Université de Montréal

A MODEL FOR LAND USE AND FREIGHT TRANSPORTATION COORDINATION IN SHANGHAI, CHINA

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Thèse présentée à la Faculté des études supérieures
en vue de l'obtention du grade de
Philosophiae Doctor (Ph.D.)
en géographie

Juin 1999

Université de Montréal

Faculté des études supérieures

Cette thèse intitulée

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a été évaluée par un jury composé des personnes suivantes :

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SUMMARY

In this thesis, we study the Land Use Design Problem in a 4-step procedure: 1) modeling mechanism analysis; 2) mathematical formulation and solution method development; 3) implementation of the solution algorithm; and 4) application of the model to land use and freight transport coordination in Shanghai.

In view of developing an approach to land use and transportation coordination planning for Chinese cities, we conduct an analysis for urbanization in China. Special features of economic development and urbanization are explored.

A review of the literature on land use and transportation is provided from various aspects: traffic generation, trip distribution, modal split, traffic assignment, land use planning and land use design problem.

An urban-form-based modeling approach is proposed in this thesis. In this modeling process, we select population density and job density as decision variables; traffic demands are functions of these densities; gravity model is used for distributing trips to Origin-Destination pairs; an equilibrium assignment model is used to solve the traffic assignment problem. Finally, the Land Use Design Problem is formulated as a two-level mathematical programming problem. At the upper level, urban planners distribute population and employment to zones to pursue the best urban activity location, while at the lower level, road users select travel routes to minimize their travel costs.

A theoretical study explores the existence of solutions to the Land Use Design Problem model. Solution methods to the problem are developed. Because of their size and complex nature, some problems may only be solved by heuristics. A robust implementation of one heuristic, known as the iterative improvement heuristic method, is developed to solve the Land Use Design Problem. To forecast freight traffic generation, a land use and freight transportation interaction analysis is conducted. And lastly, an application of the Land Use Design Problem model to Shanghai land use and freight transportation coordination is completed.

The results of the case study demonstrate that the Land Use Design Problem model could be used to achieve coordinated distribution of population and employment in an urban area. Consequently, this model and the corresponding heuristic solution method provide us with a useful tool to conduct, at the strategic level, long-term planning for land use and transportation coordination in Shanghai.

Key words. Land use planning, urban planning, transportation planning, two-level programming, mathematical programming with equilibrium constraint, variational inequality, optimization, network equilibrium, traffic equilibrium, Shanghai, China

RÉSUMÉ

Cette thèse étudie le Problème de la Conception de l'Utilisation du Sol. Elle comprend 1) l'analyse des mécanismes de modélisation; 2) la formulation d'équations mathématiques et le développement d'une méthode de solution; 3) l'implantation de l'algorithme; et 4) une application de modèle au problème de coordination de l'utilisation du sol et du transport de marchandise à Shanghai.

Afin de développer une proposition quant à la planification de l'utilisation du sol et de la coordination du transport pour les villes chinoises, nous menons une analyse de l'urbanisation en Chine. Des caractéristiques particulières du développement économique et de l'urbanisation sont explorées.

Une revue de la littérature portant sur l'étude de l'utilisation du sol et du transport est offerte selon divers points de vue: génération du trafic; distribution des déplacements; choix modal; affectation du trafic; problèmes de la planification et de la conception de l'utilisation du sol.

Une méthode de modélisation fondée sur la forme urbaine est proposée dans cette thèse. Dans ce processus de modélisation, nous avons sélectionné la densité de la population et celle de l'emploi comme variables décisionnelles; les demandes du trafic sont fonction de ces densités; le modèle de gravité est utilisé pour distribuer les déplacements pour chaque paire d'Origine-Destination; un modèle d'équilibre est suggéré pour résoudre simultanément les problèmes d'affectation du trafic. Enfin, le Problème de la Conception de l'Utilisation du Sol est formulé en un problème de programmation mathématique à deux niveaux. Au niveau supérieur, les urbanistes distribuent la population et l'emploi dans des zones afin d'identifier la meilleure localisation pour les activités urbaines, tandis qu'au niveau inférieur, les utilisateurs du réseau routier choisissent les itinéraires pour minimiser les côute de déplacements.

Une étude théorique explore l'existence d'une solution au Problème de la Conception de l'Utilisation de Sol. Les méthodes pour solutionner ce problème sont développées. En raison de leur taille et de leur nature complexe, certains problèmes ne peuvent se régler qu'au moyen d'une méthode heuristique. Une implémentation robuste d'une méthode heuristique est développée pour résoudre le Problème de la Conception de l'Utilisation du Sol. Une analyse de l'interaction de l'utilisation du sol et du transport de la marchandise permet de prévoir la génération du trafic de la marchandise. En fin, le modèle est appliqué a la coordination de l'utilisation du sol et du transport de marchandise à Shanghai.

Les résultats de cette étude démontrént que le modèle pourrait être utilisé pour effectuer une distribution coordonnée de la population et de l'emploi dans une zone urbaine. Par conséquent, le modèle et sa méthode de solution heuristique correspondante constituent un outil utile pour réaliser, au plan stratégique, une planification à long terme quant à l'utilisation du sol et à la coordination du transport à Shanghai.

Mots-Clés: Planification de l'utilisation du sol, planification urbaine, planification du transport, programmation bi-niveau, programmation mathématique avec contrainte d'équilibre, inégalité variationnelle, optimisation, équilibre du réseau, équilibre du trafic, Shanghai, Chine

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Chapter 1

Introduction and Overview

1.1 Introduction

For almost half a century, urban modeling and urban planning have been attracting many geography and regional science researchers and practitioners. This field has been the stage for many great theoretical developments and successful practices. However, the problems we are confronting in urban development are also very serious and challenging. These include worldwide urbanization, increasing greenhouse gas emission and global warming. In China, the increasing rate of urbanization imposes unprecedented pressures to social and urban systems.

Studies on China's development and urbanization are of great importance for global sustainable development. China possesses about twenty percent of the world's population (World Resources Institute, 1995). In the 1990s, China has come to experience extremely rapid economic and urban growth through great change from planned economy to market economy (Ren, 1998). There is nothing that needs such careful planning as a 'free market' economy if it is to avoid engendering disruption, deprivation and chaos, considering the volume of its population and agricultural background.

The purpose of this thesis is to provide a study on urban land use and freight transportation coordination in Shanghai. In the rest of this chapter, the problem, objective and hypothesis of study, as well as the scope and organization of the thesis will be addressed successively.

1.2 The problem

As the economy experiences rapid growth, increasing intensity of land use in urban areas and rapid urbanization in rural areas are observed in China. In coming years, enhancement of the function of metropolises and rural urbanization are irreversible. The following items may be used to generally describe economic development and urban development in China.

- China's economy has achieved an average annual growth rate of 9.8 percent for the past 20 years (Ren, 1998). It is suggested that China's economy will acknowledge high annual growth rate in the near future.
- Economic development imbalance may be observed between coastal and interior regions and between urban and rural areas;
- For the past 20 years, over 100 million rural population migrated to urban areas (China Statistical Yearbook, 1984, 1998), which puts huge pressure on urban management;
- Urban land use may be characterized by highly dense, mixed land use;
- Bicycle use is significant in urban transportation; and
- Urban traffic is extremely congested.

Because of the features of urban land use/transportation and their development tendency, urban planners and transportation planners in China are facing serious issues. One of the issues that requires much understanding is how may urban land use and freight transportation coordination be evaluated. The importance of freight transportation is acknowledged in Shanghai, the largest city of China. According to SCTPI (1991), freight transportation achieved an average increase rate of 9.5 percent from 1980 to 1990, and it used 28.5 percent of the roadway system in the Shanghai metropolitan area. Of all trucks traveling on the Shanghai's roadway system, 42.5 percent were running empty (SCTPI, 1991). One major concern on freight transportation is its efficiency. For years, urban planners and transportation planners in Shanghai have been working hard to increase freight transportation efficiency, through adjustment of urban land use distribution. Their effort, however, has not yet produced satisfactory result. A critical reason is that the planners lack efficient planning approach and tools that may generate and analyze different urban design scenarios and provide quick response, in terms of planning, to planners' keen strategic insight, obtain better solutions, and achieve land use and transportation coordination in rapidly growing metropolitan areas with mixed land use, highly dense population.

1.3 Objective of the study

This study aims at making use of urban planning and transportation planning theories and practices originated from Western countries, seeking for new urban modeling and urban planning approach that can be used for long-term, strategic urban planning, and to support reasonable and sustainable development and urbanization in China.

The objective of the study is to develop long-term, strategic insight through the development of new methodology. The study is methodological in nature. Problems will be addressed, a new planning approach for urban land use and freight transportation coordination will be suggested, mathematical formulations will be provided, and theoretical and technical analyses will be conducted to explore the existence of solutions and solution methods as well.

The new planning approach will allow urban planners and transportation planners to generate different urban design scenarios and evaluate them quickly so that planning time and cost can be reduced and planning efficiency increased. The approach can be used to estimate land use and freight transportation coordination, through adjusting population and employment densities, that reduces transportation cost and increases freight transportation efficiency.

1.4 Scope of thesis and Chapter overview

This thesis covers some issues of the studies of urban modeling and urban planning, ranging from activity location, trip generation, trip distribution, modal choice, traffic assignment, land use design, and land use and transportation coordination development. Emphasis is given to one problem: land use and freight transportation coordination.

The investigation of the problem include the following: modeling mechanism analysis, mathematical model development, analysis of existence of solutions and solution method development, computational analysis and computer code development. Our purpose is to develop a new approach for urban modeling and urban planning for large cities in China.

A case study will be conducted to demonstrate the implementation of the new urban planning approach.

There are eight chapters in this thesis. The rest of the thesis is organized as follows.

In Chapter 2, we will describe and analyze characteristics of urbanization and urban development in China by identifying the conditions of economic development, land use, and level of traffic with a view to evaluate possible modeling methods. The characteristics include unbalanced economic development, mixed land use, bicycle-oriented transportation and extremely congested road traffic. Based on these understandings, possible modeling methods to deal with these specific circumstances are discussed.

In Chapter 3, we will give a brief review of urban land use and transportation modeling, aiming at forming a general picture about the study on land use and transportation planning. We will first review the history of urban modeling. Many different theories and methods have contributed to the development of urban modeling and urban planning. Some short comments or critiques are made to those methods.

In Chapter 4, we will describe a new model for urban land use and freight transportation coordination by describing methods of urban activity location, trip generation, trip distribution and traffic equilibrium assignment, with a view to provide an efficient planning approach that may generate and analyze different urban design scenarios, provide quick response, in terms of planning, to planners' keen strategic insight, and obtain better solutions. The land use model includes an urban form-based activity location and a demand-supply coordination-based population and job distribution. The transportation model involves a trip generation by multiple regression, an entropy maximum trip distribution, and traffic equilibrium assignment.

Chapter 5 will be devoted to the theoretical analysis of the land use and transportation coordination problem, using mathematical analysis method, to investigate conditions for existence and uniqueness of solution for the problem. Solution methods to the problem will also be discussed.

In Chapter 6, we will describe the implementation of one solution method, the Iterative Improved Heuristic Method (IIHM), which is developed in Chapter 5 for solving the land use and transportation coordination problem. Some computational analysis will be conducted and detailed algorithmic issues will be discussed too, with a view to generate efficient computer codes for undertaking complex land use and freight transportation coordination problems.

In Chapter 7, we will conduct a case study, by collecting corresponding land use and freight transportation data and implementing the IIHM with the data collected, for the purpose to demonstrate the implementation of the new urban planning approach. We will first explore the urban form of Shanghai and land use and transportation interaction. For land use and transport interaction, attention will be paid to the relationship between land use and freight transportation. The coordination development for the two parts will be discussed as well.

Chapter 8 concludes this thesis. Contributions of the thesis will be summarized and possible research directions for further studies will be proposed.

Chapter 2

Problem Description and Modeling Mechanism

In this chapter, we describe and analyze characteristics of urbanization and urban development in China. The characteristics include unbalanced economic development, mixed land use, bicycle-oriented transportation, and extremely congested road traffic. Based on these understandings, possible modeling methods to deal with these specific circumstances are discussed.

2.1 Problem description

2.1.1 Background

China is changing rapidly. China's population is estimated at 1.2 billion, about three quarters of which resides in the countryside (China Statistical Yearbook, 1992). According to Schinz (1989), a country with more than thirty percent of its population living in rural areas is an agricultural country. On the other hand, China's economy has been developing very rapidly in recent years. In 1992 and 1993, its Gross Domestic Products (GDP) rose by 13.21 percent and 13.12 percent respectively. The average increase rate of GDP in the past twenty years was over 9.8 percent (China Statistical Yearbook, 1984-1998; Zhang, 1998).

This increasing rate of economic growth has also permitted a rapid urbanization.

Indeed, increasing intensity of land use in urban areas and rapid urbanization in rural areas have been observed in China. Researchers believe that in coming years, enhancement of the function of metropolises and rural urbanization are irreversible. McGee (1991) argued that in Asian 'wet rice' areas, urbanization is region-based instead of city-based.

Urbanization usually takes industrialization as its basis, and an advanced transportation system as one of its major features. China's economic development rests on constant energy supply and adequate means of transportation and communications. To coincide with open-door policies, major investments have been put on transportation improvement for both urban road network and inter-provincial highways. Obviously, this highlights city function, especially in large cities, and promotes rural urbanization. It also enlarges city's size through the development of urban fringes.

Drawbacks of unconstrained enlargement of metropolitan areas have been explored by many researchers (see, for example, Renner, 1988; Newman and Kenworthy, 1989; and Gordon, 1991, among others). In view of this, establishing planning policies on urban development is of great significance. This point becomes one of the most important issues for China's urbanization practice, because a great number of rural people are being integrated into urban areas in a comparatively short time period in China.

The urban modeling and planning methods developed for Western cities cannot be directly employed in China's context. Metropolises in China have specific economy and land use/transportation features. These are characterized by unbalanced economic development, state-planned housing and job-hunting, mixed land use, mixed urban traffic highlighted by bicycle orientation, and extremely congested road traffic. To form a reasonable modeling procedure, we should first describe these characteristics, explore possible modeling and planning methods for the context, then put forward a rationable urban land use/transportation coordination model.

2.1.2 Economic development imbalance and migration

The unbalanced development of economy in China is extensive. The imbalance may be demonstrated on at least three aspects: the difference between relatively advanced economy in the eastern part of China and backward economy in the western part; the discrepancy of coastal provinces' rapid development versus somewhat slower progress in hinterland regions; and the gap between fast growth in urban area and comparative delay in remote rural area. The existence of these imbalances provides China with huge potentials for further development, but also puts forward a virtual threat to cities for sustainable development.

The difference between a relatively advanced economy in the eastern part of China and a backward one in the western part results from geographic conditions as well as government development policies. Eastern China is mainly composed of flatlands with an excellent river system, international routes through the Pacific Ocean, and an effective railway system. Good geographic conditions and a good transportation system make economic growth possible. On the other hand, most of China's plateaus, deserts and mountains are located in the western part of the country. Transportation in the area is very inconvenient. Consequently, the economy there is marked by a certain degree of backwardness. Besides, in the 1950s and 1960s, the Chinese government deliberately isolated the country from the world market. The Chinese government has massively relied on the industrial production of coastal provinces to sustain and extend development in the interior.

The discrepancy of coastal provinces' rapid development versus somewhat slower progress in hinterland regions. The existence of this discrepancy is no doubt affected by transportation factors. In many hinterland provinces - such as Anhui and Jiangxi in East China and Henan and Shanxi in Central China - transportation conditions are not as good as those of the coastal provinces. One of the main reasons has been the development strategy selected by the Chinese government to carry out its open-door policies by favoring foreign investment in fourteen open cities located in coastal provinces. As a result, over 80 percent of the national and international investments from Sino-foreign joint ventures or foreign-owned enterprises are located in coastal provinces (Zhang, 1998). All these factors yield a faster economic growth in coastal regions, while hinterland regions are experiencing a slower rate of economic growth.

The gap between fast growth in urban areas and comparative delay in remote rural areas. The formation of the gap has a deep-rooted historical reason. China traditionally was an agricultural country. For centuries, it had maintained an agricultural society with a closed and self-supporting system. In this system, cities existed only as administration centers, or places for exchanging agricultural and craft goods. In the nineteenth century, the Chinese market was opened by Western traders. When the contemporary industrial cities initially appeared in China, at the turn of the last century, there was a big difference, with high productivity and high living standards as compared with China's traditional economy and living conditions. This is the origin of the gap between industrial urban areas and agricultural rural areas. Through several five-year plans from 1950 to 1975, the Chinese government has attempted to reduce the gaps between urban and rural areas. After having made major efforts to modernize its transportation system, the Chinese government was able to focus on economic development through the introduction of market economy mechanism. Since the beginning of 1980s, the economy has grown rapidly both in urban and rural areas. But a discrepancy still exists between the two.

The rise of agricultural productivity has released some laborers from agricultural production. This release provides cheap labor to the industrialization process, while at the same time making urban planning and management complex and difficult, especially in coastal metropolitan regions. According to Woodward and Banister (1987), up to forty percent of the rural labor force was then not needed in agriculture. In 1987, the surplus labor force exceeded sixty percent of the total in the Suzhou and Wuxi areas. The proportion of agricultural laborers dropped from seventy percent to twenty percent of the total in the Changjiang delta area (Tan, 1993; Comtois, 1993). It is reported that approximately half of this surplus of agricultural laborers was absorbed by local rural industries, while the other half migrated to metropolitan areas. Given the size of China's rural population, the volume of migration puts huge pressure on urban management. In Shanghai, the floating population (people who live in the city temporarily) is evaluated at 2 million, half of which have temporary resident permits (SCCTPI, 1991). It is reported that the number of cross-province migratory laborers reached over 20 million. The major destinations of these job-hunters are coastal cities, especially great metropolises such as Shanghai, Guangzhou and Shenzhen (People's Daily, 1994).

Before 1980, migration was subjected to the government's food assignment policies. These policies were removed during the economic reform. Officials and researchers are now seeking effective macroscopic management to deal with this problem. The recent issuing of "temporary working permits" in Shanghai is a good test. Recently, the Ministry of Labor of the central government has been implementing an "urban-rural employment cooperative plan" with a view to create a "planned market system" to solve the problem of rural laborer migration (People's Daily, 1994).

Nevertheless, as long as the economic imbalance exists, the process of rural laborers shifting to urban areas will continue. When modeling and planning an urban land use transportation system, this point should not be ignored.

2.1.3 The features of urban land use/transportation

The urban land use/transportation in China is characterized by mixed land use with overdensity, bicycle-oriented transportation and extreme traffic congestion. Owing to these features, the urban modeling and planning methods for Western cities cannot be easily introduced into China.

Mixed land use with overdensity. Historically, the population density in China, both in urban and rural areas, is relatively high. This is especially the case in the city of Shanghai. In the early nineteenth century, before the Europeans arrived, the population density in the small town of Shanghai was over 53,000 persons per square kilometer (Schinz, 1989). At that time, Shanghai was devoted to craft industries and goods distribution, and covered an area of about four square kilometers. The arrival of European powers created a new city near the former small town. Factories were built. Workers and migrants from rural areas then came to live near the factories. Consequently, from its beginnings as a modern city, Shanghai has been characterized by mixed land use with overdensity. For roughly one century, Shanghai was simultaneously administrated by three or four governments that were unable to cooperate. Therefore, the urban development of Shanghai did not benefit from a comprehensive planning for many years. In the Huangpu district, an area of 4.18 square kilometers, appointed as the Central Business District (CBD), the population density is 91,000 persons per square kilometer, while job density is only 61,000 persons. This situation is commonly observed in other large cities in China.

Significance of bicycle use in traffic mode. In contrast to North American, European and Japanese cities, Chinese cities are characterized by extensive bicycle movement in urban traffic. In well-developed countries, the main means of travel are public transit and private cars. In North America, due to low intensity of land use and advanced highway systems, private cars play an important role. In Europe and Japan, public transit either predominates, or has the same importance as private cars (Newman and Kenworthy, 1989). The situation is quite different in China. Even though the economy acknowledges a high rate of growth and individuals are getting wealthier, the use of private cars is still restricted in China. In the early 1980s, the ratio of people using transit to those using bicycles in urban traffic was 6 to 4. The ratio became 4 to 6 in the early 1990s. The increasing use of bicycles is the result of road congestion and a decline in transit service level. The increase in bicycle ownership consequently worsened road congestion. In 1990, roughly 5.44 million people owned a bicycle in Shanghai. The average speed of transit bus in urban areas was 13 kilometers per hour, and 8 kilometers per hour in the downtown core (SCCTPI, 1991).

Extremely congested traffic. The overdensity of population and the backwardness of transportation infrastructures result in highly congested urban traffic. The average road area per capita in Shanghai is 2.4 square meters. In the inner city of Shanghai, an area of about 93 square kilometers, the ratio of vehicle volume to road capacity on the major road network at peak hours has reached a high value of 0.8. On many major roads in the area, the ratio surpasses or is close to 1. Consequently, the travel speed of vehicles drops to an unacceptable low level of 10 kilometers per hour (SCCTPI, 1991). The shortage of transportation supply and excessive demand has resulted in extremely poor traffic conditions.

2.1.4 Housing and job-hunting in urban China

China has adopted a strict residence registration system called "hukow system". The system, formed in the mid 1950s, was aimed at controlling the floating population. Subsequent socialization and land communization gave the system a specific function. Through the registration system, the state provided jobs and housing to urban citizens, and provided food to rural residents. Further to reform policies established in 1978, food was no longer assigned by the state and rural surplus laborers could migrate to cities. In urban areas, reform on job and housing assignment is pretty slow. Of late, the state has not been assigning jobs to new school graduates. But for those people whose jobs were provided by the state in previous years, the state still assigns housing, through state-run enterprises. The latest reform encourages employees to purchase housing. These dwellings are built with company investments, and are sold to company employees at a discount. Therefore, it is not a virtual housing market. This difference should also be taken into account in urban modeling.

2.1.5 Urban land use/transportation development tendency

Functions of metropolitan area will be further enhanced. To improve living conditions and make full use of commercial benefits in the downtown core, it is expected that the population density will decrease through an enlargement of the size of cities. Certain industrial and residential zones will continue to emerge in peri-urban areas. Taking Shanghai as an example, a 350-square kilometer Pudong new district has been established since 1990. The area is as large as the old city proper. The new district is going to be constructed according to a land use/transportation coordination principle, which states that land use and transportation infrastructure should be designed and developed to meet the needs of desired urban form and to meet requirements of each other. The district is planned to have 200 square kilometers of urbanized area and provide housing for over 2 million people. It is expected that 1.4 million people in the inner city of Shanghai will move to the new district. As a result, the population density in the downtown core should decrease from 80,000 to 50,000 persons per square kilometer (SCCTPI, 1992).

Rural urbanization will continue. Since 1987, the output of rural industries has surpassed the output of agriculture. In peri-urban areas, such as suburban Shanghai and Suzhou, Wuxi and Changzhou, rural industrialization proceeds very rapidly. Rural industries are less controlled by the central government and more influenced by market mechanism. In peri-urban areas, rural industries are located along transportation corridors. To improve growth environment, local governments are investing in transportation infrastructures. For instance, in Shanghai county, the local government has authorized the construction of an 11-kilometer light rail transit (LRT). The line connects the city's subway system to Minhang, which is Shanghai's major high industrial base. When completed, it is expected that 700,000 people will reside along the two sides of the line. Also many rural industries will be located in the area (CRTS, 1993).

Transportation investment. Major investments will go to the transportation infrastructure, including expressway, subway and LRT. Transit priority policies will be seriously considered. Recently, China has opened the transportation infrastructure to foreign investors, following build-operate-transfer (BOT) contracts. Shanghai originally planned to build in the city proper five cross-Huangpu projects (bridge or tunnel). Recent modifications suggest an increase to seven passages. Also a passenger walk-only tunnel is under consideration. In addition, large transportation investment projects also involve an elevated expressway network including a ring road, an east-west corridor and a north-south corridor (SCCTPI, 1992).

Because of the features of urban land use/transportation and their development tendency, urban planners and transportation planners in China are facing serious issues. One of the issues that requires much understanding is how may urban land use and freight transportation coordination be evaluated.

The importance of freight transportation is widely acknowledged in Shanghai, the largest city of China. According to SCTPI (1991), freight transportation achieved an average increase rate of 9.5 percent from 1980 to 1990. There were over 100,000 trucks traveling on the roadway system of Shanghai in 1990. The truck ownership was increased at an annual rate of about 10 percent from 1985 to 1990, due to rapid economic development. Freight transportation used 28.5 percent of the roadway system in the Shanghai metropolitan area and 25.2 percent in the city proper. Of all trucks traveling on the Shanghai's roadway system, 42.5 percent were running empty (SCTPI, 1991). One major concern on freight transportation is its efficiency. For years, urban planners and transportation planners in Shanghai have been working hard to reduce the percentage of running empty trucks traveling on roads and to increase freight transportation efficiency, through adjustment of urban land use distribution, i.e., population and employment densities. Their effort, however, has not yet produced satisfactory result. A major reason for this is that the planners lack efficient planning approach that may generate and analyze different urban design scenarios quickly. New urban planning approach is needed to provide quick response, in terms of planning, to planners' keen strategic insight, obtain better solutions, and achieve land use and transportation coordination in rapidly growing metropolitan areas with mixed land use, highly dense population.

The new planning approach should allow urban planners and transportation planners to generate different urban design scenarios and evaluate them quickly so that planning time and cost can be reduced and planning efficiency increased. The approach should be able to estimate land use and freight transportation coordination, through adjusting land use distribution in different scenarios, to reduce transportation cost and increase freight transportation efficiency.

Three issues should be handled properly in this new planning approach. Firstly, the planning approach should take into consideration both land use development costs and transportation costs simultaneously. In other words, transportation costs should be incorporated with land use development costs so that an evaluation can be done for the land use and transportation coordination, through evaluating the total land use development costs and transportation costs.

Secondly, the planning approach should be able to generate different urban design scenarios quickly, from one to another. Those scenarios should meet given demographic, economic and other restrictions. Each scenario should be evaluated by evaluating its total land use development costs and transportation costs. The approach should start from an initial scenario and evaluate it. The result of the evaluation will give out the direction for an improvement. This improvement yields the next, better scenario.

Thirdly, the planning approach should use a set of easy-collecting and easy-adjusting data as its input, otherwise it is very difficult to generate different urban design scenarios from one to another quickly.

In the next section, we will provide an analysis and evaluation procedure that meets this requirement.

2.2 Modeling mechanism

Urban modeling involves land use activity location, land use and transportation interaction, and coordination evaluation. The following modeling method is proposed for the specific context of urban China.

2.2.1 Urban modeling based on urban form

Every city has an urban form. Urban form involves geographic features, land use distribution, transportation supply, and land use/transportation linkage. The geographic features include its size and shape. For example a city can be radial and have a single center. Land use distribution reflects the location issue of urban activities, such as the proportion of population and jobs in CBD, inner city, outer city and suburb, and the population density and job density in these city belts. Transportation supply determines the level of traffic constraints, including road length per capita, number of parking spaces in CBD and the vehicle-to-road ratio. Land use/transportation linkage includes origin-destination (O-D) patterns, which reflect the interaction degree between traffic zones, and selection of traffic orientation such as automobile-oriented or transit-oriented.

Newman and Kenworthy studied the urban form for 32 cities around the world. They found that, among the descriptive indices, land use distribution, transportation supply and land use transportation interaction are not independent from each other. Indeed, they are strongly connected (Kenworthy and Newman, 1987; Newman and Kenworthy, 1989). A city with an extremely low density is often characterized by intensive automobile orientation, land use distribution that has almost no concentration, and extremely poor transit performance. These cities include Detroit and Los Angeles in the U.S.A. On the other hand, a city with very high density is generally marked by an intense orientation to non-automobile traffic (public transit, cycling and walking), a very strong degree of concentration on land use distribution, and an excellent transit performance. Examples of this are cities such as Tokyo, Hong Kong and Singapore (Newman and Kenworthy, 1989). We found that most large cities in China are also in this category. The sole exception is that Chinese large cities may not yet have an excellent transit system at all.

The existence of the interrelationship among urban form-items allows us to employ the following procedure to conduct land use and transportation planning. We first select a desired urban form. **Selection of an urban form means determining a traffic orientation, automobile or non-automobile dependent, in relation to the local economic and demographic context.** After determining the traffic orientation, the planning procedure may be undertaken on two levels: to design a land use distribution to match the selected urban form, and to design a transportation structure, in relation to the level of traffic restraint of the selected urban form. If the selected urban form is significantly or extremely oriented to non-automobile dependence, it is also needed to design a corresponding transit system.

The design outputs should be evaluated to check land use transportation coordination. Indicators of the evaluation include land use intensity and degree of concentration, level of traffic restraint, and transit performance. The procedure terminates if the land use/transportation coordination is satisfied. If unsatisfactory, a new iteration is needed to readjust the land use distribution and transportation structure.

We refer to such a planning procedure as **the urban land use transportation coordination procedure based on urban form analysis**, or in short, **the urban form planning method**, by which we mean that, when people plan urban land use and transportation, they are planning an urban form.

2.2.2 Modeling traffic flows in urban China

Traffic modeling involves the well-known four steps of trip generation, trip distribution, modal choice and traffic assignment. We shall use aggregated data in traffic modeling in urban China. Because we use the urban form selection method in activity location, we can take as inputs the corresponding information of the urban form in the modeling process.

Urban form selection. In geographical term, urban form is multiplicity of land use. It is also reflected by the shape of a city, its population and job density, its transportation orientation, and a combination of all above. (Giuliano, 1989). Quantitatively, selecting an urban form means to determine the proportion and density of population and job in different city belts, including CBD, central city, inner city, outer city and suburb. To determine the density, we should know the surfaces of different zones. A GIS software can be used to generate these surface data. The selected urban form provides input information to trip generation.

Population and job density are easy-collecting and easy-adjusting. Taking these densities as input data of the urban planning approach makes it possible for the approach to generate different scenarios quickly,

Trip generation. We try to develop a simple but effective trip generation method so as to give a quick response, in terms of planning, to adjustment of land use distribution.

Generally, an urban area is divided into zones in traffic modeling process. Related geographic data of zones are its surface and location. Related demographic data of zones include population, education level, income, size of household, etc. Related economic information of zones includes number of jobs, function of land use, total output, etc.

We select surface, population and number of jobs as basic variables in our urban land use and transportation modeling procedure, from which population density, job density and composite density, defined as the summation of population density and job density, can be calculated. Traffic zones are not previously specified as industrial zones or residential zones because of mixed land use. Instead, traffic zones are grouped by their densities and geographic location.

The linear regression method can be employed to find features of trip generation for a zone group. The input variables of the regression may be selected from the basic variables, and output variables may be trip volume of residents and trucks (Mitchell and Rapkin, 1954).

Volume of trip generation is also affected by the level of economic development. We assume in this study that for a given year, the economy in different zones of a city is homogeneous. But the economy could be at different levels in different years. Differences of trip generation among zones in a given year may not be caused by economy, but possibly by the degree of population and job aggregation.

Prediction of trip generation takes as a basis the output of the base year's regression. It is then modified by the development level of the economy. We describe an economic level by two aspects: socio-economic level represented by GDP and average income, and foreign economic level represented by interprovincial and international trade. A modifier should be found to revise the future trip generation.

The method will be discussed in detail in Chapter 4.

Trip distribution. This process distributes zone-based trips to origin-destination pairs, forming an O-D matrix. Again, we should use aggregated data. Possible models are gravity model or entropy model (Mitchell and Rapkin, 1954). Detailed modeling process will be described in Chapter 4.

Equilibrium traffic assignment.

To assign origin-destination traffic to the roadway system, we use the equilibrium traffic assignment method. This is an iterative assignment process. The equilibrium traffic assignment method starts to assign all traffic between an origin-destination to the fast path that connects this origin-destination pair. This initial assignment will cause this fast path very congested and no traffic on other paths. This "fast path" is no longer fast with this assignment. Thus another fast path can be found, and some of the traffic can be moved to this fast path from the previous one. The final result of the equilibrium assignment method is an equilibrium traffic flows. Under the equilibrium status, for any two individuals traveling between a same origin-destination pair, their general costs are equal to each other, no matter what path they choose. This point of view coincides with Wardrop's User Equilibrium Principle (Wardrop, 1952), which has been widely accepted in transportation modeling to describe the natural behavior of independent road users on roadway system. Wardrop's User Equilibrium Principle is described as follows.

> User Equilibrium Principle: At equilibrium, no individual can reduce his/her general cost by unilaterally changing routes.

The equilibrium traffic assignment method will be fully demonstrated in Chapter 4.

Land use and transportation coordination

To evaluate land use and transportation coordination, we should incorporate land use development costs with transportation costs in the mathematical model that represents the land use and transportation coordination problem. To do this, we should introduce the so-called two-level mathematical programming model. In the upper level, urban planners try to appropriately locate population and jobs so as to minimize the total settlement costs and transportation costs, while in the lower level settled road users select paths with perceived minimal travel costs. The objective of the method is to find a solution with the minimum total costs subject to all given restrictions.

The two-level mathematical programming model will be discussed in detail in Chapter 4.

2.2.3 Evaluation of urban land use/freight transportation coordination

Evaluation of land use/freight transportation coordination is based on the desired urban form. Indicators for evaluation include the following:

- whether or not the desired population density and job density fits the freight transportation requirements;
- whether or not the transportation service is adequate.

After evaluation, planners determine if the present land use and freight transportation design is acceptable. If they are satisfied with the design, the land use/freight transportation coordination procedure terminates; if not, there is a need to readjust the land use distribution, or transportation structure, or both of them. Consequently, a new design is put forward after the modification, and a new run of analysis and evaluation on the land use/transportation follows.

In the evaluation system, the first item (the desired population density and job density fits the freight transportation requirements) is easier to check. We are previously given a set of control indicators for this item. The results of the traffic assignment provide forecasting performances for this item. A comparison between the two completes the evaluation.

Evaluation for transportation service is relatively difficult. How much traffic delay on the network is reasonable and acceptable? This is a difficult question. Generally, traffic congestion appears in CBD, the inner city, and on some busy roads in the outer city. Traffic delay in these places may be very serious. But given a usually large outer city, the traffic delay in the whole city could be very small. Furthermore, in places where traffic delay appears, heavy congestion mostly happens during peak hours. While in plain time, traffic performance could be reasonable through excellent. More study is needed for reaching a good explanation for this issue. The problem is out of the scope of this thesis. In this thesis, we assume that the transportation service level is previously selected.

For evaluating the efficiency of the urban system, we shall introduce the operating cost of an urban system. The operating cost is split in two: zone development cost and transportation cost. Transportation cost may be further divided into two parts: construction cost of transportation system and general cost derived from traffic delay. In the land use/transportation coordination procedure, we pursue a land use design and transportation network design with the least total operating cost.

Figure 2.1 shows the flowchart of the urban land use/freight transportation coordination procedure.

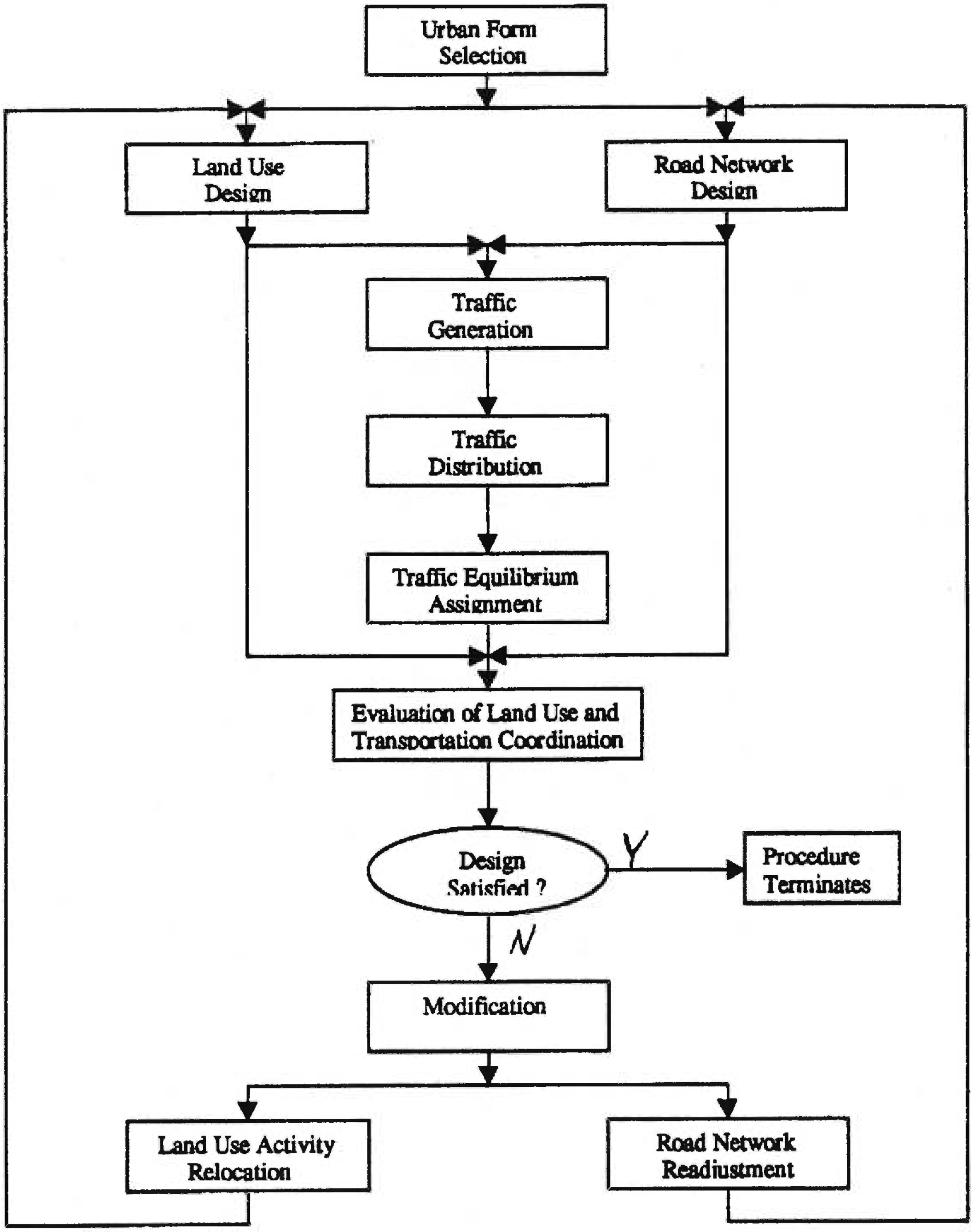

Figure 2.1: Urban Land Use/Freight Transportation Coordination Procedure

2.3 Chapter summary

In this chapter, we first described and analyzed the features of economic development and urban land use transportation system in China. These features greatly affect our modeling procedure. They also determine what methods we can employ in the modeling process. Secondly, a modeling procedure for urban land use and transportation was described. Modeling methods as well as mechanism were also discussed.

We mentioned that there are three issues that should be handled properly in the new planning approach. 1) Both land use development and transportation costs are taken into consideration simultaneously for reaching a coordination. A total settlement and transportation costs is used to evaluate a scenario, together with the problem being treated as a competitive two-level game: urban planner playing at the upper level and road users playing at the lower level. 2) The planning approach is able to generate different urban design scenarios quickly, from one to another. The approach generates a scenario and evaluates it. The result of the evaluation will give out the direction for an improvement. This improvement yields one better scenario. And 3) Population and employment density is used in the land use and transportation model. The data is easy-collecting and easy-adjusting.

Chapter 3

Literature Review

In this chapter, we provide a brief review of urban land use and transportation modeling. Both practices and theories as to urban modeling and planning are covered.

3.1 Introductory Overview

For over four decades, urban modeling has been attracting various theoretical researchers and planning practitioners in geography and urban and regional planning. A great number of research papers have been published, and productive results are achieved in this field (see, for example, Lowry, 1968; Wilson, 1970; Batty, 1976; Boyce, 1984; Erlander and Stewart, 1990).

Chronologically, the history of urban modeling and planning can be roughly divided into four periods.

In the late 1940s and 1950s, major research works of urban modeling addressed the issue of transportation planning. The purpose and content of transportation planning were aimed at easing those obvious inefficiencies of transportation systems – congestion, delay and accidents – producing proposals for capital investment and construction in existing transportation facilities, and improving the operating conditions for present or future flow movement. This planning approach remained unchanged until 1954 with the work of Mitchell and Rapkin (1954), in which they demonstrated that urban traffic is a function of land use. This means that people involved in transportation planning should simultaneously consider land use factors. Following this principle, transportation planning was successful in the 1950s. The planning process includes four steps: trip generation, trip distribution, modal choice and traffic assignment.

The 1960s is the second period of urban modeling, which focused on land use planning. Two major factors stimulated the development and practice of land use planning in that decade. The first is the success of transportation planning in the 1950s. The second is that by that time researchers had established some land use models, mainly concerned with the location of economic activity. These include Isard, who studied space economy location (Isard, 1956); Wingo, who dealt with the intra-urban location case (Wingo, 1961); and Alonso, who developed an economic theory for urban land market (Alonso, 1960). These works, together with others, prepared a concrete basis for the first generation of urban models in the early 1960s (Batty, 1976).

The 1970s and 1980s is the third period during which urban modeling methods became well developed. In this period, some new models, spatial interaction models, with the pioneering contributions of Wilson (1970) and Erlander (1980) in applying the concept of entropy and energy, were developed and applied to urban modeling. Researches and practices show that this is a successful direction to formulate the location and distribution of urban activities (see, for instance, Wilson, 1970; Erlander, 1980; Nijkamp and Reggiani, 1988; Prastacos, 1986; Erlander and Stewart, 1990).

The fourth period began in the late of 1980s. The main subjects of urban modeling and planning during that period are environment and development of Asian countries. Environment is now very close to the top of the political agenda in many countries (TRB 1991). The following question has gained widespread attention: Can cities be planned so as to be more energy-efficient? Because the current status of 'disurbanization' in many North American cities has been proven to waste energy and land, city planners around the world are seeking an urban form which is more energy-efficient. A movement toward reurbanization has already been occurring. Besides, many Asian countries are experiencing a rapid urbanization process. People are also confronted with the conflict of incompatible land uses and environment pollution (McGee, 1991). Developing new theories and new methodologies for handling these new problems has thus become essential.

Looking back at the history of urban modeling and planning, techniques and practices were first developed in North America (Batty, 1976). The urban modeling techniques were also applied in Europe in the 1970s (Freeman et al, 1968; Solesbury and Townsend, 1970; Wegener, 1982; Bertuglia , 1980; etc.). However, successful urban planning is still rarely seen in less developed countries. Because of different cultural and demographic background, urban models developed in North America and Europe cannot directly be applied to those cities (such as cities in Asia). Present methods should be modified to fit changing issues.

In the next section, we will briefly review the methods and practices of urban modeling. Comparisons and comments for those models will also be provided.

3.2 Urban Modeling: methods and practices

3.2.1 Classic transportation planning techniques

The main objective of transportation planning is to ease traffic congestion, delays and accidents. But a method that only considers congestion, delays and accidents is certainly not one that may be used to solve transportation problems, because traffic is a function of land use, and transportation systems may be greatly affected by land use.

A major achievement in the area of transportation studies was made in 1954 by Mitchell and Rapkin (1954). Following an analysis of traffic and land use data, they found that different types of land use generate different and variable traffic flows. Through an understanding of the relationships between land use and transportation, a transportation planning process should be based on a fundamental assumption: traffic demands are directly related to the distribution and intensity of land use. Based on this assumption, a classic traffic planning method was developed in the 1950s. It includes four steps: trip generation, trip distribution, modal choice and traffic assignment.

Trip generation

Four basic techniques can be used to forecast future levels of trip generation: two are land-use based and two are economy based.

- Multiple linear regression analysis. It is a statistic and econometric prediction technique, easily understood and applied. Practices have shown that on a short term, a satisfactory prediction may be achieved through this method. Disadvantages include the difficulty in determining coefficients and an assumption that coefficients determined today will still be valid in the future.

- Category analysis. This prediction method is based on the assumption that trip generation rates exhibited today by different categories will hold good in the future. The number of categories may be very large, because a smaller number of categories may not summarize all situations.

- Economic-base theory. This urban land use model mostly deals with the generation of urban activities and forecast of population in residential zones and employees in different employment sectors: basic sector of industry and non-basic sector of service.

  According to this theory, the growth of an urban (regional) system is directly related to the change of basic sector in the system. This implies that population and employees in non-basic sector are dependent on the state of the basic sector's development. This model is easy to understand and apply. But the prediction is on the macro level. It cannot provide a detailed forecast for variable zones in a studied area.

- Input-output models. Generally speaking, an economy may be divided into N different sectors. The product of one sector may be the final output of the studied urban system, and may also be an intermediate input of other sectors of the system. The outputs and inputs of these sectors are subjected to some constraints, usually expressed by a matrix. By the connection of the relationships one can predict demands for different goods and services. Because labourers are a kind of special goods, this may also be forecast. Population is a function of employment. This method has the same disadvantage as the economic-base theory. It is usually used to make a macro prediction.

Trip distribution

Various methods are aimed at solving the trip distribution problem, the main ones being growth factor method, gravity models, opportunities models and multiple linear regression models.

- Growth factor methods have been well used to distribute trips between zones. They are reliable for a short-term prediction in an area with little or no changes in land use patterns. For a long-term prediction or prediction for a fast changing area, this method is not readily applied.
- Gravity models have a long history of application. We have seen that most planning practices in the 1960s in North America used gravity models. Following a Newtonian analogy, gravity models assume that the amount of interaction between two masses i and j, T_{ij}, is proportional to the total of interaction flows leaving zone i (production), proportional to the total interaction flows terminating at zone j (attraction), and inversely proportional to some function of distance between i and j. With different constraints, gravity models have different forms ranging from fully constrained case, fully unconstrained case, production-constrained case, attraction-constrained case, and partly constrained case.
- The opportunities models are more sophisticated and complex than the gravity model. There are two basic opportunities methods of distributing future trips: the intervening opportunities method and the competing opportunities method. Both methods use the theory of probability as their theoretical foundation.
- Multiple linear regression models may also be used in trip distribution. Their advantages and drawbacks have been discussed above.

Modal choice

Predicting modal choice pattern in the four steps of the transportation planning process is very difficult, because too many uncertainties affect the modal choice pattern.

People choose their travel mode for many reasons, such as travel time, cost, convenience and comfort. Generally, there are two classes of modal choice models: trip end modal choice models and trip interchange modal choice models.

- Trip end models allocate a portion of the total travel demand to the different modes available before trip distribution. This allocation is usually achieved by multiple linear regression techniques.
- Trip interchange models allocate portions of given trip movements resulting from trip distribution to transport modes. The techniques associated with the models include gravity model, multiple regression method, and factor analysis.

Traffic assignment

Traffic volumes on the network are a very important factor in evaluating a planning scenario in urban traffic planning. Various techniques could be used to design a traffic assignment approach.

- All-or-nothing assignment methods suggest that traffic between zones always takes the shortest paths from zone to zone. Therefore, all traffic volumes for an O-D pair are assigned to this shortest path but nothing to the other paths connecting the pair. This method is usually used to create desired traffic lines.
- The minimum cost flow assignment method extends the shortest path method. By assuming that traffic for an O-D pair does not completely take the shortest path, because of the existence of capacity constraint on roads. Traffic should then be assigned to different paths by a minimal total travel cost.
- The multiple path assignment method applies concepts of the Probability Theory to the minimum cost flow assignment method. Trips are assigned to paths by probabilities, with a larger probability to a shorter path and a smaller one to a longer path.

Summing up the methods used in traffic planning in 1950s, the multiple regression and growth factor methods played central roles in trip generation, trip distribution and modal choice. These two simple prediction methods are still in effect today. However, the economic-base theory seems to be out of date, because the theory's assumption, which considered industry as a basic sector and service as an industry-dependent sector, is no longer correct today. Comparing to other methods, gravity models are excellent for formulating trip distribution. But the models did not possess a strong theoretical base until Wilson developed the entropy theory in the late 1960s (Wilson, 1967). Traffic assignment basically is a network problem. Shortest paths, multiple paths and minimum cost flow are essential in network optimization. But no travel delay and dynamic change of traffic flows can be handled in these models. Last but not least, though the classic 4-step traffic planning process introduced land use factors into traffic planning, it only treated these factors in a static way. It did not consider mutual impacts of land use and transportation on each other, and did not consider feedbacks from one to another. Yet these impacts and feedbacks do exist.

3.2.2 Land use models in the 1960s

The first generation of urban models specified by Batty(1976) and developed in the late 1950s and 1960s, may be completely characterized with its practical feature. It may also be summarized as a separate, non-feedback land use and transportation planning method.

The techniques involved in these models included linear regression, non-linear regression models, linear statistic method, gravity models, mathematical programming and hybrid approaches. Table 3.1 lists 14 urban modeling projects in the U.S.A. during the 1960s.

Lowry's model was a great contribution to land use planning in the 1960s. For the first time, the model used the economic-base theory to locate population and employment to zones in a studied area. Gravity models were used to distribute trips between zones, then these trips were assigned to the network and evaluation followed the assignment and checked feasibility of solutions. This process is still valid today in urban land use and transportation planning.

Several review articles summed up this period of urban modeling. Among these, Lowry (1968) and Harris (1968) introduced the models as a new quantitative planning method, whereas Lee (1973) pointed out some negative impacts of these practices.

Table 3.1: Urban Modeling Practice in the USA in the 1960s

Model provider	Applied to the city	Technique adopted
Hansen 1959	Washington D.C.	G
Herbert and Stevens 1960	Penn Jersey	MP
Chapin and Weiss 1962	Greensborough	LST
Crecine 1964	Pittsburgh	G
Lakshmanan 1964	Baltimore	LST
Lowry 1964	Pittsburgh	G
Hill 1965	Boston	LST
Lathrop and Hamburg 1965	New York State	G
Robinson et al 1965	San Francisco	Hybrid
Schlager 1965, 1966	S E Wisconsin	MP, O
Lakshmanan 1968	Connecticut	LST
Wendt et al 1968	Bay Area	Hybrid
Goldner 1968	Bay Area	G
Seidman 1969	Penn Jersey	NLST

MP: Mathematical Programming
LST: Linear Statistical Technique
G: Gravitation
O: Optimization
NLST: Non-Linear Statistical Technique

Indeed we should say that these early practices were not as successful as expected because a lot of them cannot be used effectively owing to various reasons. For external factors, lack of time and money and change of priorities made the practical process somewhat difficult. On the other hand, the quality of these models also limited their successful application. Considering everything being related to urban development, these practices showed excessive ambition to model and solve urban problems (Lee, 1973 and Putman, 1983).

Nevertheless, these endeavors were very valuable because much about urban land use and transport planning was learned through these applications. Firstly, people learned that putting everything related to urban development into an urban model is not realizable. In other words, no existing urban model can handle all land use and transportation factors. Secondly, the principles of the planning process, such as Lowry's model, worked well. But modifications are needed if the models are to manipulate changing status. Thirdly, a feedback process is required to achieve a balance between land use development and transportation development.

3.2.3 Spatial interaction and optimization planning: 1970s and 1980s

In the 1970s and 1980s, researchers and planners developed several new theories and methods in urban modeling and urban land use and transportation planning. Significant progress includes the introduction of entropy and spatial interaction analysis into traffic forecasting, and the development of optimization formulations for land use and transportation coordination.

Entropy and spatial interaction

The theory of maximal entropy originates from the Information Theory, a mathematical theory of telecommunication (Shannon, 1948; Jaynes, 1957). Wilson did pioneer work by introducing this statistical analysis method into spatial interaction modeling, and he developed a widely-used entropy maximizing gravity model (Wilson, 1967; 1970).

The entropy theory on spatial interaction is based on the assumption of individual choice behavior. The assumption states that all individuals (land users, transport mode users, or road users) have an equal probability to make a specific choice for a space of functioning land use, or traffic mode, or path of a trip (Wilson, 1970). Under this assumption, the spatial interaction system will tend to a balance by achieving the maximum of the entropy of individual choices.

The individual choice assumption, also known as discrete choice theory, is widely applicable to spatial interaction systems, such as residence location, employment location, modal choice, trip distribution, intermodal transfer, etc. The entropy theory provides a powerful tool for spatial interaction modeling. There are hundreds of papers involving entropy and spatial interaction. Table 3.2 lists selected papers on the topic.

Traffic planning and optimization

Traffic planning techniques improved a great deal in the 1970s and 1980s. We have

Table 3.2: Selected Papers on Entropy and Spatial Interaction: 1970s and 80s

Author(s)	Category	Author(s)	Category
Beckmann and Golob 1972	DF	Smith 1983	GT
Batty and Machie 1972	GT	Slater 1973	GT
Erlander 1977	TD	Slater 1989	GT
Erlander 1980	TD	Florian and Los 1979	TD
Erlander 1981	TD	Florian and Los 1980	TD
Erlander 1982	TD	Los 1979a	TD
Erlander 1985	TD	Charnes et al 1972	MC
Erlander and Stewart 1990	GT, RE	Hansen 1974	DF, TD
Coelho and Wilson 1977	DF, OP	Dinkal et al 1977	DF, OP
Webber 1975	GT	Nijkamp 1975	RE
Webber 1976	GT	Ben-Akiva and Lerman 1985	DF, RE
Webber 1979	GT	Anas 1983	GT
Smith 1978a	GT	Fisk 1985	GT
Smith 1978b	GT	Bennet et al 1985	RE
Jefferson and Scott 1979	GT	Senior and Wilson 1974	DF, OP
Wilson 1967	GT	Wilson 1970	GT
Wilson 1974	GT		

DF: Demand Forecasting
GT: General Theory
TD: Trip Distribution
RE: Review
MC: Modal Choice

seen that the entropy theory is a powerful tool for modeling traffic demand, trip distribution and modal choice. Progress was also achieved in traffic assignment and traffic optimization. Table 3.3 lists selected papers on advanced traffic planning and optimization.

The equilibrium assignment method was first used in the early 1970s to replace the all-or-nothing method and the multiple path assignment method (LeBlanc et al, 1975 and Florian and Ngyuen, 1976). It has been observed that people always select a path which mostly benefits them for traveling. This is the so-called user optimal principle (Wardrop, 1952). The user optimal principle, associated with the individual choice assumption, leads road traffic to an equilibrium status. At the equilibrium, every path used by road users of an O-D pair is of the same travel cost. The equilibrium assignment model has a considerably complex mathematical formulation, and produces more reliable solutions.

The most recent research on traffic assignment suggests a dynamic assignment model. Traffic movement is a dynamic process. Because a road network may be very large, the dynamic assignment problem is very complicated.

To optimize a land use/transportation system, Koopmans and Beckmann (1957) proposed a model known as Quadratic Assignment Problem, QAP for short, to formulate a facility location problem. Afterwards, the QAP model was widely applied to many problems, such as hospital layout and university campus layout. Based on the QAP formulation, Los (1979) developed a discrete-convex programming model for land use and transportation interaction.

Another important point worth mentioning in this period is that more and more optimization models were used in the practice of land use and transportation (Robert and Schneider, 1987). With the development of computer science, optimization methods are gradually outperforming traditional quantitative methods in land use and transportation modeling. It is believed that the next generation of land use location and transportation models will most probably emerge from mathematical programming formulations (Putman, 1987).

Table 3.3: Selected Papers on Traffic Planning and Optimization: 1970s and 80s

Author(s)	Category	Author(s)	Category
LeBlanc et al 1975	EQ, TP	Black and Blunden 1977	OP
Fisk and Ngyuen 1982	EQ	Coelho and Wilson 1977	OP
Fisk and Boyce 1983	EQ	Dinkal et al 1977	OP
Fisk 1984	EQ	Evans 1973	OP, TP
Boyce 1984	EQ	Los 1979	OP
Dafermos 1980, 1982	EQ	Lundquist 1973	OP, PP
Eash et al 1979	EQ	Openshaw 1977	OP
Fernandes and Friesz 1983	EQ	Senior and Wilson 1974	OP
Friesz et al 1983	EQ	Wilson et al 1981	GT, OP
Ngyuen 1976	EQ	Brotchie 1969	OP, PP
Sheffi and Daganzo 1980	EQ	Sharp and Brotchie 1972	OP, PP
Smith 1979	EQ	Brotchie 1980	OP, PP
Abdulaal and LeBlanc 1979	EQ	Sharp et al 1974	OP, PP
Boyce and Jonson 1980	EQ	Prastacos 1986	OP, PP
Erlander 1977	TP, OP	Robert and Schneider 1987	OP, PP
Erlander 1982	TP	Putman 1987	OP, GT
Florian and Ngyuen 1976	TP	Mackett 1980	OP
Florian et al 1975	TP	Allen et al 1981	OP
Florian and Spiess 1983	TP, EQ	Charnes et al 1977	OP
Los 1979	TP	Tomlin 1971	TP

EQ: Equilibrium
GT: General Theory
OP: Optimization
TP: Traffic Planning
PP: Planning Practice

3.2.4 Methodological research in urban modeling

The improvement of methodology in the 1990s is extremely interesting. New methods, new theories and new models should be developed to meet emerging needs. Mathematical programming methods have been widely used to solve the combined location-distribution-assignment problem and other integrated land use and transportation problems (de la Barra, 1989; Kim, 1989; and Putman, 1991). Mathematical programming methods are important and efficient in this field. A new trend in urban modeling consists in combining multiple techniques and theories to form new approaches.

To help form a framework for hybrid methods, the Geographic Information System (GIS) and expert systems are playing an increasing role. Both the GIS and expert system are new techniques developed in the 1980s.

A Geographic Information System is a computerized database management system for the capture, storage, retrieval, analysis, and display of spatial data (Simkowitz, 1989). The GIS has the capability to capture, store, manipulate analyze, display and output spatial information, statistical result and specified attributes. The main output of a GIS system is some thematic maps. Information contained in the map database is normally geographically referenced using a map projection.

Geographic Information Systems have been successfully applied to resource management, environment surveillance, territory planning and regional planning (TYDAC, 1988). It is also used as an important technology for transportation planning and land use/transportation interaction analysis (Simkowitz, 1989; Nyerges and Dueker, 1988; and Xu, 1993). With GIS, we can gather, manipulate and transform useful land use and transportation information in a more accurate and efficient way. As an example, GIS software can be used to calculate surfaces of zones (Xu, 1993), and the zone surfaces in turn are used to generate population and employment densities. The densities can be used as basic input variables in land use and freight transportation coordination models.

One of advantages of taking densities as input variables in urban planning models is that it allows a computer aided planning system to generate, evaluate and adjust planning scenarios in a relatively easy and efficient way.

An expert system is a computer program capable of performing analytical reasoning in a restricted knowledge domain able to perform tasks that are usually undertaken by an expert (Peterson, 1989). With an expert system, we can combine quantitative methods and qualitative approaches to analyze, synthesize and compare a variety of scenarios in a planning process.

For many years, computer programs have been widely used to generate origin-destination trips and to assign trips to road network. In the rest of this section, we describe a method that can be used to generate and compare a variety of design scenarios, and to achieve land use and transportation coordination to curtain extent.

The traffic volumes are most-wanted output in land use planning and transportation planning. The traffic volume is an important factor in evaluating a planning scenario. To get traffic volumes, a traffic assignment approach is needed to assign origin-destination trips onto the road network. Various techniques can be used to design a traffic assignment approach, including all-or-nothing assignment, minimum cost flow assignment, multiple path assignment and equilibrium assignment method (Batty, 1976; Putman, 1991).

All-or-nothing assignment method suggests that trips from an original zone to a destination zone always take the shortest path from the origin to destination. Therefore all trips are assigned to the shortest path connecting the origin and destination, nothing to the other paths connecting the zones.

Minimum-cost-flow assignment method makes an improvement to the shortest path assignment. It assumes that the trips from one zone to another do not completely go on the shortest path, because of existence of capacity constraint on road segments. The trips are then assigned to curtain different paths connecting the origin and destination by a minimal travel costs.

Multiple path assignment is a method that adjusts the minimum-cost-flow assignment with weighting techniques. Trips are assigned to paths by weights. A shorter path receives a larger weight and longer path smaller weight (Wang, 1993).

When people travel from one place to another they always take a path that most benefits them. This is the so-called user optimal principle (Wardrop, 1952). The most beneficial path may not always be the shortest in distance, because path travel time is proportional to traffic volume on that path. The path travel time increases as traffic volume does. Road users observe and compare road traffic conditions, and select paths that are fastest in time. Each individual follows this process. The accumulation of these selections, as a whole, reaches an equilibrium status on the road network. At this equilibrium status, every path that connects a same origin and destination, has a same travel time. The equilibrium assignment method is a smart method that assigns origin-destination trips to road network to achieve this equilibrium status (Florian and Nguyen 1976; Wu, 1987; Zhang et al, 1993; and Lu, 1993).

The traffic equilibrium status is related to both a given road network and a fixed origin-destination trip distribution. For a given road network, the traffic equilibrium status varies as the origin-destination trip distribution is changed. On the other hand, for a fixed origin-destination trip distribution, the traffic equilibrium status varies as the road network is adjusted. In other words, when land use distribution is adjusted, or population and employment densities are adjusted, or the road network is changed, then the traffic equilibrium status varies too. This observation is the basis for us to seek a land use and transportation coordination through adjustment of population and employment densities.

To do this, we need a new model called two-level mathematical programming model. The two-level mathematical programming problem is an optimization problem with a special constraint function, which is implicitly determined by another optimization problem (Chen, 1994). It is also a mathematical model for two-person, nonzero-sum games with perfect information and specified play order. In the case of urban land use and transportation coordination, we have two players in this game: urban planners against road users. In the upper level, the urban planners try to select zone population and employment densities and road capacities to minimize total settlement and transportation costs; while in the lower level, road users select travel routes to minimize their perceived trip costs. The game is nonzero-sum because it is not true that one's loss must turn out the other's gain, and vice versa. For instance, a bad population and employment distribution could cause road users to spend more time for their home-work trips, while at the same time the total settlement and transportation costs are higher too.

This new urban design and planning approach is to combine elements of GIS and ideas of traffic equilibrium assignment and bi-level programming model to provide understanding and help building scenarios on land use and freight transportation coordination.

Chapter 4

An Urban Land Use and Transportation Coordination Model

In this chapter, we describe our land use and transportation modeling process. The land use modeling process includes an activity location based on urban form selection and a population and job distribution based on demand-supply coordination. The transportation modeling process consists of a trip generation by multiple regression, a trip distribution, and a traffic equilibrium assignment. A model for simultaneously considering the land use development and the transportation development will also be addressed in this chapter.

The remainder of this chapter is organized as follows. Section 4.1 discusses urban form-based activity location. The definition of urban form is given and descriptions of urban form are provided. Section 4.2 introduces the Land Use Design Problem (LUDP) which aims at locating population and jobs in a way that minimizes transportation and settlement costs. Trip generation is the topic of Section 4.3. A method that uses urban form data and economic development information to predict trip production and attraction is addressed in the section. Section 4.4 deals with the trip distribution problem. We shall use gravity model to solve the problem.

4.1 Urban form-based activity location

4.1.1 Definition of urban form

Urban form involves geographic features, land use distribution, transportation structure, and land use/transportation linkage. Geographically, each city has visible features. For example, a city is medium-sized and monocentral, or large-sized and multicentral. Land use distribution can be subitemized as land use intensity and degree of concentration, for example, a city with high density and highlighted CBD. Transportation structure is characterized by traffic restraints and traffic orientation, such as average road area per capita, parking spaces in the CBD, and vehicle-road-length rate. Land use/transportation linkage reflects the interaction degree of land use and transportation, usually expressed by origin-destination (O-D) trip distribution matrices.

Research conducted by Newman and Kenworthy (Kenworthy and Newman, 1987; Newman and Kenworthy, 1989) has shown that strong interrelationships exist among urban factors. To analyze these interrelationships, they created a level system for the urban factors, except for the geographic features. There are five levels: extremely low, low, medium, high, very high. Newman and Kenworthy found that, in modern society, a city with an extremely low land use intensity and degree of concentration always has very low traffic restraints and intensive automobile orientation and, further, an extremely poor transit system and very high gasoline use. In contrast, a city that is organized with a very high density and very strong degree of concentration must relate to strong traffic restraints and intensive non-auto modes – public transit, cycling, or walking (Newman and Kenworthy, 1989). Our own field study in Shanghai also proves that these interrelationships exist.

We select one urban factor, namely urban population and job density, from among the above-mentioned urban factors, to describe the urban form quantitatively. We can do it in this way because the existence of interrelationships among these factors. Therefore, selecting an urban form is to choose for each traffic zone a lower and upper bound for population density and job density.

Table 4.1: Urban Form: Selections of Traffic Orientation and Descriptions

	Land Use Description		Transportation Description	
Transportation Orientation	Land use intensity	Degree of concentration	Level of traffic restraint	Transit performance
intensely auto-oriented	extremely low density	almost none	very unrestrained	extremely poor throughout
predominantly auto-oriented	low density	some	lightly restrained	some good but weak overall
balanced auto and non-auto modes	medium density	centralized	moderate to average transit	some excellent but good overall
substantially non-auto oriented	high density	strong	significantly restrained	uniformly very good
intensely non-auto oriented	very high density	very strong	highly restrained	excellent throughout

Source: Newman and Kenworthy (1989).

Quantitatively, we define urban form as land use intensity and degree of concentration. Land use intensity includes population density and job density in different city belts (CBD, city core, inner city, outer city and suburb). Degree of concentration is represented by proportion of population and jobs distributed in these city belts. Through this quantitative definition, we may use land use attributes to describe urban form.

4.1.2 Urban form-based activity location

The first step in our land use modeling process is selecting urban form. Selecting an urban form means to determine a desired traffic orientation in accordance with the levels listed in Table 4.1. Once an urban form has been chosen for a city, some control restraints associated with the urban form should be set up accordingly.

On the land use side, the size of the city, division of the city belts as well as traffic (or economic) zones should be given. On the demographic side, size of population and jobs in the metropolitan area should be given; and upper bounds and lower bounds for population and job density in different city belts are required.

On the transportation side, we need to embed a road network into the area, determining its topological structure and link parameters. If population and employment distribution are predetermined, finding the network may be described as a Network Design Problem, which is a well-studied optimization problem (see, for example, Dantzig et al, 1979; Abdulaal and LeBlanc, 1979; Marcotte, 1983; LeBlanc and Boyce, 1986; and Marcotte, 1986; among others).

We now briefly discuss the issue of employment structure in an urban area. Jobs in zones are further divided into jobs in industry and jobs in service. Theoretically, jobs could be further subitemized (see, for example, Blunden and Black (1984) among others). But for our purpose to develop a macroscopic land use and transportation model, we think the division of two different classes of jobs is appropriate, not only for the possibility of collecting data, but also for our objective to develop a strategic planning method.

We then have four basic variables associated with a zone: surface, population, jobs in industry and jobs in service, with which three fundamental densities may be calculated. They are population density, industrial job density and service job density. Assuming that the surfaces of zones are previously given, we need to assign people and jobs to zones. What our urban-form-based activity location method is concerned with is that people and jobs should be distributed into zones to make a desired urban form which, as shown in the last section, is determined by population density and job densities on land use aspect.

Therefore we use the following sentences to describe an urban form selection.

Given a metropolitan area which is divided into M smaller traffic zones, **selecting an urban form** on land use side is to set, for each zone, a lower bound and an upper bound for population density, industrial job density and service job density respectively.

Once an urban form is selected, land use activities are located into traffic zones, subject to density restraints and candidate restraints. The consequence of the location process is a distribution of population and jobs in traffic zones, the latter being used as basic variables in our land use transportation coordination procedure.

4.2 Land Use Design Problem

Parallel to the transportation network design problem, we may define a Land Use Design Problem. The problem could be briefly stated as follows: For a metropolitan area with pre-divided zones and a given fixed road network, assign population and jobs into zones to mostly fit the network in the sense of minimizing transportation and settlement costs.

4.2.1 The problem

When an urban form is selected, we should have the following information:

- a metropolitan area which is predivided into M traffic (or economic) zones;
- a fixed road network in the metropolitan area;
- the total (desired or designed) population R in the area;
- the total (desired or designed) industrial jobs, E_1, in the area;
- the total (desired or designed) service jobs, E_2, in the area;
- a lower bound and an upper bound for population density associated with each zone;
- a lower bound and an upper bound for industrial job density associated with each zone; and
- a lower bound and an upper bound for service job density associated with each zone.

The Land Use Design Problem (LUDP) consists in optimally balancing the transportation, investment and maintenance costs of a metropolitan area with a fixed road network subject to congestion, where users behave according to Wardrop's user-optimum principle (Wardrop, 1952). The problem may be stated as: assign R residents, E_1 industrial jobs and E_2 service jobs to M zones, to minimize the total settlement costs plus transportation costs, subject to population density and job density constraints, as well as user optimum constraints.

Los (1979) studied another version of land use design model. In Los (1979), the problem was defined as to assign M discrete activities to M discrete locations, such that each activity is located in one and only one place, so as to minimize an objective function which represents a tradeoff between site costs and transportation costs. Los formulated the problem basically as a quadratic assignment problem of the Koopmans-Beckmann type (Koopmans and Beckmann, 1957), and user equilibrium was not involved.

There are three major differences between Los' land use design model and ours. Firstly, Los distinguished land use into different types such as residence, industry and commerce, while we use a density triplet (population density, industrial job density, and service job density) to implicitly describe the land use function of a zone. Secondly, the decision variables in Los' are discrete while they are continuous in ours. Thirdly, we introduce the user-optimum constraints to our land use design model.

Asakura and Sasaki (1986) suggested an optimal land use design model with traffic congestion. This model is a two-level optimization problem: an upper-level problem and a lower-level problem. In the upper-level problem, urban planners allocate a list of land use activities into zones so that the sum of the total development costs of land use and total transportation costs are minimized. In the lower-level problem, urban citizens seek their residence and select their trip routes to minimize their transportation costs. There was no detailed analysis on subproblems of the model. No solution method was provided.

In the LUDP, settlement costs may include capital investment and running costs of building and operating zones with desired population and job densities. Transportation costs could be measured by link (or path) travel time, or other generalized traffic costs, but it should be carefully transferred to capital cost, to be comparable to settlement costs.

Six bounds shall be attached to each zone in the studied area in the LUDP: a lower bound and an upper bound for population density, industrial job density and service job density respectively. Notice that the bounds may be different from one zone to the next. Throughout this thesis, we always assume that for each of three densities, the upper bound is larger than or equal to its lower bound, which should be non-negative. With this assumption we can deal with different planning situations: designing a totally new area or reshaping one that is already built.

Under the density constraints, virtual densities of population and jobs are variable, and so are O-D matrices. Therefore, the result of traffic assignment is also changeable accordingly although the road network is fixed.

The term of user-equilibrium, or user-optimum, was first provided by Wardrop (1952). The early studies on the user-equilibrium were limited to the case of single mode traffic (Beckmann et al, 1956; Florian et al, 1975; Evans, 1976). It was Dafermos who first introduced multiple modes with interdependent costs into the user-equilibrium trip assignment problem (Dafermos, 1971 and 1972). The multimodal equilibrium will be discussed in Section 4.5.

4.2.2 Mathematical formulation

A road network is composed of nodes and links. There are two different types of nodes, intersections and centroids. The centroids are used to represent zones. Throughout this thesis, the subscript a represents a link of the road network, p a path, i a zone in the studied area, and k represents an O-D pair.

We use the following notations.

N: set of nodes, including centroids and intersections;
I: set of centroids representing zones, $I \subset N$;
A: set of directed links;
Δ_i: surface of zone i, $\Delta = (\Delta_i, i \in I)$;
x_i: population density of zone i, $x = (x_i, i \in I)$;
y_i: industrial job density of zone i, $y = (y_i, i \in I)$;
z_i: service job density of zone i, $z = (z_i, i \in I)$;
$\underline{x}_i$ and $\bar{x}_i$: lower and upper bound for population density of zone i;
$\underline{y}_i$ and $\bar{y}_i$: lower and upper bound for industrial job density of zone i;
$\underline{z}_i$ and $\bar{z}_i$: lower and upper bound for service job density of zone i;
u_a: capacity of link a, $u = (u_a, a \in A)$;
v_a: total flow on link a;
$v = (v_a, a \in A)$: total flow vector;
g_k: trip demand of O-D pair k from origin $i \in I$ to destination $j \in I$, that is $k = (ij)$.

In the land use design problem, we first require a set of population and job balance

$$\Delta^T x = R, \quad \Delta^T y = E_1, \quad \Delta^T z = E_2, \tag{4.1}$$

where R is the total population, E_1 is the total industrial jobs and E_2 is the total service jobs as defined in Subsection 4.2.1. We also impose the following coordination constraints for population density and job densities,

$$l_i(x, y, z) \geq 0, \ \forall i \in I, \tag{4.2}$$

and a set of boundary constraints

$$\underline{x} \leq x \leq \bar{x}, \quad \underline{y} \leq y \leq \bar{y}, \quad \underline{z} \leq z \leq \bar{z}. \tag{4.3}$$

The constraints (4.1) and (4.3) are self-explanatory. The reason for setting constraints (4.2) is that according to economic base theory, the population and the number of jobs, in a city as well as in zones, should have a basic relationship to maintain quality of life (for instance, the number of service jobs should be around 0.12 times the population, see Lowry, 1964 or Batty, 1976, among others). In most practical cases, we may make the following assumption to coordination constraints.

Assumption 4.1 *$l_i(x, y, z)$ is linear and zone-separable, that is*

$$l_i(x, y, z) = a_i x_i + b_i y_i + c_i z_i + d_i.$$

Under assumption 4.1, (4.1) through (4.3) is a linear system of equations and inequalities. We need for the system a further but rational assumption.

Assumption 4.2 *The linear system consisting of (4.1) through (4.3) has at least one solution.*

Let Φ denote the set of all solutions of the system (4.1) through (4.3). Under Assumption 4.2, Φ is non-empty and convex.

Let O_i be the trip production of zone i, and D_j the trip attraction of zone j. Denote by O and D the production vector and attraction vector. Assume that both trip production and attraction are linear functions of densities, that is

$$O = O(x, y, z), \quad D = D(x, y, z) \tag{4.4}$$

where both $O(x, y, z)$ and $D(x, y, z)$ are vector-valued linear functions.

We may use a gravity model to determine the amount of trips traveling between O-D pair $k = ij$ (see Wilson, 1967; Evans, 1970, among others),

$$g_k = \eta_{ij} O_i D_j f(d_{ij}), \ \forall k \in K \tag{4.5}$$

where $\eta_{ij} = \eta_{ij}(O, D)$ is a function of O and D, d_{ij} is the distance between i and j, $f(d_{ij})$ is travel impedance between i and j, and K is the set of all O-D pairs.

The origin-destination demands, $g_k, k \in K$, should be assigned to directed paths between O-D pair k. We use P_k to denote the set of paths connecting O-D pair k and let $P = \bigcup_{k \in K} P_k$.

In any traffic assignment, the flows on path p, h_p, satisfy the following conservation and non-negativity constraints

$$\sum_{p \in P_k} h_p = g_k, \forall k \in K \tag{4.6}$$

$$h_p \geq 0, \forall p \in P$$

Let $h = (h_p, p \in P)$ be a multicommodity path flow vector. When h satisfies (4.6), h is said to be feasible to the LUDP. Denote, by $\Omega(g)$, the set of all feasible multicommodity flow vectors. It is easy to see that $\Omega(g)$ is a convex set for any given g, and determined, indirectly but completely, by $(x, y, z) \in \Phi$ by (4.4) through (4.6).

For a feasible multicommodity flow vector h, the link flows v_a are given by

$$v_a = \sum_{k \in K} \sum_{p \in P_k} \delta_{ap} h_p, \ \ \forall a \in A, \tag{4.7}$$

where δ_{ap} has the value 1 if link a is on path p and 0 otherwise. We refer to $v = (v_a, a \in A)$ as the link load associated with the feasible multicommodity path flow vector h.

We suppose, for the sake of simplicity, that the travel time over a link $a \in A$, denoted by $s_a(v_a)$, is a function of only its flows v_a, although from a general point of view, we should also take into account impacts from other link flows. The travel time of path p, denoted by $S_p(v)$, is then the sum of the link travel times of the links on the path, i.e.,

$$S_p(v) = \sum_{a \in A} \delta_{ap} s_a(v_a), \ \ p \in P_k, \ \ k \in K. \tag{4.8}$$

Two different traffic optimum principles were stated by Wardrop (1952): system optimization versus user-equilibrium. The user-equilibrium has been widely accepted in traffic assignment because it describes the natural behavior of independent road users. It states that at equilibrium no road user can reduce his/her travel time by unilaterally changing route. Let $\mu_k(v)$ be the least path travel time, associated with the link load v, for O-D pair k:

$$\mu_k(v) = \min_{p \in P_k} S_p(v), \ k \in K, \tag{4.9}$$

then Wardrop's user-equilibrium principle may be mathematically described as

$$S_p^*(v^*) - \mu_k^*(v^*) \begin{cases} = 0 \ if \ h_p^* > 0, \\ \geq 0 \ if \ h_p^* = 0 \end{cases} p \in P_k, k \in K \tag{4.10}$$

subject to (4.6) through (4.8). The superscript (*) is used to indicate equilibrium status.

It has been shown that a link load $v^* \in \Omega(g)$ is a user-equilibrium, if and only if it satisfies the following variational inequality

$$s(v^*)^T(v - v^*) \geq 0, \tag{4.11}$$

for all elements v of the convex set $\Omega(g)$ (see, for example, Smith, 1979 and Dafermos, 1981).

Now we are ready to address the Land Use Design Problem (LUDP). The LUDP may be stated as finding appropriate population density and job densities for each zone in a studied area, which minimizes the total transportation costs and settlement costs, subject to population and job balance, land use coordination, density constraints, and network equilibrium constraints. Mathematically, we could formulate the LUDP as follows.
(LUDP)

$$\min s(v)^T v + \sum_{i \in I} b_i(x, y, z) \tag{4.12}$$

subject to

$$s(v)^T(v' - v) \geq 0, \ \forall v' \in \Omega(g), \tag{4.13}$$

$$O = O(x, y, z), \quad D = D(x, y, z), \tag{4.14}$$

$$g_k = \eta_{ij} O_i D_j f(d_{ij}), \ \forall k = ij \in K, \tag{4.15}$$

$$v \in \Omega(g), \quad (x, y, z) \in \Phi. \tag{4.16}$$

where $b_i(x, y, z)$ is the settlement cost of zone $i \in I$ at densities (x, y, z).

In the above formulation, LUDP is a generalized bi-level (or two-level) programming problems (or, a mathematical programming problem with equilibrium constraints). In the upper level, urban planners try to appropriately locate population and jobs so as to minimize the total settlement costs and transportation costs, while in the lower level, through the variational inequality (4.13), settled road users select paths with perceived minimal travel costs. Indeed, the variational inequality constraints (4.13) are equivalent to a convex minimization problem if the Jacobian matrix $\nabla_v s(v)$ is symmetric.

Solution methods for the LUDP involves, coping with our urban form selection, a method for trip generation, one for trip distribution, and one for combined modal choice and traffic assignment equilibrium. In the next three sections, we will respectively discuss these subproblems. Existence of solution for the LUDP and solution methods will be discussed in detail in Chapter 5.

4.3 Trip generation

The trip generation is a regression process based on the information from urban form analysis. In the process, land use characteristics and demographic data are selected as input data, truck trips produced from and attracted by zones are output data. The objective of the method is to provide a quick response to a constantly adjustable activity location.

Input and output variables

The basic data used in the method is surfaces of zones, population, industrial jobs and service jobs located in each zone, production and attraction of truck trips associated with zones. These data can be collected through a comprehensive traffic survey.

From the basic data, the following may be calculated: population density, industrial job density, service job density and composite density. Together with the basic variables, we have the following candidates for input (or explanatory) variables.

X_1 : surface;
X_2 : population;
X_3 : industrial jobs;
X_4 : service jobs;
X_5 : population density;
X_6 : industrial job density;
X_7 : service job density;
X_8 : composite job density($X_8 = (X_3 + X_4)/X_1$); and
X_9 : composite density($X_9 = (X_2 + X_3 + X_4)/X_1$).

In a regression equation, any combination of these variables with no surplus may be taken as input.

The output variables (also known as dependent variables) include

Y_1 : truck trip production; and
Y_2 : truck trip attraction.

We should determine a regression equation for each of the above output variables.

Zone group

Experiments showed that data that are not grouped display no statistic regularity. There are many ways to cluster data. Blunden and Black (1984) used 7 classes to distinguish different urban land use. SCCTPI (1991) differentiated the land use of Shanghai into 14 classes by their functions, and recently added geographic factors (SCCTPI, 1992).

Assuming that generation of truck trips vary according to population density and job densities, we categorize zones into groups by using their geographic features and densities. Zones are first classified into city belts, that is, CBD, city core, inner city, outer city, and suburb. Then, for zones in the same city belt, they are subdivided into groups by their densities.

Zone grouping process

1. divide city into belts;
2. determine density intervals; and
3. group zones.

Regression model

The following multiple linear regression model may be used to determine the trip generations.

$$Y = a_0 + \sum_{i=1}^{n} a_i Z_i$$

where

Y is a dependent variable (it could be any output variable listed above);
$(Z_i, i = 1, ..., n)$ are a group of explanatory variables with no surplus;
a_i is the regression coefficient, $i = 0, 1, ..., n$; and
n is the regression dimension.

By using transportation survey data, we may easily calibrate the coefficients in the regression equation (see, for example, Irving, 1974), and the equation may be employed to estimate trip generation for changing land use.

Furthermore, from the regression process, we get a regression equation that reflects the relationship of trip generation with population density and job densities, under the base year economic condition. We assume that this relationship will still be valid for a prediction year with a minor modification, that is, we keep the linear relationship, but multiply it by a modifier which reflects the change of trip generation rate due to a change in the economic situation.

4.4 Trip distribution

A wide variety of trip distribution models exist in applications which may be divided into two major categories: one using aggregate data and one employing disaggregate data. The aggregate methods are developed based on the assumption that the amount of the interaction between two masses is proportional to the total of production of one mass and the total of attraction of another, and inversely proportional to some function of impedance, which is a transplantation of Newtonian analogy in Physics. The theoretical verification of the assumption was derived by Wilson (1967) by information minimization. The disaggregate methods, on the other hand, are based on individual behavior analysis which suggests that individuals select a trip to maximize its utility. Discrete choice theory provides a fundamental basis for the methods (McFadden, 1973; Ben-Akiva and Lerman, 1985).

Interestingly, despite extreme differences in the foundation of the two methods, there are strong 'similarities' between the two (Anas, 1983). It has been proved that the doubly-constrained gravity model based on aggregate data is identical to a multinomial logit model of joint origin-destination choice based on disaggregated data.

The general form of the aggregate models may be written as

$$g_{ij} = \eta_{ij} O_i D_j f(d_{ij}) \tag{4.17}$$

such that

$$\sum_{j \in I} g_{ij} = O_i, \ i \in I \tag{4.18}$$

$$\sum_{i \in I} g_{ij} = D_j, \ j \in I \tag{4.19}$$

$$g_{ij} \geq 0, \ \forall i, j \in I, \tag{4.20}$$

where

g_{ij} is the predicted trip demand between zone i and zone j;

O_i is the number of trips originating from zone i;

D_j is the number of trips terminating in zone j;

d_{ij} is the distance between zones i and j;

$f(d_{ij})$ is the impedance between i and j; and

η_{ij} is a balancing coefficient.

What the trip distribution process does in the aggregated methods is first to select impedance function $f(d_{ij})$, and then to determine the balancing coefficients η_{ij}. Generally, there are three ways to select the impedance function, using experimental data (growth model, see Fratar, 1954), using gamma function (gravity model, see Batty, 1976 and Erlander, 1980 for instance), and using negative exponential function (entropy maximizing, see Wilson, 1967; Evans, 1970; among others).

The travel impedance can be either calibrated by exogenous values, or by endogenous ones. Ideally this should be endogenous and derived from the traffic assignment. It is quite clear that using endogenous, rather than exogenous travel impedance, would greatly complicate the solution procedure for the LUDP model. Furthermore, this may even lead to unforeseen model inconsistency or bad structural properties. For this reason, we still use exogenous impedance in our model. One of the consequences of the use of exogenous impedance is that these exogenous values may differ greatly from the travel times obtained from the traffic assignment sub-model, and the results produced by overall model can be erroneous. The best action in such a case is to modify the travel impedance according to the traffic assignment results and run the model again in the hope of achieving consistency.

For determining the balancing coefficients, we may employ the matrix balancing method.

Let us rewrite (4.17) as

$$g_{ij} = \alpha_i \beta_j c_{ij} \tag{4.21}$$

where (c_{ij}) is the input matrix. In the growth model, c_{ij} is the base year trip demand between i and j; in the entropy model $c_{ij} = e^{-\theta d_{ij}}$ and $c_{ij} = d_{ij}^{-\lambda} e^{-\theta d_{ij}}$ in the gravity model.

In this reformulation, η_{ij} is separated into α_i and β_j, where α_i represents the production balancing factor for zone i, and β_j the attraction balancing one for zone j.

The matrix balancing method takes as input a matrix (c_{ij}), an origin production vector $O = (O_i)$, and a destination attraction vector $D = (D_j)$, to compute a predicted and balanced O-D matrix (g_{ij}) by finding balancing coefficients α_i and β_j which satisfy equation (4.21), as well as (4.18) through (4.20).

Notice that (4.18) and (4.19) imply

$$\sum_{i \in I} O_i = \sum_{j \in I} D_j. \tag{4.22}$$

Any survey or prediction data should be rounded to satisfy (4.22). But even if (4.22) is satisfied there is still the possibility that no solution exists for the system of equations (4.21) and (4.18) through (4.20). To guarantee the existence of the solution, Bacharach (1970) gave out a necessary and sufficient condition, which will be stated in Chapter 5.

The following iterative method could be used to balance matrices (Fratar, 1954 and Furness, 1965).

Matrix Balancing Algorithm

Step 0 (Initialization) Select a maximum number of balancing iteration, n_0, and a convergence parameter $\epsilon > 0$. Set $n = 0$ (n is the iteration count) and set $\alpha_i^0 = 1, \beta_j^0 = 1$ for all $i, j \in I$.

Step 1 (Balancing rows) For all $i \in I$, compute

$$\alpha_i^{n+1} = \frac{O_i}{\sum_j \beta_j^n c_{ij}}.$$

Step 2 (Balancing columns) For all $j \in I$, compute

$$\beta_j^{n+1} = \frac{D_j}{\sum_i \alpha_i^{n+1} c_{ij}}.$$

Step 3 (Stopping test) Compute the relative error of two successive iterations

$$e = \max\{\max_i\{\frac{\alpha_i^{n+1} - \alpha_i^n}{\alpha_i^{n+1}}\}, \max_j\{\frac{\beta_j^{n+1} - \beta_j^n}{\beta_j^{n+1}}\}\},$$

if $e \leq \epsilon$ or $n = n_0$ **then** stop, otherwise set $n = n + 1$, return to **Step 1**.

The proof of the convergence of the matrix balancing method may be found in Evans (1970). It is worth noting that a more complicated balancing method, namely three-dimensional balancing, was proposed in Evans and Kirby (1974). In addition to trip production and attraction, the impedance distribution of O-D pairs is the third dimension to be involved in the three-dimensional matrix balancing.

Chapter 5

Existence of Solutions and Solution Methods

This chapter is devoted to the theoretical analysis of the Land Use Design Problem. The conditions of existence and uniqueness of solution to the problem are investigated, and solution methods are also discussed. Because we introduce the equilibrium into our trip behavior assumption, and adapt gravity model in trip distribution, our solution methods for the LUDP must be able to solve the two latter problems as well. We shall first discuss the existence and uniqueness of solution and solution methods for the two latters. Fortunately, quite good analytical properties exist for the two well-studied problems in the literature.

This chapter is organized as follows. Section 5.1 introduces basic definitions for later use. Section 5.2 discusses the trip distribution problem, focusing on analytical properties of O-D pair demands as a function of trip production and attraction. The equilibrium problem will be discussed in Section 5.3. Most of our attention will be focused on the analytical properties of path flows or link loads that are treated as a point-to-set mapping of O-D pair demands. In Sections 5.4, the LUDP will be investigated . The conditions of existence and uniqueness of solutions to the problem will be derived, and solution methods will be suggested. Section 5.5 concludes the chapter.

5.1 Preliminary Notes

In this section, we introduce some definitions of matrix connection, set-valued mapping, and monotonicity of vector functions.

A matrix A is said *disconnected* if A may be rewritten as

$$\begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix}$$

by successively interchanging the elements of two rows, or, of two columns (i.e., carring out the elementary transformation of row or column). A matrix is called *connected* if it is not disconnected. (Regarding a graph or a network, if the graph is connected, so is its node-to-node adjacency matrix.)

We now introduce the concept of monotonicity of a vector mapping. Let $s(v)$ be a mapping from a subset $\Omega \subset R^n$ into R^n. $s(v)$ is said to be *monotone* on Ω if

$$(s(v') - s(v''))^T(v' - v'') \geq 0, \quad \forall v', v'' \in \Omega;$$

$s(v)$ is said to be *strictly monotone* on Ω if

$$(s(v') - s(v''))^T(v' - v'') > 0, \quad \forall v', v'' \in \Omega \text{ and } v' \neq v'';$$

$s(v)$ is said to be strongly monotone on Ω if there exists an $\alpha > 0$ such that

$$(s(v') - s(v''))^T(v' - v'') > \alpha ||v' - v''||^2, \quad \forall v', v'' \in \Omega;$$

where $|| \cdot ||$ denotes the Euclidean norm on R^n.

In the case where $s(v)$ is the gradient of some differentiable function f, then the above definitions of monotonicity correspond to the concepts of convexity of f. When $s(v)$ itself is differentiable, we have the following relationship: $s(v)$ is monotone (strictly monotone) on Ω if and only if $\nabla s(v)$ is semi-positive definite (positive definite) for all $v \in \Omega$, and $s(v)$ is strongly monotone on Ω if and only if there exists a positive α such that $\nabla s(v) - \alpha E$ is positive definite for all $v \in \Omega$, where E represents the identity matrix.

The concept of set-valued mapping will often be used in the rest of the chapter. Here is a brief introduction to the concept.

Let X and Y be two sets. A *set-valued mapping* $F : x(\in X) \longrightarrow F(x)(\subset Y)$ is a mapping that maps any $x \in X$ to a subset $F(x)$ of Y. If for any $x \in X$, it has $F(x) = y \in Y$, F then reduces to an ordinary single-valued mapping.

A set-valued mapping F is said to be *lower semicontinuous* at $x^0 \in X$ if for any sequence in X, $\{x^k\} \longrightarrow x^0$, and for any $y^0 \in F(x^0)$, there exists a sequence $\{y^k\} \subseteq Y$ such that $y^k \in F(x^k)$ for sufficient large k and $y^k \longrightarrow y^0$.

A set-valued mapping F is said to be *upper semicontinuous* at $x^0 \in X$ if for any sequence in X, $\{x^k\} \longrightarrow x^0$, and for any $y^k \longrightarrow y^0$ such that $y^k \in F(x^k)$, one must have $y^0 \in F(x^0)$.

If at $x^0 \in X$, F is both lower semicontinuous and upper semicontinuous, F is said to be *continuous* at x^0. (Strictly speaking, for the definitions of the continuity of set-valued mapping, X and Y should be topological spaces.)

5.2 Trip distribution

In the LUDP proposed in Chapter 4, we assumed that trips are distributed according to Wilson's entropy maximization (or information minimization) principle (Wilson, 1967). For a given trip production vector $O = (O_i, i \in I) > 0$, and an attraction vector $D = (D_j, j \in I) > 0$ such that

$$\sum_{i \in I} O_i = \sum_{j \in I} D_j \tag{5.1}$$

we used the following system of equations to model trip demand g_{ij} for the O-D pair $ij, i, j \in I$ (see Section 4.4),

$$g_{ij} = \alpha_i \beta_j c_{ij} \tag{5.2}$$

such that

$$\sum_{j\in I} g_{ij} = O_i,\ i \in I \tag{5.3}$$

$$\sum_{i\in I} g_{ij} = D_j,\ j \in I \tag{5.4}$$

$$g_{ij} \geq 0,\ \forall i, j \in I, \tag{5.5}$$

where $c_{ij} \geq 0$ is the pre-given impedance for traveling from i to j and $\alpha_i, i \in I$, and $\beta_j, j \in I$, are parameters to be determined.

In the above formulation, it is apparent that $g_{ij} = 0$ if $c_{ij} = 0$. Furthermore, if $c_{ij} > 0$ and g is a solution of (5.2) – (5.5), then one must have $g_{ij} > 0$ because $O > 0$ and $D > 0$. For $c_{ij} > 0$, compose the function $Z(g_{ij}) = g_{ij} ln \frac{g_{ij}}{c_{ij}e}$ in which e is the natural exponent and ln is the natural logarithmic function. Let

$$K' = \{k = ij | c_{ij} > 0, i, j \in I\}$$

and define

$$Z(g) = \sum_{k\in K'} Z(g_k) = \sum_{k\in K'} g_k ln \frac{g_k}{c_k e}$$

then the system of equations (5.2) through (5.5) is equivalent to the following optimization problem

$$\min Z(g) = \sum_{k\in K'} g_k ln(g_k/ec_k) \tag{5.6}$$

subject to (5.3), (5.4) and

$$g_k > 0,\ \forall k \in K'. \tag{5.7}$$

In fact, the constraint set of problem (5.6) is convex. Function $Z(g)$ is twice continuously differentiable and its second order partial derivatives are

$$\frac{\partial^2}{\partial^2 g_k} Z(g) = \frac{1}{g_k} > 0, \ \forall k \in K', \quad \frac{\partial^2}{\partial g_k \partial g_{k'}} Z(g) = 0, \ \ \forall k, k' \in K', \ \ k \neq k'.$$

This shows that the Hessian matrix of $Z(g)$ is positive definite, and $Z(g)$ has only one minimum point if it has feasible solutions. In the case of existence of feasible solutions, the first order derivatives of the Lagrangian function of the problem must vanish at the minimum, i.e.,

$$ln(\frac{g_{ij}}{ec_{ij}}) + 1 + \alpha_i + \beta_j = 0, \ \forall k = ij \in K', \tag{5.8}$$

where α_i and β_j are the Lagrange multipliers associated with constraints (5.3) and (5.4).

Solving (5.8), we get

$$g_{ij} = e^{-\alpha_i} e^{-\beta_j} c_{ij}, \ \forall ij \in K'.$$

This is the same form as that in (5.2). We have thus proved the following theorem.

Theorem 5.2.1 *(Wilson, 1967) The system of equations (5.2) through (5.5) is equivalent to the optimization problem (5.6) subject to (5.3), (5.4) and (5.7).* □

By the above theorem, the uniqueness of solutions to the system of equations (5.2) through (5.5) can be easily achieved.

Corollary 5.2.1 *(Bacharach, 1970 and Evans 1970) The system of equations (5.2) through (5.5) has at most one solution.*

Proof The system of equations (5.2) through (5.5) is equivalent to the minimization problem (5.3), (5.4), (5.6) and (5.7) by Theorem 5.2.1. But $Z(g)$ in (5.6) has a positive definite Hessian matrix, so it is convex. This completes the proof. $\square$

Notice that the Lagrange multipliers are not unique to this point, because when (α, β) solves (5.2) – (5.5), so does $(\lambda\alpha, \beta/\lambda)$ for any scalar $\lambda > 0$. For simplicity, we henceforth always take $\alpha_1 = 1$ to make (α, β) unique. This does not imply any loss of generality, for it always holds $\alpha > 0$ and $\beta > 0$ when (5.2) – (5.5) has a solution for $O > 0$ and $D > 0$.

The existence of solutions for the system of equations (5.2) through (5.5) is guaranteed by (5.1) when $c_{ij} > 0$ for all $i, j \in I$.

Theorem 5.2.2 *(Bacharach, 1970 and Evans 1970) Assume $c_{ij} > 0$ for all $i, j \in I$, then (5.2) through (5.5) has solutions if and only if (5.1) is valid, that is, $\sum_{i \in I} O_i = \sum_{j \in I} D_j$.*
$\square$

In the case that the positivity is not valid for some c_{ij}, Bacharach (1970) provided a general result. Let I' and J' be subsets of I such that

$$c_{ij} = 0, \ \forall i \in I', \ j \in J'. \tag{5.9}$$

Theorem 5.2.3 *(Bacharach, 1970) The system of equations (5.2) through (5.5) has solutions if and only if, for any subsets I' and J' in (5.9), it holds*

$$\sum_{i \in I'} O_i \leq \sum_{j \in \bar{J}'} D_j, \quad \sum_{j \in J'} D_j \leq \sum_{i \in \bar{I}'} O_i. \tag{5.10}$$

Notice that (5.1) is a special case of (5.10).

As was addressed in Section 4.4, the unique solution of (5.2) through (5.5) may be determined by an iterative method. For completeness and convenience, we rewrite the method as follows.

Algorithm For Trip Distribution (Fratar, 1954 and Furness, 1965)

Step 0 (Initialization):

Select a control parameter $\epsilon > 0$. Set $n = 0$ and $\alpha_i^0 = \beta_j^0 = 1, \quad \forall i, j \in I$.

General Step: Compute

$$\alpha_i^{n+1} = \frac{O_i}{\sum_j \beta_j^n c_{ij}}, \forall i \in I,$$

$$\beta_j^{n+1} = \frac{D_j}{\sum_i \alpha_i^{n+1} c_{ij}} \quad \forall j \in I,$$

if

$$\max\{\max_i\{\frac{\alpha_i^{n+1} - \alpha_i^n}{\alpha_i^{n+1}}\}, \max_j\{\frac{\beta_j^{n+1} - \beta_j^n}{\beta_j^{n+1}}\}\} \leq \epsilon,$$

then stop, **else** set $n := n + 1$ and repeat the *General Step.*

The convergence of the algorithm is addressed in the following.

Theorem 5.2.4 *(Bacharach, 1970 and Evans, 1970) The above Fratar-Furness algorithm converges to the unique solution of the system of equations (5.2) through (5.5), if*

(B1) condition (5.10) is valid; or

(B2) condition (5.1) is valid and $c_{ij} > 0$ *for all* $i, j \in I$. □

Hereinafter we always assume that either (B1) or (B2) holds. Hence (5.2) through (5.5) defines a single-valued mapping $g = g(O, D)$ from a subset, which is defined by (5.1) or (5.10), of R_+^{M+M} into $R_0^{M\times M}$, where M is the number of traffic zones, R_0 is the set of non-negative real numbers and R_+ the set of positive real numbers.

We next introduce some analytical properties of the trip distribution g_{ij} as the function of production $O = (O_i)$ and attraction $D = (D_j)$.

Let

$$f_k(O, D, \alpha, \beta) = \begin{cases} \sum_{j\in I} \alpha_k \beta_j c_{kj} - O_k, & k = 1, 2, ..., M, \\ \sum_{i\in I} \alpha_i \beta_{k-M} c_{i,k-M} - D_{k-M}, & k = M+1, M+2, ..., M+M, \end{cases} \tag{5.11}$$

and let $f = (f_k)$, then $f(O, D, \alpha, \beta) = 0$ has a unique solution (α^0, β^0) at (O^0, D^0) provided it satisfies (B1) or (B2). For this formulation, we have the following theorem.

Theorem 5.2.5 *(Bacharach, 1970) Suppose that* $C = (c_{ij})$ *is connected (see Section 5.1 for the definition) and* $f(O^0, D^0, \alpha^0, \beta^0) = 0$. *Then there exists a function* $\phi(O, D)$ *defined on pairs* (O, D) *in a neighborhood of* (O^0, D^0) *and satisfying* $\sum_i O_i = \sum_j D_j$,

(i) such that $(\alpha, \beta) = \phi(O, D)$ *provides the unique solution of* $f(O, D, \alpha, \beta) = 0$;

(ii) being continuous in O, D; *and*

(iii) having continuous partial derivatives with respect to O *and* D. □

Obviously we have the following

Corollary 5.2.2 *Under the assumptions of Theorem 5.2.5, there exists a function* $\psi(O, D)$ *defined on pairs* (O, D) *in a neighborhood of* (O^0, D^0) *and satisfying* $\sum_i O_i = \sum_j D_j$,

(i) such that $g = \psi(O, D)$ *provides the unique solution to (5.2)–(5.5);*

(ii) being continuous in O, D; *and*

(iii) having continuous partial derivatives with respect to O *and* D. □

We subsequently show an explicit way to determine the partial derivatives of g with respect to O and D.

Let $A = (a_{ij})$ be a square matrix of dimension n. The ith column of A is denoted by a^i, $i = 1, 2, ..., n$, and the jth row $a_j, j = 1, 2, ..., n$. E represents the identity matrix. The dimension of E is omitted here and should be appropriate to the context when it applies.

For a vector b, we use $\langle b \rangle$ to denote the matrix taking b as its diagonal and 0 for others. $\bar{b}$ is the vector resulting from the deletion of the first element of b (therefore $\bar{b}$ is $(n-1)$-dimensional if b is of dimension n). $\bar{A}$ is the matrix obtained by removing the first row from A, and A_{11} the matrix by removing both the first row and the first column of A.

Theorem 5.2.6 *(Bacharach, 1970) Let* $U = (O, D)$, *then we have*

$$\frac{\partial g_{ij}}{\partial U_l} = (\lambda_{il} + \lambda_{M+j,l}) g_{ij}, \forall i, j \in I \text{ and } l = 2, 3, ..., M + M,$$

where $\Lambda = (\lambda_{kl})$ *is a matrix of order* $2M \times (2M - 1)$, *of the form*

$$\Lambda = \begin{pmatrix} 0 & 0 \\ \Gamma & -\Gamma\Pi \\ -\Pi^T\Gamma & \Pi^T\Gamma\Pi + \langle D\rangle^{-1} \end{pmatrix},$$

where

$$\Gamma = B_{11}^{-1}\langle \bar{O}\rangle^{-1}, \quad \Pi = \bar{G}\langle D\rangle^{-1}, \quad \text{and} \quad B = E - \langle O\rangle^{-1} G \langle D\rangle^{-1} G^T,$$

and

$$G = (g_{ij}) = (\alpha_i \beta_j c_{ij}). \ \square$$

The proof of the theorem may be found in Bacharach (1970) (Chapter 5). The elements of Λ are referred to as the 'growth rates' which reflect relative rates of change of the α and β with respect to $(\bar{O}, D)$. The first row of Λ is 0 because we set $\alpha_1 = 1$. The dimension of Λ is $2M$ by $(2M - 1)$ because O_1 is a linear combination of $\bar{O}$ and D. Notice that $\bar{\Lambda}$ is symmetric, which means that the effect of variation of the lth element of (O, D) on the kth element of (α, β), $l, k = 2, 3, ..., M + M$, is identical to the one of the kth element of (O, D) on the lth element of (α, β).

5.3 Equilibrium assignment

In Section 4.2 we have achieved a variational inequality formulation for equilibrium assignment problems. For $g = (g_k)$ the given O-D demands, a link load $v^* \in \Omega(g)$ is said to be an equilibrium assignment if and only if the following variational inequality holds

$$s(v^*)^T(v - (v)^*) \geq 0, \tag{5.12}$$

for all $v \in \Omega(g)$, where $s(v)$ is the user cost function, which is continuous and strictly decreasing. And $\Omega(g)$ is defined by

$$\Omega(g) = \{h | \sum_{p \in P_k} h_p = g_k, \ h_p \geq 0, \ \forall k \in K\} \tag{5.13}$$

and the link load v is determined by

$$v_a = \sum_{k \in K} \sum_{p \in P_k} \delta_{ap} h_p, \ \forall a \in K. \tag{5.14}$$

It is easy to see that $\Omega(g)$ is nonempty, convex and compact. Furthermore, as a point-to-set mapping from g-space to h-space, $\Omega(g)$ is upper semi-continuous on its domain (Chen and Florian, 1994).

The existence of solutions of the variational inequality (5.12) - (5.14) was investigated by many authors (see Dafermos, 1980 and 1982; Aashtiani and Magnanti, 1981; among others). The following theorem is due to Smith (1979) and Aashtiani and Magnanti (1981).

Theorem 5.3.1 *(Smith, 1979; Aashtiani and Magnanti, 1981) If the user cost function $s(v)$ is continuous and positive, then the equilibrium assignment problem formulated as (5.12) - (5.14) has solutions.* □

Assuming $s(v)$ is continuous, we denote by $\Omega^*(g)$ the solution set of the variational inequality (5.12) - (5.14). Harker and Pang (1990) and Chen and Florian (1994) have proved that $\Omega^*(g)$, a point-to-set mapping from g-space to h-space, is also upper semi-continuous provided $s(v)$ is continuous.

Theorem 5.3.2 *(Harker and Pang, 1990; Chen and Florian, 1994) If the user cost function $s(v)$ is continuous, then the solution mapping $\Omega^*(g)$ defined by (5.12)–(5.14) is upper semi-continuous on g.* □

The uniqueness of the solution to (5.12) - (5.14) may be derived upon the strict monotonicity of $s(v)$.

Theorem 5.3.3 *(Smith, 1979; Aashtiani and Magnanti, 1981) If $s(v)$ is continuous and strictly monotone, then the variational inequality (5.12) - (5.14) has at most one solution.* □

A direct consequence of the above is the following.

Corollary 5.3.1 *If* $s(v)$ *is continuous and strictly monotone, then the mapping* $\Omega^*(g)$ *is single-valued and varies continuously on* g. □

Because we assume $s(v)$ is link-separable, the condition of strict monotonicity of $s(v)$ is equivalent to that of each $s_a(v_a)$ for all $a \in A$. We thus impose the following assumption in the rest of the chapter.

Assumption 5.1 The link user cost function $s_a(v_a)$ is continuously differentiable and strictly monotone for all $a \in A$. □

It is well known (see Ortega and Rheinboldt, 1970) that $s(v)$ is strictly monotone on the set of feasible flows if and only if the Jacobian matrix of s is positive definite for all feasible v. Thus Assumption 5.1 implies that $\nabla s_a(v_a)$ is positive definite for all $a \in A$.

Various solution methods exist for the variational inequality problem(see Harker and Pang, 1990 for a detail review). For example, we may use the following general iterative approaches to solve the variational inequality problem $VIP(\Omega, s)$ (see Wu et al, 1993). The approaches consist in creating a sequence $\{v^k | v^k \in \Omega\}$ such that each v^{k+1} solves the problem $VIP(\Omega, s^k)$:

$$s^k(v^{k+1})^T(v' - v^{k+1}) \geq 0, \quad \forall v' \in \Omega,$$

where $s^k(v)$ is some approximation to $s(v)$. For instance, the linear approximation is

$$s^k(v) = s(v^k) + B(v^k)(v - v^k).$$

In the case of using the above linear approximation, the method turns to the Projection method when $B(v)$ is a constant and positive symmetric definite matrix (Dafermos, 1980); the Newton's method when $B(v) = \nabla s(v)$; the Quasi-Newton method when $B(v) \approx \nabla s(v)$ (Josephy, 1979); the Symmetrized Newton method when $B(v) = \frac{1}{2}(\nabla s(v) + \nabla s(v)^T)$ (Hammond, 1984); and Linearized Jacobi method when $B(v) = diag(\nabla s(v))$, among many others.

5.4 Land Use Design Problem

5.4.1 Model analysis and existence of solutions

In section 4.2 the Land Use Design Problem is defined as to find population densities and job densities (x, y, z) which solves the problem

$$\min s(v)^T v + \sum_{i \in I} b_i(x, y, z) \tag{5.15}$$

subject to

$$s(v)^T(v' - v) \geq 0, \quad \forall v' \in \Omega(g), \tag{5.16}$$

$$g_{ij} = g_{ij}(O, D), \ \forall k = ij \in K, \tag{5.17}$$

$$O = O(x, y, z), \tag{5.18}$$

$$D = D(x, y, z), \tag{5.19}$$

$$(x, y, z) \in \Phi, \tag{5.20}$$

$$v \in \Omega(g). \tag{5.21}$$

where

I is the set of centroids (zones);
K is the set of O-D pairs;
v' and v are link loads of feasible flow vectors;
$s(v)$ is the link user cost vector;
x, y, z are density vectors for population, industrial jobs and service jobs respectively;
$b_i(x_i, y_i, z_i), i \in I$ is the settlement cost for zone i;
$O(x, y, z)$ and $D(x, y, z)$ are vector-value functions in x, y and z;

Further, as was mentioned in Chapter 4, Φ is the solution set of the following system of equations and inequalities.

$$\Delta^T x = R, \quad \Delta^T y = E_1, \quad \Delta^T z = E_2, \tag{5.22}$$

$$l_i(x_i, y_i, z_i) \geq 0, \ \forall i \in I, \tag{5.23}$$

$$\underline{x} \leq x \leq \bar{x}, \ \ \underline{y} \leq y \leq \bar{y}, \ \ \underline{z} \leq z \leq \bar{z} \tag{5.24}$$

where

R is the total population to be assigned in the studied area, E_1 and E_2 are total number of jobs in industry and service respectively;

Δ_i is the surface of zone i and $\Delta = (\Delta_i : i \in I)$;

$\underline{x}$, $\bar{x}$, $\underline{y}$, $\bar{y}$, $\underline{z}$, $\bar{z}$ are lower and upper bound vectors for population and jobs respectively;

$l_i(x_i, y_i, z_i), i \in I$ is a given linear function;

$g = (g_{ij})$ is the trip demand, with respect to O and D, determined by (5.2) – (5.5); and

$\Omega(g)$ is the feasible flow set, with respect to O-D demand g, defined by (5.13) – (5.14).

In the previous sections of this chapter, we have shown that under some rational conditions, the equilibrium flow v^* in 5.16 is a continuous and single-valued mapping of the traffic demand g, and g in turn is a continuous and single-valued mapping of trip generation O and attraction D. We next investigate properties of the constraint set Φ, the production O and the attraction D as functions of (x, y, z).

First we investigate conditions for ensuring the non-emptiness of the constraints set Φ (Assumption 4.1). Evidently, we should have, from (5.22) and (5.24),

$$\Delta^T \underline{x} \leq R \leq \Delta^T \bar{x}, \ \Delta^T \underline{y} \leq E_1 \leq \Delta^T \bar{y}, \ \Delta^T \underline{z} \leq E_2 \leq \Delta^T \bar{z}. \tag{5.25}$$

We further assume, in this thesis, that the relationship among densities of a zone (constraint (5.23)) is

$$\omega x_i \leq z_i, \ \forall i \in I, \tag{5.26}$$

that is, the service jobs should be no less than a fixed percentage, ω, of the population in every zone. To ensure (5.26) having a solution, we should impose the condition

$$\omega R \leq E_2 \tag{5.27}$$

$$\omega \underline{x}_i \leq \bar{z}_i \tag{5.28}$$

Hereinafter we shall refer to (5.25), (5.27) and (5.28) as the density constraint standard, and throughout the rest of the chapter we impose the following assumption.

Assumption 5.2 The density constraint standard is satisfied for the constraint set Φ.

Under Assumption 5.2, Φ is non-empty. Next we turn our attention to trip generation. We may assume that $c_{ij} > 0$ for all $ij \in K$ without loss of generality.

Assumption 5.3 The travel impedance between zones is positively finite.

Under Assumption 5.3, g will always have a unique solution provided $\sum_i O_i = \sum_j D_j$ (Corollary 5.2.2). We may now further explore this solution as it varies in (x, y, z).

In Chapter 4, we mentioned that O_i and D_j are linear functions which are first determined by a regression method by transportation survey data of a base year, then modified by multipliers which reflect predicted future social and economical changes. Following several transportation planning practices in China (SCCTPI, 1991 and 1992; JCPB, 1992), we bring some reasonable simplifications into the model.

1. The trips produced by a zone could be written as

   $$O_i = o_{i0} + o_{i1}\Delta_i x_i + o_{i2}\Delta_i y_i + o_{i3}\Delta_i z_i$$

   where o_{i0}, o_{i1}, o_{i2} and o_{i3} are coefficients determined by base year transportation survey data. And o_{i1} may be further subitemized into a triplet $(o^i_{hw}, o^i_{ho}, o^i_n)$ standing for, respectively, the production rate of home-based work trips, home-based other trips and non-home-based trips. They may vary from a class of zones to another, but may not necessarily differ from zone to zone.

2. The trips attracted by a zone could be written as

   $$D_j = d_{j0} + d_{j1}\Delta_j x_j + d_{j2}\Delta_j y_j + d_{j3}\Delta_j z_j$$

where d_{j0}, d_{j1}, d_{j2} and d_{j3} are fixed regression coefficients.

3. In future years, the production rates of home-based other trips and non-home-based trips will change, but the rates of home-based work trip remain unchanged. On the attraction side, the attraction rates of industrial jobs are sustained in future years, but those of service jobs will move to a new level.

By the above simplification and specification, we may write trip productions and attractions in a future year as

$$O_i = o_{i0} + (o^i_{hw} + \tau o^i_{ho} + \sigma o^i_n)\Delta_i x_i + o_{i2}\Delta_i y_i + o_{i3}\Delta_i z_i, \tag{5.29}$$

$$D_j = d_{j0} + d_{j1}\Delta_j x_j + d_{j2}\Delta_j y_j + \varphi d_{j3}\Delta_j z_j, \tag{5.30}$$

where τ, σ and φ are multipliers.

To ensure the existence of solutions to the trip distribution, the necessary and sufficient condition is, by Theorem 5.2.2, $\sum_i O_i = \sum_j D_j$ under Assumption 5.3. In the future year, the condition turns to the following form based on the previous specification.

$$\sum_{i\in I}(o_{i0}+o_{i1}\Delta_i x_i+o_{i2}\Delta_i y_i+o_{i3}\Delta_i z_i) = \sum_{j\in I}(d_{j0}+d_{j1}\Delta_j x_j+d_{j2}\Delta_j y_j+\varphi d_{j2}\Delta_j z_j). \tag{5.31}$$

In an optimization process these densities x_i, y_i and z_i will vary in their domain moving to a 'coordinate position'. It is noted that to keep (5.31) valid when some (x, y, z) varies in its domain, one may slightly modify the multiplier φ by taking

$$\varphi = \frac{\sum_i O_i - \sum_j (d_{j0} + d_{j1}\Delta_j x_j + d_{j2}\Delta_j y_j)}{\sum_j d_{j3}\Delta_j z_j}. \tag{5.32}$$

(It is also possible to modify the multiplier σ on the production side. Decision is relied on different confidences on total production or attraction. In this thesis, we keep production multipliers unchanged but attraction one modifiable.)

Now we begin to discuss the existence of solutions to the LUDP and solution methods. First we have the following existence theorem for the LUDP.

Theorem 5.4.1 *Suppose Assumption 5.2 and 5.3 are valid and link user costs* $s_a(v_a), a \in A$ *are continuous, and let* φ *be taken as in (5.32). Then*

(i) g *is a single-valued, continuous function of* (x, y, z) *on its domain;*

(ii) g *is partially differentiable with respect to* x, y, z*; and*

(ii) the LUDP defined by (5.15)–(5.21) has a solution.

Proof Under Assumption 5.2, Φ is non-empty, then $O = O(x, y, z)$ and $D = D(x, y, z)$ are well defined. An initial selection of τ, σ and φ shall make (5.1) valid for at least one point in Φ. Furthermore for any $(x, y, z) \in \Phi$ such that $\sum_i O_i(x_i) = \sum_j D_j(y_j, z_j)$, where O_i and D_j is given in (5.29) and (5.30) respectively, Corollary 5.2.2(i) guarantees the existence and uniqueness of solution of g with respect to O and D. This solution is continuous in O and D, and has continuous partial derivatives with respect to O and D by Corollary 5.2.2(ii) and (iii). But O and D are both linear functions of (x, y, z) respectively. This proves the assertion (i) and (ii). However g in turn well defines the feasible flow set $\Omega(g)$. Then, according to Theorem 5.3.2, the solution mapping $\Omega^*(g)$ defined by (5.16) is upper semi-continuous. Notice that the set (v, x, y, z) is compact, it turns then out the assertion (iii) of the theorem(see Harker and Pang, 1990). □

Under the conditions of Theorem 5.4.1, (5.17)–(5.19) may be merged into $g = g(x, y, z)$, then $\Omega(g)$ could be rewritten as

$$\Omega(g) = \{h | \Lambda h = g(x, y, z), (x, y, z) \in \Phi \bigcap D(g)\}$$

where Λ is the path-OD pair incidence matrix and $D(g)$ is the domain of $g(x, y, z)$.

Under Assumption 5.1, for each $g(x, y, z)$, the variational inequality (5.16) has a unique link loads and a unique least path cost μ_k corresponding to OD pair $k \in K$. By using μ, we may rewrite the LUDP as the following.

$$\min \mu^T g(x, y, z) + \sum_{i \in I} b_i(x, y, z) \tag{5.33}$$

subject to

$$S(h) - \Lambda^T \mu \geq 0, \tag{5.34}$$

$$h^T(S(h) - \Lambda^T\mu) = 0, \tag{5.35}$$

$$\Lambda h - g(x, y, z) = 0, \tag{5.36}$$

$$h \geq 0, \tag{5.37}$$

$$(x, y, z) \in \Phi. \tag{5.38}$$

Theorem 5.4.2 *Under Assumption 5.1 through 5.3, (5.33)–(5.38) is equivalent to (5.15)–(5.21).*

Proof Evidently, for each given g, a path flows h is a solution of variational inequality problem (5.16) if and only if h is a solution of the following linear problem of variable q,

$$\min \quad S(h)^T q \tag{5.39}$$

subject to

$$\Lambda q = g$$

$$q \geq 0.$$

Under Assumption 5.1, (5.16) has a unique link load solution v^*. Let h be any path realization of v^*, thus h is a solution of the above linear programming problem. Let μ be the solution of the dual problem. From duality, we have

$$S(h) - \Lambda^T\mu \geq 0, \tag{5.40}$$

by complementary slackness condition, we get

$$h^T(S(h) - \Lambda^T\mu) = 0, \tag{5.41}$$

from (5.35) and (5.36), we have

$$v^T s(v) = h^T S(h) = h^T\Lambda^T\mu = \mu^T g(x, y, z).$$

This completes the proof. □

(5.33) through (5.38) is apparently a one-level mathematical program, but it is still very hard problem in nature, since to find a feasible solution of it, one must solve a variational inequality problem. This presentation of the LUDP, however, provides us a useful form to develop certain heuristics for the problem. We will, in the next two subsections, propose two different methods: a sensitivity analysis based heuristic algorithm which makes use of the differentiability of μ, and a simplified sensitivity analysis based heuristic method aimed to solve large-sized practical problem.

5.4.2 Sensitivity analysis-based heuristics for LUDP

To begin, let us quote some useful results on sensitivity analysis of variational inequality from literature.

We have shown in the previous section that for any given $g = g(x, y, z)$, there exists a unique least path cost μ correspondent to g. Thus an implicit function $\mu(g)$ is well defined on the domain of g. Furthermore, by Theorem 5.4.1(i), μ may be also defined as an implicit function of (x, y, z) on Φ under the conditions of Theorem 5.4.1.

Theorem 5.4.3 *Suppose Assumptions 5.1 through 5.3 are valid. Let φ be taken as in (5.32). Then in any open neighborhood of $(x, y, z) \in \Phi$, there exist points $(\bar{x}, \bar{y}, \bar{z})$ such that the implicit function $\mu(x, y, z)$ is differentiable at $(\bar{x}, \bar{y}, \bar{z})$.*

Proof Under the conditions of the theorem, μ is a single-value function of $(x, y, z) \in \Phi$ by Theorem 5.4.1(i). Then the theorem follows Tobin (1986) and Kyparisis (1990). □

Apparently, $\mu(g)$ could be found by solving the system (5.34) – (5.37). For $g = \bar{g}$ given, assume $(\bar{h}, \bar{\mu})$ is a solution to (5.34) – (5.37) ($\bar{\mu}$ is unique, but $\bar{h}$ may not be unique). Remove those h_k with value 0 from the system, (5.34)–(5.37) reducing to

$$S(\bar{h}) - \bar{\Lambda}^T \bar{\mu} = 0, \tag{5.42}$$

$$\bar{\Lambda}\bar{h} - \bar{g} = 0, \tag{5.43}$$

where $\bar{\Lambda}$ is the reduced origin-destination/path incidence matrix. Take the derivative of (5.42)–(5.43) with respect to g, we have

$$J_{(h,\mu)}\begin{pmatrix}\nabla_g h\\ \nabla_g \mu\end{pmatrix} + J_g = 0,$$

where $J_{(h,\mu)}$ and J_g are the Jacobi matrices of (5.42)– (5.43) on (h,μ) and g respectively. If $J_{(h,\mu)}$ is invertible at $(\bar{h},\bar{\mu})$, then the derivative of (h,μ) with respect to g at the point $\bar{g}$ may be expressed as

$$\begin{pmatrix}\nabla_g h\\ \nabla_g \mu\end{pmatrix} = -J^{-1}_{(h,\mu)}J_g,$$

We further let

$$J^{-1}_{(h,\mu)} = \begin{pmatrix}J_{11} & J_{12}\\ J_{21} & J_{22}\end{pmatrix},$$

then it follows that

$$\nabla_g \mu = J_{22}.$$

Tobin and Friesz (1986) have shown that when $\bar{h}$ is a nondegenerate extreme path flow solution to (5.16), then $J_{(h,\mu)}$ is nonsingular at $(\bar{h},\bar{\mu})$, and further,

$$J_{22} = [\bar{\Lambda}\nabla S(\bar{h})^{-1}\bar{\Lambda}^T]^{-1}$$

Thus we have

Theorem 5.4.4 *(Tobin and Friesz, 1986) Suppose the user cost function $s(v)$ is strongly monotone, and $\bar{h}$ is a nondegenerate extreme path flows to (5.18), then*

$$\nabla_g \mu = [\bar{\Lambda}\nabla S(\bar{h})^{-1}\bar{\Lambda}^T]^{-1}.$$

□

Now we may provide a heuristic method for solving the LUDP based on the differentiability of μ, which is first introduced by Friesz et al (1990) for the general mathematical programs with variational inequality constraints.

Sensitivity Analysis-Based Heuristic Algorithm(SABHA) for the LUDP

Step 1 (Initialization) Select an $(x^0, y^0, z^0) \in \Phi$. Determine φ by (5.32). Select an $\epsilon > 0$ and set $l = 0$.

Step 2 (Origin/Destination demand) Compute $g^l = g(x^l, y^l, z^l)$.

Step 3 (Least path cost) Calculate $\mu^l = \mu(g^l)$.

Step 4 (Descent direction) Compute $\nabla F(x^l, y^l, z^l)$ where $F(x, y, z) = \mu^T g + \sum_i b_i(x, y, z)$.

Step 5 (Determine step size) Select a step length t^l.

Step 6 (Update) Find $(x^{l+1}, y^{l+1}, z^{l+1}) \in \Phi$ by letting

$$(x^{l+1}, y^{l+1}, z^{l+1}) = \left[(x^l, y^l, z^l) + t^l \nabla F(x^l, y^l, z^l)\right]_L^U.$$

where $[\cdot]_L^U$ meaning the updated point should be stayed in the feasible region.

Step 7 (Stop condition) **If** for all $i \in I$

$$|x_i^{l+1} - x_i^l| + |y_i^{l+1} - y_i^l| + |z_i^{l+1} - z_i^l| < \epsilon$$

then stop, **else** let $l = l + 1$ and go to *Step 2*.

In the above SABHA, Step 2 can be completed by the Fratar and Furness method described in Section 5.2. Step 3 can be accomplished by any method addressed in Section 5.3. In Step 4, we are going to find the gradient of F at (x^l, y^l, z^l). It can be done by the methods addressed in Theorem 5.4.4, Theorem 5.2.6 and the chain rule.

A step length should be determined in Step 5. We may not use the line search method here, because the evaluation of the line search function at each point involves solving a variational inequality which is non-smooth along the line. We may only employ, however, some heuristic methods to select a step length (this is what makes our algorithm heuristic). The possible methods include using a predetermined step size sequence (Friesz et al, 1990), and using so-called Armijo-like steps (Friesz et al, 1990; and Wu and Florian, 1993).

In Step 6 we update (x, y, z) to a new point in Φ. Because all of the densities have lower and upper bound restricts, it should be rounded up to stay in Φ if they go out of Φ by the step length t^l.

Step 7 provides a stop rule for the algorithm. We require that the computation should continue until the distance of the two successive points in Φ generated by the algorithm is less than the pre-determined parameter ϵ.

5.4.3 An iterative improvement heuristic method

In the previous subsection, we proposed a sensitivity analysis-based heuristic for solving the Land Use Design Problem by making use of the differentiability property of μ with respect to (x, y, z). The methods, however, may only be used to solve small-sized problems, because the number of the partial derivatives in the SABHA becomes unacceptably large when it is applied to practical problems with intermediate size and large size. Let us use an example to explain that.

Suppose that an area has 100 zones. Then the O-D demand matrix is of the order 100×100, with 10,000 elements. The same size is also shared by μ, the least path cost matrix. When computing the derivatives of g with respect to O and D, we need to calculate the inverse of a matrix of order 100, by Theorem 5.2.6. But for computing the derivatives of μ with respect to g, we have to calculate first the matrix $\nabla S(\bar{h})^{-1}$, then the matrix $\nabla_g \mu = [\bar{\Lambda} \nabla S(\bar{h})^{-1} \bar{\Lambda}^T]^{-1}$, where $S(\bar{h})$ is the reduced path cost vector and $\bar{\Lambda}$ is the reduced path/OD pair incidence matrix. Suppose that in a solution to an equilibrium assignment in the LUDP of the 100-zone area, there are in average 10 different non-zero extreme path flows connecting an O-D pair, then the total different paths is 100,000, $\nabla S(\bar{h})$ is of an order 100,000 and $\nabla_g \mu$ is of an order 10,000. Furthermore, because we do not know exactly how many non-zero extreme paths an O-D pair will have in a specific solution, we may be forced to use more space for calculating the matrices. It is unacceptable from practical point of view.

To avoid computing a huge number of derivatives of μ, we propose, in this section, an iterative improvement heuristic method to solve the LUDP. We may use the same techniques as used in SABHA to calculate O-D demand g and the least path cost μ. In step 4 of finding a descent direction, instead of treating μ as variable in (x, y, z), we may treat it temporarily as constant. Then we need only to calculate the derivatives for g and b, but not for μ. Those derivatives may be found in a reasonable time and space complexity.

We next suggest a method to determine a step size for searching an improving point. When $g^l = g(x^l, y^l, z^l)$ and $\mu^l = \mu(g^l)$ are determined at (x^l, y^l, z^l), we first compute $\nabla F(x^l, y^l, z^l)$ for $F(x, y, z) = (\mu^l)^T g(x, y, z) + \sum_i b_i(x, y, z)$ where μ is temporarily taken as constants μ^l, then find a feasible solution $(\bar{x}^l, \bar{y}^l, \bar{z}^l)$ along the direction $-\nabla F(x^l, y^l, z^l)$, and then search an improving point by a discrete search method along the segment connecting (x^l, y^l, z^l) and $(\bar{x}^l, \bar{y}^l, \bar{z}^l)$.

$(\bar{x}^l, \bar{y}^l, \bar{z}^l)$ could be determined by solving the following linear programming problem.

$$\min \nabla F(x^l, y^l, z^l)^T (x, y, z) \tag{5.44}$$

subject to $(x, y, z) \in \Phi$.

It is noted that the direction $d^l = (x^l, y^l, z^l) + (\bar{x}^l, \bar{y}^l, \bar{z}^l)$ may not be a descent direction for $F(x, y, z)$. We only expect that it could be a descent direction with a large probability. We should make a further search and if it is a descent direction the search will also identify an improving point.

To complete this process, we select a step size t first. t could be 0.5, or 0.618, or any other positive number which is less than 1. By taking $t^l = t$, we move to the point $(x^l, y^l, z^l) + t^l d^l$, compute the value of objective function at the point. If the value decreases, an improved point is found. If not, reduce t^l by multiplying t and compute the value of objective function at $(x^l, y^l, z^l) + t^l d^l$. This search will be continued until t^l is less than a pre-given positive but sufficient small number.

We describe the iterative improvement heuristic method below.

Iterative Improvement Heuristic Method (IIHM) for the LUDP

Step 1 (Initialization) Select step size $0 < t < 1$, an $\epsilon > 0$ and a current minimal cost $cost^* = INF$. Set $l = 0$, $t^l = 1$ and select a $(x^l, y^l, z^l) \in \Phi$,

Step 2 (Origin/Destination demand) Compute $g^l = g(x^l, y^l, z^l)$.

Step 3 (Least path cost) Calculate $\mu^l = \mu(g^l)$ and $c^l = \mu^T g + \sum_i b_i$.

Step 4 (Comparison and Decision) If $c^l < cost^*$, go to *Step 5*. If $c^l >= cost^*$, set $t^l := t^l t$. If $t^l < \epsilon$, stop; otherwise, set $(x^l, y^l, z^l) = (x^l, y^l, z^l) + t^l d^l$, go to *Step 2*.

Step 5 (Descent direction) Compute $\nabla F(x^l, y^l, z^l)$ where $F(x, y, z) = \mu^T g(x, y, z) + \sum_i b_i(x, y, z)$. Find $(\bar{x}^l, \bar{y}^l, \bar{z}^l)$ by solving the linear programming problem 5.44.

Step 6 (Update) Set $(x^*, y^*, z^*) = (x^l, y^l, z^l)$, $d^{l+1} = (x^l, y^l, z^l) + (\bar{x}^l, \bar{y}^l, \bar{z}^l)$, $t^{l+1} = t$, $(x^{l+1}, y^{l+1}, z^{l+1}) = (x^l, y^l, z^l) + t^{l+1} d^{l+1}$, $l := l + 1$, go to *Step 2*.

5.5 Chapter conclusion

In this chapter, we concentrated our attention on the existence of solutions and solution methods for the LUDP. We first introduced the solution method to the trip distribution problem and differentiability of the solution. We also introduced the solution methods to the equilibrium assignment problem and differentiability of the solution. We then showed that under reasonable conditions (continuous link cost, standard density constraint, and positively finite traveling impedance), the LUDP have solutions, and the problem is well defined. We also discussed solution methods to the LUDP. Because of the highly complex nature of the problem, only heuristics are expected to solve them. A sensitivity analysis-based heuristic method, which makes use of the differentiability of solution to the trip distribution problem and the equilibrium problem, was designed to solve small-size LUDP problems, an iterative improvement heuristic method to solve intermediate and large-size LUDP problems.

Chapter 6

IIHM for LUDP: implementation

Chapter 4 introduced the mathematical model for the Land Use Design Problems (LUDP), and Chapter 5 proposed two solution methods to solve the problems: the Sensitivity Analysis Based Heuristic Algorithm (SABHA) and the Iterative Improvement Heuristic Method (IIHM). Iterative Improvement Heuristic Method is a solution method in Operation Research, which solves a problem by iteration and at each iteration an improved solution is found or the solution searching process terminates if no improvement can be made. In this chapter, we discuss some technical issues: problem decomposition, implementation of algorithm and development of flow charts of algorithms. We shall discuss the implementation of one method, the IIHM, including some detailed algorithmic issues. Computing code is developed according to this implementation.

We have seen that the LUDP is a very complicated optimization problem, which includes several subproblems, such as the variational inequality problem for multi-mode traffic assignment; the determination of partial derivatives to provide descent directions; the linear programming problem to determine line search scope. Because of the specific network structure the LUDP possesses, some of the subproblems, namely the variational inequality problem, may be solved by an efficient, linearized Simplicial Decomposition Method (SDM). Simplicial Decomposition Method is a solution method in Operations Research, which decomposes a large size, difficult problem into a series of smaller, easy ones in a way of moving from an extreme point (solution) to another one.

The linearized Simplicial Decomposition Method will be discussed in Section 6.1. In Section 6.2, an implementation of the IIHM for the LUDP will be described in detail. Section 6.3 concludes the chapter.

6.1 The linearized Simplicial Decomposition Method

There are many solution methods (see Section 5.3) for solving variational inequality problems: find $x^* \in \Omega$ such that

$$s(v^*)^T(v - v^*) \geq 0, \forall v \in \Omega, \tag{6.1}$$

where Ω is a non-empty, convex, closed and compact subset of R^n, and s is a cost function vector. If s is continuous and strictly monotone, then there is the unique $v^* \in \Omega$ to satisfy (6.1).

In the LUDP, however, the variational inequality, which is derived from the multi-mode traffic assignment problem, possesses a specific network structure, and then may be efficiently solved by using the linearized Simplicial Decomposition Method (SDM). Instead of solving a large, difficult problem, the SDM solves a series of decomposed small, easy problems. The SDM shares the same features with the column generation method in linear programming and convex programming. In fact, the SDM is working on the simplicial representation of the feasible set in terms of its extreme points. Holloway (1974), Von Hohenbalken (1975, 1977) and Sacher (1980), among others, developed the SDM for convex problems. Bertsekas and Gafni (1982), Lawphongpanich and Hearn (1983) and Pang and Yu (1984) applied the SDM to traffic equilibrium problems. Recently Wu and Florian (1993) used the SDM to solve the transit equilibrium assignment problem.

We assume, in the LUDP, that elements of Ω may be written as combinations of all extreme points of Ω (flow vectors), that is, for any $v \in \Omega$, we have the expression $v = A\lambda$ for some $\lambda \in \Lambda$, where A is an $n \times m$ matrix with extreme points as its columns; n is the number of links and m is the number of extreme points. And $\Lambda = \{\lambda : \sum_{i=1}^{m} \lambda_i = 1, \lambda_i \geq 0\}$.

The problem (6.1) may be restated as: find $\lambda^* \in \Lambda$ such that

$$s(A\lambda^*)^T(A\lambda - A\lambda^*) \geq 0.$$

There is no need to find all extreme points in advance (that is also impossible). Instead, an extreme point can be generated as needed. Suppose that, at a certain iteration, we have determined the extreme points $v^1, v^2, ..., v^l$. Denote by Ω^l the subspace of flow vector generated by $v^1, v^2, ..., v^l$. We solve (6.1) with restriction $v \in \Omega^l$. Let x^l be the solution. Then we solve the following linear programming problem: find $v \in \Omega$ to minimize $s(x^l)^T v$. It is clear that if v^l is one solution to the minimization problem, then it is also the unique solution to (6.1). Otherwise the solution to the minimization problem is a new extreme point of Ω. Notice that the minimization problem is the shortest path problem under network structure.

We state the Simplicial Decomposition Algorithm (SDA) as follows.

ALGORITHM SDA

Step 0 (Initialization): Select a small positive real number δ and a positive and convergent monotone sequence $\{\epsilon_l\}$ such that $\epsilon_l \to 0$ as $l \to \infty$.

Select any extreme point $v^0 \in \Omega$, let $A^1 = \{a^0\}$, $G^1 = \infty$ and $l = 1$.

Step 1 (Restricted problem): Find $x^l \in H(A^l)$ such that

$$s(x^l)^T(v - x^l) \geq -\epsilon_l, \ \forall v \in H(A^l), \tag{6.2}$$

where $H(A^l)$ is the convex hull of columns of A^l. Denote by D^l the set of columns of A^l with zero weight in the expression of x^l as a convex combination of columns of A^l.

Step 2 (Shortest path problem): Find v^l to solve

$$\min\{s(x^l)^T v : v \in \Omega\}.$$

Step 3 (Stop criterion): Compute gap function

$$g(x^l) = s(x^l)^T(x^l - v^l). \tag{6.3}$$

If $g = 0$, **then** stop, x^l is the solution to (6.1).

Step 4 (Update): **If** $g(x^l) \geq G^l - \delta$, let $A^{l+1} = A^l \cup v^l$ **else** $A^{l+1} = (A^l - D^l) \cup v^l$. Let $G^{l+1} = min\{G^l, g(x^l)\}$. Set $l := l + 1$. Go to *Step 1*.

The introduction of parameter ϵ_l in *Step 1* allows us to approximately solve the master variational inequality problem. Lawphongpanich and Hearn (1984) showed that when $s(v)$ is strongly monotone with constant α, and if $\hat{v}$ solves (6.1) exactly, then $||x^l - \hat{v}||^2 \leq \epsilon_l/\alpha$. They also proved that if $s(v)$ is strongly monotone, and the SDA generates an infinite sequence $\{x^l\}$, then $\{x^l\}$ converges to the solution of (6.1).

The restricted variational inequality problem could be solved by any method mentioned in Section 5.3. We use the Linearized Jacobian Method (LJM) to solve the problem in this chapter. To solve the problem, we select an initial point $v^0 \in H(A^l)$, then find $v^{k+1} \in H(A^l)$ for $k = 0, 1, ...$, to solve the following problem.

$$\min s(v^k)^T(v - v^k) + \frac{1}{2\alpha}(v - v^k)^T DJ(v^k)(v - v^k) \tag{6.4}$$

where $DJ(v^k)$ is the diagonal of the Jacobian matrix ∇s evaluated at v^k. Notice that ∇s is positive definite for s is strongly monotone.

Using the specific structure of the feasible region, we can restate (6.4) as to find $\lambda \in \Lambda^l$ to solve

$$\min \hat{s}(\lambda^k)^T(\lambda - \lambda^k) + \frac{1}{2\alpha}(\lambda - \lambda^k)^T D(\lambda^k)(\lambda - \lambda^k). \tag{6.5}$$

where $\hat{s}(v^k) = (A^l)^T s(A^l\lambda^k)$ and $D(\lambda^k)$ is the diagonal of $(A^l)^T DJ(v^k)A^l$, and $\Lambda^l = \{\lambda : \sum_{i=1}^{l} \lambda_i = 1,\ \lambda_i \geq 0\}$.

(6.5) is a quadratic problem with one constraint. It can be solved by using an efficient iterative algorithm suggested by Dussault et al (1986). The general form of the problem is

$$\min g(x) = \frac{1}{2}x^T \Delta x + c^T x \tag{6.6}$$

subject to

$$a^T x = b,$$

$$l \leq x \leq u.$$

where Δ is a diagonal matrix with positive diagonal elements, and $a \geq 0$. The Lagrangian problem of (6.6) is

$$\min g(x) + \mu(a^T x - b) \quad \text{subject to } l \leq x \leq u. \tag{6.7}$$

For any given μ, (6.7) could be easily solved because the objective function is separable. Further, because $r(\mu) = a^T x(\mu)$ is non-increasing and continuous, (6.7) could be solved by line search methods.

6.2 An implementation of the IIHM

We describe an implementation of the IIHM for the LUDP in this section. The major work of the IIHM can be decomposed into the following block components.

Block components of the IIHM

1. Initialize system conditions and input problem data;
2. Select an initial solution (for population and job density);
3. Determine impedance for traveling among O-D pairs;
4. Determine traffic production and attraction;

5. Form O-D demand matrix;
6. Solve the equilibrium assignment problem;
7. Compute the total settlement cost and travel costs. Check if the total cost gets decreased from the previous solution. If the cost is decreased, go to block 8, otherwise go to block 10;
8. Determine a direction where there exists a possibility to get a better solution;
9. Determine a search interval, go to block 12;
10. Modify search step length;
11. Check conditions for termination. If conditions are met, terminate the IIHM, otherwise go to block 12;
12. Form a new solution (for population and job density), Go back to block 4.

The detail work in each block is explained below.

1. The input data of the problem include
    - network data: zones, nodes, links;
    - zone information: surface, location, group index;
    - group information;
    - O-D pair information: demand, impedance;
    - link information: length, capacity, travel cost.
2. There are many ways to select an initial solution (x, y, z). In this implementation, we select an initial solution in such a way that for each element, the density of the element in each zone locates at, relatively, a 'same' level in its feasible interval. To do this, we first put densities on their respective lower bound. Then we move the densities up by a same amount, the maximally possible amount neither violating

upper bound constraint for any variable, and nor overpassing the constraint of regional total amount. We will either reach an initial solution, or upper bound will be reached for some variables. In the latter case, those saturated variables should be moved out from the variable set which may move further up. Continuing this process, we may get an initial solution.

3. The original impedance for traveling among O-D pairs could be a pre-determined matrix. It can also be produced by using a shortest path algorithm.
4. Traffic production and attraction of zones are calculated by using (5.29), (5.30) and (5.32).
5. Form O-D demand matrix by matrix balancing algorithm (Section 5.2).
6. Solve the equilibrium assignment problem by SDM.
7. Compute the total settlement cost and travel costs derived by selected densities. Travel costs are determined in the previous assignment process.
8. Compute derivatives for O-D demand functions with respect to densities according to Theorem 5.2.6.
9. Determine search direction by solving linear programming problem (5.44).
10. Decrease step length by multiplying to it by a positive small real number less than 1.
11. If step length is less than a given tolerance, terminate the IIHM.
12. Form new solution (x, y, z) by moving from present solution along search direction by present step length.

In block 6 of the flow chart of the IIHM, we need to solve an equilibrium assignment problem at each iteration. The problem is solved by using the Simplicial Decomposition Method (SDM). The following is the block components of the SDM.

Block components of the SDM

1. Select initial solution;
2. Compute gap function;
3. Check termination conditions. If termination conditions are satisfied, exit the SDM, otherwise go to block 4;
4. Update solution;
5. Solve restricted variational inequality problem, go back to block 2.

The detail work in each block of SDM is explained below.

1. Select initial extreme point solution discussed at Step 0 of algorithm SDA in 6.1, using shortest path algorithm.
2. Compute gap function using (6.3), to determine the gap between the previous solution and current solution.
3. Check stop criterions by using the gap computed at block 2. If stop criterions for gag checking are satisfied, exit SDM.
4. Update extreme point solution by adding new extreme point to the previous solution, and dropping those with zero weight contribution to present solution to (6.2).
5. Solve restricted variational inequality problem (6.4) by using the Linearized Jacobian Method.

In block 5 of the SDM, we need to solve a variational inequality problem in a restricted domain at each iteration. We use the Linear Jacobian Method (LJM) to solve the problem. The following is the block components of the LJM.

Block components of the LJM

1. Select any initial solution.

2. Compute travel costs and corresponding derivatives.
3. Form quadratic problem;
4. Solve quadratic problem;
5. Check stop criterion. If stop criterion is satisfied, exit the LJM, otherwise go to block 6;
6. Update to the new solution. Go back to block 2.

The detail work in each block of LJM is explained below.

1. Select any initial traffic flow vector v and coefficient vector λ.
2. Compute travel costs $s(v)$ corresponding to the traffic vector v and their derivatives with respect to v.
3. Form the quadratic problem (6.5) by using the coefficient vector λ and derivatives of travel costs $s(v)$ with respect to v.
4. Solve quadratic problem (6.5) by using one of line search methods, with a view to find a new traffic flow vector v and coefficient vector λ.
5. Compare the previous solution with current one. If stop criterion is satisfied, exit the LJM, otherwise go to block 6;
6. Move to the new traffic flow vector v and coefficient vector λ.

6.3 Chapter Conclusion

In this chapter, we discussed technical issues of solving the land use design problems using the Iterative Improvement Heuristic Method. The linearized Simplicial Decomposition Method is employed to convert a large, difficult problem into a series of small, easy problems. An implementation of the IIHM for the LUDP was described in detail. Block components of the implementation were provided. Our computing code is developed based on these block components and will be used in land use and freight transport coordination in the next chapter.

Chapter 7

Land Use and Freight Transport Coordination: A Case Study

In this chapter, we apply the LUDP to land use and freight transport coordination in Shanghai urban district. The exploration of urban form is focused on land use intensity and degree of concentration. For land use and freight transport interaction, attention will be paid to the trip generation of freight transportation and coordinated land use design.

In Section 7.1, a case study on the urban form of Shanghai will be conducted. In Section 7.2, we explore the relationship between land use and freight transport in Shanghai. In Section 7.3, we apply the LUDP model to Shanghai's freight transport and land use design.

7.1 An introduction to Shanghai

In Section 4.1.1, we briefly introduced Newman and Kenworthy's work on urban form. In this section we follow their method to analyze the urban form of Shanghai. Corresponding data are collected. These data include surface, population and employment density in different city belts (CBD, inner city and outer city), road supply, parking spaces in CBD, total vehicles per kilometer of road, traffic speed and average speed of public transport. These are almost all the data that Newman and Kenworthy used in their research.

7.1.1 Data preparation

Area and Population

Shanghai is located at the east end of the lower Yangtze Delta . In 1950, the population in Shanghai was 5.03 million in the metropolitan area of 636.18 square km, including 4.19 million residing in an 82.4 square km urban district. The administrative division of Shanghai was changed several times. The greatest change occurred in 1958, when ten counties of the Jiangsu province were shifted to Shanghai's jurisdiction, making the area of Shanghai increasing to 6340 square km from 636 square km in 1949. Figure 7.1 illustrates the urban district of Shanghai. The information on area and population changes is listed in Table 7.1. The 1986 data will be used in the urban form analysis.

Table 7.1: Change of Area and Population in Shanghai

	Metropolitan		Urban District		Town and County	
Year	Population million	Area sqkm	Population million	Area sqkm	Population million	Area sqkm
1949	5.02	636	4.18	82	0.83	529
1957	6.89	654	6.09	116	0.79	513
1960	10.53	6340	6.41	158	4.14	6141
1970	10.73	6340	5.86	158	4.92	6141
1982	11.81	6340	6.26	230	5.53	6110
1986	12.32	6340	7.30	504	5.02	5838
1990	12.83	6340	7.84	750	4.99	5590

Source: Zhang and Wang (1985), Shanghai Statistics 1987,1991 (SSY, 1987, 1991)

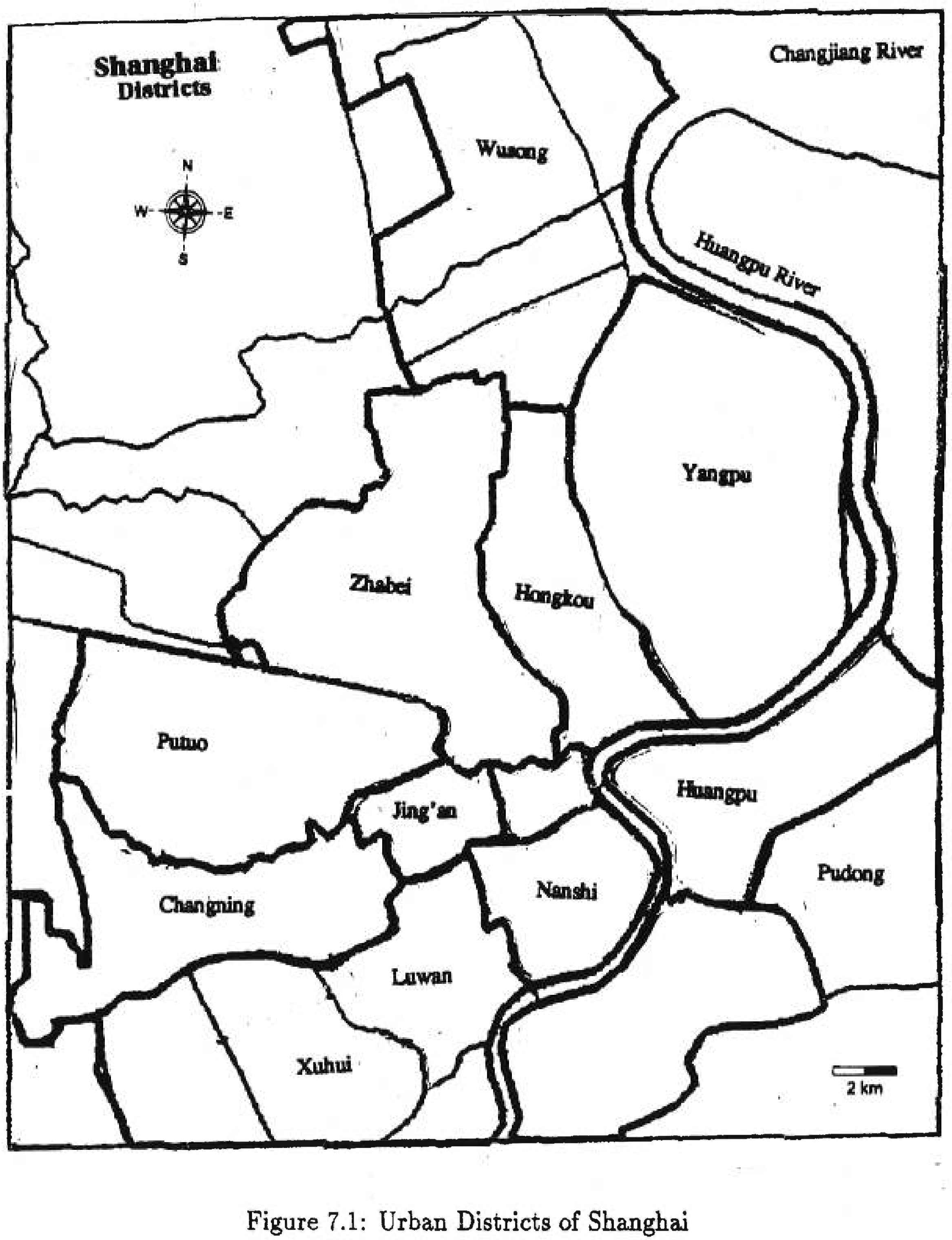

Figure 7.1: Urban Districts of Shanghai

Public Transit System

For quite a long time, the public transit system, including buses and trams but no train, had been a main and efficient means of travel in Shanghai. The number of public transit passengers increased every year until 1988. But in 1988, the increase rate significantly declined. Then in 1990, the amount dropped three percent compared to 1989. The decrease in the amount of transit passengers was not attributable to a decrease in the total passenger trips, but to a change in the structure of modal split: more people used bicycles rather than transit for working trips. Table 7.2 shows the performance of transit per year.

Table 7.2: Transit Performance of Shanghai

Year	Total length of transit lines	Number of transit lines	Number of buses on operation	Yearly amount of passengers	Highest daily passengers
	(km)	(line)	(vehicle)	(billion)	(million)
1981	5,291	236	3,974	3.685	11.54
1982	5,428	247	4,189	3.842	12.26
1983	6,854	268	4,456	4.109	12.72
1984	7,019	276	4,703	4.555	14.1
1985	10,138	297	5,036	5.01	15.41
1986	14,146	331	5,505	5.185	15.34
1987	15,780	348	5,859	5.542	17.5
1988	17,443	368	5,988	5.599	17.1
1989	17,368	372	6,087	5.509	16.88
1990	18,593	390	6,293	5.45	

Source: Shanghai Statistics 1990 and SCCTPI (1991)

1. Length and number of transit include the figures of long distance buses.
2. Figures from 1987 include corporate-owned buses.

Private cars were rarely used in Shanghai. It is estimated that it might increase steadily in the near future. In 1984 there were only 9200 cars, belonging to corporates or taxi companies registered in Shanghai. In 1990 the figure was 41450. Adding trucks, there was a total of approximately 200,000 motorized vehicles. What makes transportation management tasks more difficult is the uncontrollable increase of bicycles since 1980.

Bicycle ownership since 1949 is listed in Table 7.3. Bicycle ownership increased smoothly before 1975, but was increased rapidly since 1978. The rapid increase in bicycle ownership is partly due to an increase in standard of living, but it is also due to the decline of transit service: low bus speed, often behind schedule, and extremely crowded. It is noticed that bicycle ownership dropped down from 6.71 million in 1987 to 5.44 million in 1989. The administration authority of the city requested a bicycle re-registration for all bicycles in use in 1989.

Table 7.3: Bicycle Ownership in Shanghai since 1949

Year	1949	1964	1970	1975	1980	1985	1986	1987	1989
Ownership (million)	0.46	0.89	1.29	1.77	3.69	4.24	4.91	6.71	5.44

Source: SCCTPI(1991).

Traffic Speed

According to the Transportation Engineering Research Institute of the Public Security Bureau of Shanghai, the average speed of motor vehicle on the main roads in Shanghai was 19.1 km per hour in 1986. But it declined to 17.5 km per hour in 1990. From the road survey conducted by SCCTPI, the motor vehicle speed on Zhongshan ring road was 19 km per hour in 1986 but decreased to 15.6 km in 1991. From a remote sensing project in 1988 the motor vehicle speed in peak hour on the center of the city was 11.9 km per hour.

Road supply

In 1990, there were 4713 km of roads, of which 1663 km are in urban district. In urban district the road density is 2.22 km per square km, the road area rate is 3.5 percent and average road length per capita is 0.23 meters. In the entire metropolitan area, the average road length per capita is 0.38 meters.

Parking Spaces in the City Core

In the CBD there were 1351 parking spaces in 1987 associated with 310,000 jobs, that is 4.4 parking spaces per 1,000 jobs.

Total vehicles per km of road

At the end of 1990 there were 160,000 motorized vehicles in Shanghai, making about 90 vehicles per km on urban district roads and 35 vehicles per km on whole city roads.

Average Speed of Public Transportation

According to SCCTPI (1991), average speeds of public transports in Shanghai in 1990 are as follows: bus, 13 km an hour; tram, 30 km an hour; ferry, 14 km an hour; accounting for an averaged total of 13 km an hour.

City belts and Densities

Following the SCCTPI (1991), some geographic areas are defined as follows. Metropolitan Shanghai: 6340 square km, urban district: 504.10 square km, suburb: 5835.90 square km. Urban district is further subdivided into CBD, inner city and outer city, CBD: 4.18 square km, inner city: 89.15 square km and outer city: 410.77 square km. Population and job densities for these different areas are shown in Table 7.4.

Table 7.4: Population and Job Densities in Different Belts in Shanghai

	Population			Area		Jobs[2]		
	(mil)	percent	density	(sq km)	percent	(mil)	percent	density
Metropolis	12.32	100	1943	6340	100	7.62	100	1202
Urban District	7.3	59	14481	504.1[3]	8	4.82	63	9562
Suburb	5.02	41.7	860	5835.9	92	2.80	37	480
CBD	0.4	3.25	95693	4.18	0.066	0.31	4.05	74163
Inner City	4.47	36	50140	89.15	1.41	2.63	34	29446
Outer City	2.43	20	5916	410.77	6.48	1.88	25	4577

Source: SCCTPI (1991)

1. statistical data of 1986;
2. data of home survey in 1986;
3. not including Baoshan District and Pudong New District.

7.2 Freight traffic generation

This section explores the interaction of land use with freight transport generation in Shanghai urban district, by using Geographic Information System (GIS) software and the multiple linear regression method. Land use data and demographic data are used as input variables. A GIS software is employed to record land use data. Land use distributions are strongly related to freight transportation generation. Final results seem to display the link between land use and goods movement generation rather well.

7.2.1 Introduction

The multiple linear regression method has been widely applied to trip generation. The early version of the method usually takes historic records (time-based) of items as observations. Practices have shown that in the short term, a satisfactory prediction can be achieved by this method. Later researchers also adopt as observations the object records of different places (zone-based). For instance, land use and transportation data of different cities over the world are used to statistically analyze the relationships between urban form and automobile dependence (Kenworthy and Newman, 1987; and Newman and Kenworthy, 1989). It has been observed that zone-based regression seems to perform better than time-based regression. Recently GIS has been getting more and more attention for collecting and manipulating land use and transportation data (Simkowitz, 1989). With the help of a GIS software, land use and transportation data can be gathered more extensively and precisely, thus better information may be provided to support zone-based multiple regression.

In this section, with the support of a GIS software, we use the zone-based regression method to explore the interaction of land use with freight transport generation in Shanghai.

Several transportation surveys were conducted in Shanghai in 1986. A home-based survey included data on residing place, working place and working trip of each individual. A truck transportation survey, taken on December 25, 1986, contains information on capacity, load volume, type of loaded goods, trip origin and trip destination, for each individual truck and each trip on that day.

A great deal of research has been done on passenger transportation analysis in Shanghai (SCCTPI, 1990 and 1992; and Chen, 1992). Comparatively, research on freight transportation in Shanghai is relatively limited.

Using a GIS software allows us to use the surface of land use, together with other land use data and demographic data, to analyze freight transportation and land use interaction, which is useful for developing a trip generation method based on zone information pertaining to geographic feature and land use intensity.

7.2.2 Data preparation

This study uses two main type of data. One is land use and demographic data (population and employment) and the other is freight transportation data. The following is a brief description of these data.

Land use

Figure 7.2 is the land use map of Shanghai with latitude and longitude. A map with latitude and longitude is a requisite condition to employ a GIS software. The map covers about 2,000 square km of land, which includes the whole city proper (CBD, inner city and outer city) of Shanghai, as well as a large part of suburban areas.

There are nine different types of land uses on the map: built-up area, industry, institutions, utilities, warehouses, parks, airport, special use and agriculture. The built-up area has mixed land use: residential, commercial, business and entertainment. Utility could be train station and river port.

By using SPANS, a GIS software, we measure the surface of different land uses for each traffic zone. If land for special use and agriculture is not counted, the total area of the other seven land uses in the city is about 200 square kilometers, of which the built-up area occupies 64.25% of land and the industrial area accounts for 14.91%. These are the two large categories of land uses (see Table 7.5).

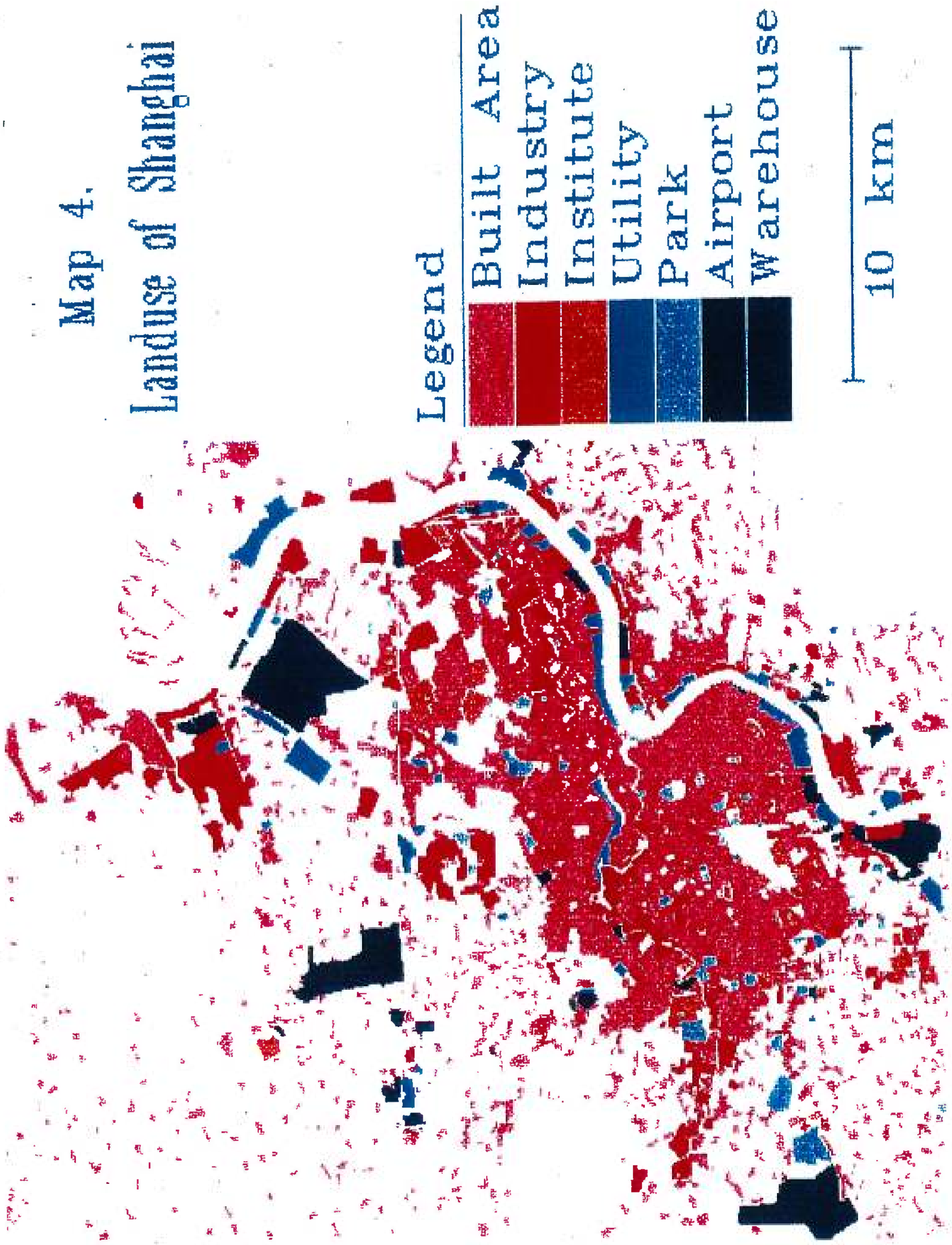

Figure 7.2: Land Use Map of Shanghai

Table 7.5: Land Use Classification

Class	Description	Percentage
1	built-up	64.25
2	industry	14.91
3	utilities	4.96
4	parks	2.29
5	warehouses	2.44
6	institutions	3.10
7	airports	8.05
total		100.00

Economic zone, population and employment

The city of Shanghai is divided into 30 large traffic zones, which include 98 intermediate traffic zones which, in turn, include 503 small traffic zones. Figure 7.3 shows the geographic distribution of the intermediate zones in the city proper. The figure covers the same area that the land use map (Figure 7.2) covers. There are 78 intermediate zones in the map (zones 1 to 33, and 35 to 79). According to SCCTPI (1992), zones 1 and 2 are the CBD of the city. The inner city is composed of zones 3 to number 28, and zones 29 to 53 form the outer city. Zones 54 to 98 are suburban areas. Zone 34, not on the map, is located beneath zones 33 and 35.

Population and employment data are based on the home-based survey conducted in 1986. The data are also organized in accordance with the intermediate traffic zone system (see Appendix A).

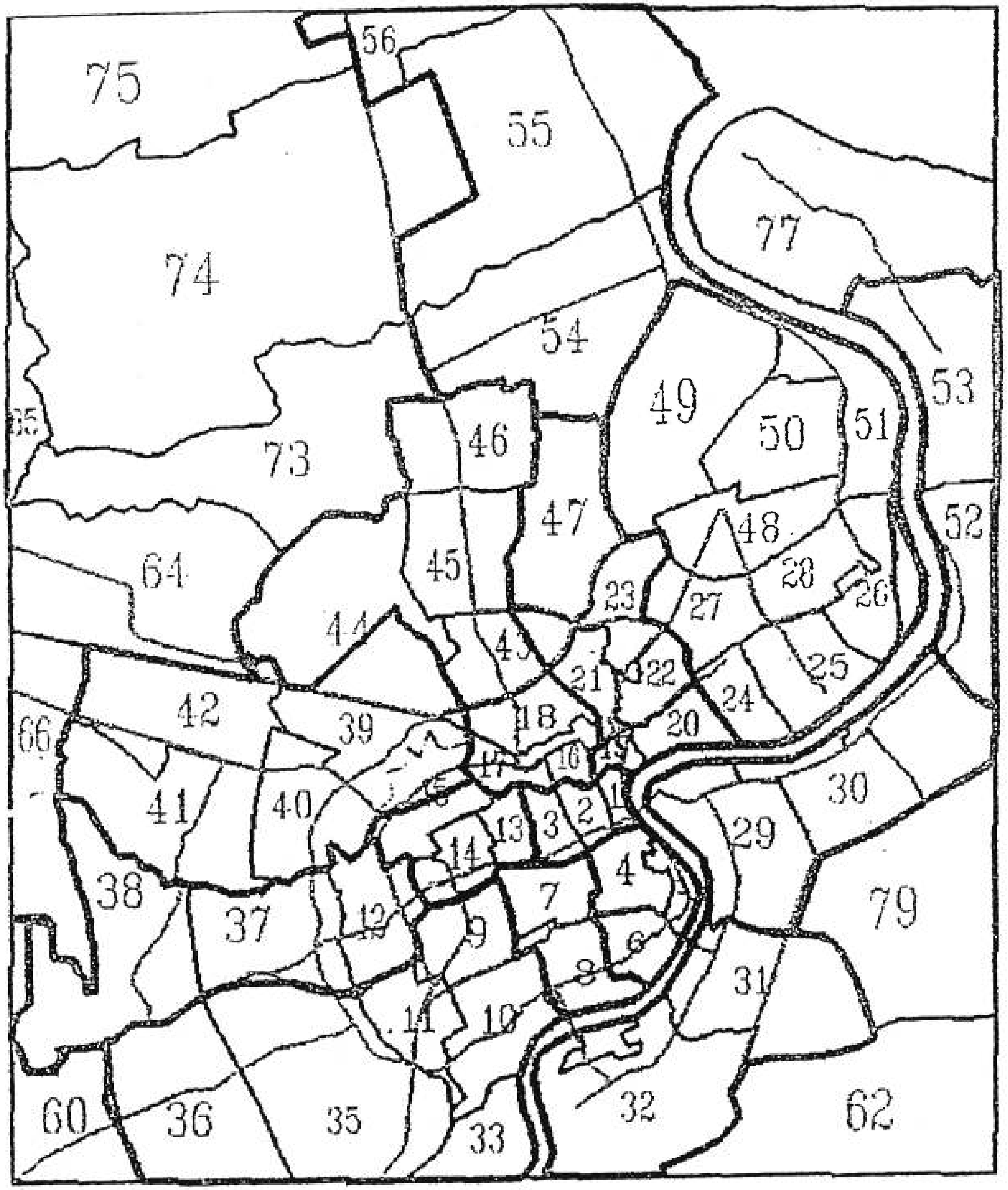

Figure 7.3: Traffic Zones in city proper of Shanghai

Freight transportation data

A freight transportation survey was conducted in 1996. The survey includes information on number of trips, traveling mileage, type of commodity for each trip, for the surveyed truck on the day of December 25, 1996. 79,368 trucks were surveyed on that day, which are about 99 percent of total freight vehicles in Shanghai in 1986. Among those surveyed trucks, 55,028 trucks made at least one trip on that day, and they made 281,346 trips in total on that day, with a total mileage 3,330,297 kilometers. Of the total trips made on that day, 165,292 trips were unloaded, which yields the percentage of unloaded trips about 42 percent. On the other hand, 165,292 trips out of 281,346 total trips, nearly 60 percent, were either starting from or terminating at the inner city, an area about 90 square kilometers.

The truck transportation survey recorded the following for each motor vehicle and each trip: loaded goods type, load volume, trip origin and destination. The goods are roughly divided into 16 categories. The goods production and attraction for each goods category and for each economic zone is obtained from the original information. A preliminary calculation shows that unloaded trips represented about 42% of total trips. Among loaded trips, construction materials, everyday goods, iron and steel, heavy industrial goods, and agricultural goods are listed, respectively, on the first five largest goods generation. The total amount of goods movement for these five categories is about 70 percent of the sixteen categories (see Table 7.6). Furthermore, agricultural goods and everyday goods generation together, is about one quarter of total goods generation.

Calculation also shows that, except agricultural goods and everyday goods, the goods movement generation are either of the feature of area concentration (such as iron and steel produced from Iron and steel plant) or of the feature of timeliness (such as construction materials, which are always associated with construction fields). While the movement of agricultural goods and everyday goods are strongly linked to population density and employment density. Therefore, in the rest of this chapter, we focus our attention on the exploration of relationships between densities and agricultural goods and everyday goods. These data are listed in Appendix A.

Table 7.6: Goods Type Classification

Rank	Type of goods	Percentage
1	construction materials	23.37
2	everyday goods	18.19
3	iron and steel	16.07
4	heavy industrial goods	6.81
5	agricultural goods	6.43
6	chemical goods	5.51
7	soil	4.32
8	coal	4.18
9	garbage	3.11
10	cement	2.81
11	others	2.79
12	timber	1.86
13	ore materials	1.22
14	petroleum	1.21
15	industrial materials	1.12
16	containerized goods	0.94
Sum		100.00

7.2.3 Selection of variables

Selection of input variables

Land use characteristics and demographic data are selected as input variables, also known as independent variables, in the interaction analysis. The data could be both simple, such as the surface of a built-up area or population, and composite, such as population density.

Although there are 7 different land use distributions, we may not use all of that information in our analysis, for we do not have detailed job classification associated with detailed land use. We may have two choices in the land use aspect for selecting independent variables: taking as input variables the surface of built-up area, or the surface of *general built-up* area. By *general built-up*, we mean the land use of built-up, utilities, industry, warehouses, institutions and parks.

The following are input variable candidates.

X_1: surface of *general built-up* area;

X_2: surface of built-up area;

X_3: population;

X_4: jobs;

X_5: population density($X_5 = X_3/X_2$); and

X_6: composite density($X_6 = (X_3 + X_4)/X_1$).

Selection of output variables

Goods movement data are selected as output variables (also called dependent variables). As explained in Section 7.2.2, we select agriculture goods and everyday goods as output variables. We consider production and attraction for both these types of goods.

Candidates for output variables are:

Y_1: attraction of agriculture goods;

Y_2: attraction of everyday goods; and

Y_3: composite goods attraction ($Y_3 = Y_1 + Y_2$).

Y_4: production of agriculture goods;

Y_5: production of everyday goods; and

Y_6: composite goods production ($Y_6 = Y_4 + Y_5$).

Data group

A primary computation shows that the data without grouping appear with no statistical regularity. According to Newman and Kenworthy (1989), the interactions of urban activities are widely related to land use intensity and degree of concentration. We believe that the movement regularity of agriculture goods and everyday goods are also subject to different land use intensities and geographic belts of the city. Therefore we group the data in two features: the geographic characteristics of a given zone, and its land use intensity. We use composite density as an indicator of land use intensity.

According to SCCTPI (1992), the city proper of Shanghai is divided into three belts: CBD, inner city, and outer city. Further, two major rivers, Huangpu River and Suzhou Creek, greatly affect the economy and transport of the city. Therefore we take these factors into account for data grouping as well.

In short, by their geographic features and composite densities, the intermediate traffic

Table 7.7: Traffic zone classes and their characteristics

Class	Geographic Characteristics	Composite Density	Members
		thou/sqkm	
1	CBD	>200	1, 2, 19
2	inner city (near river)	100–200	5, 20, 24
3	inner city (core)	100–200	3, 4, 7, 9, 11, 13–18, 22
4	inner city (near river)	50–100	6, 8, 25, 26, 29
5	inner city (edge)	<100	12, 21, 23, 27, 28, 37, 43, 48
6	warehouse	50–100	10, 39, 40
7	outer city (Puxi)	< 40	33, 35, 36, 38, 41, 42, 44–47, 49–51
8	outer city (Pudong)	20–60	30, 31, 32, 52, 53

zones are grouped into eight classes (see Table 7.7).

7.2.4 Regression for intermediate zone system

Simple regression We first apply the simple linear regression method to the intermediate zone system. We in turn choose X_1 the surface of *general built-up* area, X_2 the surface of built-up area, X_3 the population and X_4 jobs as input, and Y_1 through Y_6 as output. The results of the regression may be found in Appendix C. As an example, Table 7.8 gives out the results of regression taking X_1 as input and the composite goods attraction Y_3 and production Y_6 as output respectively.

In Table 7.8, the value of slope related to a class roughly reflects the amount of composite goods generation (attraction or production) per square kilometers of *general built-up* land of this class. It shows us a clear picture that from CBD, inner city core to inner city edge, the composite goods generation per unit of *general built-up* land decreases in step. But the zones near the rivers possess a higher attraction rate. This consequence well fits the real situation in Shanghai. For classes 6, 7 and 8, however, the fitness is not as good as desired. The correlations of the regression are very small.

Multiple regression Next we apply the multiple regression method to the intermediate zone system to pursue better regression lines. We only apply the method to classes 3, 4, 5, 7, and 8. Because classes 1, 2 and 6 only have three observations respectively, but for conducting the multiple regression method, it is necessary that the number of observations be larger than the number of input variables. We in turn take as the output variable attraction and production of agriculture goods, everyday goods and composite goods.

Notice that not any arbitrary combination of input variables can be a valid Group for the multiple regression. For instance, X_1 and X_2 is not a valid group, because both of them are surface variables and general built-up area includes built-up area. Therefore X_1 and X_2 must be in different groups. Further X_1 and X_5 is not a valid group too, because general built-up area includes build-up area and industrial, utility and institutional areas it cannot simply work with population variable as a group of input variables.

Thus we may choose three different groups of input variables. The first group is

Table 7.8: The Result of Simple Regression

(input: surface of general built-up area)

	Class	intercept	slope	correlation
composite goods attractio	1	1595	15506	0.9985
	2	7508	7663	0.8633
	3	101	5208	0.9732
	4	573	3787	0.9542
	5	383	3081	0.8940
	6	-199	6681	0.9924
	7	6801	1329	0.4242
	8	540	1073	0.6223
composite goods production	1	1349	10505	0.9983
	2	8168	7037	0.9552
	3	-6717	7614	0.7776
	4	-673	4723	0.8452
	5	1825	2433	0.6241
	6	32359	13	0.0014
	7	6269	1928	0.6637
	8	969	790	0.4773

composed of X_1 (surface of *general built-up* area), X_3 (population) and X_4 (employment). Correlations for different output variables are listed in Table 7.9. In Table 7.9, 20 out of 30 elements are larger than 0.9; 3 elements larger than 0.8 but smaller than 0.9; 2 elements larger than 0.7 but smaller than 0.8; and 5 elements larger than 0.6 but smaller than 0.7. The smallest element is 0.6775.

The second group includes the variables of X_2 (surface of built-up area) and X_5 (population density). Correlations for different variables are listed in Table 7.10. In Table 7.10, 7 out of 30 elements are larger than 0.9; 2 elements larger than 0.8 but smaller than 0.9; 5 elements larger than 0.7 but smaller than 0.8; and 6 elements larger than 0.6 but smaller than 0.7. The smallest element is 0.1650.

And the third group contains X_1 (surface of *general built-up* area) and X_6 (composite density). Correlations for different variables are listed in Table 7.11. In Table 7.11, 5 out of 30 elements are larger than 0.9; 8 elements larger than 0.8 but smaller than 0.9; 4 elements larger than 0.7 but smaller than 0.8; and 4 elements smaller than 0.6 but smaller than 0.7. The smallest element is 0.1778.

All these tables display a better fitness of land use and demographic data with freight transportation data on different zone groups, especially for those groups containing zones in CBD and inner city. The tables also show that when the number of input variables increases, the fitness of transportation data with land use data is improved. In group one (Table 7.9), we use three variables as input variables, It comes out that two third correlations are larger than 0.9, while in group two and three, two variables are used as input variables, then only about one third and one sixth correlations larger than 0.9 respectively. The best fitness (correlation) is achieved at the first group of variables, where we use surface of built-up land, population and number of jobs as inputs.

Table 7.9: The Correlation of Multiple Regression with inputs X_1, X_3, X_4

(input: X_1, X_3, X_4)

Cls	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
3	0.6755	0.8725	0.9563	0.9043	0.9665	0.9511
4	0.9680	0.9965	0.9921	0.9231	0.9556	0.9913
5	0.9684	0.8029	0.8873	0.9617	0.9334	0.9932
7	0.7474	0.6984	0.7845	0.6687	0.6965	0.6755
8	0.9925	0.9595	0.9898	0.9581	0.9253	0.9244

In Table 7.12, we list corresponding coefficients of regression lines for the first group of input variables. Some of the coefficients (high-lighted) listed in Table 7.12 will be used as freight traffic generation parameters in the next section.

Table 7.10: The Correlation of Multiple Regression with inputs X_2, X_5

Cls	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
3	0.7400	0.6418	0.7973	0.6952	0.6463	0.7231
4	0.9796	0.9482	0.9638	0.9383	0.9325	0.9637
5	0.8048	0.8042	0.9083	0.7463	0.6985	0.7229
7	0.4187	0.1650	0.2159	0.3630	0.4281	0.3900
8	0.6237	0.4478	0.5825	0.5553	0.4945	0.6343

Table 7.11: The Correlation of Multiple Regression with inputs X_1, X_6

Cls	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
3	0.6661	0.8665	0.9463	0.5650	0.7362	0.7882
4	0.9267	0.9042	0.9144	0.8553	0.8727	0.8224
5	0.9346	0.6192	0.8240	0.8553	0.7729	0.8083
7	0.3797	0.1778	0.2509	0.1929	0.2045	0.2313
8	0.4722	0.8459	0.7948	0.4243	0.6922	0.6378

7.3 Land use and freight transport coordination

In this section we apply the LUDP model to Shanghai's land use and freight transport coordination development. We shall use the Iterative Improvement Heuristic Method (IIHM), which is developed in Chapter 6, to solve this problem. It is noted that the purpose of this section is not to provide a land use and transportation planning scenario for the city of Shanghai, but to demonstrate an approach to conduct the land use and transportation coordination development, and to show that the Iterative Improvement Heuristic Method can be used to achieve this coordination development.

We first describe input data and model parameters to execute the IIHM. Data for this application are also quoted from SCCTPI (1990, 1992). In the previous section, we mentioned that the city of Shanghai is divided into 30 large traffic zones, or 98 intermediate traffic zones, for different traffic planning purposes. We shall use the large zone division in this application. In this division, zones 1 to 18 form the city proper, and zones 19 to 30

Table 7.12: Coefficients of Multiple Regression with inputs: X_1, X_3, X_4

	Cls	Correl	b0	b1	b2	b3
Y_1	3	0.6754	1064.39	1016.25	-0.0027	0.0120
	4	0.9679	-232.63	936.84	0.0030	-0.0059
	5	0.9684	-1266.91	807.35	0.0124	-0.0068
	7	0.7474	-121.66	198.31	0.0213	0.0196
	8	0.9925	-2448.12	614.37	0.0714	-0.0840
Y_2	3	0.8725	868.37	2174.43	0.0018	0.0268
	4	0.9964	3764.62	2995.67	0.0032	-0.0351
	5	0.8029	3432.00	1099.25	-0.0252	0.0672
	7	0.6984	2058.25	328.99	-0.0174	0.1786
	8	0.9596	-1462.93	625.48	0.0287	-0.0060
Y_3	3	0.9563	1932.37	3190.62	-0.0009	0.0388
	4	0.9920	**3531.98**	3932.51	0.0062	-0.0410
	5	0.8873	2165.78	1906.59	-0.0128	0.0604
	7	0.7845	**1936.55**	527.31	0.0040	0.1982
	8	0.9898	-3910.26	1239.86	0.1001	-0.0900
Y_4	3	0.9043	948.90	1016.00	-0.0041	0.0098
	4	0.9231	-251.33	787.65	0.0074	-0.0046
	5	0.9617	- 966.42	924.23	0.0119	-0.0075
	7	0.6687	-126.44	296.53	0.0194	0.0208
	8	0.9581	-2773.21	474.89	0.0509	-0.0881
Y_5	3	0.9665	868.47	2174.75	0.0020	0.0301
	4	0.9556	2993.31	2563.67	0.0028	-0.0322
	5	0.9334	4034.42	2037.00	-0.0337	0.0591
	7	0.6965	1854.34	787.90	-0.0211	0.2014
	8	0.9253	-1763.26	1255.63	0.0302	-0.0079
Y_6	3	0.9511	1932.34	3190.50	-0.0011	0.0412
	4	0.9913	**2954.28**	3243.47	0.0074	-0.0528
	5	0.9932	2444.23	2433.38	-0.0231	0.0755
	7	0.6755	**2123.16**	377.47	0.0059	0.0998
	8	0.9244	-3533.22	1442.52	0.0791	-0.0573

are the suburban area. Figure 7.4 shows the zones of the city proper of Shanghai and its freight transport network. This is the base network of our land use and freight transport coordination analysis.

The network has 60 nodes (including zone centroids) and 218 links (see Figure 7.4, in which each undirected link should be interpreted as two opposite directed links). Nodes 1 to 18 are centroids of zones. Nodes 19 to 60 are highway intersections. The network parameters are listed in Appendix B.

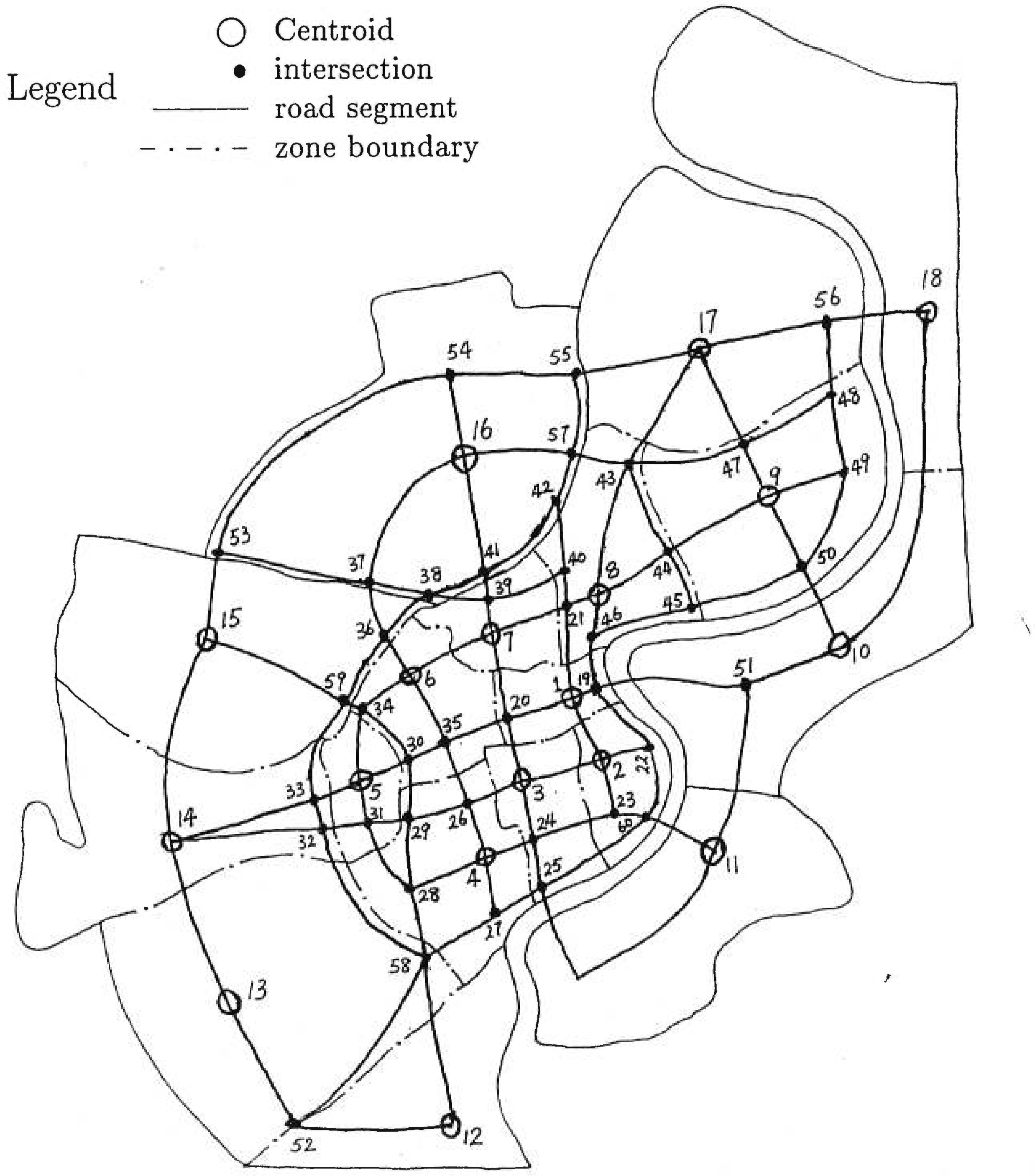

Figure 7.4: Freight transport network of city proper of Shanghai

Population and employment data of the city proper of Shanghai are extracted from SCTTPI (1990, 1992). Table 7.13 includes, for each zone, the surface, population, number of jobs, as well as corresponding densities. Table 7.14 is the trip matrix from origins to destinations. This matrix is taken as the original impedance matrix in our trip distribution process (refer to equation (4.21)).

Table 7.13: Shanghai: zone characteristics

zone	surface	population		employment	
	sqkm	number (thousand)	density	number (thousand)	density
1	4.18	372.8	89.19	265.8	63.59
2	6.86	584.8	85.25	233.4	34.02
3	7.61	482.2	63.36	234.8	30.85
4	15.11	535.3	35.43	306.2	20.26
5	5.62	226.6	40.32	140.7	25.04
6	10.35	603.5	58.31	391.4	37.82
7	7.20	522.2	72.53	204.9	28.46
8	13.15	735.7	55.95	292.2	22.22
9	23.25	790.4	34.00	508.1	21.85
10	25.66	364.4	14.20	163.1	6.36
11	21.33	185.7	8.71	115.1	5.40
12	22.40	76.3	3.41	67.1	3.00
13	44.14	124.6	2.82	111.0	2.51
14	29.16	282.8	9.70	161.3	5.53
15	34.91	448.3	12.84	185.9	5.33
16	47.07	392.6	8.34	256.7	5.45
17	35.53	138.5	3.90	114.5	3.22
18	33.15	92.0	2.78	39.0	1.18

Table 7.14: OD demand (number of trucks)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	71	56	56	66	37	57	46	55	73	30	27	20	20	29	36	41	24	16
2	94	73	73	87	48	75	61	73	96	39	35	26	27	39	48	54	31	22
3	81	63	63	75	41	64	53	63	82	34	30	22	23	33	41	47	27	19
4	89	69	69	82	46	71	58	69	90	37	33	25	25	37	45	51	30	21
5	49	38	38	45	25	39	32	38	50	20	18	13	14	20	25	28	16	11
6	95	74	74	88	48	75	62	73	96	40	35	26	27	39	48	55	31	22
7	87	68	68	81	45	69	57	68	89	37	33	24	25	36	44	51	29	20
8	102	79	79	94	52	81	66	79	103	42	38	28	29	42	51	59	34	24
9	110	86	86	102	56	88	72	85	112	46	41	31	32	45	56	64	37	26
10	55	43	43	51	28	44	36	43	56	23	21	15	16	23	28	32	18	13
11	41	32	32	38	21	32	26	31	41	17	15	11	11	17	20	23	13	9
12	27	21	21	25	13	21	17	21	27	11	10	7	7	11	13	15	9	6
13	32	24	25	29	16	25	20	24	32	13	12	9	9	13	16	18	10	7
14	51	40	40	47	26	41	33	40	52	21	19	14	15	21	26	30	17	12
15	68	53	53	63	35	54	44	53	69	28	25	19	19	28	34	39	23	16
16	64	50	50	59	33	51	42	50	65	27	24	18	18	26	32	37	21	15
17	33	25	26	30	17	26	21	25	33	13	12	9	9	13	16	19	11	7
18	24	19	19	22	12	19	16	19	25	10	9	6	7	10	12	14	8	5

In our model, we use population, jobs in industry and in service, and surfaces of zones as basic data of urban form. For the city proper of Shanghai, we only have total number of jobs for each zone. To use the LUDP model, we have to separate it into two: one for industry and one for service. As was addressed in Chapter 4, selecting an urban form is to set a lower bound and an upper bound for densities for each zone. The lower bound and upper bound for population density and job densities for each zone are listed in Table 7.15. These bounds are obtained based on their corresponding zone densities and some adjustments are made.

First we should set up a lower and upper bound for population, jobs in industry and in service at each zone. For example, the current population of zone 1 is 372,800. It should be dropped to between 300,000 to 350,000 according to Shanghai Transportation

Institute (Chen, 1994). The current total jobs of zone 1 is 265,800. It should be divided to as jobs in industry between 80,000 to 100,000 and jobs in service between 120,000 to 200,000 (Chen, 1994). Then we may calculate the lower and upper bound for population density by dividing the lower and upper bounds for population with the surface of the zone. It happens to be 71.77 and 83.73 in Table 7.15. The lower and upper bounds for job densities can be obtained in the same way. In Table 7.15, we do not list lower and upper bounds for population and jobs but for their densities, because those densities are used in our computation. Bounds for population and jobs can be computed by using the densities and the surfaces of zones.

Sum up respectively population lower bounds and upper bounds for all zones, we get the lower and upper bounds for population in the studied area, which is 5,544,000 and 7,326,000. Then the total population should be between the lower and upper bounds and smaller than the current total population 6,960,000 as well. Finally we set total population as 5,850,000. E1 and E2 are determined in the same way. Thus, for the planning year, we set total population $P = 5,850,000$, total jobs in industry $E_1 = 2,470,000$, and total jobs in service $E_2 = 1,015,000$ (refer to equations (4.1) to (4.3)).

Table 7.15: Shanghai: zone parameters

zone	class	density bounds (thousand/sqkm)					
		population		industrial jobs		service jobs	
		lower	upper	lower	upper	lower	upper
1	1	71.77	83.73	19.14	23.92	28.71	47.85
2	2	72.89	84.55	17.49	23.32	11.66	14.58
3	2	52.56	63.07	15.77	21.02	10.51	15.77
4	2	29.78	35.08	9.93	13.24	6.62	7.94
5	2	28.47	39.15	12.46	17.79	5.34	10.68
6	2	48.31	57.97	25.12	30.92	4.83	9.66
7	2	62.50	72.22	16.67	25.00	6.94	12.50
8	2	41.83	55.51	13.69	19.01	4.56	9.13
9	2	25.81	34.41	15.05	19.35	3.01	6.02
10	3	10.13	14.03	3.90	5.46	0.78	1.95
11	3	6.75	8.72	4.22	6.56	0.70	1.88
12	3	2.23	3.57	2.23	2.68	0.45	0.89
13	3	2.27	3.17	1.36	2.27	0.32	0.45
14	3	7.54	10.29	2.74	4.12	0.69	1.71
15	3	10.03	15.75	3.44	4.58	0.86	1.72
16	3	6.37	10.62	3.19	5.31	0.64	1.49
17	3	3.66	7.04	1.97	3.10	0.42	0.84
18	3	2.41	4.52	0.60	1.21	0.15	0.45

We divide zones of the city proper of Shanghai into three classes by their geographic features and densities. The first class is the central city, including zone 1. The second class is the inner city, consisting of zones 2 to 9. The third class is outer city, including zones 10 to 18. For future years, trip production and attraction of zones obey the following relations.

$$O_i = o_{i0} + \tau o_{i1}\Delta_i x_i + \sigma o_{i2}\Delta_i y_i + o_{i3}\Delta_i z_i, \tag{7.1}$$

$$D_j = d_{j0} + d_{j1}\Delta_j x_j + d_{j2}\Delta_j y_j + \varphi d_{j3}\Delta_j z_j, \tag{7.2}$$

where

Δ_i is the surface of zone i;

x_i is the decision variable for population density of zone i;

y_i is the decision variable for industrial job density of zone i;

z_i is the decision variable for service job density of zone i;

o^{i}_{i1} is the trip generation rate of population for zone i;

o_{i2} is the trip generation rate of industrial jobs for zone i;

o_{i3} is the trip generation rate of service jobs for zone i;

d_{j1} is the trip attraction rate of population for zone j;

d_{j2} is the trip attraction rate of industrial jobs for zone j;

d_{j3} is the trip attraction rate of service jobs for zone j;

τ, σ and φ are multipliers for future year modification;

o_{i0} and d_{j0} are constants.

We assume that for zones in a same class, their corresponding parameters for trip generation and attraction are identical. Certainly these parameters may be selected in a better way in urban planning practice. The class parameters we use are given in Table 7.16.

Table 7.16: Shanghai: class parameters

Cls	o_0	o_1	o_2	o_3	d_0	d_1	d_2	d_3	τ	σ	φ
1	3100	2.1	3.3	6.2	3700	1.9	3.9	7.2	1.1	1.0	1.1
2	2954	2.1	3.3	5.0	3531	1.9	3.9	6.2	1.1	1.0	1.1
3	2123	2.1	3.3	4.2	1936	1.9	3.9	5.2	1.1	1.0	1.1

The objective functions of the LUDP consist of two parts. One is transportation costs and the other, settlement costs. For simplicity purposes, we assume in this application that unit settlement costs are identical from zone to zone. By this assumption, we may delete the settlement costs from the objective function. Then the objective function is of a very simple form, i.e.,

$$Z(g) = \sum_{k \in P} \mu_k(g_k) g_k$$

where g_k is the trip demand for O-D pair k, and μ_k is the least path travel time for O-D pair k. Notice that when using the SDM to solve the traffic assignment problem, we may get $\mu_k(g_k)$ for given g_k for each k, at each iteration of the IIHM. Therefore the evaluation of the objective function becomes much easier.

Link travel cost functions we use in this study are polynomial functions, i.e.,

$$s_a(v_a) = \alpha_a \left[1 + \beta \left(\frac{v_a}{c_a}\right)^p\right],$$

where α_a is the free flow travel cost of arc a, c_a is the capacity of arc a, and β is a penalty parameter. Data for α_a and c_a are given in Appendix B. And we take $\beta = 0.002$ and $p = 3$ in this study.

To execute the IIHM, we need to select a step length. The step length should be between zero and one. In our experimental computation, we in turn use three different step lengths. They are 0.3, 0.5, and 0.618.

The computation performance for various step lengths is given in Table 7.17. We observe that the optimal values obtained by different step lengths are close, ranging from 876860.19 to 881232.63. But the number of iterations and CPU times they took are of significant difference. The fastest scenario, with step length 0.618, took 21 iterations or around 122 minutes to get the local minimum, while the slowest one, with step length 0.5, took 30 iterations or about 145 minutes to do the same job.

Table 7.19 shows a coordinate distribution of population and employment in zones using step length 0.618. It is noted that distribution results by using different step lengths are pretty close. Table 7.18 lists the transportation costs for the iterations (scenarios) with cost improvement using step length 0.618. It is interesting to compare the transportation costs of the coordinate distribution of population and employment with that of the original distribution. Transportation costs for the original distribution is around 961223, while that of the coordinate distribution is around 876860, which is about 10 percent (or about 2 months of time) less than the original one.

Table 7.17: IIHM Performance

Step length	Number of iterations	Number of improvements	Optimal value	CPU time (minutes)
0.3	27	13	879543.55	139.77
0.5	30	14	881232.63	145.21
0.618	21	12	876860.19	122.50

Table 7.18: Transportation costs for iterations with improvement

iteration with improvement	transportation cost (minutes)
1	961223.44
2	948745.27
3	939093.55
4	930117.38
5	916247.36
6	908534.65
7	901103.57
8	892554.10
9	888663.94
10	882775.39
11	879537.48
12	876860.19

Table 7.19: Coordinate distribution of population and employment

Zone	population	jobs in industry	jobs in service
1	306.01	84.76	122.99
2	509.88	127.79	84.88
3	410.92	128.67	85.41
4	471.70	167.23	110.80
5	168.08	76.42	34.02
6	514.89	271.77	57.37
7	460.35	128.21	55.10
8	568.97	194.98	69.34
9	633.51	376.36	86.56
10	296.83	129.26	38.31
11	174.65	114.28	30.14
12	60.03	49.95	19.94
13	100.20	60.03	19.98
14	261.80	113.07	40.92
15	400.35	159.80	54.92
16	367.52	203.70	63.69
17	110.14	69.99	29.85
18	40.11	19.89	14.92

7.4 Conclusion and discussion

In this chapter, we applied the LUDP model to land use and freight transport coordination in Shanghai urban district, with a view to demonstrate the proposed land use/transportation planning method, including data collection and manipulation, implementation of the LUDP model and performance analysis.

We first provided a brief introduction to Shanghai. Transportation conditions in Shanghai were described. Land use, demographic and freight transportation data were collected.

Relationship between land use and freight transportation was discussed. We applied the multiple linear regression method to freight traffic generation with the support of a Geographic Information System software. The application shows that with the help of GIS software, land use and transportation data can be gathered more extensively and precisely, thus better information may be provided to support zone-based multiple linear regression.

Both single and multiple linear regression methods were used to generate traffic production and attraction parameters. The multiple regression method outperformed the single regression Method, in the sense that the multiple regression method generated traffic forecast equations with high correlation. Different groups of items were used as input variables in the multiple regression model. The best fitness (correlation) of the regression is achieved at the group including surfaces of zones, population and number of jobs of zones. This result explains that traffic generation is proportionally related to population density and job densities.

We then applied the LUDP to land use and freight transport coordination. We divided the urban district of Shanghai into 18 large-sized zones connected with a freight transport base network of 60 nodes and 218 links. The 18 zones are further grouped to three classes. The three classes represent three different city belts: city core, inner city and outer city. The lower bound and upper bound for population and jobs in industry and in service were set up for each zone. Corresponding density bounds for each zone were determined accordingly. The total population, total jobs in industry and in service in the studied area were properly determined too.

The mathematical problem for the Shanghai land use and freight transportation coordination was then formed. To find and compare different solutions for this problem, we used the Iterative Improvement Heuristic Method to obtain feasible population and employment distributions and to select, among those feasible solutions, one solution that meats the requirement of land use and transportation coordination.

It takes a little over two hours (123 minutes) for the computer system to generate 21 feasible solutions for the given problem. These 21 solutions represent 21 different scenarios for population and employment distribution that meet all given restrictions.

The solutions were generated in the following way. It first generates an initial feasible solution, computes the total costs (zone development costs plus transportation costs) for this solution. It then evaluates the feasible solution. The result of the evaluation gives out the direction for an improvement. This improvement yields the next, better scenario. It then adjusts the population and employment distribution to obtain a new solution, computes the total costs for this new solution. Compare the total costs of the new solution with that of the old one. The solution with smaller total costs is kept as the new initial solution for further possible improvement. Because we assume the unit settlement costs are identical from zone to zone, the difference of two total costs is just the difference of two transportation costs. Therefore the solution with smaller transportation costs is kept as the new initial solution. This process of getting a new solution and comparing the new solution with the old one continues until no better solution can be found according to pre-determined searching rules.

Of all 21 solutions generated for the given problem, 12 solutions get better transportation costs than previous ones. Among these 12 improved solutions, transportation cost deduction is significant. The total transportation cost deduction for these 12 improvements is about 10 percent of the transportation costs of the original solution. This result explains that in an urban area, the total transportation costs can be dropped down to a curtain extent by adjusting population and job distribution.

This result of the application is pretty interesting and exciting. It demonstrates that the proposed land use and transportation planning approach could be used to achieve a coordinate distribution of population and employment in an urban area, therefore it meaningful.

Several points may be concluded from this experimental case study. Firstly, as a new urban modeling and planning approach, our method can be used in long-term, strategic urban planning. This approach is also helpful for conducting traffic optimization analysis for urban construction projects, such as construction of airport, subway network and metropolitan highway system. Consequently, the LUDP model and the corresponding heuristic solution method provides us with a useful tool to conduct, at the strategic level, long term planning for the land use and transportation coordination in metropolitan areas.

Secondly, selecting appropriate lower and upper density bounds of zones is decisive for forming a desired urban form. In fact, density bounds are only constraints used to manipulate the urban form in the LUDP. The computation results of our case study shows that, if unit settlement costs are identical or almost identical for zones, then the land use and transportation coordination planning method trends to distribute population and employment as concentrated as possible. The concentration of population and employment distribution do reduce transportation costs, but over-concentrated distribution worsens life quality. Therefore, it is worth making great efforts to carefully set up density bounds in a practical application.

The rationale of using identical unit settlement cost is as follows. In urban land use and transportation coordination study, our studied areas are metropolitan areas. We notice that the economic development experiences imbalance from region to region. And for a given metropolitan area, it also experiences imbalance from time to time. The development imbalance, however, does not and should not exist among different zones within the metropolitan area for any specific year, because those zones are planned under one jurisdiction and support the same local economy. Therefore, identical or almost identical unit settlement costs can be used as zone development cost. The use of identical settlement cost simplifies the solution process as well, as indicated in the previous section.

Thirdly, social and economical changes of the future year must be taken into consideration. In the LUDP model, traffic production and attraction are linear functions of population density and job densities. These functions are determined by the multiple linear regression method using base year's transportation survey data. When applying the LUDP in metropolitan areas, these functions should be modified by multipliers that reflect social and economical changes in the future year. These multipliers must be carefully determined. When identical unit settlement cost is used for zone development, the multipliers that reflect changes in the future year can also be set identical from zone to zone.

Fourthly, Geographic Information System software is very useful in collecting, storing, displaying, manipulating and transforming land use and geographic data. With the help of GIS software, land use and transportation data may be gathered more extensively and precisely. In this study, GIS software was used only to collect land use and geographic data. It already showed its advantage for calculating zone surfaces for different land use distribution. We can further use GIS software to display land use distribution of a scenario and demonstrate scenario impacts.

Lastly, we have the following technical conclusions for the Iterative Improvement Heuristic Method and the implementation of the IIHM.

1. The IIHM seems to be a good heuristic method for solving large-scale mathematical programming problems with variational inequality constraints.
2. The SDM is useful to break down large problems into several small problems, which are much easier to solve.
3. The implementation for the IIHM proposed in this chapter is relatively efficient.
4. In accordance to common sense, the search with step length 0.618 seems a better search method than ones with other search step lengths, in the sense of getting the same result by using less CPU time.

Chapter 8

Conclusion

In this thesis, we have studied the land use and freight Transportation coordination Problem in the following aspects: modeling mechanism analysis, mathematical formulation and solution method development, implementation of solution algorithm, case study of urban form analysis and land use freight transport interaction and the application of the LUDP model to land use and freight transport coordination in Shanghai.

With the objective of developing a land use and freight transportation coordination planning approach for Chinese cities, we conducted an analysis for economic development and urbanization in China. Special features in the economic development and urbanization were explored.

Our major points of this exploration may be addressed as follows. Industrialization and urbanization in China are an essential part of growth. Like most developing countries, China is marked by regional inequalities. The increasing rate of migration caused by regional inequalities imposes unprecedented presures to urban systems. In urban areas, mixed land use is commonly found, bicycles are largely used as major transportation vehicles, urban traffic is extremely congested, and job-hunting and housing are under the control of a plan system.

Based on these understandings, we concluded that when modeling land use and transportation in urban China the following must be concerned: 1) Urban planners seek for methods to achieve land use and transportation coordination; 2) Urban planners need efficient tools to compare different land use and transportation design scenarios; and 3) Only aggregate data may be used in trip generation and distribution.

The new urban modeling approach

An urban-form-based modeling approach has been proposed in this thesis. In this modeling process, we select population density and job density as decision variables; traffic demands are functions of these densities; the gravity model is used for distributing trips to O-D pairs; the traffic equilibrium assignment model was used to solve the traffic assignment problem. Finally, the Land Use Design Problem is formulated as a two-level mathematical programming problem. At the upper level, urban planners distribute population and employment to zones to pursue the best urban activity location, while at the lower level, road users select traffic modes and travel routes to minimize their travel costs.

A theoretical study was conducted to explore the existence of solutions to the Land Use Design Problem. Solution methods to the problem were developed. With the nature of difficult problems, the problem can only be solved by heuristics, when the size of problems are large.

A robust implementation of one heuristic, namely iterative improvement heuristic method, was developed to solve the Land Use Design Problem.

A case study has been conducted for the purpose to demonstrate the implementation of the new urban planning approach. Corresponding land use and freight transportation data were collected and relationship between land use and freight transportation was discussed. A land use and freight transportation interaction analysis was conducted to forecast freight traffic production and attraction. Lastly, an application of the LUDP model to Shanghai land use and freight transportation coordination was completed.

The results of the application are pretty exciting. It demonstrates that the LUDP could be used to achieve, in certain degree, a coordinate distribution of population and employment in an urban area. Consequently, the LUDP and the corresponding heuristic solution method provides us with a useful tool to conduct, at the strategic level, long term planning for the land use and transportation coordination in metropolitan areas.

Assumption, restriction and limitation

Several assumptions and restrictions are made in our models to simplify analyses and ensure existence of solutions. We discuss these assumptions and restrictions next.

1. Only two classes of jobs are defined: industrial and service jobs (Section 2.1). Actually one may define much more classes. But using too many classes may not be a good idea in our study, because our purpose is to develop a macroscopic land use and transportation model, and to provide a tool to conduct strategic, long term land use and transportation planning. However, as long as we can divide jobs into three or four classes, we may use three or four classes too.
2. Link travel cost functions (or delay functions) are link-separable (Section 2.2.2). This assumption states that the travel time over a link (a road segment) is determined only by flows of this link, but not affected by flows of other links. This certainly loses some generality, because it is easy to see that flows of other links also affect the travel time of this link. This simplification, however, is necessary for us to develop solution algorithms. Without this simplification it is very difficult to develop any acceptable algorithms.
3. Link travel cost functions are continuously differentiable and strictly monotone (Assumption 3.1). This assumption is commonly used in transportation planning models. In practice we often use polynomial functions as link travel cost functions. Polynomial functions are continuously differentiable and strictly monotone in transportation models.
4. For each zone, population and number of service jobs meet a fundamental requirement: for a given percentage, the number of service jobs must be larger than or

equal to the percentage of population (Assumption 3.2). This assumption imposes a restriction on population and service job distribution. It is meaningful and simple. One may impose other forms of restrictions on population and employment distribution, but should ensure that solutions exist under those restrictions.

5. The travel impedance among zones is positively finite (Assumption 3.3). This restriction may easily be satisfied. Travel impedance is always positive, and as long as the road network is connected (there are paths for any origin-destination pairs), this impedance is finite.

Although we made a lot of simplification, the LUDP is still very difficult to solve. It is believed that in the social sciences there may not be any simple problem. This assertion is certainly true for the type of problems explored in this study. To solve these problems, one may only use heuristic methods to find local optimal solutions with a very long computation time. This is a great limitation!

Future development

There are several directions in which further research could be conducted. On the practical aspect, it is of great importance to apply the LUDP model to real practical projects on land use and transportation coordination planning in cities of China. For completing such practical projects, we need

- to conduct more detailed case studies to determine land use parameters and highway network parameters;
- to carefully set the lower bounds and upper bounds for population densities and job densities in different zone classes;
- to conduct a survey or a case study to find the employment data in industry and in service;
- to define factors which effect transit trip general cost and bicycle trip general cost, and to find formulas to calculate these costs;
- to define factors which effect zone settlement cost, and to determine formulas to compute the cost.

On the aspect of mathematical model and solution algorithm, we may further take several other issues into account in the LUDP. These issues include

- detailed transit network analysis and design and transit assignment;
- goods distribution center, distribution network, and freight transportation optimization;
- development of better heuristic methods to solve the LUDP and LUTCP. For instance, we could use the tabu search method to search a better solution when we stop at a local optimal point using IIHM (Glover, 1986; Crainic et al, 1993);
- development of efficient implementation for the existing solution algorithms and new solution algorithms.

Appendix A

Land use and freight transport data

b_area: built-up area;
popu: population;
a_attr: agricultural goods attraction;
d_attr: daily used goods attraction;
a_prod: agricultural goods production;
d_prod: everyday goods production;
l_zone: large zone number.

ne	area	b_area	popu	jobs	a_attr	d_attr	a_prod	d_prod	l_zone
	0.757	0.73	62823	122179	2125	10984	852	8243	1
	1.36	1.343	179169	100759	5107	17595	2508	13145	1
	1.421	1.291	140780	42819	2384	6057	571	5359	1
	3.069	3.041	348584	93433	3127	11669	1128	8564	2
	1.327	1.244	105183	58904	4124	12362	6036	12047	2
	2.367	1.809	141018	81080	1724	8247	1349	7745	2
	2.828	2.444	309833	109674	5051	9781	986	7952	3
	3.66	2.609	172407	125159	3354	11270	955	14332	3
	2.302	1.828	189413	72989	5191	7227	1011	7855	4
0	4.038	2.326	215496	111997	6232	19808	14361	26079	4
1	3.311	2.66	130386	121170	5977	11157	3561	11976	4
2	5.314	4.705	226626	140692	5190	13209	1675	14835	5
3	1.807	1.72	170543	55236	2505	5767	946	5299	6
4	2.774	2.541	190952	118109	6148	8575	1639	8308	6
5	4.673	2.975	242044	218051	6334	18782	16683	24284	6
6	1.626	1.363	140258	37786	2465	8512	675	8830	7
7	1.487	1.121	114031	40077	1394	5819	6639	7301	7
8	3.326	3.294	267939	127029	6310	11928	1425	13514	7
9	0.704	0.697	115524	47125	3219	9499	1699	7236	8
0	2.15	1.477	175134	77843	3862	23445	5852	15831	8
1	2.212	1.733	143613	53476	2070	6069	771	6743	8
2	2.3	1.939	168711	58478	3919	6193	1912	8444	8
3	2.429	2.075	132678	62293	2064	4974	1731	6756	8
4	2.609	1.643	194678	147372	5197	20169	3707	23855	9
5	4.924	2.689	147338	170901	3637	12800	7654	16607	9
6	4.84	1.98	56205	83511	4048	15581	6396	21750	9
7	3.431	2.171	196518	70529	3396	5414	903	4171	9
8	2.889	2.524	195633	35772	3220	5768	1626	4982	9
9	5.901	4.607	228160	89863	5400	18963	6126	16173	10
0	4.868	3.524	48970	31164	1488	2549	798	2134	10
1	2.201	1.381	83284	27450	2555	2109	1986	2600	11
2	4.161	2.182	153172	103926	2296	5005	741	6006	11
3	2.813	0.098	54895	53267	2995	9740	2348	10820	12
5	5.255	3.464	100778	107446	5668	20285	4775	26395	13
6	1.897	1.847	23772	3556	985	6030	3229	7321	13
7	5.232	3.735	245893	126146	4891	11446	2337	12285	14
8	7.69	1.838	36933	35125	4692	11362	6132	10920	14
9	3.783	2.864	188630	46690	3630	22061	12481	13244	15
0	5.305	3.696	204476	91141	15455	19913	7197	23886	15
1	3.575	2.166	38486	45203	1888	4606	6681	5585	15
2	0.443	0.443	16681	2903	888	3380	1983	4217	15
3	3.322	2.797	100152	76040	1765	12016	1686	15433	16
4	4.577	4.4	141061	37479	3983	10104	1883	9672	16
5	3.43	0.404	15430	71022	1003	23889	2581	17712	16
6	0.878	0.837	58301	11968	1375	3803	757	3524	16
7	3.925	3.269	77692	60217	3730	11317	3675	11882	16
8	4.426	2.941	65908	44077	2948	8770	902	8951	17
9	9.324	2.021	18086	26284	1508	8735	1869	17450	17
0	1.824	1.449	46771	12972	886	3893	259	4758	17
1	1.926	0.401	7718	31127	1600	3272	3322	3483	17
2	1.506	0.609	54961	24550	420	603	253	670	18
3	2.774	0.841	37029	14456	555	1758	332	1583	18

Appendix B

Road network data

Cost unit: minute
Capacity unit: thousand vehicles per hour

Table B.1: Road Network Data of Shanghai

link	from node	to node	cost	capacity
1	1	2	1.7	36.0
2	1	19	0.4	48.0
3	1	20	1.7	48.0
4	1	21	2.1	36.0
5	2	1	1.7	36.0
6	2	3	1.8	36.0
7	2	22	1.0	36.0
8	2	23	0.9	36.0
9	3	2	1.8	36.0
10	3	20	1.6	48.0
11	3	24	1.0	48.0
12	3	26	1.2	36.0
13	4	24	1.2	36.0
14	4	26	1.4	36.0
15	4	27	1.1	36.0
16	4	28	2.1	36.0
17	5	30	1.1	48.0
18	5	31	0.9	36.0
19	5	33	1.0	48.0
20	5	34	1.6	36.0
21	6	7	2.2	36.0
22	6	34	1.1	36.0
23	6	35	1.3	36.0
24	6	36	0.8	36.0
25	7	6	2.2	36.0
26	7	20	2.4	48.0
27	7	21	2.2	36.0
28	7	39	0.8	48.0
29	8	21	0.9	36.0
30	8	43	3.2	48.0

link	from node	to node	cost	capacity
31	8	44	1.9	36.0
32	8	46	0.8	48.0
33	9	44	2.9	36.0
34	9	47	1.4	36.0
35	9	49	1.7	36.0
36	9	50	1.6	36.0
37	10	18	6.2	36.0
38	10	50	2.1	36.0
39	10	51	2.0	36.0
40	11	60	2.2	36.0
41	11	25	5.7	36.0
42	11	51	3.1	36.0
43	12	52	3.2	36.0
44	12	58	3.6	36.0
45	13	14	3.4	36.0
46	13	52	2.8	36.0
47	14	13	3.4	36.0
48	14	15	3.8	36.0
49	14	32	3.2	36.0
50	14	33	3.1	48.0
51	15	14	3.8	48.0
52	15	53	1.7	36.0
53	15	59	3.6	36.0
54	16	37	3.5	36.0
55	16	41	2.9	48.0
56	16	54	2.0	48.0
57	16	57	2.2	36.0
58	17	43	3.2	48.0
59	17	47	2.7	36.0
60	17	55	2.9	36.0

link	from node	to node	cost	capacity
61	17	56	3.1	36.0
62	18	10	6.2	36.0
63	18	56	2.2	36.0
64	19	1	0.4	48.0
65	19	22	2.1	36.0
66	19	46	1.2	36.0
67	19	51	3.3	48.0
68	20	1	1.7	48.0
69	20	3	1.6	48.0
70	20	7	2.4	48.0
71	20	35	1.4	48.0
72	21	1	2.1	36.0
73	21	7	2.2	36.0
74	21	8	0.9	36.0
75	21	40	0.8	36.0
76	22	2	1.0	36.0
77	22	19	2.4	48.0
78	22	60	2.0	38.0
79	23	2	0.9	36.0
80	23	24	2.2	36.0
81	23	60	0.6	36.0
82	24	3	1.0	48.0
83	24	4	1.2	36.0
84	24	23	2.2	36.0
85	24	25	1.1	36.0
86	25	11	5.7	36.0
87	25	24	1.1	36.0
88	25	27	1.2	36.0
89	25	60	2.5	48.0
90	26	3	1.2	36.0

link	from node	to node	cost	capacity
91	26	4	1.4	36.0
92	26	29	1.2	36.0
93	26	35	1.4	36.0
94	27	4	1.1	36.0
95	27	25	1.2	36.0
96	27	58	2.0	48.0
97	28	4	2.1	36.0
98	28	29	1.7	36.0
99	28	31	2.1	36.0
100	28	58	2.0	36.0
101	29	26	1.2	36.0
102	29	28	1.7	36.0
103	29	30	1.6	36.0
104	29	31	1.0	36.0
105	30	5	1.1	48.0
106	30	29	1.6	36.0
107	30	34	1.4	36.0
108	30	35	0.9	48.0
109	31	5	0.9	36.0
110	31	28	2.1	36.0
111	31	29	1.0	36.0
112	31	32	1.1	36.0
113	32	14	3.2	36.0
114	32	31	1.1	36.0
115	32	33	0.7	48.0
116	32	58	3.5	36.0
117	33	5	1.0	48.0
118	33	14	3.1	48.0
119	33	32	0.7	48.0
120	33	59	2.2	48.0

link	from node	to node	cost	capacity
121	34	5	1.6	36.0
122	34	6	1.1	36.0
123	34	30	1.4	36.0
124	34	59	0.6	36.0
125	35	6	1.3	36.0
126	35	20	1.4	48.0
127	35	26	1.4	36.0
128	35	30	0.9	48.0
129	36	6	0.8	36.0
130	36	37	1.0	36.0
131	36	38	1.2	48.0
132	36	59	1.7	48.0
133	37	16	3.5	36.0
134	37	36	1.0	36.0
135	37	38	0.9	36.0
136	37	53	3.1	36.0
137	38	36	1.2	48.0
138	38	37	0.9	36.0
139	38	39	1.6	36.0
140	38	41	1.7	48.0
141	39	7	0.8	48.0
142	39	38	1.6	36.0
143	39	40	1.9	36.0
144	39	41	0.5	48.0
145	40	39	1.9	36.0
146	40	42	1.4	36.0
147	40	21	0.9	39.0
148	41	16	2.9	48.0
149	41	38	1.7	48.0
150	41	39	0.5	48.0

link	from node	to node	cost	capacity
151	41	42	2.4	48.0
152	42	40	1.4	36.0
153	42	41	2.4	48.0
154	42	57	1.3	48.0
155	43	8	3.2	48.0
156	43	17	3.2	48.0
157	43	44	1.7	36.0
158	43	47	2.9	36.0
159	43	57	1.2	36.0
160	44	8	1.9	36.0
161	44	9	2.9	36.0
162	44	43	1.7	36.0
163	44	45	1.0	36.0
164	45	44	1.0	36.0
165	45	46	2.1	36.0
166	45	50	2.6	36.0
167	46	8	0.8	48.0
168	46	19	1.2	36.0
169	46	45	2.1	36.0
170	47	9	1.4	36.0
171	47	17	2.7	36.0
172	47	43	2.9	36.0
173	47	48	2.0	36.0
174	48	47	2.0	36.0
175	48	49	1.5	36.0
176	48	58	1.6	36.0
177	49	9	1.7	36.0
178	49	48	1.5	36.0
179	49	50	1.7	36.0
180	50	9	1.6	36.0
181	50	10	2.1	36.0
182	50	45	2.6	36.0
183	50	49	1.7	36.0
184	51	10	2.0	36.0

link	from node	to node	cost	capacity
185	51	11	3.1	36.0
186	51	19	3.3	48.0
187	52	12	3.2	36.0
188	52	13	2.8	36.0
189	52	58	4.6	36.0
190	53	15	1.7	36.0
191	53	37	2.6	36.0
192	53	54	4.9	36.0
193	54	16	2.0	48.0
194	54	53	4.9	36.0
195	54	55	2.2	36.0
196	55	17	2.9	36.0
197	55	54	2.2	36.0
198	55	57	1.9	48.0
199	56	17	3.1	36.0
200	56	18	2.2	36.0
201	56	48	1.6	36.0
202	57	16	2.2	36.0
203	57	42	1.3	48.0
204	57	43	1.2	36.0
205	57	55	1.9	48.0
206	58	12	3.6	36.0
207	58	27	2.0	48.0
208	58	28	2.0	36.0
209	58	32	3.5	36.0
210	58	52	4.6	36.0
211	59	15	3.6	36.0
212	59	33	2.2	48.0
213	59	34	0.6	36.0
214	59	36	1.7	48.0
215	60	11	2.2	36.0
216	60	22	2.0	38.0
217	60	23	0.6	36.0
218	60	25	2.5	48.0

Appendix C

Results of Simple Linear Regression

Traffic Zone Class 1 : (CBD, Composite Density > 200 thou / sqkm)

		Intercept	Slope	Correlation
X1	Y1	-31.802	3738.534	0.903
	Y2	1626.921	11767.896	0.995
	Y3	1595.115	15506.435	0.999
	Y4	-65.540	1863.035	0.820
	Y5	1414.931	8642.044	0.996
	Y6	1349.400	10505.069	0.999
X2	Y1	-17.616	3792.002	0.915
	Y2	1843.484	11750.018	0.992
	Y3	1825.864	15542.024	1.000
	Y4	-68.998	1901.081	0.835
	Y5	1571.056	8632.069	0.993
	Y6	1502.066	10533.142	1.000
X3	Y1	412.794	0.026	0.995
	Y2	5634.199	0.059	0.801
	Y3	6046.994	0.085	0.876
	Y4	-3.685	0.014	0.998
	Y5	4313.566	0.044	0.808
	Y6	4309.884	0.058	0.882
X4	Y1	3932.567	-0.005	-0.128
	Y2	8636.860	0.045	0.404
	Y3	12569.417	0.040	0.274
	Y4	2244.940	-0.006	-0.290
	Y5	6655.544	0.032	0.392
	Y6	8900.496	0.026	0.261

Traffic Zone Class 2 : (Inner City, Near River, Composite Density 100 – 200 thou / sqkm)

		Intercept	Slope	Correlation
X1	Y1	2973.746	700.257	0.643
	Y2	4533.747	6962.661	0.794
	Y3	7507.486	7662.921	0.863
	Y4	8501.353	-1628.172	-0.817
	Y5	-333.534	8664.739	0.933
	Y6	8167.800	7036.575	0.955
X2	Y1	841.706	2442.228	0.692
	Y2 -	12441.708	21379.727	0.753
	Y3 -	11599.960	23821.926	0.828
	Y4	13213.797	-5510.172	-0.853
	Y5 -	24546.719	28728.955	0.955
	Y6 -	11333.036	23218.861	0.973
X3	Y1	3157.284	0.008	0.520
	Y2	1854.348	0.106	0.877
	Y3	5011.609	0.114	0.929
	Y4	8335.618	-0.020	-0.720
	Y5	-374.543	0.111	0.868
	Y6	7961.057	0.091	0.899
X4	Y1	3064.725	0.014	0.925
	Y2	13764.649	0.052	0.423
	Y3	16829.389	0.066	0.531
	Y4	7807.333	-0.028	-0.991
	Y5	5065.960	0.129	0.993
	Y6	12873.282	0.101	0.984

Traffic Zone Class 3 : (Inner City, Core, Composite Density 100 – 200 thou / sqkm)

		Intercept	Slope	Correlation
X1	Y1	283.590	1532.852	0.809
	Y2	-182.235	3675.263	0.930
	Y3	101.363	5208.112	0.973
	Y4	-4547.174	2966.696	0.615
	Y5	-2169.986	4647.712	0.866
	Y6	-6717.167	7614.410	0.777
X2	Y1	93.173	1895.218	0.776
	Y2	727.768	3918.594	0.769
	Y3	820.939	5813.813	0.842
	Y4	-120.548	1473.188	0.237
	Y5	703.276	4167.017	0.602
	Y6	582.729	5640.205	0.446
X3	Y1	2523.711	0.009	0.353
	Y2	4018.552	0.026	0.521
	Y3	6542.262	0.035	0.510
	Y4	3012.232	0.000	0.007
	Y5	6335.015	0.017	0.253
	Y6	9347.253	0.018	0.142
X4	Y1	1661.759	0.028	0.812
	Y2	3203.530	0.067	0.922
	Y3	4865.283	0.095	0.968
	Y4	-2463.679	0.061	0.690
	Y5	1875.663	0.087	0.885
	Y6	-588.018	0.148	0.824

Traffic Zone Class 4 : (Inner City, Near River, Composite Density 50 -- 100 thou / sqkm)

		Intercept	Slope	Correlation
X1	Y1	-436.321	937.885	0.962
	Y2	1009.070	2849.698	0.945
	Y3	572.757	3787.581	0.954
	Y4	-3704.735	1890.267	0.826
	Y5	3030.857	2832.967	0.762
	Y6	-673.879	4723.234	0.845
X2	Y1	978.232	969.172	0.814
	Y2	5716.829	2795.155	0.759
	Y3	6695.067	3764.325	0.776
	Y4	1822.449	976.176	0.349
	Y5	13206.696	772.128	0.170
	Y6	15029.158	1748.299	0.256
X3	Y1	2573.787	0.007	0.334
	Y2	11157.183	0.015	0.226
	Y3	13730.974	0.022	0.253
	Y4	5556.995	-0.007	-0.142
	Y5	20073.082	-0.032	-0.393
	Y6	25630.082	-0.039	-0.320
X4	Y1	3545.606	0.001	0.023
	Y2	15049.041	-0.015	-0.143
	Y3	18594.645	-0.014	-0.103
	Y4	1753.707	0.025	0.307
	Y5	13543.765	0.016	0.123
	Y6	15297.471	0.041	0.207

Traffic Zone Class 5 : (Inner City, Edge, Composite Density < 100 thou / sqkm)

		Intercept	Slope	Correlation
X1	Y1	-121.853	906.471	0.851
	Y2	505.226	2174.814	0.782
	Y3	383.376	3081.285	0.894
	Y4	772.652	186.285	0.413
	Y5	1052.699	2246.946	0.616
	Y6	1825.352	2433.231	0.624
X2	Y1	104.562	1089.348	0.827
	Y2	96.922	2949.192	0.858
	Y3	201.483	4038.540	0.947
	Y4	603.166	300.061	0.539
	Y5	-224.734	3348.788	0.743
	Y6	378.425	3648.851	0.757
X3	Y1	575.557	0.016	0.786
	Y2	6939.613	0.009	0.175
	Y3	7515.172	0.025	0.384
	Y4	758.360	0.004	0.494
	Y5	8904.701	0.002	0.032
	Y6	9663.075	0.006	0.087
X4	Y1	1220.772	0.026	0.765
	Y2	3360.357	0.067	0.758
	Y3	4581.129	0.093	0.848
	Y4	819.182	0.008	0.582
	Y5	3115.401	0.081	0.697
	Y6	3934.586	0.089	0.720

Traffic Zone Class 6 : (Warehouse, Composite Density 50 --100 thou / sqkm)

		Intercept	Slope	Correlation
X1	Y1	-24865.174	7611.803	0.999
	Y2	24666.350	-930.752	-0.597
	Y3	-198.824	6681.051	0.992
	Y4	29607.611	-4173.688	-0.916
	Y5	2751.423	4186.708	0.497
	Y6	32359.129	12.998	0.001
X2	Y1	-13397.491	7372.212	0.819
	Y2	21040.744	-150.825	-0.082
	Y3	7643.276	7221.379	0.908
	Y4	27119.453	-5325.159	-0.990
	Y5	22163.285	-369.216	-0.037
	Y6	49282.742	-5694.376	-0.528
X3	Y1	-20414.764	0.142	0.309
	Y2	38339.180	-0.087	-0.929
	Y3	17924.416	0.055	0.135
	Y4	2869.564	0.042	0.152
	Y5	-78595.109	0.491	0.966
	Y6	-75724.930	0.533	0.967
X4	Y1	2161.910	0.075	0.405
	Y2	23647.770	-0.037	-0.962
	Y3	25809.680	0.039	0.235
	Y4	10880.909	0.006	0.050
	Y5	4142.193	0.203	0.988
	Y6	15023.113	0.209	0.935

Traffic Zone Class 7 : (Outer City, Puxi, Composite Density < 40 thou / sqkm)

		Intercept	Slope	Correlation
X1	Y1	1238.674	317.477	0.504
	Y2	5562.274	1011.553	0.402
	Y3	6800.946	1329.030	0.464
	Y4	2028.108	276.060	0.373
	Y5	4241.433	1652.761	0.625
	Y6	6269.538	1928.822	0.663
X2	Y1	1043.281	779.182	0.641
	Y2	7326.857	1111.758	0.229
	Y3	8370.137	1890.941	0.342
	Y4	2387.267	373.704	0.262
	Y5	6870.935	1962.135	0.385
	Y6	9258.202	2335.838	0.416
X3	Y1	971.221	0.029	0.690
	Y2	7233.002	0.041	0.246
	Y3	8204.219	0.071	0.368
	Y4	3103.390	-0.001	-0.027
	Y5	7819.198	0.050	0.284
	Y6	10922.592	0.049	0.252
X4	Y1	987.308	0.037	0.672
	Y2	2380.976	0.179	0.821
	Y3	3368.282	0.216	0.869
	Y4	1959.553	0.028	0.438
	Y5	3183.570	0.185	0.806
	Y6	5143.123	0.213	0.844

Traffic Zone Class 8 : (Outer City, Pudong, Composite Density 20 – 60 thou / sqkm)

		Intercept	Slope	Correlation
X1	Y1	696.096	247.165	0.352
	Y2	-156.148	825.580	0.706
	Y3	539.949	1072.744	0.622
	Y4	865.504	-14.024	-0.028
	Y5	103.967	804.202	0.548
	Y6	969.469	790.178	0.477
X2	Y1	846.722	360.828	0.438
	Y2	1142.479	739.324	0.539
	Y3	1989.200	1100.152	0.543
	Y4	642.505	105.128	0.179
	Y5	1446.578	674.723	0.392
	Y6	2089.082	779.851	0.401
X3	Y1	344.409	0.015	0.709
	Y2	168.524	0.030	0.851
	Y3	512.933	0.044	0.865
	Y4	527.474	0.004	0.262
	Y5	-487.623	0.041	0.937
	Y6	39.851	0.045	0.908
X4	Y1	854.752	0.015	0.559
	Y2	757.597	0.041	0.909
	Y3	1612.349	0.056	0.843
	Y4	808.596	0.000	0.017
	Y5	451.631	0.053	0.945
	Y6	1260.227	0.054	0.841

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ACKNOWLEDGEMENTS

First of all, I would like to express my profound gratitude to my thesis director, Professor Claude Comtois, for his extensive time, valuable suggestions and unfailing help during my entire Ph.D. study. I benefited very much from his constant encouragement, confidence and patience. His help is greatly appreciated and I will remember him forever.

I am particularly grateful to my co-director, Professor Michel Gendreau, for his penetrating analysis, valuable comment, and insightful suggestions. Many profitable discussions with him greatly improved the quality of this thesis.

I am deeply indebted to Professor Michael Florian for his concern, encouragement and generous support. His help is greatly appreciated and will remain in my memory.

My sincere thanks go to Jia Hao Wu and Yang Chen for their comments and discussions on many interesting subjects within and beyond this thesis.

I warmly thank my wife and son for their patience and understanding during the entire period of my study.

Finally, I would like to express my appreciation to the Canadian International Development Agency, the Département de Géographie and the Université de Montréal for their financial support, and to the Centre de Recherche sur les Transports for their efficient staff assistance and excellent research atmosphere.