path which MRT is involved of all OD pairs $\mathbf{J}_i$ in $\mathbf{G}_i$. It represents transportation sustainability from node i to all possible destinations. $S_{loc}[\mathbf{G}_i(\mathbf{J}_i)]$ is affected by local structural properties, such as transit availability between node i and its neighbor-node. By averaging $S_{loc}[\mathbf{G}_i(\mathbf{J}_i)]$ over all subgraphs, the local green connectivity efficiency of $\mathbf{G}(\mathbf{J})$, $S_{loc}[\mathbf{G}(\mathbf{J})]$, can be yielded, as shown in Eq. (4.5b). $\mathbf{X}$ is the set of districts of the studied city, and $\|\mathbf{X}\|$ is the number of districts.

The local green connectivity efficiency can be normalized by the factor $S_{loc}[\mathbf{G}_i(\mathbf{J}_i)^{\mathbf{ideal}}]$, which is the maximum value of $S_{loc}[\mathbf{G}_i(\mathbf{J}_i)]$. In the ideal case of $\mathbf{G}_i(\mathbf{J}_i)$, $\mathbf{G}_i(\mathbf{J}_i)^{\mathbf{ideal}}$, electric automobile path is adopted from node i to its all neighbor-nodes. The normalized local green connectivity of $\mathbf{G}(\mathbf{J})$, $S_{loc}^{N}[\mathbf{G}(\mathbf{J})]$, is formulated as Eq. (4.6).

$$S_{loc}^{N}[\mathbf{G}(\mathbf{J})] = \frac{1}{\|\mathbf{X}\|} \sum_{i \in \mathbf{X}} \frac{S_{loc}[\mathbf{G}_i(\mathbf{J}_i)]}{S_{loc}[\mathbf{G}_i(\mathbf{J}_i)^{\mathbf{ideal}}]} \tag{4.6}$$

4.3.2 Mobility model

Mobility is a significant indicator of transportation system performance. Hsu and Shish (2008) proposed mobility model in transportation networks, and the mobility is defined as the reciprocal of shortest travel time between an OD pair. This study applied the same concept to formulate the mobility model in the multimodal networks. A traveler's travel time of an OD pair q is defined as the sum of his/her travel time on each mode used in the path, transfer time occurred during the trip, and access and egress time of the transit if the traveler takes the public transport. The study focuses on the mobility of the path which MRT is involved for each OD pair. Therefore, the travel time of an OD pair is based on the transport modes used in path m. Let t_{mq} represent the travel time between OD pair q with path m. This study formulates the global mobility model shown as follows:

$$M_{glob}[\mathbf{G}(\mathbf{J})] = \frac{1}{\|\mathbf{J}\|} \sum_{q \in \mathbf{G}(\mathbf{J})} \frac{1}{t_{mq}} \tag{4.7}$$

where $1/t_{mq}$ is defined as the mobility between OD pair q with path m. A greater t_{mq} and a consistently smaller $1/t_{mq}$ mean that the mobility between the OD pair with path m is worse, i.e. travelers are less likely to travel between OD pair q with path m. In Eq. (4.7), the global mobility of $\mathbf{G}(\mathbf{J})$, $M_{glob}[\mathbf{G}(\mathbf{J})]$, is the mean of the reciprocal of the travel time of the path which MRT is involved between OD pairs. The global mobility of the proposed multimodal networks will be higher than that of current multimodal networks. The green extended arcs shorten MRT access time for some travelers and reduce the overall travel time of entire trips. Consequently, the mobility of paths involving the green extended arcs of OD pairs increase. The global mobility can be regarded as the travel convenience between any two districts in the studied city.

For the purpose of a consistent analysis, the value of $M_{glob}[\mathbf{G}(\mathbf{J})]$ can be normalized to be in the interval [0, 1] by factor $M_{glob}[\mathbf{G}(\mathbf{J})_{\mathbf{ideal}}]$, which is the global mobility of the ideal case. In the ideal case of $\mathbf{G}(\mathbf{J})$, $\mathbf{G}(\mathbf{J})_{\mathbf{ideal}}$, electric automobile path is adopted for each OD pair, i.e. travelers can move from the origin to the destination in the most efficient and sustainable way. Consequently, $M_{glob}[\mathbf{G}(\mathbf{J})_{\mathbf{ideal}}]$

is the maximum value of $M_{glob}[\mathbf{G}(\mathbf{J})]$, and the normalized global mobility of $\mathbf{G}(\mathbf{J})$, $M^N_{glob}[\mathbf{G}(\mathbf{J})]$, can be shown as Eq. (4.8):

$$M^N_{glob}[\mathbf{G}(\mathbf{J})] = \frac{M_{glob}[\mathbf{G}(\mathbf{J})]}{M_{glob}(\mathbf{G}(\mathbf{J})_{\mathbf{ideal}})} \tag{4.8}$$

By normalization in Eq. (4.8), the value of $M^N_{glob}[\mathbf{G}(\mathbf{J})]$ is a nonnegative real number with the maximum value of 1. Eq. (4.8) can easily be used to compare global mobility under various conditions, and can provide information about the difference of network performance between real and ideal cases.

Then this study formulates local mobility model shown in Eq. (4.9a), $\mathrm{M}_{loc}[\mathbf{G}_i(\mathbf{J}_i)]$, to analyze the mobility from node i to its neighbor-nodes. The subgraph of node, $\mathbf{G}_i$, is composed of node i, its neighbor-nodes, and their corresponding multimodal networks. The OD pair set $\mathbf{J}_i$ denotes all OD pairs from node i to its neighbor-nodes. $\|\mathbf{J}_i\|$ is the number of those OD pairs. t_{my} is the travel time of the path m which MRT is involved of the OD pair y. The local mobility represents the travel convenience from a district to all the other districts. $M_{loc}[\mathbf{G}_i(\mathbf{J}_i)]$, is calculated by averaging the mobility of the path which MRT is involved of all OD pairs $\mathbf{J}_i$ in $\mathbf{G}_i$. $M_{loc}[\mathbf{G}_i(\mathbf{J}_i)]$ is affected by local structural properties, such as transit availability between node i and its neighbor-node. By averaging $M_{loc}[\mathbf{G}_i(\mathbf{J}_i)]$ over all subgraphs, the local mobility of $\mathbf{G}(\mathbf{J})$, $M_{loc}[\mathbf{G}(\mathbf{J})]$, can be yielded, as shown in Eq. (4.9b). $\mathbf{X}$ is the set of districts of the studied city, and $\|\mathbf{X}\|$ is the number of districts.

$$M_{loc}[\mathbf{G}_i(\mathbf{J}_i)] = \frac{1}{\|\mathbf{J}_i\|} \sum_{y \in \mathbf{G}_i(\mathbf{J}_i)} \frac{1}{t_{my}} \tag{4.9a}$$

$$M_{loc}[\mathbf{G}(\mathbf{J})] = \frac{1}{\|\mathbf{X}\|} \sum_{i \in \mathbf{X}} M_{loc}[\mathbf{G}_i(\mathbf{J}_i)] \tag{4.9b}$$

The local mobility can be normalized by the factor $M_{loc}[\mathbf{G}_i(\mathbf{J}_i)^{\mathbf{ideal}}]$, which is the maximum value of $M_{loc}[\mathbf{G}_i(\mathbf{J}_i)]$. In the ideal case of $\mathbf{G}_i(\mathbf{J}_i), \mathbf{G}_i(\mathbf{J}_i)^{\mathbf{ideal}}$, electric automobile path is adopted from node i to its all neighbor-nodes. The normalized local mobility of $\mathbf{G}(\mathbf{J})$, $M^N_{loc}[\mathbf{G}(\mathbf{J})]$, is formulated as Eq.(4.10).

$$M^N_{loc}[\mathbf{G}(\mathbf{J})] = \frac{1}{\|\mathbf{X}\|} \sum_{i \in \mathbf{X}} \frac{M_{loc}[\mathbf{G}_i(\mathbf{J}_i)]}{M_{loc}[\mathbf{G}_i(\mathbf{J}_i^{ideal})]} \tag{4.10}$$

4.4 Case Study

This section presents a case study to demonstrate the application of the proposed models. The green connectivity efficiency and mobility of Taipei City both in global and local scales are examined.

The study investigated thirty representative OD pairs of Taipei City based on Taipei metropolitan OD matrix of home-based work trip (Department of Transportation, 2012). The path that is currently involved with MRT of these OD pairs is examined before and after introducing green transfer nodes and green extended arcs. The destination node is set on the MRT transport node as most important working places can be reached within the walking distance from MRT stations.

Google Maps is applied to assess travel time of automobiles, buses and MRT. Travel time of electric motorcycles is estimated by UrMap, which provides motorcycle routes. The study examined the global green connectivity efficiency and mobility with thirty investigated OD pairs. The local green connectivity efficiency and mobility reflected the sustainability and convenience from each district to all other districts in Taipei City. In addition, the Euclidean distance between studied origins and their closest MRT stations is within one kilometer.

The results of the analysis (Table 4.1) for the proposed networks, incorporating green transfer nodes and green extended arcs, show that green connectivity efficiency and mobility in the proposed networks are better than those in the current networks, thereby confirming the advantage of introducing convenience stores as green transfer nodes. The difference in the normalized global mobility is more than that in the normalized local mobility, and the reason is discussed as follows. The main purposes of introducing convenience stores as green transfer nodes are to make the MRT system more accessible to travelers. Latora and Marchiori (2002) indicated that Boston subway transportation system is a very efficient transportation system on a global scale. Therefore, travelers efficiently enter the MRT systems can significantly improve the global mobility. The global mobility and local mobility are both more than 55%, which shows that the proposed networks are small-world networks. Travelers can travel from any district to any other districts with green transportation in Taipei City in a rather efficient way. For current networks, the normalized global and local green connectivity efficiencies are both more than 90% because the study focuses on how to improve the current path relating to MRT. For proposed networks, the normalized global and local green connectivity efficiencies are both 100%. The reason is that no emission is discharged when travelers use the path of walking –

electric motorcycle – MRT. The result in the sustainability aspect is the same as the ideal case that travelers use electric automobiles for the entire tip.

Table 4.1 Normalized mobility and green connectivity efficiency comparison

	Global mobility	Local mobility	Global green connectivity efficiency	Local green connectivity efficiency
Proposed networks	0.56647	0.57073	1	1
Current networks	0.38714	0.43752	0.93863	0.94860

Next, this study further examined local mobility of each district as shown in Table 4.2. The local mobility demonstrated the efficiency of moving from one district to another. The 12 districts of Taipei City are listed in a descending order of local mobility improvement. It is suggested that Wan-hua district has significant improvement, which is around 33.32%. The government should consider introducing green transfer nodes and green extended arcs first in this district. In the proposed network, travelers in Wan-hua and Xin-yi districts can reach any important destinations more efficiently than those in other districts as their local mobility is more than 66%. Local mobility of Sung-shan district increases from 38.46% to 54.85%. Though the current local mobility of Sung-shan is relatively low among twelve districts in Taipei City, it can be effectively improved by using green transfer nodes to access MRT stations. Eight out of twelve districts increase their local mobility more than 10% in the proposed networks.

For current networks, Xin-yi district has the highest local mobility, more than 55%, which means it is more efficient to access any district in Taipei City with current transit system than other districts. The local mobility of Da-an is also relatively high, which is more than 50%. It is implied that MRT stations in Xin-yi and Da-an districts can carry travelers to any important destinations more efficiently than MRT stations in other districts.

Table 4.2 Local mobility comparison

	Current networks	Proposed networks
Wan-hua	0.44390	0.77714
Sung-shan	0.38465	0.54853
Da-tong	0.40125	0.55728
Bei-tou	0.45876	0.59626
Nan-gang	0.44852	0.57890
Jhon-jheng	0.41938	0.54918
Jhong-shan	0.38684	0.49426
Xin-yi	0.55953	0.66639
Da-an	0.50014	0.59297
Nei-hu	0.33219	0.42293
Wen-shan	0.47202	0.55524
Shih-lin	0.44308	0.50971

4.5 Summary

This study explored green transportation connectivity efficiency in multimodal networks by conceptually applying the shortcuts of small-world networks. The shortcuts refer to the green extended arcs which connect green transfer nodes (convenience stores) to MRT stations. Both green connectivity efficiency model and mobility model in global and local scales are developed. The local and global green connectivity efficiencies and mobility of the transportation network in Taipei City are examined. Furthermore, the local mobility of different districts in the studied city is compared.

The results show that the global mobility and local mobility are both more than 55% in the proposed networks, which are current networks incorporating green transfer nodes and green extended arcs. Travelers can travel from any district to any other districts with green transportation in Taipei City in a rather efficient way. Therefore, the proposed networks are small-world networks. In regards to the local mobility improvement of districts in Taipei City, Wan-hua district outperforms the other districts, which is around 33.32%. Thus, the first trial of making convenience stores as green transfer nodes can be conducted in Wan-hua district. In the proposed network, the local mobility of Wan-hua and Xin-yi districts is more than 66%. Thus, travelers in Wan-hua and Xin-yi districts can reach any important destinations more efficiently than those in other districts. Local mobility of Sung-shan district increases from 38.46% to 54.85%. It is also effectively improved by using green transfer nodes to access MRT stations. Besides, eight out of twelve districts increase their local mobility more than 10% in the proposed networks.

For current networks, Xin-yi district has the highest local mobility, more than

55%, followed by Da-an district, which is also more than 50%. It means it is more efficient to access any district in Taipei City with current transit system from Xin-yi and Da-an districts. That is, MRT stations in Xin-yi and Da-an districts can carry travelers to any important destinations more efficiently than MRT stations in other districts.

Chapter 5

Conclusions

This chapter summarizes the important findings as well as some managerial implications with respect to each part of this dissertation. Furthermore, future research areas that extend from this dissertation are also discussed.

5.1 Research summary

The purpose of this dissertation is to investigate green transportation strategies in multimodal networks and to assess corresponding travel efficiency from a network point of view. The methodology and important findings of each part of this dissertation are summarized as follows.

In the first part of this dissertation, the study provided green transportation strategies while preserving mobility and accessibility, and developed a green index to assess the environmental impacts of transportation in multimodal networks. The green index reveals the concept of promoting green transportation, which is maximizing the usage of transport modes with low emission efficiency, e.g. walks, bicycles, electric motorcycles, and MRT, in a trip. This study simulated thousands of representative OD pairs in Taipei City to observe the mobility difference between automobiles and multimodal transport. The results indicate that automobile mobility for short trips (0.4 km-2.5 km in Euclidean distance) is much higher than that of multimodal transport. These results imply that travelers hardly use multimodal transportation for short trips because of the relatively long travel time. Therefore, green single mode transport is a more viable strategy for sustainable transport. This study suggests commuters rent electric motorcycles with the Easycard at a nearby convenience store at their trip origin and return the vehicles to another store near their work places. More than 50%

of trips are less than 5 kilometers in Taipei City and thus can be handled using this green transportation strategy. For medium and long trips (2.5 km-20 km in Euclidean distance), this study focused on increasing MRT accessibility for commuters. Electric motorcycles are effective green feeder modes from convenience stores to MRT stations. The proposed strategy leads to the multimodal pattern, origin – electric motorcycle – MRT – destination, with improvement in both mobility and sustainability compared to the current multimodal transport pattern, origin – bus – MRT – destination. Commuters living in an area with relatively low population density, 5000 people per square kilometer in Taipei City, should adopt the electric rental service at the convenience store. Besides, if the current MRT accessibility at origins is relatively high, around 0.8 in Taipei City, the electric motorcycle is also a better option. Electric feeder buses can be an alternative of green feeder modes for long trips. In addition, when the population density at origins increases, the electric feeder bus is more competitive. The simulation results of the case study show that the average mobility improved ratio of medium and long trip lengths is 0.38, which is 27.5% in terms of the travel time reduction. According to home based work mode choice tour elasticity of transit in-vehicle time investigated by Frank et al. (2008), this study can infer an increase in green transportation usage to approximate 10.53%.

In the second part of this dissertation**,** the study explored green transportation connectivity efficiency in multimodal networks by conceptually applying the shortcuts of small-world networks. The shortcuts refer to the green extended arcs which connect green transfer nodes (convenience stores) to MRT stations. Both green connectivity efficiency model and mobility model in global and local scales are developed. The results show that the global mobility and local mobility are both more than 55% in the proposed networks, which are current networks incorporating convenience stores. Travelers can travel from any district to any other districts with green transportation in Taipei City in a rather efficient way. Therefore, the proposed networks are small-world networks. In regards to the local mobility improvement of districts in Taipei City, Wan-hua district outperforms the other districts, which is around 33.32%. Thus, the first trial of making convenience stores as green transfer nodes can be conducted in Wan-hua district. In the proposed network, the local mobility of Wan-hua and Xin-yi districts is more than 66%. Thus, travelers in Wan-hua and Xin-yi districts can reach any important destinations more efficiently than those in other districts. Local mobility of Sung-shan district increases from 38.46% to 54.85%. It is also effectively improved by using green transfer nodes to access MRT stations. Besides, eight out of twelve districts increase their local mobility more than 10% in the proposed networks.

The study results comply with parts of the future transportation. The future transportation lies in Automated, Connected, Electric, Shared (ACES) vehicles (Pyle, 2015). The electric motorcycle rentals fit into the concept of Connected, Electric and Shared vehicles. By providing electric motorcycle rentals at convenience stores in Taipei City, travelers have better connection to MRT systems. This dissertation suggests that the authorities should encourage travelers to use rental electric motorcycles for short trips, and to use them as feeder modes to MRT stations for medium and long trips. The proposed green transportation strategies enhance better connection between the local road network and MRT. As MRT is more accessible, it is more inclined to reduce the transportation impacts for medium and long trips. This dissertation also suggests that the connectivity efficiency of important OD pairs with green transportation is effectively improved either in global or local scales. By making convenience stores as green transfer nodes, travelers can reach any important destinations with MRT systems more efficiently. It will also attracts travelers to use MRT for their trips. Making green transport modes, such as electric motorcycles, MRT, more accessible to traveler benefits green transportation promotion. The results of this dissertation provide a reference for public transportation planners in Taipei.

5.2 Directions for future research

According to the proposed models and important findings of this dissertation, several directions for future research are discussed.

(1) In the first part of dissertation, more OD pair data can be collected so that the simulation can depict the reality more accurately. The distribution of the parameters in the simulation may vary with the OD pair data in different cities or regions.

(2) When implementing electric motorcycle rentals at the convenience store, more research is needed to explore how to efficiently distribute the systems. In addition, more comprehensive supporting measures should be studied for the potential community opposition to the reduction of regular motorcycle parking spaces of their nearby convenience stores.

(3) The modal split of home-based work trip may change when proposed green transportation strategies are adopted. After incorporating convenience stores to current transportation networks, the attraction of travelers switching to MRT from other transport modes can be further discussed.

(4) The relationship between shortest travel time path and least emission path in the multimodal networks can be further discussed. Future study can apply

multi-objective optimization approach to explore the multimodal viable path with the shortest travel time and the least emission.

(5) The cost of preserving or enhancing overall green transportation mobility with the strategy the dissertation proposed can be investigated. For instance, the investment of public electric motorcycle and its docking station at convenience stores and MRT stations. The external cost such as the safety of riding electric motorcycles in the city could be also considered.

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Glossary of symbols

Part I: *Strategies for green transportation while preserving mobility and accessibility*

$G(N, A)$	A multimodal network, where N is the set of nodes and A is the set of arcs
V, v	The set of modes, a mode
N_v, A_v	N_v is the set of nodes of mode v, A_v is the set of arcs of mode v
$[i, s]$	The node-state pair, which indicates the path from the origin to node i with state s
C_i^s	The current shortest path cost from the origin to node i with state s
w_i^s	The number of transfers in the current shortest viable path $[i, s]$
N_i^s	The predecessor node to node i in the current shortest viable path $[i, s]$
S_i^s	The state of the current shortest viable path up to node N_i^s
L_i^s	The cost of the last shortest path $[i, s]$ with less than w_i^s transfer
Qnow	The sets contain the labeled node-state pairs with h model transfers
Qnext	The sets contain the labeled node-state pairs with $h+1$ model transfers
M_r^v	The mobility of an OD pair r with mode v
t_r^a	The automobile(a) travel time of OD pair r
R	The set of origin-destination pairs within Taipei City
t_r^v	The mode v travel time of OD pair r
C_r^m	The inter-connectivity ratio for r with multimodal m, which includes MRT

t_r^m The total multimodal(m) travel time of OD pair r

α The access time to MRT stations

δ The waiting time occurred in access

G_p The green level of a path p

e_k The emission efficiency of mode k

d_k The travel distance in kilometers of mode k

Y_r The travel cost of a single mode of an OD pair r

τ The value of a unit in-vehicle travel time

b The driving/riding time

l The parking cost at destinations

ε The unit distance variable cost

d The actual travel distance

τ' The value of a unit out-of-vehicle time

g The average time of finding parking spaces

o The average walking time from the parking lot to the destination

Q_r The travel cost of multiple modes of an OD pair r

t_u Mode u in-vehicle travel time

f_u The transit fare of mode u

θ The sum of the access and egress walking time of the transit system

π The total transfer waiting time

λ A random multiplier

φ The bus waiting time

β The ratio of bus stop access time and bus riding time to multimodal travel time which excludes bus waiting time

$t_r^{m'}$ The travel time of multiple modes accommodating proposed strategies of an OD pair r

Δ The time saved by the proposed strategy

x The walking time from home to its nearest convenience store

Part II: *Small-world network theory in the study of green transportation connectivity efficiency in multimodal networks*

G(N, A) The multimodal network, where **N** is the set of nodes and **A** is the set of arcs

$\mathbf{N}^s$ The set of origin nodes

$\mathbf{N}^t$ The set of transport nodes

J The set of all origin-destination pairs

$\|\mathbf{J}\|$ The total number of **J**

G_p The green level of a path p

e_k The emission efficiency of mode k

d_k	The travel distance in kilometers of mode k
G_{mq}	The green level of the path m which MRT is involved of the OD pair q
$\mathbf{G}(\mathbf{J})$	The set of all OD pairs $\mathbf{J}$ in the multimodal networks $\mathbf{G}$
$S_{glob}[\mathbf{G}(\mathbf{J})]$	The global green connectivity efficiency of $\mathbf{G}(\mathbf{J})$
$S_{glob}[\mathbf{G}(\mathbf{J})_{ideal}]$	The global green connectivity efficiency of $\mathbf{G}(\mathbf{J})$ in the ideal case
$S_{glob}^{N}[\mathbf{G}(\mathbf{J})]$	The normalized global green connectivity efficiency of $\mathbf{G}(\mathbf{J})$
y	The OD pair from node i to its neighbor-node
$\mathbf{G}_i$	The subgraph of node i, which is composed of node i, its neighbor-nodes, and their corresponding multimodal networks
$\mathbf{J}_i$	The set of all OD pairs from node i to its neighbor-nodes
$\lVert\mathbf{J}_i\rVert$	The total number of $\mathbf{J}_i$
$S_{loc}[\mathbf{G}_i(\mathbf{J}_i)]$	The local green connectivity efficiency of $\mathbf{G}_\mathbf{i}(\mathbf{J}_i)$
$S_{loc}[\mathbf{G}(\mathbf{J})]$	The local green connectivity efficiency of $\mathbf{G}(\mathbf{J})$
$S_{loc}[\mathbf{G}_i(\mathbf{J}_i)^{\mathbf{ideal}}]$	The local green connectivity efficiency of $\mathbf{G}_\mathbf{i}(\mathbf{J}_i)$ in the ideal case
$S_{loc}^{N}[\mathbf{G}(\mathbf{J})]$	The normalized local green connectivity efficiency of $\mathbf{G}(\mathbf{J})$
$\mathbf{X}$	The set of districts of the studied city
$\lVert\mathbf{X}\rVert$	The total number of $\mathbf{X}$
t_{mq}	The travel time of OD pair q with path m
$M_{glob}[\mathbf{G}(\mathbf{J})]$	The global mobility of $\mathbf{G}(\mathbf{J})$
$M_{glob}[\mathbf{G}(\mathbf{J})_{\mathbf{ideal}}]$	The global mobility of $\mathbf{G}(\mathbf{J})$ in the ideal case

$M_{glob}^{N}[\mathbf{G}(\mathbf{J})]$	The normalized global mobility of $\mathbf{G}(\mathbf{J})$
$\mathrm{M}_{loc}[\mathbf{G}_i(\mathbf{J}_i)]$	The local mobility of $\mathbf{G_i}(\mathbf{J}_i)$
$M_{loc}[\mathbf{G}(\mathbf{J})]$	The local mobility of $\mathbf{G}(\mathbf{J})$
$M_{loc}[\mathbf{G}_i(\mathbf{J}_i)^{\mathbf{ideal}}]$	The local mobility of $\mathbf{G_i}(\mathbf{J}_i)$ in the ideal case
$M_{loc}^{N}[\mathbf{G}(\mathbf{J})]$	The normalized local mobility of $\mathbf{G}(\mathbf{J})$

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Education

Sept. 2007- July. 2015	Ph.D., Transportation & Logistics Management National Chiao Tung University
Sept. 2004- Jan.2006	Chalmers University of Technology, Göteborg, Sweden M.D., Management of Logistics and Transportation
Sept. 2001- Jun. 2005	National Chiao Tung University B.M., Transportation Technology and Management

Professional experience

Sept. 2010- Jun.2011; Sept. 2006- Jun. 2008	Lecturer of Supply Chain Management, Logistics Management. Department of Marketing and Logistics Management, Yu Da University of Science and Technology ● Certificate of Lecturer, issued by Ministry of Education, 2007
Feb.-Jun. (2008-2011)	Teaching assistant of Liner Algebra, School of Management, National Chiao Tung University ● Outstanding Teaching Assistant Award, 2009, 2010, 2011.
Mar. 2006- Mar. 2007	Special assistant to Manager, OEC Group

Publication

A. Journal Papers

1. Chaug-Ing Hsu and Hsien-Mei Wang, "Strategies for Green Transportation While Preserving Mobility and Accessibility: A Case Study of Taipei City," Journal of Urban Planning and Development. (Accepted)

Working papers:

2. Chaug-Ing Hsu and Hsien-Mei Wang, "Small-world Network Theory in the Study of Green Transportation Connectivity Efficiency in Multimodal Networks," paper prepared to submit to International Journal.

B. Refereed conference papers

1. Chaug-Ing Hsu and Hsien-Mei Wang, 2010. 11, "Green Transportation in Multimodal Networks," Paper presented at the 57th Annual North American Meetings of the Regional Science Association International, Denver, U.S.A., November 10-13, 2010.

2. 許巧鶯、姜翔騰、王憲梅，2013. 6，「先進環保車輛購買決策之研究—以台北市計程車業者為例」，兩岸經貿暨觀光第十四屆學術研討會論文集，327-337 頁，民國一○二年六月。