A BALANCE OF CAR OWNERSHIP UNDER USER DEMAND

AND

ROAD NETWORK SUPPLY CONDITIONS

By

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THESIS

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DECLARATION

I hereby declare that the thesis entitled "A Balance of Car Ownership under User Demand and Road Network Supply Conditions" is original and has not been submitted for other degrees or the like in this University or any other institutes. It does not contain any material, partly or wholly, published or written previously by others, except those references quoted in the text.

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ABSTRACT

Car ownership relates to both user demand and the network supply. When considering this problem, the conventional approach has been mainly concerned with an estimation of car ownership from the user demand viewpoint and has ignored the supply conditions of the road network. Previous related studies have usually modelled car ownership as a function of demography and household characteristics such as income and household size, and have not considered the constraints of the road network. However, road traffic conditions and the availability of parking spaces at home-ends or destination-ends could affect the desire to own a car. The absence of consideration of road network supply constraints in previous modelling of car ownership and usage might be due to the fact that much of these works are of North American and European origins, where space constraints in low density development areas are not important issues for affecting the car ownership and usage. By contrasting with the Hong Kong's road network, it is one of the most densely and busiest road networks worldwide. Thus, the effects of road network supply constraints on car ownership should be fully understood in Hong Kong.

In this study, car ownership has been examined from both the demand and supply aspects. On the demand side, an aggregate car ownership model was calibrated by using a set of socio-economic factors. The total number of licensed private cars and motorcycles (in terms of passenger car units) in Hong Kong was estimated in a demand model. A reliability analysis has been devised to incorporate the degree of uncertainty in territory-wide car ownership estimation. By conducting surveys using both revealed and stated preference questions, the effects of the changes of economic

factors and fiscal measures on car ownership demand were assessed. Disaggregate car ownership choice (logit-type) models have been calibrated for car ownership and non-car ownership households, respectively. Zonal car ownership households were estimated using the planning data of Hong Kong.

On the supply side, the concept of a reserve capacity of car ownership was introduced. Reserve capacity of car ownership is referred to as the greatest additional amount of car ownership that can be accommodated in a traffic zone. A bilevel programming model has been proposed to determine the maximum zonal car ownership that the road network can accommodate, under the existing road capacities and parking space constraints. A heuristic sensitivity analysis based solution algorithm has been derived for solving the reserve capacity problems on car ownership. Artificial road networks were used to test the proposed model and the solution algorithm. A case study in Hong Kong was used to illustrate the application of the proposed model in practice.

In the case study, a study road network in Tuen Mun and Yuen Long Corridor of Hong Kong was used for demonstrating the concept of balancing car ownership from user demand and road network supply conditions. With car ownership demand estimated by the disaggregate car ownership choice models and the maximum car ownership determined by the bilevel programming model, a balanced car ownership in the study area has been obtained. The balanced car ownership shows that it is the most efficient scenario in terms of total network travel time and utilization of network facilities. With taking into account of user demand, the balanced car ownership indicates that transport infrastructure improvements should be carried out

if the degree of satisfaction of car ownership demand under road network supply conditions is below an acceptance level. This new approach helps the authority estimate car ownership consistently from the view of demand-and-supply.

The concept of balancing car ownership has been extended to the problem of balancing parking demand and supply. A bilevel programming model, together with a solution algorithm, has been proposed to investigate the effects of balancing the demand and supply of parking spaces. It was found that balanced parking space optimizes journey time and increases utilization of parking spaces.

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NOTATION

The following notations are used in Chapters 2-4 unless otherwise specified.

ALF	average annual licenses fee per private car in 1990 constant prices (HK$)
acc	accessibility index
C	car ownership or the number of cars
CAR	territory-wide car ownership (total number of licensed private cars and motorcycles in pcu) in Hong Kong
$\tilde{CAR}$	estimated territory-wide car ownership in Hong Kong
$Dinc$	monthly disposable household income
e	relative errors of the actual (or observed) and projected values of the key factors (%)
FRT	average first registration tax per private car in 1990 constant prices (HK$)
GDP	gross domestic product in 1990 constant prices (HK$million)
inc	monthly household income
P	motoring cost at constant prices
PET	average petrol price per litre in 1990 constant prices (HK$)
POP	population
$POPDEN$	population density (persons per km^2)
PUB	annual passenger trips on public transport (in millions)
$park$	residential parking supply
$RAIL$	annual railway passenger kilometrage (in millions)
S	saturation level
X_i	socio-economic variable i
Y	income per person at constant prices
Z^2	model goodness-of-fit statistics

Subscripts

G	GDP in 1990 constant prices (HK$million)
P	population

proj	projected values
R	average first registration tax per private car in 1990 price terms (HK$)
r	area
T	annual passenger trips on public transport (in millions)
t	time
t-1	time for one-year lagged
1990	at the year of 1990

Superscripts

c	values at current price terms (HK$)
′	transformed values (taking a log-difference transformation)

The following notations are used in Chapters 5-7 unless otherwise specified.

Sets

A	the set of links in the road network
I	the set of origin zones (or production zones)
J	the set of destination zones (or attraction zones)
R	the set of paths in the network
R_w	the set of paths between origin-destination (O-D) pair $w \in W$
W	the set of O-D pairs

Vectors

$\mathbf{c}(\mathbf{v})$	a vector of link travel time functions
$\mathbf{c}^{+}(\mathbf{f})$	a vector of path travel time functions
$\mathbf{d}$	a vector of parking delays
$\mathbf{D}$	a vector of trip attractions
$\mathbf{f}$	a vector of path flows
$\mathbf{g}$	a vector of O-D travel times (journey times)
$\mathbf{h}$	a vector of the number of parking spaces supplied
$\bar{\mathbf{h}}$	a vector of the number of spare public parking spaces
$\mathbf{O}$	a vector of trip productions

$\mathbf{p}$	a vector of trip generation/production rate
$\mathbf{q}$	a vector of trip attraction rate
$\mathbf{T}$	a vector of O-D demand by car
$\mathbf{u}$	a vector of the number of cars
$\mathbf{v}$	a vector of all link flows
$\mathbf{z}$	a vector of accessibility measures in origin zones
$\mathbf{z}'$	a vector of accessibility measures in destination zones
Λ	O-D/path incidence matrix where entries δ_{wr} are 1 if path $r \in R_w$, and 0 otherwise
Δ	link/path incidence matrix where entries δ_{ar} are 1 if path $r \in R$ uses link a, and 0 otherwise
Φ_i	trip production/O-D incidence matrix
Φ_j	trip attraction/O-D incidence matrix

Variables

$c_a(v_a)$	travel time (hrs) on link $a \in A$
$d_j(\overline{D}_j)$	parking delay at destination zone $j \in J$
D_j	trip attraction by car at destination zone $j \in J$ (pcu/hr)
$\overline{D}_j$	balanced trip attraction by car at destination zone $j \in J$ (pcu/hr)
f_r	flow (pcu/hr) on path $r \in R$
g_{ij}	O-D travel time (journey time) (hrs)
h_j	the number of parking spaces supplied in destination zone $j \in J$
$\bar{h}_j$	the number of public parking spaces available in destination zone $j \in J$
O_i	trip production by car at origin zone $i \in I$ (pcu/hr)
$p_i, p_i(z_i)$	trip production rate of each car in origin zone $i \in I$
$q_j(z'_j)$	trip attraction rate of each parking space in destination zone $j \in J$
t_{ij}	travel demand between O-D pair (i, j)
u_i	the number of cars owned by the residents in zone i
v_a	flow (pcu/hr) on link $a \in A$

z_i	accessibility measures for producing car trips in origin zone $i \in I$ that measures the expected maximum utility of travel on the road network as perceived from origin i
z'_j	accessibility measures for attracting car trips in destination zone $j \in J$ that measures the expected maximum utility of travel on the road network as perceived to destination j
δ_{ar}	entry is 1 if path $r \in R$ uses link $a \in A$, and 0 otherwise

Constants

c_a^0	free-flow travel time (hrs) of link $a \in A$
d_{0j}	free-flow parking access time (hrs) in zone j
e	a pre-determined parameter for reflecting the effect of accessibility on trip rates
e_j	employment in zone j
F_j	parking charge in zone j (expressed in terms of equivalent time (hrs))
$h_j^{\max}$	an upper limit of supply of parking space in zone j
h_j^{occ}	pre-occupied parking spaces in zone j
q_i	population in zone i
S_a	capacity (pcu/hr) of link $a \in A$
$u_i^{\min}$	a lower limit of the number of cars in zone i
α	a dispersion parameter for gravity-type trip distribution model
β	a pre-determined parameter for the trip production rate
β_0	a pre-determined parameter that measures the additional number of trips that would be generated from a given origin i if the zonal accessibility increased by unity
β_1	a pre-determined parameter that measures the additional number of trips that would be generated from a given origin i if the zonal population increased by unity
β_2	a pre-determined parameter that measures the additional number of trips that would be generated from a given origin i if the zonal car ownership increased by unity

δ	a pre-determined parameter that reflects the sensitivity of O-D generalized travel time on accessibility measures
ϕ_{1k}	a pre-determined proportion of public parking spaces supplied in zone k
ϕ_{2k}	a pre-determined proportion of cars that parked in public parking spaces in zone k
γ_0	a pre-determined parameter that measures the additional number of trips that would be attracted to a given destination j if the zonal accessibility increased by unity
γ_1	a pre-determined parameter that measures the additional number of trips that would be attracted to a given destination j if the zonal employment increased by unity
γ_2	a pre-determined parameter that measures the additional number of trips that would be attracted to a given destination j if the number of zonal available parking spaces increased by unity
η	a pre-determined parameter for the trip attraction rate
θ	a pre-determined parameter that reflects the sensitivity of the utility of travel between any given O-D pair $w \in W$ due to changes in the network's performance
ω	a pre-determined error tolerance
m	a pre-determined maximum number of iterations

The following acronyms are used throughout this thesis:

Adj. R^2	Adjusted coefficient of determination
ALF	Annual License Fee
BPR	Bureau of Public Roads
CDA	Combined trip distribution/assignment
cif	cost-insurance-freight
CPI	Consumer Price Index
CSTS	cross-section/time-series
CTS-2	Second Comprehensive Transport Study
ETDA-VDC	Equilibrium Trip Distribution/Assignment with Variable Destination Costs
FRT	First Registration Tax
GA	Genetic algorithm
GDP	Gross Domestic Product
LL	Log-likelihood
LLP	Lower-level problem
MSA	Method of Successive Averages
NDP	Network design problem
O-D	Origin-Destination
pcu	Passenger car units
RP	Revealed preference
SAB	Sensitivity analysis based
SP	Stated preference
TCS	Travel Characteristics Survey
UE	User equilibrium
ULP	Upper-level problem
V/C	Link flow/Capacity ratio
VIF	Variance Inflation Factor (i.e. the inverse of the tolerance value for collinearity)

1 INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

Car ownership is defined as the number of cars owned and can be expressed per person, per adult or per household. One simple and traditional way of assessing the general trend and level of car ownership is to take the number of cars per thousand of population, generally referred to as the car ownership level (Organization for Economic Co-operation and Development, 1982). The development of multi-ownership has made it necessary to create two indicators. They are the proportion of households with at least one car and the proportion of households with several cars, respectively.

Good forecasts of car ownership levels are critical in preparing adequate travel demand forecasts. Car ownership variables are typically encountered in most travel demand model components, including trip frequency choice, destination choice, and mode choice models.

Many economic and socio-demographic variables may influence the household/individual car ownership decision. Some are concerned with the budget constraints (income, purchase price of cars, motorization costs, etc.), while others determine the mobility need and more general taste for a car (age, activity, residential location, type of household, accessibility to public transport, etc.). These variables are referred to as from the view of user demand.

Road network supply conditions are all transport facilities provided on a road network. For example, road capacity, length and width of roads, junctions, degree of speed, traffic signals, parking space, and so on. These facilities also have potential to influence the car usage and in turn car ownership. Attention is paid to road capacity and parking space in this research.

1.2 THE NEED FOR THE STUDY

Most large urban cities or countries are facing the same transportation problem - heavy pressure on the transport system owning to continuous growth of travel demand.

It is often recognised that the level of car ownership in a city or country is one of the key factors influencing the travel demand and thus the level of demand for transport facilities including roads, intersections and parking spaces. An increase in car travel contributes to more congestion, and hence a demand for additional roadspace. Thus, car ownership is a major determinant to the development of the transport infrastructure. However, when the car ownership demand cannot be catered for by the existing transport infrastructure, transport policies and fiscal measures for controlling car ownership growth become important particularly in many densely populated cities. These measures can affect many dimensions of travel behaviour but are likely to be most significant in terms of users' choice of car ownership. Therefore, the level of car ownership is an indicator for setting transport policies to control the number of cars.

In the previous related studies, more attention was given to the user demand on car ownership. Car ownership demand has usually been estimated by a set of household characteristics, demographic, socio-economic factors and/or public transport services at a fixed time point or over a period of time using various forecasting techniques (e.g. Ben-Akiva *et al.*, 1981; Bhat and Pulugurta, 1998; Button *et al.*, 1993; Kitamura, 1992; Mannering and Winston, 1985; Pendyala *et al.*, 1995; Schimek, 1996; Train, 1986). However, the constraints in travelling on a road network such as road capacities and parking spaces have not been considered in those car ownership forecasting models. The absence of consideration of network supply constraints in previous modelling of car ownership and usage might be due to the fact that much of these works are of North American and European origins, where space constraint in low density development area is not an important issue for affecting the car ownership and usage. On the other hand, in Asian cities with high density development like Singapore, the space for expansion of road network is limited and hence the length of public roads was considered for modelling car ownership (Chin and Smith, 1997). However, it is believed car ownership and usage are more likely to be constrained by the capacity of the road system rather than the length of roads.

By contrasting with the situation in Hong Kong, Hong Kong is a city with the highly dense road network worldwide in terms of the number of vehicles per kilometer of road network (The Economist, 1999). With such a crowded and spatially dense road network, Hong Kong's road network is one of the busiest road networks in terms of 1,000 vehicle-kilometers per year per kilometer of road network. Thus, the effects of network supply constraints on car ownership and usage should be examined in Hong Kong. The comparison of road networks in America, Europe and Asia is illustrated in Figures 1.1 and 1.2. It can be seen that most of the crowded road networks are found in Asian countries/cities.

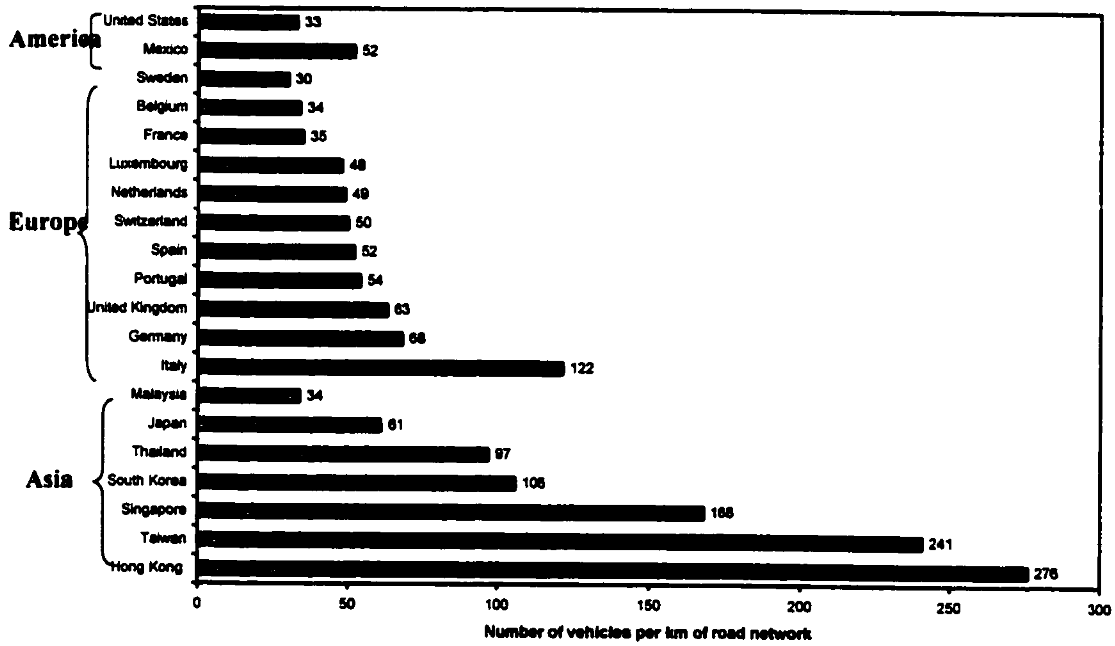


Figure 1.1 Density of Road Network by Location (1996 or latest)

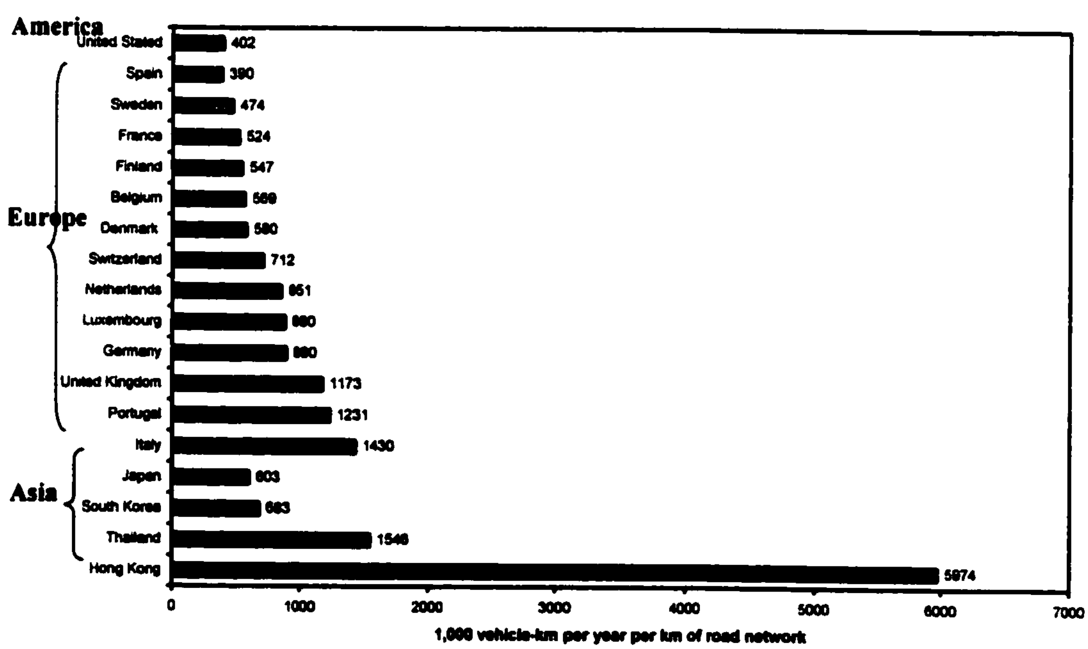


Figure 1.2 Utilization of Road Network by Location (1996 or latest)

In this study, car ownership is investigated from both user demand and road network supply points of view. Car ownership demand is estimated using a number of demographic, socio-economic factors on the one hand, while maximum car ownership is determined under the given road network supply conditions on the other. Car ownership demands for the whole territory and for sub-regional areas are estimated using statistical techniques.

In view of network supply conditions, the proposed car ownership model is described as a bilevel programming model taking into account car ownership estimation and traffic assignment. Although route choice or network flow is a short-term decision, the proposed model can be applied to a whole day that splits in several time periods. Note that steady state is assumed for each of these periods. For example, the time periods can be classified into the four conventional peak periods: morning peak, interpeak, evening peak and off peak. The most critical reserve capacity of zonal car ownership within a typical day can then be obtained from the results of the four study periods. For the long-term strategic planning purposes, the effects of different scenarios of zonal car ownership growth on alternative strategic networks can be assessed using the proposed model. The level of car ownership demand by zones can then be determined under the given supply conditions for different alternative networks.

Hence, the importance of balancing car ownership can examine based on the results of the demand-and-supply viewpoints. The findings could be used to demonstrate car ownership estimation from a different approach.

1.3 OBJECTIVES OF THE RESEARCH

The objectives of this research are to study the balance of car ownership from user demand and road network supply conditions by:

i. investigating the factors which potentially affect car ownership;

ii. estimating territory-wide car ownership from an aggregate car ownership model. 'Territory-wide car ownership' is referred to as the total car ownership (i.e. the total number of licensed private cars and motorcycles) in the Hong Kong territory;

iii. constructing the probability distribution of territory-wide car ownership estimates;

iv. calibrating the probability of car ownership and non-car ownership from disaggregate car ownership choice models;

v. estimating car ownership by traffic zone;

vi. determining the maximum number of cars at each traffic zone that can be accommodated by a road network; and

vii. balancing car ownership by traffic zone under user demand and network supply conditions coherently.

1.4 STRUCTURE OF THE THESIS

The thesis is composed of eight chapters. The first chapter presents the background of the research. A literature review of existing car ownership models in both aggregate and disaggregate estimation, current car ownership model in Hong Kong together with bilevel programming models for transportation optimization problems is given in Chapter 2.

Chapter 3 presents the results of the calibrated aggregate car ownership model for Hong Kong and the reliability of territory-wide car ownership estimates based on the simulated probability distribution of car ownership.

Chapter 4 outlines the survey for data collection and describes the results of the developed disaggregate logit-type car ownership choice models using the survey data.

In Chapter 5, a bilevel programming model of car ownership is proposed to determine the maximum car ownership under the road network supply conditions. The road network supply conditions are referred to as the road capacity and parking supply. Maximum car ownership is determined so as to find the reserve capacity for car ownership that can accommodate in a road network.

A case study in Hong Kong is presented in Chapter 6 to demonstrate the application of the proposed car ownership models in practice. A balance of car ownership under user demand and network supply conditions has been obtained.

In Chapter 7, the concept of balancing car ownership under demand and supply conditions is extended to the problem of balancing parking demand and supply. A bilevel programming model is proposed to determine the minimum number of parking spaces supplied to satisfy the elastic parking demand. Finally, the contribution of this thesis is summarized and recommendations for further research are given in Chapter 8.

2 LITERATURE REVIEW

This research is believed to be the first thorough investigation of the interaction between car ownership modelling from both user demand and road network supply. The former is concerned with car ownership forecasting models and the latter is related to the reserve capacity of car ownership. There is no single study in the literature which deals coherently with car ownership demand and road network supply for car ownership in a comprehensive manner. However, it has been possible to derive the relevant information from previous works in a wide range of subjects. A collective review of literature has been carried out to discover ideas in connection to the balance of car ownership under user demand and network supply. Section 2.1 presents some previous related works on car ownership models by aggregate and disaggregate approaches. Section 2.2 gives a brief review on the existing car ownership model used in Hong Kong. These two sections concern car ownership models from the view of user demand. In order to investigate the effects of the network supply conditions on car ownership, bilevel programming model is applied to determine the maximum car ownership under the constraints of the given road network. Thus, Section 2.3 outlines the bilevel programming models and illustrates with some transportation optimization problems.

2.1 OVERVIEW OF EXISTING CAR OWNERSHIP MODELS

The literature on car ownership modelling can be divided into two general categories. The first one includes aggregate econometric models that are time series or cross-sectional models. The other one uses disaggregate data to model car ownership demand. Most of these studies are based on the notion that households choose, from among a number of car owning alternatives, that alternative which affords the greatest utility. The usage of disaggregate data, which allows for variation of variables across data sample, makes it possible to estimate the effects of contributing factors. This approach generally relies more on behavioural theory than the aggregate approach.

2.1.1 Aggregate Car Ownership Models

2.1.1.1 Time series extrapolation models

Early aggregate forecasts of the total car ownership levels were derived from the extrapolation of past and current trends of car ownership rates, combined with some hypotheses concerning the evolution of the total population. It is clear that car ownership rates should not increase infinitely in time, for this reason the incremental curves which are usually put forward to model this phenomenon are S-shaped (called 'sigmoid') functions. The sigmoid curve has generally been approximated by either a lognormal (Farrell, 1954; Cramer, 1959) or logistic curve (Tanner, 1977).

A widely used approach is to fit the trend of car ownership demand as a logistic curve (Tanner, 1977). In the logistic curve,

$$\frac{dC_t}{dt} = aC_t(S - C_t) \qquad (2.1)$$

where C_t is the car ownership level at time t; S is the saturation level; a is a constant. The solution of this differential equation makes car ownership rate a logistic function of time as below:

$$C_t = \frac{S}{1 + b\exp(-aSt)} \tag{2.2}$$

where b is an integration constant.

In this model, with a fixed saturation level, time is assumed to act as a surrogate for multiplicity of social and economic factors influencing car ownership levels. This assumption can hold only if the relationships between time and the real causal influences remain substantially the same in the future. Since only time acts as the variable in the model, neither the effect of the changes in transport related policies nor the influence of economic variables can be evaluated. Moreover, the constant saturation level of car ownership may not be true in practice, as attitudes tend to change with time. These largely limit the usefulness of this approach.

2.1.1.2 Aggregate economic models

Rather than taking time as the only explanatory variable, a number of socio-economic variables was incorporated into the basic extrapolative model. Tanner (1978) developed the modified logistic model to reflect the influences of household income and car ownership costs.

$$C_t = S\left[1 + \frac{S - C_0}{C_0}\left(\frac{Y}{Y_0}\right)^{-bS}\left(\frac{P}{P_0}\right)^{-cS} e^{-aS(t-t_0)}\right]^{-1} \tag{2.3}$$

in which, for year t, C_t is the number of cars per person, Y is income per person at constant prices, P is the cost of motoring at constant prices, C_0, Y_0 and P_0 are the corresponding values in the base year t_0, and a, b and c are constants to be determined.

Tanner (1983) extended the existing logistic model to include lagged or inertia effects in a model. These effects were represented directly by taking weighted averages on the socio-economic variables in two successive time periods, rather than by means of a time trend variable. Such a model provides a method of explaining the 'time' trend in the previous related models and of resolving inconsistencies between short-term and long-term elasticities.

The above two modified versions, however, can only partially solve the problems of time series extrapolation models. For example, it allows income and motoring costs to affect the rate of growth of car ownership but not its ultimate saturation level. The models are still dependent on the concept of a saturation level. As Button *et al.* (1980) and Pearman and Button (1980) pointed out, "it is difficult to define whether saturation means a ceiling level of car ownership that is never exceeded, an average long-term level of car ownership, or a statistical parameter for a sigmoid growth curve". In addition, changes to lifestyle patterns might well affect saturation levels. For instance, individuals may well choose to own more than one vehicle for personal use, such as a 'town car', recreational vehicles, etc. Under such circumstances, quite visible in many societies, a ceiling level of car ownership that can never be exceeded is quite fallacious. As a consequence of introducing of income and motoring cost, there is a need to forecast these variables to the target date. This requires substantially greater informational inputs and can never be done with certainty.

Button *et al.* (1992, 1993) related car ownership to a set of causal variables by quasi-logistic approach. Taking C as the aggregate car ownership level per capita, S as the ultimate saturation level, X_1, ..., X_n as a set of socio-economic variables and a, b_1, ..., b_n as parameters, then the model can be depicted as

$$C = \frac{S}{1 + e^{-a} X_1^{-b_1} X_2^{-b_2} \cdots X_n^{-b_n}} \tag{2.4}$$

The model was developed by the relationship between car ownership and major causal variables, such as gross domestic product of the countries at constant prices, country-specific dummy variables and time trend. However, there were empirical reasons to suspect that the relationship between car ownership and the major causal variables is not stable over time (TRRL, 1979; Button *et al.*, 1992, 1993). In addition, variables may be highly correlated with other factors, which can lead to the problems of multi-collinearity.

2.1.1.3 Alternative econometric models

Since policy sensitivity is important to transport planners and extrapolative framework has severe defects, econometric models are alternative methods for forecasting the levels of car ownership at regional or urban level. Although aggregate economic models mentioned in previous section incorporate a set of socio-economic variables, an ultimate saturation level is still difficult to define. In this section, alternative econometric models are presented to forecast car ownership level on the basis of cross-sectional, time-series and combined cross-section/time-series (CSTS) data.

The general equation is listed as below:

$$C_r = \beta_0 + \sum_{i=1}^{n} \beta_i X_i \tag{2.5}$$

where C_r is car ownership in area r, X_i is socio-economic variable i and β_0 and β_i are parameters to be determined.

The model was usually calibrated on cross-sectional data using multiple regression technique (Shindler and Ferreri, 1967; Button, 1973; Said, 1992). The effects of income, household characteristics such as household size and number of adults in a household, relative accessibility of transit and highway services, population density, and social composition were investigated in their studies.

Other than cross-sectional data, the model can be calibrated using time-series data (Ashworth and Weaver, 1981; Chin and Koh, 1989; Fan, 1995; Chin and Smith, 1997; Prevedouros and An, 1998). Ashworth and Weaver (1981) studied the relationship between gross domestic product per head and the number of persons per car, given the effect of urbanization, the effect of exchange rates reflecting real income and the effect of secular growth. The number of cars per country in Europe was estimated in their study.

Chin and Koh (1989), Fan (1995) and Chin and Smith (1997) all studied car ownership in Singapore. Chin and Koh (1989) applied econometric techniques in analyzing car ownership. Logarithmic regression equation was formulated to test the importance of transport policy and economic variables on car ownership. The growth trend of private cars in Singapore was modelled by Fan (1995) using time-series data. It was found that only real gross domestic product was the most reliable factor for explaining variations in private car ownership in Singapore. Chin and Smith (1997) studied the effect of government fiscal policy on car ownership in Singapore. Disposable income per capita, price of cars (including import duties), price index of transport, length of public roads and fiscal fees were used to estimate the number of cars per capita. The breakdowns of total fiscal fees were also considered. The models were estimated in log-linear form by ordinary least squares method.

Prevedouros and An (1998) modelled the historical car ownership trend and predicted the future level of car ownership in some selected developed and developing countries. Among the examined variables, gross domestic product was found to be the important determinant on national car ownership.

Apart from modelling based on cross-sectional or time-series data, the econometric models can be calibrated using a combined CSTS data set. Khan and Willumsen (1986) developed policy-sensitive models of car ownership using data from different countries and time periods. Multiple linear/log-linear regression equations for car ownership were formulated on six independent variables: gross national product per capita, population density, purchase and registration tax per car, ownership tax per car, import duty per car and price per litre of fuel. Johansson and Schipper (1997) studied the long-run fuel demand of cars using three components: car stock, fuel intensity and mean driving distance per car per year. These three components were modelled separately. In the sub-model of car stock, lagged car stock, petrol price and national income are assumed in a log-linear relationship, while taxation and population density are presented in linear form. That is, a semi-log relationship of car stock was estimated with respect to the five variables in a pooled CSTS model.

2.1.1.4 Demographic models

In order to identify long term dynamics on car ownership, a proven demographic method, longitudinal analysis, was studied. The Swedish (Swedish Road and Traffic Research Institute) car ownership forecasting model developed by Jansson (1989, 1990) focused on diffusion process for car ownership. The diffusion process consists of two stages – vertical diffusion and horizontal diffusion. Vertical diffusion corresponds to a genuine change in taste, while horizontal diffusion corresponds to the population turnover effect. The model was calibrated on longitudinal cohort data, each cohort consisting of all males or all females born in a particular year. Janssson (1989) attempted to demonstrate the diffusion process by studying the car ownership development paths of different generations. Further development of the model (Jansson, 1990) took account of the influence of changing incomes and prices in different stages of the life cycle of each generation. Diffusion models were also applied on car ownership structure in Taiwan on the basis of traditional logistic curves (Lee and Shiaw, 1996).

In addition, behavioural patterns of car ownership in different life cycle stages of successive cohorts were studied by Madré (1990), Gallez (1994) and Axhausen

(1995). The results found by Axhausen (1995) show that the size of the previous car fleet has a different impact on the current fleet size at different stages of the life cycle. The analysis also underlines the need for a dynamic approach to car ownership modelling, as it shows that there are strong effects of the previous experiences of the persons and households concerned.

2.1.2 Disaggregate Car Ownership Models

Many of the models based on disaggregate data utilize a discrete choice, random utility approach. Such models, because they are related to the individual/household decision-making unit, are most likely to be behavioural or explanatory rather than merely correlative that characterized in most of the aggregate car ownership studies. In the previous related studies, car ownership as well as other travel related choices have been modelled in the form of logit or probit with the use of disaggregate data.

2.1.2.1 Models of car ownership

Disaggregate car ownership models usually take the form of discrete choice models. Within the classes of disaggregate discrete choice models, two general decision mechanisms have been used for car ownership modelling: the ordered-response choice mechanism and the unordered-response choice mechanism. The ordered-response mechanism is based on the hypothesis that an uni-dimensional continuous latent car ownership propensity index determines the level of car ownership. The unordered-response mechanism is based on the random utility maximization principle, likes multinomial logit model.

Burns *et al.* (1976) developed multinomial logit models to estimate the probability of homogeneous groups of households choosing to own a specific number of cars, in the belief that households faced with different choice set weigh benefits of increased mobility and costs of owning cars. Bates *et al.* (1978) developed a model for zonal forecasts of the proportions of households owning 0, 1 and 2-or-more cars. Binary logit specification was used to formulate the model for spliting car owning and non-car owning groups first, and then another model to divide the car owning group into single- and multi-car ownership groups. There are other studies on car ownership logit models (Purvis, 1994; Han and Algers, 1996; Lim and Chishaki, 1997) in which household characteristics, socio-economic characteristics, vehicle- and travel-related characteristics and the effects of accessibility and generations were investigated.

Kitamura and Bunch (1990) and Pendyala *et al.* (1995) developed multinomial ordered-response probit models (Maddala, 1983) for estimating car ownership. The ordered-response probit model assumes the presence of a latent variable that cannot be measured directly, but is related to the observed choice, the number of cars in this case. A panel data set from Dutch National Mobility Panel Data Survey (Van Wissen and Meurs, 1989) was used. These studies were concerned with the number of cars owned by a household (0, 1, and 2-or-more), observed at equidistant discrete time points. The indirectly utility (latent ordinal preference index) was expressed as a function of a set of household descriptions, accessibility of mass transit, and descriptors of the size of the community and its level of public transport.

In the study of Pendyala *et al.* (1995), the elasticities of car ownership with respect to household income were found to change over time and the changes differed by the type of household structure. At each single time point, single person households had the most elastic relationship between car ownership and household income, while families had the least elastic relationship. Moreover, households were more elastic to increase in income rather than to decrease in income, i.e. their behaviour is asymmetric.

Allen and Perincherry (1996) developed a two-stage vehicle availability model. The first stage uses a traditional multi-dimensional lookup table to estimate the proportion of 0, 1, 2, and 3+ vehicle households on the demographic effects of household size, workers and income groups. The second stage uses an incremental logit method to introduce the effects of transit accessibility and development density.

Among the two mechanisms of discrete choice models, Bhat and Pulugurta (1998) identified their advantages and disadvantages. Ordered-response logit model was compared with multinomial logit model using several data sets. The multinomial logit model, because it allows alternative-specific effects of exogenous variables, appears to be able to capture a flexible pattern of elasticity effects of variables across alternatives. The ordered-response logit model, on the other hand, is constrained to have a more rigid trend in elasticity effects. This comparative analysis offers strong evidence that the appropriate choice mechanism is the unordered-response structure for making household's car ownership decision.

2.1.2.2 Models of car ownership and use

The amount that a household drives affects the number of vehicles that it chooses to own. Conversely, the number of vehicles a household owns affects the amount it drives. Models developed by Mannering and Winston (1985), Train (1986), and Hensher *et al.* (1989) all described the joint decisions of choices of car ownership and usage. A combination of continuous/discrete choices was adopted, with the discrete choice being the choice of number and type of vehicles to own and the continuous choice being the amount to drive. The amount of drive is estimated conditionally upon the number and types of vehicles chosen. The probability that choosing a particular number and type of vehicles depends, structurally, on the amount the household would drive annually.

Kitamura (1987, 1989) applied similar method to model the longitudinal relationship between household car ownership and trip generation. Mobility was represented using a linear regression model and household car ownership was represented by an ordered-response probit model. The model allows for the presence of serial correlation among the errors associated with each of the endogenous variables (Kitamura, 1987). The synchronous, inertial and cross-lagged correlations among endogenous and exogenous variables were examined. The symmetry of the change in household car ownership and mobility was emphasized in the study of Kitamura (1989). Three types of car ownership models, cross-section, symmetric-effect and asymmetric-effect, were used to investigate the dynamic behaviour of car ownership. It was found that both car ownership and utilization have asymmetric effects, which reflects the household's long-term considerations rather than short-term responses to changes.

In addition to formulation of car ownership and utilization model based on the utility maximization theory, De Jong (1990) developed a joint model of household car ownership and car use with explicit allowance for fixed and variable costs. The results show that increasing the fixed costs will be a drop in car ownership. This drop is much greater than in the case of higher variable costs.

2.1.2.3 Models of car ownership and other travel choices

Despite the interaction between car ownership and utilization, great efforts have been made to incorporate in a behaviourally consistent way that the interaction of how many cars households choose to own and other travel-related decisions they make.

Lerman and Ben-Akiva (1976) considered the relationship between car ownership and the travel modes to work chosen by households. Multinomial logit model was used in a joint structure that captures the complex inter-relationship of car ownership and travel-to-work decisions. In their model, car ownership was represented by the number of cars per licensed driver. This variable had direct influence on the choice of travel mode, and thus indirectly influenced the choice of car ownership via the inter-relation between these two choices. The effects of accessibility, vehicle costs, disposable income, the number of licensed drivers and housing type were examined in the model development.

Kitamura (1988) developed a dynamic model system of household car ownership, in which three interrelated components: car ownership, mechanized trip generation and modal split were included. The level of car ownership was represented as a function of household attributes, mobility measures and modal split from the preceding observation time point using an ordered-response probit model. The trip generation model predicts the weekly number of trips made by mechanized modes in a household, and the modal split model predicts the fraction of trips that are made by public transport. Trip generation and modal split are assumed to be dependent upon car ownership at the same time point. Household car ownership is assumed to be influenced by the trip generation and modal split from the previous time point. The model system was calibrated on a set of panel data. It was found that the number of drivers in the household is the predominant and most significant factor influencing car ownership.

2.2 CAR OWNERSHIP MODEL IN HONG KONG

The existing car ownership model used in Hong Kong is a part of the enhanced Second Comprehensive Transport Study (CTS-2) model (Transport Department and Wilbur Smith Associates, 1993; 1995). The CTS-2 model is based on the fall in the number of cars which took place in the early 1980's when the first registration taxes (FTR) and annual license fees (ALF) were sharply increased. However, a stock and property market crash occurred at that time and change in the way that vehicle statistics were kept from a vehicle registration basis to a vehicle licensing basis, may have affected the analysis.

The explanatory variables of car ownership model include the zonal household income distribution, an accessibility index and the number of residential car parking spaces per household. The inputs and outputs of the model are illustrated in Figure 2.1. The impact of car ownership and car usage costs on car ownership is reflected by the revised household income, which can be assessed in the following steps:

(a) estimate disposable household income from total household income;

(b) subtract increases in car ownership/usage costs from disposable household income to create a revised disposable income;

(c) calculate the revised total household income equivalent to the revised disposable income; and

(d) use the revised total income to calculate car ownership.

The estimates of disposable household income were based on the weightings given for the Consumer Price Indices (CPI) as shown in the following Table 2.1. CPI provides a measure to reflect changes in the price level of consumer goods and services purchased by households. Different CPIs are compiled to reflect the impact of consumer price changes on households in different expenditure ranges. The CPI(A), CPI(B) and Hang Seng CPI (HSCPI) are compiled based on the expenditure patterns of households in the relatively low, medium and high expenditure ranges.

The CPIs shown in Table 2.1 were derived from the results of the Household Expenditure Survey conducted in 1989/1990. So the monthly household income ranges relate to prices in 1989/90. As the CTS-2 model was calibrated using the data in 1992, the household income ranges were converted to 1992 accordingly for estimation of the disposable household income.

Table 2.1 Consumer Price Indices

Item	CPI(A)	CPI(B)	HSCPI
Monthly Household Income Range (HK$89/90)	$2,500-$9,999	$10,000-$17,499	$17,500-$37,499
Mid-point of Household Income Range (HK$92)	$8,370	$17,175	$34,350
Fixed Expenditure(1)	64.94%	61.47%	57.19%
Disposable Income(2)	35.06%	38.53%	42.81%

(1) Includes foodstuffs, housing, and fuel and light.

(2) Includes drinks and tobacco, clothing and footwear, durable goods, miscellaneous goods, transport and vehicles, and services.

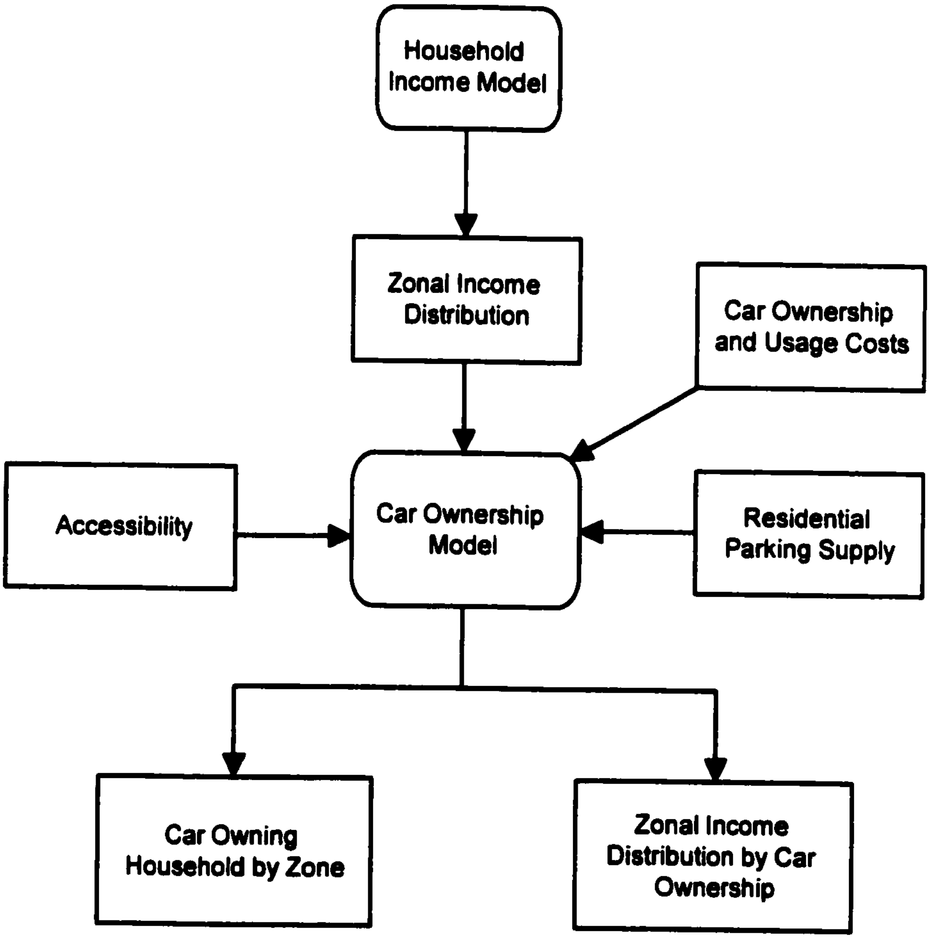


Figure 2.1 Structure of the Car Ownership Model in Hong Kong

Based on the above weights of CPIs, the following Equation (2.6) was obtained by regression method:

$$Dinc = 0.336 \times Inc + 0.268 \times 10^{-5} \times Inc^2 \qquad (2.6)$$

where *Inc* = monthly total household income; *Dinc* = monthly disposable household income; and with R^2 = 0.9999. With the use of the above regression equation, the disposable household income can be estimated with the given total household income.

Two basic formulations, a modified linear model and a binary logit model, were investigated for estimating car owning households. The basic equations used to forecast car owning households were of the following form:

$$Linear = (a + b \times inc + c \times Log(inc)) \times f(acc) \times g(park) \qquad (2.7)$$

$$Logit = \frac{1}{1 + Exp(a + b \times inc + c \times Log(inc) + f(acc) + g(park))} \qquad (2.8)$$

where *Linear* and *Logit* are the proportion of car owning households;

inc is the monthly household income, *acc* is the accessibility index and *park* is the residential parking supply;

a, *b* and *c* are the calibration parameters; *f* and *g* are the respective functions.

The accessibility index used in the above equations was measured by the average public transport generalized cost to reach the closest 600,000 employment opportunities and was then converted to a set of five categories for use in the model. The choice of 'closest 600,000 employment opportunities' for the accessibility index was proposed by the CTS-2 consultant in view of the population/employment size of the traffic zone.

The number of residential parking space by traffic zone was estimated by the parking demand study (Ove Arup & Partners, 1995). In the parking demand study, the number of parking space is projected by the land use planning data while taking the location constraints and the parking supply guidelines into account. The residential parking supply was also converted into a set of four categories in the above car ownership model. This has the advantage of making input decisions easier, particularly when the medium range includes the usual values for new urban developments.

The models were calibrated using the data collected from the travel characteristics survey (TCS) in 1992 (Transport Department and MVA Asia, 1993). The logit model was found to have better performance for classifying the car ownership and non-car ownership groups. The model shows that car owning households increase with income, with worsening accessibility and with increasing availability of parking spaces. In the sub-division of car owning households into single-car and multi-car ownership groups, the linear model was found to be performed better than the logit model when checking the results of the calibration against TCS data. However, only household income is significant in the split between single- and multi-car owning households. Therefore, it can be concluded that accessibility and parking availability affect the initial decision to own a car, but once the conditions are appropriate, the decision to have more than one car is solely related to affordability.

2.3 Bilevel Programming Models

Bilevel (or two level) programming problem is an optimization problem with a special constraint function, which is implicitly determined by another optimization problem. It can be described as a Stackelberg duopoly game (Aubin, 1979; Stackelberg Von, 1952) for two persons (leader and follower) with perfect information and specified play order. Bilevel programming allows for a hierarchical structure in which a decision maker at one level of a hierarchy may have an objective function, and decision spaces are determined, in part, by another level. In addition, decision makers have control instruments that may allow them to influence policies at another level, thereby improving their own objective functions. An additional important feature of bilevel programming problems is that control of the decision variables is partitioned among the decision makers. In traditional single-level programming problems, one decision maker is assumed to have control over all the variables. Bilevel programming approaches have advantages over single-level programming, which include the ability to explicitly model the sequential decision-making process and interactions between different levels of decision processes or systems.

2.3.1 Definition

In general, a bilevel programming problem is defined as follows.

(ULP) $$\min_{x} F(x,y) \tag{2.9}$$

$$s.t. \quad G(x,y) \leq 0 \tag{2.10}$$

where y solves for fixed x

$$\text{(LLP)} \qquad \underset{y}{Min}\, f(x,y) \tag{2.11}$$

$$s.t. \qquad g(x,y) \leq 0 \tag{2.12}$$

ULP is defined as an upper-level problem and LLP a lower-level problem. The decision maker at the upper level influences the lower-level decision maker by setting x, thus restricting the feasible constraints set by the lower-level decision maker. The upper-level decision maker also interaction with the lower-level decision maker via the objective function of the lower-level decision maker. It should also be noted that the decision variable of the lower-level problem is expressed as a function of the decision variable of the upper-level ($y(x)$).

2.3.2 Applications

Transport planning involves a number of the bilevel programming problems. Transport operators (or system controllers) behave like leaders to optimize their objectives, possibly the cost of operating the system, efficiency of the system and use of certain resources, while the travellers at the lower level optimize their own objective, for example, journey time.

Based on the above ideas, car ownership problem can be treated as a bilevel programming problem. The system controller in the upper-level problem optimizes car ownership subject to the given network supply conditions with considering the travel behaviour of network users. The network users in the lower-level problem optimize their journey times with taking into account the car ownership obtained in the upper-level.

Although car ownership problems have not been treated as bilevel programming problems in the transportation science literature, applications such as network design problem, origin-destination matrix estimation problem and traffic signal control problem have been solved by bilevel programming models in the previous related studies. A review of the various applications of the bilevel programming techniques is given as below.

2.3.2.1 Network design problem

The network design problem (NDP) involves the optimal decision on the expansion of a street and highway system in response to a growing demand for travel. Such problems become important as the growth rate of demand for travel on the roads is faster than the urban transportation system that can accommodate, while resources available for expanding the system capacity remain limited. The decision variable of NDP can be posed in two different forms: a discrete form dealing with the addition of new roadway segments to a network (LeBlanc, 1975; Poorzahedy and Turnquist, 1982), and a continuous form dealing with the optimal capacity increases of existing roadway segments (Abdulaal and LeBlanc, 1979; Davis, 1994).

Bilevel programming applications for the NDP can be classified into two categories. The first one is the formulation of the NDP as a linear bilevel network design problem that includes the works of LeBlanc and Boyce (1986), Ben-Ayed *et al.* (1988, 1992). A piecewise linear travel cost function was used in the lower-level problem in their studies. LeBlanc and Boyce (1986) first gave an explicit formulation of the NDP as a bilevel programming problem; their formulation, however, requires the assumption of linear improvement cost function, which may not be realistic. Ben-Ayed *et al.* (1988) reformulated the link improvement functions of LeBlanc and Boyce (1986) and gave greater generality in representing the travel cost functions. Ben-Ayed *et al.* (1992) proposed a new formulation that has the ability to incorporate any piecewise linear function.

The second category is the formulation of the NDP as a non-linear problem that includes the works of Harker and Friesz (1984), LeBlanc and Boyce (1986), Marcotte (1986), Kim and Suh (1988) and Suh and Kim (1989, 1992). In addition to a linear bilevel NDP formulation, LeBlanc and Boyce (1986) also proposed a nonlinear bilevel network design model that utilizes a user equilibrium (UE) route choice problem as the lower-level problem. Marcotte (1986) proposed a nonlinear bilevel network design model where the lower-level problem has been substituted with an equivalent variational inequality problem (Dafermos, 1980; Marcotte, 1983; Friesz *et al.*, 1992). A detailed analysis of the deterministic UE constrained network design problem was given in what producing several heuristics based on the bilevel programming approach.

Later, Kim and Suh (1988) proposed a nonlinear bilevel network design model that adopts a combined distribution and assignment problem with an entropy constraint as the lower-level problem. Suh and Kim (1989, 1992) also formulated a bilevel network design model with budget constraint in the upper-level, while the lower level is a UE route choice problem. Apart from the formulation of bilevel network design model in view of the Stackelberg game theory, Harker and Friesz (1984) developed an iterative optimization-equilibrium algorithm using Cournot-Nash game theory (Friedman, 1977) in the formulation of a bilevel NDP.

2.3.2.2 Origin-destination matrix estimation problem

In most of the transport planning studies and/or traffic impact assessment, the mostly difficult and expensive input data to obtain is the origin-destination (O-D) demand matrix. This is so because the O-D demand data has not been directly observable. On the contrary, it requires extensive and expensive surveys that involve home or roadside interviews. However, link flows are easily obtainable within reasonable precision by simply counting the traffic at certain checking points. Consequently, the problem of estimating or adjusting an O-D matrix from traffic counts has attracted considerable attention (Nguyen, 1984; Fisk, 1989).

Conventional methods for O-D matrix estimation assume that the route choice proportions between each O-D pair are determined independent from the estimation process. Namely, the users' route choices are considered to be independent of the O-D travel demand. This assumption of independence has the following inherent shortcomings (Yang *et al.*, 1992; Yang, 1995a). On the one hand, O-D matrix is estimated from observed link flows with fixed route choice proportions. On the other hand, the O-D matrix is, in general, assigned to the network with user equilibrium. As a result, there is an inconsistency in using one set of route choice proportions to obtain an O-D matrix from link flows, and another set to obtain the link flow distribution by assigning the O-D matrix to the network. In a network with bottlenecks, this shortcoming becomes more apparent.

To overcome the aforementioned deficiency, it is necessary to combine the O-D matrix estimation and the network equilibrium assignment into one process so that the effects of traffic congestion on travel times and hence on route choices are taken into account explicitly. Oh (1992) examined the simultaneous estimation of O-D matrices and proposed three different solution methods: penalty function method, extrapolation method and perturbation method.

Yang *et al.* (1992) and Yang (1995a, 1996) formulated the general congested O-D matrix adjustment problem and studied various efficient, heuristic solution algorithms. The generalized least squares estimation model has been combined with equilibrium traffic assignment in the form of a bilevel optimization problem. The upper-level problem seeks to minimize the sum of error measurements in traffic counts and O-D matrix, while the lower-level problem represents a network equilibrium assignment which guarantees that the estimated O-D matrix and corresponding link flows satisfy the UE conditions. This bilevel model has the advantage that it presumes equilibrium assignment but does not require counts for all links nor does it require counts to be error-free. Florian and Chen (1995) presented a bilevel programming formulation of the congested O-D matrix adjustment problem, and developed a coordinate descent solution method. It has been shown that the bilevel programming approach has a number of advantages. In particular, the estimated O-D matrix can be consistent with the hypothesized route choice behaviour.

2.3.2.3 Other applications

Apart from the aforementioned two transport modelling problems, a number of other transport related problems can also be described by the bilevel programming formulation, such as signal control problem (Yang and Yagar, 1995), inflow control problem on urban freeway networks (Yang *et al.*, 1994) and congestion pricing (Yang and Lam, 1996; Yang and Bell, 1997), etc.

Yang and Yagar (1995) presented a bilevel programming model for assigning traffic flows and optimizing signal timings in saturated road networks. Both queuing and congestion are explicitly taken into account in predicting equilibrium flows and setting signal split parameters when the O-D travel demand is fixed. The lower-level problem represents a network equilibrium assignment with queues on saturated links, while the upper-level problem is to determine signal splits to optimize a system objective function, taking account of drivers' route choice behaviour in response to signal split changes. A gradient descent algorithm was developed to solve the proposed bilevel traffic assignment/signal control problem.

Wong and Yang (1997) extended the concept of reserve capacity to a general signal-controlled road network. A bilevel programming method was presented for setting traffic signals to maximize the reserve capacity of the network. The maximum possible increase in traffic demand was to be determined by setting traffic signals at individual intersections, with taking account of drivers' route choice behaviour simultaneously.

On-ramp traffic control problems have been studied by Yang *et al.* (1994) and Yang and Yagar (1994) using the bilevel programming method. Inflows on urban freeway network are controlled with user-equilibrium flows. However, the effects of ramp queuing were ignored and so congestion increased (Yang *et al.*, 1994). In the study of Yang and Yagar (1994), a bilevel programming formulation was presented for the traffic assignment and traffic control problem in the traffic corridor system involving explicitly ramp queuing. Ramp metering rates were determined to optimize some performance measures of the whole system, while taking into account users' route choice changes in response to freeway control.

Road pricing is another application of the bilevel programming method. Yang and Lam (1996) studied combined traffic assignment and road pricing problem in general road networks with both queuing and congestion. An efficient strategy was developed to find a coordinated link toll pattern for reducing peak-hour traffic congestion. Optimal road tolls, with a network equilibrium constraint and fixed demand, were determined. Another study of road pricing was given by Yang and Bell (1997), in which road pricing is used to restrain traffic demand to a desirable level for satisfying environment capacity constraints. A particular link toll pattern could be obtained by solving an elastic-demand network equilibrium problem with queues, and substituting the calculated queuing delay with an equivalent amount of toll. However, the link toll pattern that could hold demand to a given level may not be unique. A bilevel programming approach was used to determine the best toll pattern among the feasible solution based on pre-specified criteria.

2.3.3 Solution Algorithms

A number of solution algorithms have been proposed to solve the bilevel programming problem. The algorithms can be grouped into two main categories: the local search methods and the global approaches. With reference to the related literature, there are mainly three local search methods, namely, sensitivity analysis based (SAB) methods, penalty function methods and genetic algorithms (GAs). The first two methods have been widely used to solve the nonlinear bilevel programming problems. GAs are also popularly adopted for solving the non-convex optimization problems in recent years. These three methods are reviewed in details as below.

2.3.3.1 Sensitivity analysis based methods

As implied by the implicit formulation of the bilevel programming problem, the optimal solution of the lower-level problem, for given upper-level variable x, defines a point-to-point mapping $y(x)$: $X \rightarrow Y$, if the uniqueness assumption is imposed on the optimal solutions of the lower-level problem for fixed x. Then, the bilevel programming problem is an one-level optimization problem with variable x through an implicit function $y(x)$. A major issue for solving such a problem is how to obtain the gradient information of the upper-level's objective function with respect to x through that of $y(x)$ in order to obtain the descent direction at the current feasible point.

Fiacco (1976) has derived a nonlinear sensitivity analysis theory for solving general mathematical programming problems. Tobin (1986) has also presented sensitivity analysis results for variational inequalities. Friesz *et al.* (1990) advocated the theory of variational inequality sensitivity analysis to develop local expression for the derivatives of $y(x)$ in terms of the upper-level variables. Under some assumptions such as regularity conditions and strict complementarity conditions, the gradient of $y(x)$ with respect to x, $\nabla_x y(x)$, can be computed explicitly in order to obtain the descent directions.

Sensitivity analysis methods for solving standard network equilibrium assignment problems have been studied and applied extensively in recent years. Tobin and Friesz (1988) proposed an approach for sensitivity analysis of restricted equilibrium assignment problems and developed a method to calculate the derivatives of the equilibrium link flows with respect to perturbation parameters in both the link cost function and O-D demands. Friesz *et al.* (1990) applied sensitivity analysis theory to the development of solution methods for network design problems. Based on the sensitivity analysis results of Tobin and Friesz (1988), Yang *et al.* (1994) and Yang and Yagar (1994, 1995) developed efficient algorithms for the bilevel traffic control problems with user-equilibrium flows. Yang (1995b) also extended the sensitivity analysis method to the queuing network equilibrium problems with ramp metering control and traffic signal control. In addition, Yang (1997) presented a sensitivity analysis method designed for the network equilibrium problem with elastic demand.

Generally, sensitivity analysis based methods may not necessarily converge to even local optimal solutions because $y(x)$ is not differentiable in some cases. However, the computational results in the previous related studies have suggested that this category of local search methods is promising and efficient, especially for nonlinear bilevel programming problems.

2.3.3.2 Penalty function approach

Penalty function methods are another common solution procedures for solving the solution of the bilevel programming problem. Shimizu and Aiyoshi (1981), Aiyoshi and Shimizu (1984) have proposed penalty function methods to transform the bilevel problem into an one-level problem by appending the upper-level objective as the objective function of the one-level problem, while the penalized lower-level problem and its stationary conditions of the penalized problem were considered as constraints.

Ishizuka and Aiyoshi (1992) proposed a variant of the penalty function, so called "double penalty method" for solving the bilevel problems. In their procedures, not only the lower-level problem was penalized but also the upper-level. An approximate problem was formulated by using the penalty function of the upper-level problem as the objective and that of the lower-level problem as the constraints. It was shown that the sequence to the optimal solutions of the approximate problems converges to an optimal solution of the original bilevel problem.

Refinements to improve the efficiency of penalty function methods were proposed by White and Anandalingam (1993) for the linear bilevel programming problems. A duality gap-penalty function format approach was developed, in which the duality gap of the lower-level problem was the penalty function. This method makes it capable of obtaining a global optimal solution for the linear bilevel programming problem.

2.3.3.3 Genetic algorithms

Genetic Algorithms (GAs) have been widely used for solving the non-convex optimization problems in recent years. Thus, other than the above two methods for solving the non-linear bilevel programming models, GA-based approach can be employed to solve the hierarchical optimization problems. A bilevel programming problem can be converted to a one-level programming problem by using the first order conditions of the lower-level problem. Consequently, a GA-based heuristic procedure is adopted to solve this one-level programming problem.

GA is a simulated annealing method, which has recently been used in transportation research. GAs are based on the mechanisms of evolution and natural genetics (Holland, 1975; Goldberg, 1989). Each point of a random population in GA represents a possible solution to the problem and a scheme is used for coding each point of the pre-determined population. Each coded point is referred to as an individual or chromosome and consists of a list of genes, where each gene can assume a finite number of values (1 or 0 in case of binary coding). Each point in the population is evaluated to obtain their fitness by using an objective function. After evaluating all the points in the population of a particular generation (i.e. iteration), a set of operators is used to create new points from the fitter ones through recombination steps. The new set of points constitutes the population for the next generation. The procedure iterates until optimum solutions are obtained.

Three basic operators are used to generate a new population of points; they are reproduction, crossover and mutation. Reproduction is an operation through which individuals are copied into the mating pool based on its fitness. Fitter individuals have higher chance of surviving in the subsequent generation. Crossover is the operation where two individuals (parents) are selected randomly from the mating pool (i.e., after reproduction) and the genetic information of two selected individuals is exchanged at the selected sites to form two new individuals (children). Crossover is controlled by a crossover probability. Mutation is carried out at the level of genes on the chromosome obtained after the crossover. Each gene of a selected chromosome is allowed to mutate to the other possible value: change a 0 to 1 or vice versa, with a certain probability so called the mutation probability. After the stage of mutation, the new generation is then obtained.

GAs have been successfully applied to a variety of non-convex optimization problems, for examples, network equilibrium problem (Ge and Yang, 1998), O-D estimation from traffic counts (Reddy and Chakroborty, 1998), and the combined traffic control and assignment problem (Lee and Hazelton, 1996). However, the choice of the control parameters and the convergence properties of the algorithm are still subject to debate. For instance, the larger the population size, the greater is the probability of reaching to the global optimum solution. However, the searching time will increase significantly.

2.4 SUMMARY

In this chapter, the various types of aggregate and disaggregate car ownership models have been reviewed. The factors that were used for estimating car ownership have also been investigated and summarized in Table 2.2. In addition, the current car ownership model in Hong Kong has been examined. These models have been used to estimate car ownership demand from the point of user view.

In view of network supply, the reserve capacity of car ownership under road network supply conditions can be determined by a bilevel programming model. The proposed bilevel programming model can cater for the time of day element by splitting a typical day into four study periods, such as morning peak, inter-peak, evening peak and off-peak. As a result, the O-D matrices can be disaggregated by time of day or by the four study periods. Assuming the O-D demand follows a uniform distribution within each study period, the reserve capacities of car ownership can be determined by the proposed model for different time periods. Subsequently, the critical time period with the lowest reserve capacity of car ownership can then be determined for each traffic zone.

Thus, a brief review on the bilevel programming models, their applications on transport problems and three solution algorithms for the bilevel problems was given. It was found that the sensitivity analysis based algorithm is the most common approach for solving the nonlinear bilevel programming problems in the previous related studies. Note that all the above-mentioned solution algorithms may only obtain the local optimums and cannot guarantee to obtain the global optimal solutions. Sensitivity analysis based solution algorithm can be applied for solving the proposed bilevel car ownership problem in view of given road network supply conditions if the study network is not very large. However, it is inapplicable to large-scale network problems due to computational burden limitations. Therefore, another heuristic algorithm will be required to solve the captioned problem with a larger-scale road network (Maher and Zhang, 1999).

Table 2.2 Summary of Factors that have been found to Influence Car Ownership

Factor	Reference
Household/individual characteristics	
Income (household or per person)	Ben-Akiva *et al.* (1981); Button *et al.* (1993); Gallez (1994); Han & Algers (1996); Hensher *et al.* (1989); Jansson (1989; 1990); Kitamura (1987; 1988; 1989); Kitamura & Bunch (1990); Madré (1990); Pendyala *et al.* (1995); Said (1992); Shindler & Ferreri (1967); Tanner (1978); Train (1986)
Disposable income (household or per person)	Bates *et al.* (1978); Burns *et al.* (1976); Chin & Smith (1997); Lerman &Ben-Akiva (1976)
Household size	Allen & Perincherry (1996); Hensher *et al.* (1989); Kitamura & Bunch (1990); Lerman & Ben-Akiva (1976); Pendyala *et al.* (1995); Said (1992); Shindler & Ferreri (1967); Train (1986)
Housing type	Han & Algers (1996); Lerman & Ben-Akiva (1976)
The number of licensed drivers in a household	Kitamura (1987; 1988; 1989); Kitamura & Bunch (1990); Lerman & Ben-Akiva (1976); Pendyala *et al.* (1995)
The number of adults in a household	Han & Algers (1996); Kitamura & Bunch (1990); Said (1992)
The number of workers in a household	Han & Algers (1996); Hensher *et al.* (1989); Kitamura (1988); Kitamura & Bunch (1990); Train (1986)
Residential density	Kitamura (1989); Pendyala *et al.* (1995); Shindler & Ferreri (1967);
Residential location	Han & Algers (1996); Jansson (1989); Lerman & Ben-Akiva (1976)
Socio-economic characteristics	
Gross domestic product	Ashworth & Weaver (1981); Button *et al.* (1992; 1993); Fan (1995); Prevedouros & An (1998)
Gross national product	Khan & Willumsen (1986); Johansson & Schipper (1997)
Population density	Khan & Willumsen (1986); Johansson & Schipper (1997); Tanner (1977); Train (1986)
Vehicle- and transport- related characteristics	
Price of cars	Ben-Akiva *et al.* (1981); Chin & Koh (1989); Chin & Smith (1997); Fan (1995)
Car ownership costs (registration tax, ownership tax, import duty, etc.)	Burns *et al.* (1976); Chin & Koh (1989); Fan (1995); Hensher *et al.* (1989); Jansson (1990); Khan & Willumsen (1986); Lerman & Ben-Akiva (1976)
Car usage costs (petrol price)	Burns *et al.* (1976); Chin & Smith (1997); Fan (1995); Hensher *et al.* (1989); Jansson (1990); Khan & Willumsen (1986); Tanner (1978)
Accessibility of transit and highway services	Allen & Perincherry (1996); Han & Algers (1996); Kitamura (1987; 1988; 1989); Kitamura & Bunch (1990); Lerman & Ben-Akiva (1976); Pendyala *et al.* (1995); Train (1986)
Length of public roads	Chin & Koh (1989); Chin & Smith (1997)

3 AGGREGATE CAR OWNERSHIP MODEL

Car ownership has been one of the major determinants for the development of the transport infrastructure over the past three decades. Hong Kong, a city of more than 6.5 million people with a land area of only 1,096 square kilometres, is one of the most densely populated cities in the world. Expressed in terms of population, the number of private cars in various Asian countries and regions is shown in Table 3.1 together with the gross domestic product (GDP) per head.

Table 3.1 Car Ownership and GDP in Various Asian Countries and Regions

	Population density (per km^2, 1996)	Cars per 1,000 persons (1996)	GDP per head (US $, 1996)
Hong Kong	5,924	52	24,760
Japan	332	373	41,080
Singapore	5,476	116	27,480
South Korea	458	152	10,660
Taiwan	596	193	12,800

Source: The Economist (1999) Pocket World in Figures.

It can be seen in Table 3.1 that Hong Kong and Singapore have similar population density and GDP per head, however, car ownership in Hong Kong is only 45% of Singapore. It is known that policies have been adopted to suppress car ownership in Singapore since mid-1970s. These policies consist of high import duties, vehicle registration fees, road-use pricing and annual road taxes as well as a vehicle quota scheme introduced in 1990 to regulate the growth of vehicle population (Fan, 1995). When compared with the policies implemented in Hong Kong, fiscal measures were heavily utilized in Hong Kong in two periods of 1974-5 and 1982 to restrain car ownership. A first registration tax (FRT), i.e. a purchase tax, on the value of a vehicle and annual license fees (ALF) for vehicles driven on public roads has drastically increased and interrupted the rising trend in private cars and motorcycles in Hong Kong. With the rapid development in Hong Kong and the fast growth of its economy, the high demand for car ownership could not be ignored despite geographical constraints. In terms of buying power, the potential for car ownership in Hong Kong is very high.

In Hong Kong, the existing car ownership model, which is a part of the enhanced second comprehensive transport study (CTS-2) model (Transport Department and Wilbur Smith Associates, 1989; 1993 and 1995), includes household income distribution, public transport accessibility, residential parking supply, car ownership costs and usage costs as its input factors. The discrepancy between the actual car ownership and the car ownership estimated by the CTS-2 model was significant. This was partly due to the prediction of the future value of the explanatory variables and partly due to the model error. This is because the projections made by the model were based on input assumptions. These input data included projections of land use developments for the territory, economic growth forecasts, international traffic projections, transport infrastructure networks, and future transport costs. Table 3.2 shows the number of vehicles estimated by the CTS-2 model and the actual values for the categories of cars and motorcycles and the total number of vehicles in 1991 and 1996 respectively.

Table 3.2 Number of Vehicles (thousands) in Hong Kong

	1991			1996		
	CTS-2	Actual	Error (%)	CTS-2	Actual	Error (%)
Cars and Motorcycles	214	229.8	-6.9	233	316.0	-26.3
Total Vehicles	375	386.9	-3.1	432	475.1	-9.1

The projections of the vehicles that were made by the CTS-2 in 1990 were too low during these two years, especially for the category of cars and motorcycles. Although the relative error was only 9% in the total vehicles, it was about 26% in the category of cars and motorcycles in 1996. The relative error in the category of cars and motorcycles was about three times of that of the total vehicles. A similar pattern was found in 1991; however, the relative errors were smaller than those in 1996. The results indicate that the CTS-2 model cannot capture the growth of the vehicle ownership accurately, particularly for the growth of cars and motorcycles. The errors might also come from the inaccurate prediction of some of the fundamental inputs. Therefore, there is a need to revise the current model for the estimation of car ownership in Hong Kong. The reliability of the prediction of the future values of the model inputs should also be studied so that the estimation results would be more robust.

The conventional car ownership model represents a static description of the number of cars a household has at a given point of time. It can be argued that a household would optimize its vehicle holdings over a span of time. Knowledge of a household's income, car ownership, along with the lifecycle stage and/or household structure would lead to a fairly reasonable estimate of that household's travel patterns. It is important to incorporate the dynamic trends in the car ownership forecasting process, which can be accomplished through the use of longitudinal data or time-series data (Jansson, 1989; Kitamura, 1992). A review of car ownership models is given in the Chapter 2.

3.1 METHODOLOGY

In order to assess the long-run effect of the key factors affecting car ownership, a car ownership model based on annual data is calibrated for modelling the historical car ownership trend. Car ownership is defined as the total number of licensed private cars and motorcycles, and converted to passenger car units (pcu) in order to be compatible with the results obtained in the following chapters and by the conventional transport model such as CTS-2. Private cars are assumed with a pcu factor of 1.0 and motorcycles a factor of 0.33. It should be noted that total car ownership in Hong Kong is very car based. For example, in December 1997 from Hong Kong Transport Department's published statistics, the number of licensed private cars was 314,833 while the number of licensed motorcycles was only 23,511. Therefore, total pcu was 322,592; i.e. 97.59% of pcu value was made up of cars.

With advanced mathematical techniques, it is possible to incorporate reliability analyses (Asakura and Kashiwadani, 1991; Lam and Tam, 1998) in the estimation of territory-wide car ownership. The following four-stage process (Hertz, 1979) is the methodology adopted for assessing the reliability of estimated territory-wide car ownership:

1. Identification of the key factors behind the estimates of car ownership.
2. Estimation of how these key factors affect the estimates.

3. Establishment of probability distributions for the key factors, which specify the range and shape of the probable future outcome over which each factor is likely to vary.

4. Estimation of the combined probability of outcome.

Basically, the first and second stages involve data collection and calibration of the private car estimation model. Instead of using one specific estimate of each factor, it is appropriate to use a wide range of probable values within the respective probability distribution. At the third stage, the probability distributions for each of the factors are established on the basis of historical or sample data. The last stage makes use of the Monte-Carlo simulation technique (Ross, 1991) to consider a number of possible outcomes for each key factor with their values selected at random within their probability distributions. As a result, the car ownership estimate becomes a derived random variable with an associated probability distribution. Hence, the reliability of the estimated car ownership can be obtained from the combined probability distribution of the key factors. The reliability analysis would assess the probability of reaching specific car ownership levels in given time periods. The new approach would give a better insight into the demand for car ownership.

3.2 Factors Influencing Private Car Ownership in Hong Kong

A car ownership estimation model that relates various factors (social, economic and fiscal) to the number of licensed private cars has been calibrated for Hong Kong (Tam and Lam, 1997a). The analysis was performed using quarterly data. This was mainly a pilot study for investigating the effects of various factors to the number of licensed private cars in Hong Kong. The results show that population, GDP, monthly household disposable income, government expenditure in transport infrastructure, FRT and ALF significantly affect the number of licensed private cars. Another study of Hong Kong car ownership (Prevedouros and An, 1998) considered GDP with one-year time lag and railway passenger mileage as the potential factors influencing car ownership.

In fact, there are many factors influencing the number of licensed private cars and motorcycles in Hong Kong. For instance, socio-economic factors such as population, population density, the number of driving license holders, the gross domestic product, household incomes or disposable incomes, the unemployment rate and the government's expenditure on transport infrastructure all affect car ownership. As far as the transport-related variables are concerned, factors like public transport accessibility, parking supply, road length and passenger road or rail mileage may also affect car ownership. In addition, government policies such as increasing the first registration tax and annual license fee and electronic road pricing (ERP) schemes would also affect the desire to own private cars and motorcycles.

In this study, the choice of the variables was based on the findings of the previous related studies and the availability of relevant data. The following eight key variables affecting car ownership were chosen for analysis:

1. Annual gross domestic product (HK$(1990) million)
2. Annual passenger trips on public transport (millions)
3. Annual railway passenger kilometrage (millions)

4. Average annual license fee per private car (HK$(1990))
5. Average first registration tax per private car (HK$(1990))
6. Average petrol price per litre (HK$(1990))
7. Population
8. Population density (persons per km^2)

where US$1 = HK$7.8 in 1990 price terms.

The annual GDP (in HK$ million) at 1990 constant prices was derived from the product of the GDP volume index published by the Hong Kong Census and Statistics Department (1982-96) and the 1990 GDP value of HK$582,549 million for Hong Kong. The average FRT and ALF were calculated on the basis of the medium cost-insurance-freight (cif) value or taxable value (on or after 1994) and engine size of the private cars. All the monetary valued variables for analysis are converted into the monetary value at year 1990 with the use of the consumer price index B (CPI(B)) that reflects the changes in the price level of consumer goods and services purchased by Hong Kong households. The CPI(B) was compiled based on the expenditure patterns of households in the medium expenditure ranges (HK$10,000-HK$17,499 during October 1989-September 1990).

It is important to distinguish the registered vehicles and licensed vehicles in Hong Kong. All vehicles must of course be registered when shipped into Hong Kong, with the new ones subject to a FRT. The current level of the FRT is more than double the cif value of an automobile despite the fact that the taxation basis has been changed in 1994. The new FRT is based on the taxable value of the private cars instead of cif value of the vehicles. In addition, any vehicle that uses public roads is required to pay an annual license fee (of HK$6,860 in year 1990 for a car with a medium-sized engine). As of December 1997, 90% of the registered private cars and 75% of the registered motorcycles were licensed.

It is observed from the historical data that ALFs have tripled and FRTs have doubled since May 1982. These two fiscal measures appeared to be effective to suppress the level of private cars 28% (from 194,889 to 139,572) over the following five years. The number of private cars returned to the previous 1982 level in 1990. The drastic increases in taxes introduced in 1982 were unlikely to be repeated. Over the past ten years, the changes in FRT and ALF were more or less in line with inflation. In addition, there has been no increase in the overall rate of FRT and ALF since March 1991. In the period between April 1991 and December 1997, the number of private vehicles (cars and motorcycles) has been increased by 56.0%. Figure 3.1 shows the trend of the number of licensed private vehicles from 1981 to 1997 in Hong Kong.

Two more variables, one being the parking supply (or parking cost) and another being cost of motoring, may be significant to the effect on car ownership (OCED, 1982; Han and Algers, 1996). If Government restricts availability of parking spaces particularly residential spaces, then this would have a direct impact on car ownership (if you cannot afford to park, you cannot afford to buy). Cost of motoring perhaps is already taken account of by the inclusion of petrol price, ALF and FRT. However, as currently structured the model would not take into account the effect on car ownership of a policy change such as ERP. So 'cost of motoring' is a more general variable. However, due to data was not available in Hong Kong, these two variables cannot be included in the analysis.

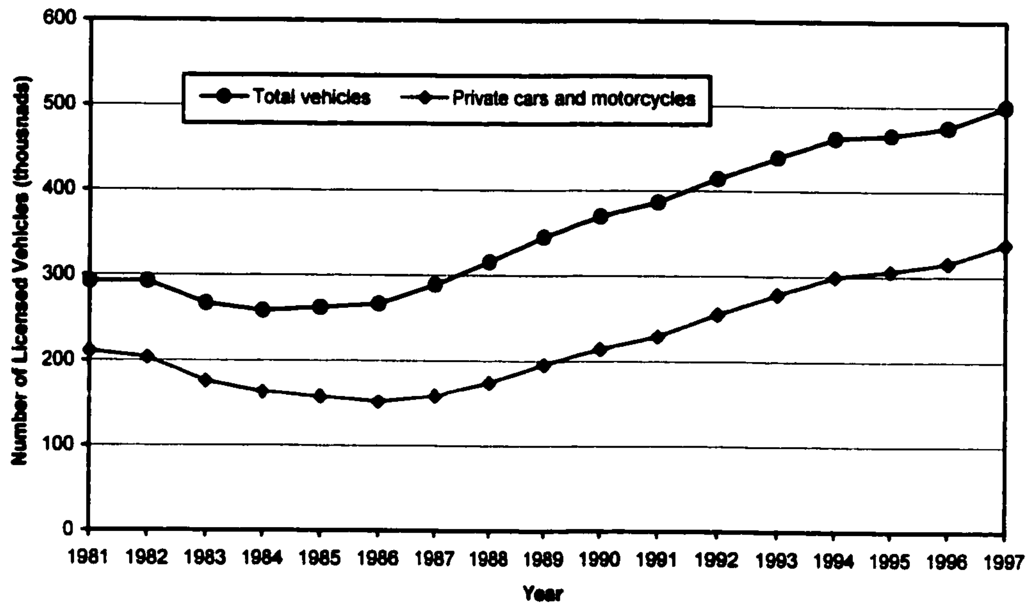


Figure 3.1 Trends of Licensed Vehicles in Hong Kong, 1981- 1997

3.3 ESTIMATION OF TERRITORY-WIDE CAR OWNERSHIP

A territory-wide car ownership model for Hong Kong is calibrated using historical data from 1981 to 1996. Data on 1997 is used to validate the estimation model. The proposed model is aimed to predict the annual territory-wide car ownership in the future years. The dependent variable, territory-wide car ownership, is expressed in terms of pcu for the total number of the licensed private cars and motorcycles. Correlation analysis was carried out to investigate which factors or independent variables are highly correlated with the total number of the licensed private cars and motorcycles in pcu. These factors may have significant effects on the territory-wide car ownership. The coefficients of correlation indicate the relationships between the territory-wide car ownership and these factors. The larger coefficient values imply that they are more closely correlated. Table 3.3 shows the correlation coefficients between various factors and the total number of licensed private cars and motorcycles in pcu.

It can be seen that all factors, except petrol price and ALF, were statistically significant correlated with the total number of licensed private cars and motorcycles in pcu. Annual GDP, annual passenger trips on public transport and railway passenger kilometrage, population and population density are positively correlated with the territory-wide car ownership. This means that these five factors may have positively effects on car ownership. For instance, an increase in GDP would increase household income and hence make more people to desire to own their cars. An increase in population would lead to higher probability for increasing the number of private vehicles. Annual passenger trips on public transport and railway passenger kilometrage were found to be positively correlated with the territory-wide car ownership. Increase in demand for public transport implies an increase in travel demand and so leads to higher possibility of owning cars. However, it can also negatively affect the territory-wide car ownership. This is because public transport serves as a substitute for private transport. Average ALF, FRT and petrol price are the costs for owning and using cars. Therefore, they are negatively correlated with the total number of licensed private cars and motorcycles (in terms of pcu). It implies that the territory-wide car ownership would decrease when the ALF, FRT and petrol price increase.

Table 3.3 Correlations between Territory-wide Car Ownership and the Key Factors

	CAR	*GDP*	*PUB*	*RAIL*	*ALF*	*FRT*	*PET*	*POP*	*POPDEN*
CAR	1.000								
GDP	0.843*	1.000							
PUB	0.666*	0.956*	1.000						
RAIL	0.727*	0.974*	0.989*	1.000					
ALF	-0.420	0.050	0.319	0.218	1.000				
FRT	-0.818*	-0.693*	-0.511#	-0.576#	0.492	1.000			
PET	-0.099	0.041	0.184	0.165	0.596#	0.388	1.000		
POP	0.831*	0.982*	0.947*	0.962*	0.042	-0.613#	0.072	1.000	
POPDEN	0.821*	0.984*	0.955*	0.968*	0.065	-0.605#	0.080	1.000*	1.000

* Correlation is significant at the 0.01 level.
# Correlation is significant at the 0.05 level.

CAR - Territory-wide car ownership;
PUB - Annual passenger trips on public transport;
ALF - Average annual license fees per private car;
PET - Average petrol price per litre;
POPDEN - Population density.

GDP - Annual gross domestic product;
RAIL - Annual railway passenger kilometrage;
FRT - Average first registration tax per private car;
POP - Population;

The correlation analysis can also examine the independence of the independent variables. If the variables were highly correlated, the problem of multicollinearity would exist. The impact of multicollinearity can be substantial on the estimation of the regression coefficients and their statistical tests. High degrees of multicollinearity can result in regression coefficients with incorrect magnitude and/or even with wrong signs. It can also be difficult to determine the contribution of each independent variable if the effects of the variables are confounded (Hair *et al.*, 1998).

However, it can be found that the correlation among some of the variables was significant. For examples, GDP was highly correlated (0.984) with population density; annual passenger trips on public transport was highly correlated (0.989) with annual railway passenger kilometrage; and population density has a high correlation of 0.955 with annual passenger trips on public transport and of 0.968 with annual railway passenger kilometrage. Therefore, in order to avoid multicollinearity, one or more highly correlated variables should be omitted in the regression model even though these independent variables were significant to the territory-wide car ownership.

In order to take into account the delayed reactions and resistance to changes in behaviour, time-lagged effects on the independent variables were also considered. The dependent variable was estimated as a function of the independent variables and their time lagged effects. The linear, semi-logarithmic and logarithmic functional forms have been examined by the ordinary least squares method to calibrate the most suitable model for estimating the territory-wide car ownership.

Stepwise regression was adopted to select the subset of the most significant variables on territory-wide car ownership. It was found that autocorrelation of the error terms existed. Therefore, a log-difference transformation on the dependent and independent variables were performed to adjust the serial correlation of the error. The autocorrelation was then purged by using ordinary least squares on the transformed data. The results indicate that only GDP, average FRT and annual passenger trips on public transport are statistically significant whereas the other variables are not statistically significant at the 5% level and so have been dropped from the model.

The territory-wide car ownership estimation model based on transformed data has been calibrated and presented as follow:

$$CAR'_t = 6.96\times 10^{-2} + 0.93\times\frac{GDP'_{t-1}}{POP'_{t-1}} - 0.21FRT'_{t-1} - 3.42PUB'_t \quad (3.1)$$

(3.99) (3.43) (-2.62) (-4.97)

where CAR'_t = transformed territory-wide car ownership (i.e. total number of licensed private cars and motorcycles in pcu) at time t; GDP'_{t-1} = transformed GDP at time $t-1$ in 1990 constant prices; POP'_{t-1} = transformed population at time $t-1$; FRT'_{t-1} = transformed average first registration tax per private car at time $t-1$ (in 1990 price terms); and PUB'_t = transformed annual passenger trips on public transport at time t. The ratio GDP'_{t-1}/POP'_{t-1} is to express GDP in terms of per capita at time $t-1$, which yields a higher significant coefficient than that of using the total GDP at time $t-1$. The adjusted coefficient of determination ($Adj.\ R^2$) of the regression model was found to be 0.862.

GDP per capita is often regarded as synonymous with income per capita. It is expected that the higher the GDP, the greater is the territory-wide car ownership. Hence, the sign is positive. High population density would create sufficient demand for public transport to reap frequency scale economies. As public transport can be a substitute for private transport, the sign of the coefficient of passenger trips on public transport is therefore negative. FRT is the cost for owning a car, so the sign of course negative. Thus, the model signs are all logically correct.

The territory-wide car ownership model gives a high explanatory of 86.20% in estimating the total number of licensed private cars and motorcycles in pcu. The t-statistics of the coefficients were shown in the parentheses and they are all significant at the confidence level 95%. The Durbin-Watson test for first-order and Box-Pierce portmanteau test for higher-order serial correlation of the error (Makridakis *et al.*, 1983) have been performed. It was found that no correlated errors were detected. The residual analysis shows that the problem of heteroscedasticity has not existed. The normality test was also conducted. As a result, it was found that the assumption of normality in the residual terms was adequate.

The degrees of multicollinearity can be examined by using the following two measures: the tolerance value and its inverse - the variance inflation factor (VIF) (Hair *et al.*, 1998). Tolerance is the amount of variability of the selected independent variable not explained by the other independent variables. Thus very small tolerance values (and so large VIF values) imply high collinearity. It was found that the three independent variables have the tolerance values of greater than or equal to 0.60, and the corresponding VIF values of greater than or equal to 1.30. It means that the degree of collinearity was acceptable.

The yearly estimated territory-wide car ownership from 1982 to 1996 was compared with the observed values in order to assess the accuracy of the regression model. By conducting statistical tests on the relationship between observed and estimated territory-wide car ownership (transformed and original), the accuracy of the fitting can be examined and the results are presented in Equations (3.2) and (3.3), respectively.

Based on transformed data:

$$CAR'_t = 3.60 \times 10^{-18} + 1.0 \times \hat{CAR}'_t \qquad Adj.\ R^2 = 0.885 \qquad (3.2)$$

(0.000) (10.051)

Based on original data:

$$CAR_t = -6.00 + 1.03 \times \hat{CAR}_t \qquad Adj.\ R^2 = 0.992 \qquad (3.3)$$

(-1.063) (39.289)

where CAR_t is the observed territory-wide car ownership at time t, $\hat{CAR}_t$ is the estimated territory-wide car ownership at time t and t-statistics are shown in the parentheses. The results show that the constants in Equations (3.2) and (3.3) are statistically insignificant and the coefficients of the estimated territory-wide car ownership are highly significant and close to one. The models (3.2) and (3.3) are 88.5% and 99.2% fit of the transformed and original data, respectively. In order to test the bias of the fitted model, a quadratic term of the estimated territory-wide car ownership is included in the model and presented in the Equation (3.4) for transformed data and Equation (3.5) for original data.

Based on transformed data:

$$CAR'_t = 1.00 \times C\hat{A}R'_t + 0.26 \times C\hat{A}R'^2_t \qquad Adj.\ R^2 = 0.896 \qquad (3.4)$$

(11.059) (0.328)

Based on original data:

$$CAR_t = 0.98 \times C\hat{A}R_t + 9.27 \times 10^{-5} \times C\hat{A}R_t^{\ 2} \qquad Adj.\ R^2 = 0.999 \qquad (3.5)$$

(32.562) (0.746)

The results show that the coefficients of the quadratic estimated territory-wide car ownership are statistically insignificant and can be excluded from both the models (3.4) and (3.5). Thus, based on the above two statistical tests, it was found that the estimated values of territory-wide car ownership obtained by the regression model (3.1) are best fitting the observed values.

Figure 3.2 shows the results of the comparison. It can be observed that only a total of 14 data points, but not 16 data points, are presented in Figure 3.2. The two missing data points are due to the transformation of the data and the lagged variables included in the calibrated model. It can be seen that the deviation from the 45° line (observed values = estimated values) is small.

Based on model (3.1), the effect of each independent variable on territory-wide car ownership can be assessed by the regression coefficients. However, the regression coefficients cannot directly reveal the facts as the independent variables were in terms of different units of measurement. Thus, standardized regression coefficients were adopted to reflect the relative impact on territory-wide car ownership due to a change in one standard deviation of each of the independent variables. The results show that one-year lagged GDP per capita has a positive effect on the growth of the total number of licensed private cars and motorcycles (in terms of pcu); while one-year lagged average FRT and annual passenger trips on public transport have negative effect on territory-wide car ownership. Annual passenger trips on public transport was found to be the most relatively important, GDP per capita is the second important and average FRT is the least relatively important on territory-wide car ownership.

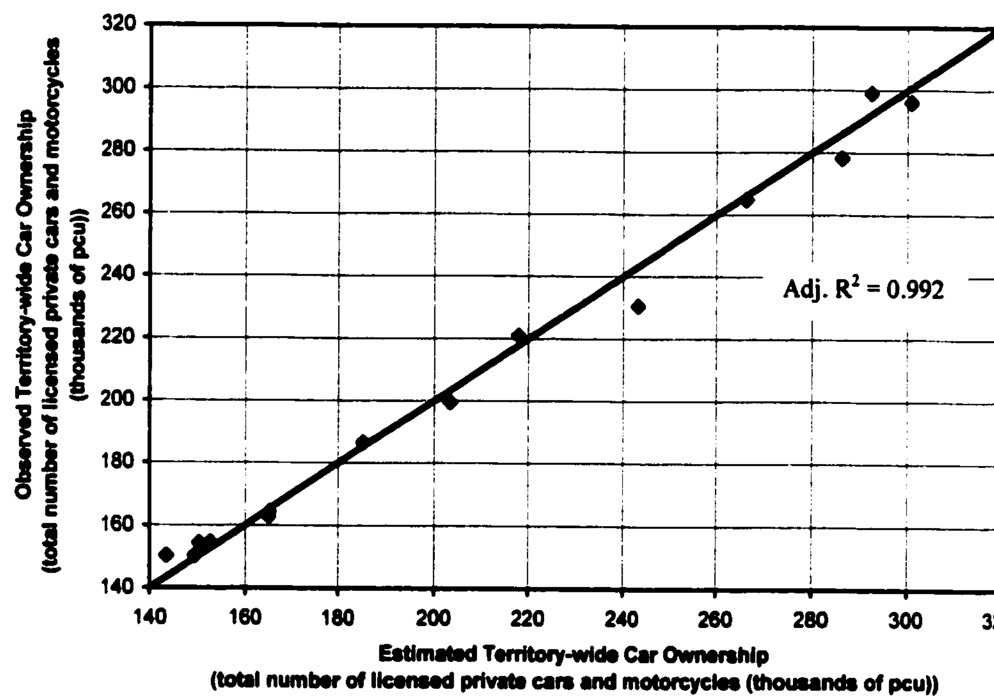


Figure 3.2 Validation of Territory-wide Car Ownership Model using Data from 1981 to 1996

When the territory-wide car ownership was estimated by model (3.1) using the observed values of the independent variables in 1997, it was found that the total number of licensed private cars and motorcycles is equivalent to 320,350 pcu. By comparison with the observed value of 322,590 pcu, the result obtained from the regression model (3.1) underestimates the territory-wide car ownership by 0.69% only. If the 1997 values of the territory-wide car ownership and of the key factors (i.e. independent variables) are unknown, the projected values of the key factors can then be used for forecasting the territory-wide car ownership by the calibrated model (3.1). It was found that the forecasted territory-wide car ownership is 311,370 pcu in 1997, which is underestimated by 3.48%.

Although the model (3.1) gives a good estimation of the territory-wide car ownership from 1981 to 1996, the reliability of the model may reduce in the future, particularly when there are large variations in the input factors. As only the average value of the key factors is to be projected for forecasting the territory-wide car ownership in the model (3.1), the variations of these factors have not been considered in the forecasts. Thus, in order to provide more reliable and robust results in the forecasts, the model needs to be improved by considering the effects of variation of each key factor on the territory-wide car ownership.

3.4 PROBABILITY DISTRIBUTIONS FOR THE KEY FACTORS

Projection from historical data is usually applied to estimate the future values of the key factors for car ownership forecasting purposes. Thus, the variations on the key factors are due to the projection errors. A reliability analysis is applied to the estimation of territory-wide car ownership in model (3.1) to assess the uncertainty of the projections on the key factors. In the reliability assessment of the estimated territory-wide car ownership in 1997, the probability distributions of the relative errors (e) of actual (or observed) and projected values of the key factors are established and justified by Chi-square, Kolmogorov-Smirnov and Anderson-Darling tests (Law and Kelton, 1991) for goodness-of-fit at a 5% level of significance. The data for the observed and projected values of the key factors were collected up to the year of 1996.

$$Relative\ error\ (e) = \frac{Actual\ value - Projected\ value}{Projected\ value} \times 100\% \qquad (3.6)$$

For the factor of GDP, the distribution of the relative errors (e_G) of the actual and projected GDP has been examined. $GDP_{proj}(1+e_G)$ was used for forecasting, where GDP_{proj} was projected by the Hong Kong Economic Services Branch and adopted for CTS-2 (Transport Department and Wilbur Smith Associates, 1993). The generalized distribution for the relative errors, e_G, was assumed to be a normal distribution. The distributions of the relative errors are shown in Figure 3.3. Due to the fact that only very small samples were available, the theoretical distribution in Figure 3.3 seems not to be normal from such a poor empirical distribution. However, the goodness-of-fit tests show that the hypothesis of non-normal distribution was insignificant.

For the factor of population, the distribution of the relative errors (e_P) of the actual and projected populations by the Hong Kong Census and Statistics Department (1978, 1984 and 1992) has been derived. In total 50 samples were obtained from several projections between 1976 to 1996. It was found that the generalized pattern of e_P follows a Weibull function. Population is expressed as $POP_{proj}(1+ e_P)$ for forecasting purposes, where POP_{proj} is the projected population. Figure 3.4 shows the empirical and theoretical distributions of the relative errors of the actual and projected population from 1976 to 1996.

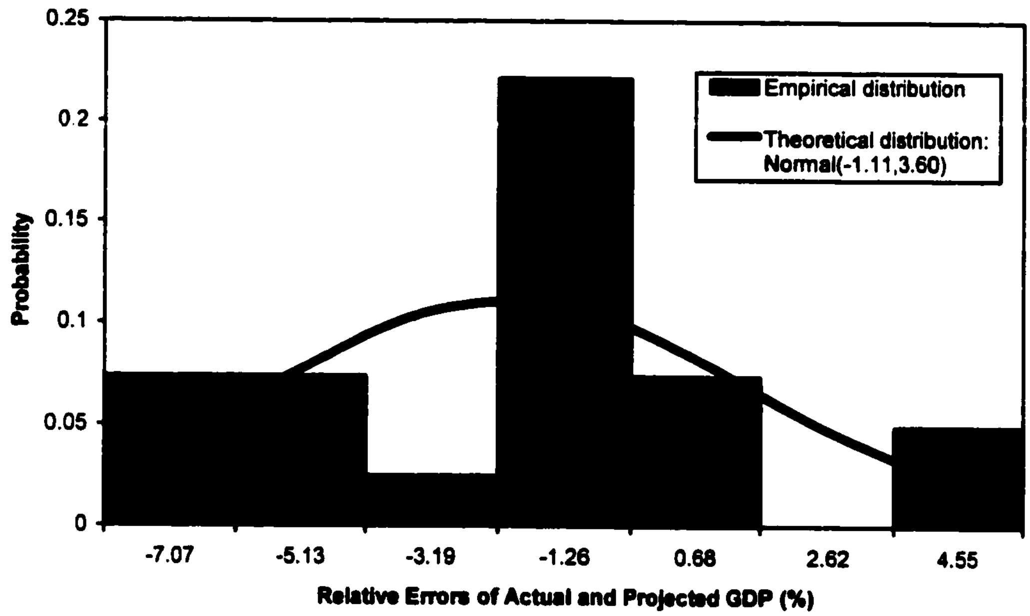


Figure 3.3 Empirical and Theoretical Distributions of the Relative Errors of Actual and Projected GDP

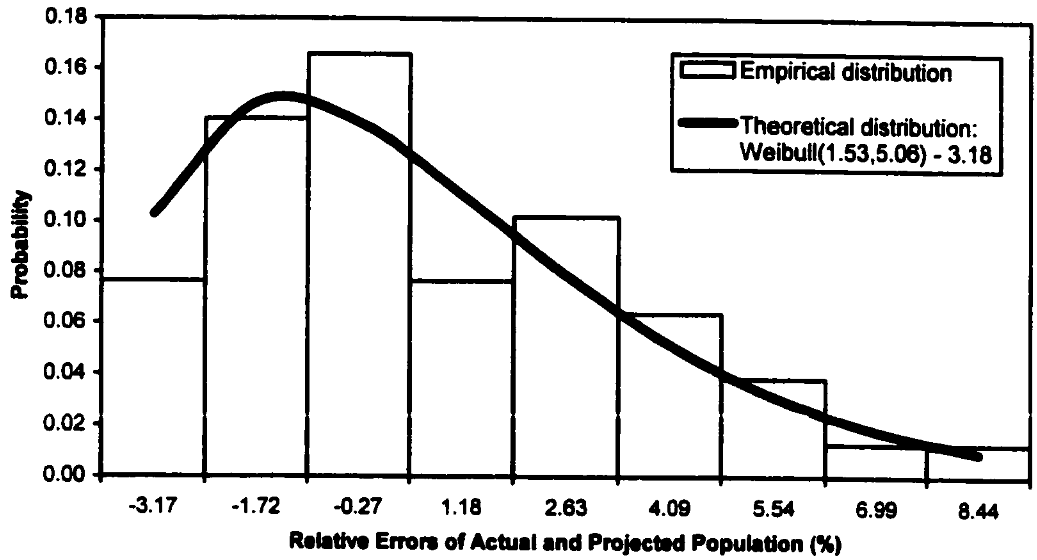


Figure 3.4 Empirical and Theoretical Distributions of the Relative Errors of Actual and Projected Population

The annual passenger trips on public transport were projected using extrapolation. The distribution of the relative errors of the observed and projected annual passenger trips on public transport (e_T) was then established. It was found that the generalized pattern of e_T follows a Beta distribution and the results are shown in Figure 3.5. The annual passenger trips on public transport is expressed as $PUB_{proj}(1+ e_T)$ for forecasting, where PUB_{proj} is the projected annual passenger trips on public transport.

Not only the net value of FRT but also the car choice would affect the average value of FRT. Therefore, the projection of future average FRT can be divided into two parts: one for FRT itself and another for car choice proportion. In the projection of FRT for different types of cars, an exponential smoothing process with damped trend effect was carried out to forecast the future FRT by type of private cars. On the other hand, the distribution of car choice proportion was generalized based on the past pattern. It was found that the car choice proportion could be fitted by a Gamma distribution. However, for forecasting purposes, it is required to estimate the parameters of this Gamma distribution for the future years. As GDP can reflect household income and in turn affect the choice of car types, GDP is therefore used to estimate the parameters of the Gamma distribution. By combining the results of FRT and car choice proportion for different types of cars, the projected average FRT at current monetary value, FRT^{c}_{proj}, can be determined for the future years.

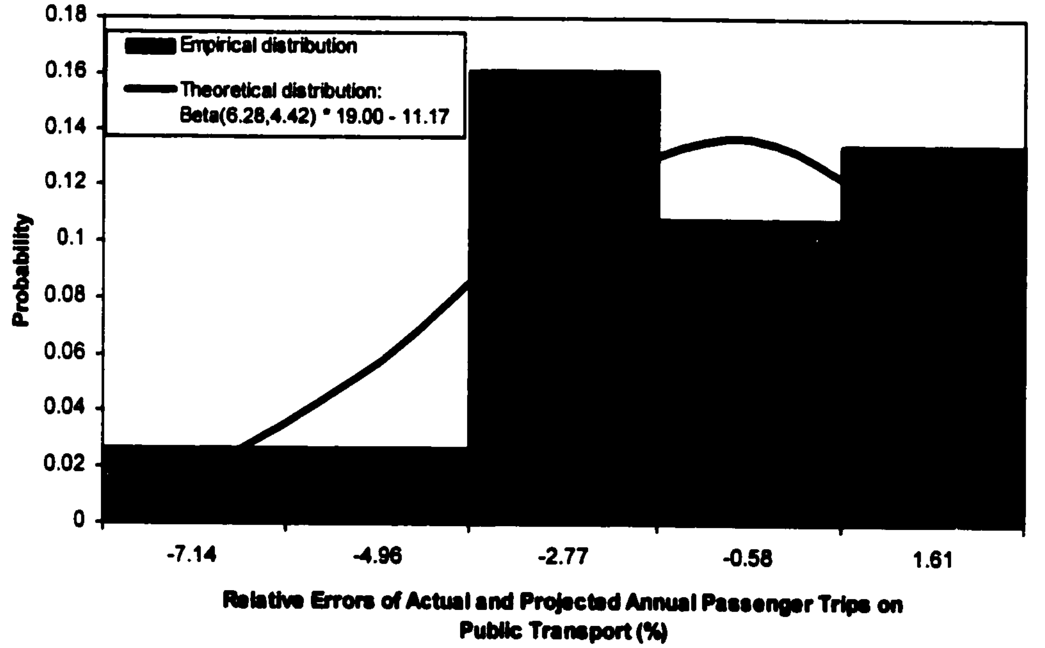


Figure 3.5 Empirical and Theoretical Distributions of the Relative Errors of Actual and Projected Annual Passenger Trips on Public Transport

The distribution of the relative errors (e_R) can then be derived using the actual and projected values of FRT. The generalized distribution of the relative errors was found to be lognormal and shown in Figure 3.6. For forecasting purposes, the average FRT at current price terms is expressed as $FRT^{c}_{proj}(1+e_R)$, while the average FRT at 1990 constant price terms converted by GDP is expressed as

$$FRT^{c}_{proj}(1+e_R)\times\frac{GDP_{1990}}{GDP_{proj}(1+e_G)}. \tag{3.7}$$

A distribution of general model error was included in the reliability analysis to assess the uncertainty in the coefficient estimates in the model and also the estimated error of the territory-wide car ownership model. The generalized pattern of the relative errors of the actual and estimated territory-wide car ownership was found to follow a normal distribution. Figure 3.7 shows the empirical and theoretical distributions of the relative errors of the model.

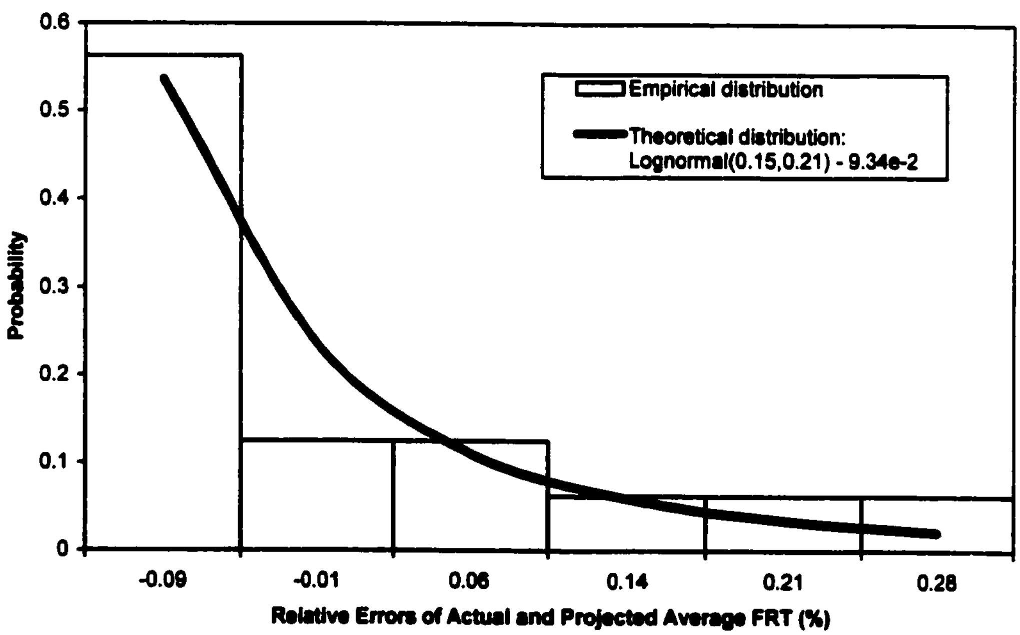


Figure 3.6 Empirical and Theoretical Distributions of the Relative Errors of Actual and Projected Average First Registration Taxes

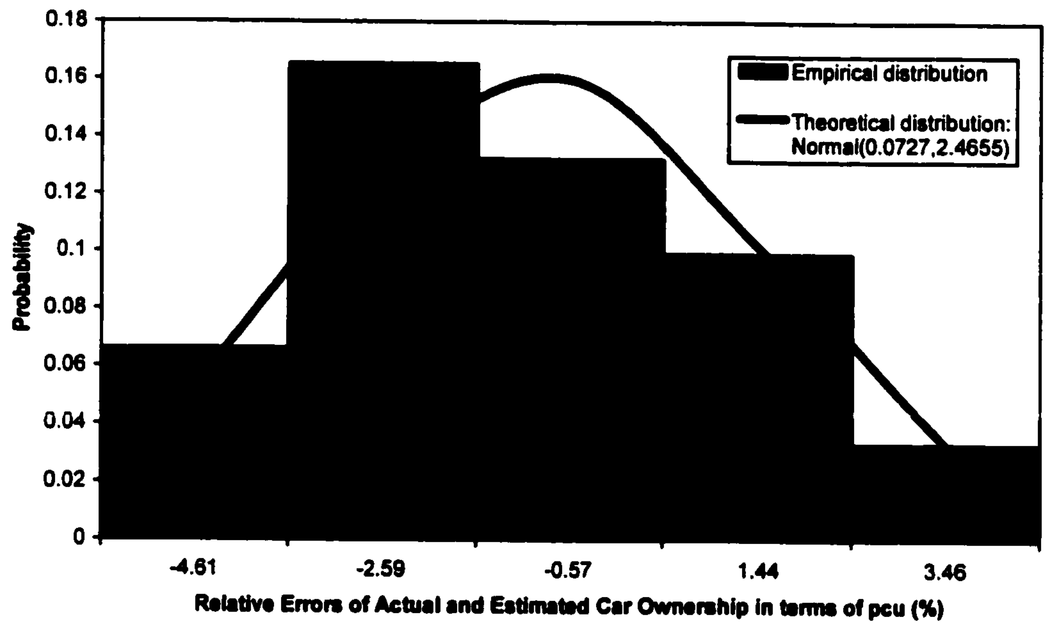


Figure 3.7 Empirical and Theoretical Distributions of the Relative Errors of the Territory-wide Car Ownership Model

As far as the probability density functions of the forecasting errors of the key factors are concerned, their parameter values are summarized in Table 3.4. These probability density functions present the generalized patterns for the forecasting errors of the key factors. However, it is believed that different values of means and variances of these factors should be obtained for different years although the distribution functions remain unchanged. On the basis of the derived probability distributions, the Monte-Carlo simulation method can be used to estimate the probability distribution of the territory-wide car ownership.

Table 3.4 Probability Density Functions of the Forecasting Errors of the Key Factors

Factor (relative errors)	Probability density function
Annual GDP	Normal (-1.1105, 3.5966)
Population	Weibull (1.5337, 5.0581) – 3.1802
Average FRT per private car	Lognormal (0.1480, 0.2057) – 0.0934
Annual passenger trips on public Transport	Beta (6.6817, 4.6483) × 19.44 – 11.4823
Model error	Normal (0.0727, 2.4655)

Notes:

$$Normal(\mu,\sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\mu)^2}{2\sigma^2}} \quad ; \quad Weibull(\alpha,\beta) = \alpha\beta^{-\alpha} x^{(\alpha-1)} e^{-\left(\frac{x}{\beta}\right)^{\alpha}}$$

$$Lognormal(\mu,\sigma) = \frac{1}{x\sqrt{2\pi\sigma_l^{\,2}}} e^{\frac{-(\ln x-\mu_l)^2}{2\sigma_l^{\,2}}} \quad where \quad \mu_l = ln\left(\frac{\mu^2}{\sqrt{\mu^2+\sigma^2}}\right),$$

$$\sigma_l = \sqrt{ln\left(\frac{\mu^2+\sigma^2}{\mu^2}\right)}$$

$$Beta(\alpha_1,\alpha_2) = \frac{x^{(\alpha_1-1)}(1-x)^{(\alpha_2-1)}}{B(\alpha_1,\alpha_2)} \quad where \quad B(x_1,x_2) = \int_0^1 t^{x_1-1}(1-t)^{x_2-1}dt$$

3.5 Reliability of Territory-wide Car Ownership Estimates

Data in 1997 was used to assess the reliability of the territory-wide car ownership estimates. With the use of the Monte-Carlo simulation method and the above data representing the base scenario, the combined probability of the estimated car ownership has been derived. The simulation experiment was continued for a sufficiently large number of simulations till the results achieved a steady state. It means that the performance measures in several successive simulations calculated on the basis of all the cumulated results fall within a close confidence interval (Malini and Raghavendra, 1996). The objective is to ensure that errors due to chance are minimized and are under control. The tolerance specified for convergence was set to 0.01 for both mean and standard deviation of the simulation outcomes. It was found that 1,268 simulations were required for the reliability analysis of the territory-wide car ownership estimates. The results of the reliability analysis for the territory-wide car ownership in 1997 are summarized in Table 3.5. The cumulative distribution function of the simulated territory-wide car ownership is shown in Figure 3.8.

Table 3.5 Results of Reliability Analysis of Territory-wide Car Ownership in 1997

Observed car ownership (thousands)	322.5916
Simulated mean car ownership (thousands)	314.0341
Simulated median car ownership (thousands)	311.8522
Standard deviation of simulated car ownership	29.6984
Probability of reaching observed value or greater	35.53%
90% confidence interval of the simulated car ownership (thousands)	270.6250 < car ownership < 366.7188

Note: units of car ownership = pcu for the total number of licensed private cars and motorcycles

The reliability analysis incorporates the variations of the key factors affecting the territory-wide car ownership. It can give an interval within a particular probability and/or probability of a specific territory-wide car ownership level. The observed pcu (licensed private cars and motorcycles) in 1997 is 322,590, while the simulated average pcu is 314,030. It can be observed that the value obtained from simulation model underestimates by 2.65%. If the projected values of those factors were used for forecasting, the estimated territory-wide car ownership was found to be 311,370 pcu which was underestimated by 3.48%. The underestimation in the car ownership model (3.1) as well as the reliability analysis is mainly due to inaccurate projections of the future values of the key factors. However, using a wide range of probable values in accordance with the specific probability distributions for estimation is more robust than using a single value (or point estimate) for each of the input factors.

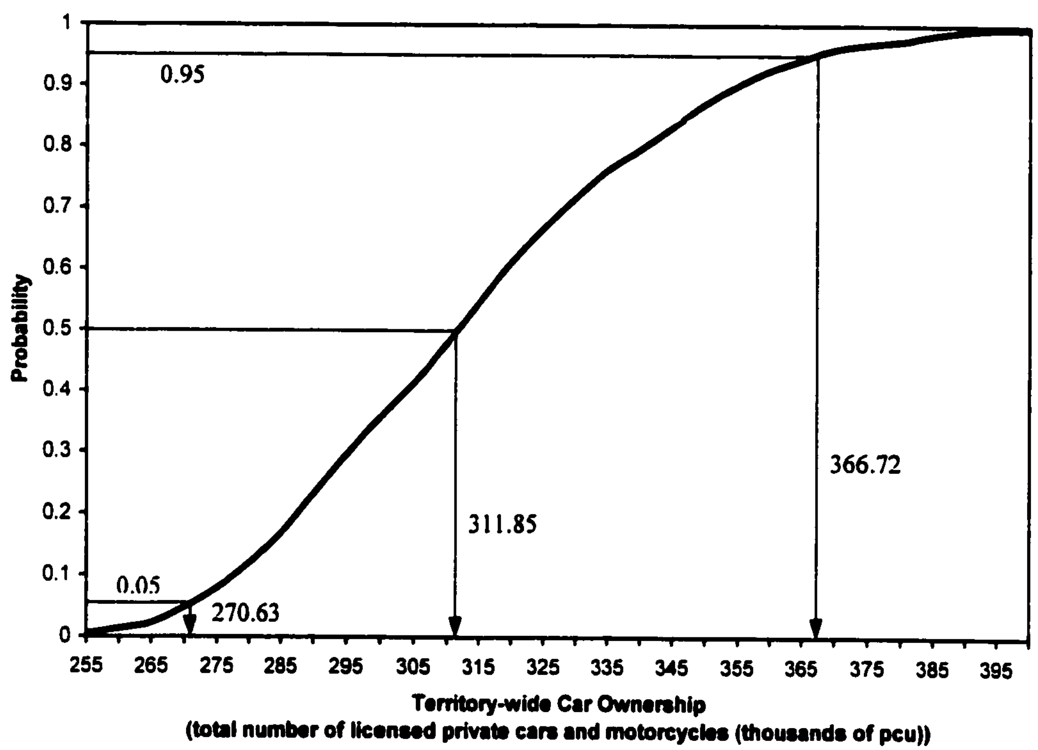


Figure 3.8 Cumulative Distribution Function of Territory-wide Car Ownership Estimates for 1997 in Hong Kong

The probability of reaching observed value (322,590 pcu) or greater is 35.53%. The median car ownership estimate is 311,850 pcu, which is close to the simulated mean value (314,030 pcu). In addition, there is 95% probability of territory-wide car ownership estimates less than 366,720 pcu and 95% probability of territory-wide car ownership estimates greater than 270,630 pcu.

The low, medium and high scenarios for territory-wide car ownership forecasts with different probabilities were produced using the results of the reliability analysis to compare with the results obtained by the CTS-2 model (Transport Department and Wilbur Smith Associates, 1993). The three scenarios are shown in Table 3.6 together with the scenarios given by the CTS-2 model. It can be found that all the three scenarios given by the CTS-2 model underestimate the actual territory-wide car ownership in 1997. For example, the medium scenario of CTS-2 analysis underestimated the actual value by 3.66%.

The reliability analysis not only gives the average value of the estimated territory-wide car ownership, but also presents different scenarios in terms of the probability of territory-wide car ownership estimates. Therefore, this analysis which can give a better insight into the variability of territory-wide car ownership will be highly useful in establishing strategic policies and planning future transport infrastructure.

Table 3.6 Car Ownership Scenarios in 1997

Low Scenario		Medium Scenario	High Scenario	
Probability	Car Ownership	Car Ownership	Probability	Car Ownership
5%	270.6250	311.8522	95%	366.7188
10%	277.6563	311.8522	90%	354.6875
15%	283.1875	311.8522	85%	347.0000
20%	287.5000	311.8522	80%	340.3125
25%	291.4063	311.8522	75%	333.5938
CTS-2 estimates	305.6692	310.7837	CTS-2 estimates	315.8983
Actual car ownership		322.5916		

Note: units of car ownership = total number of licensed private cars and motorcycles (thousands of pcu)

3.6 SUMMARY

This chapter presents the development of the aggregate car ownership model and examines the reliability of the territory-wide car ownership estimates in Hong Kong. The sensitivity analysis of the forecasting model has been given: how to assess the uncertainty of the projected values of the explanatory variables so that the estimation results would be more robust. The major underlying factors affecting the total number of licensed private cars and motorcycles (in terms of pcu) were investigated. The territory-wide car ownership estimation model related to one-year lagged GDP per capita, one-year lagged average FRT per private car and annual passenger trips on public transport has been calibrated for predicting the territory-wide car ownership in Hong Kong. The inclusion of reliability analysis through the use of probability distributions for the key factors appears very useful. The use of low, medium and high scenarios for the territory-wide car ownership estimates is consistent with the approach taken by the Administration in strategic studies in Hong Kong. Therefore, the model could be a useful tool for planners and this approach would give a better insight into the need for transport infrastructure.

4 DISAGGREGATE CAR OWNERSHIP MODEL

The total number of licensed private cars and motorcycles in Hong Kong has been estimated and presented in Chapter 3. In Chapter 4, zonal car ownership demand is to be estimated. Disaggregate car ownership models for Hong Kong are calibrated to estimate car ownership and multi-car ownership at zonal level based on the results of revealed preference (RP) and stated preference (SP) surveys in Hong Kong.

By means of RP data, the probabilities of the choices of household car ownership and multi-car ownership can be obtained. Zonal car ownership can then be estimated by using these two probabilities provided that the number of households by traffic zone is known. SP models are developed to examine the response of car ownership due to the economic changes and fiscal measures. The SP results can be used to confirm the findings of RP models.

4.1 BACKGROUND

Traditionally, collection of data is based on direct observation or by interview surveys where respondents are asked to choose the actual travel alternatives, i.e. RP data. These RP survey methods are one of the most appropriate tools for deriving utilities and calibrating models of travel behaviour. In practice, limitations of these methods (Kroes and Sheldon, 1988; Ortúzar and Willumsen, 1994) are basically associated with survey costs and the difficulty of distinguishing the effects of attributes that could not be observed or measured directly, e.g. those related to notions such as quality or convenience. Moreover, the RP methods cannot be used directly to evaluate demand or to assess response under conditions which do not yet exist.

It is against the backdrop of such problems that the uses of SP methods become an attractive option for studying travel behaviour. SP observations can be obtained by conducting relatively inexpensive surveys where respondents are presented with hypothetical alternatives and asked to indicate which of these alternatives is preferred (Bates, 1988). The SP methods are easier to be adopted as the researcher defines the conditions which are being evaluated by the respondents; they are more flexible (being capable of dealing with a wider variety of variables); and they are cost effective as each respondent can provide multiple observations for variations in the explanatory variables (Kroes and Sheldon, 1988).

SP approaches involve asking respondents to express preferences for hypothetical scenarios that have been characterized in terms of their attributes. Responses can be elicited through judgmental ranking or rating tasks, or through choices made from hypothetical choice sets (Hensher, 1994).

In the case of rankings, individuals are asked to rank a set of alternatives in order of preference. Ratings are giving both order and degree of preference to each option. Individuals typically select a 5 or 10-point scale to represent an underlying continuous distribution of interval scaled rates. In the case of choices, individuals are asked to choose their most preferred option from the alternatives in the choice set. Therefore, in this case, the response corresponds with the usual discrete choice-

RP approach, except for the fact that both alternatives and choices are hypothetical. The comparison of SP data in the form of rankings, ratings and choices has been studied by Ortúzar and Garrido (1994).

For estimation of choice models, SP data have certain advantages over RP data (Ben-Akiva *et al.*, 1991). RP data is criticized for insufficient variation in explanatory variables, high levels of collinearity and inability to incorporate new alternatives that differ in substantive ways from existing ones. However, a commonly criticism of SP data is that because it is not based on real market behaviour, it may not reflect the current distribution of choices (Swait *et al.*, 1994). SP also presents some difficulties, especially in the design of unbiased experiments and in interpretation of the results. Recently, most of researches used pooled RP and SP data for analysis to take advantage of the complementary strengths of each data source (Morikawa, 1994; Swait *et al.*, 1994).

SP methods are popularly used for analyzing travel behaviour and policy in the non-existing scenarios. Zhao *et al.* (1996) have investigated the drivers' route choice behaviour in response to different types of travel time information. Axhausen and Polak (1991) used a SP approach to study the choice of parking type. SP was also applied on the travel choice experiments (Fowkes and Wardman, 1988; Hensher *et al.*, 1988). In addition, the choice of car ownership has been examined by SP method (Tam and Lam, 1997b; Ng and Lam, 1998).

In Hong Kong, there are about 276 vehicles per kilometre of road, which is one of the highest vehicle densities in the world. The number of licensed vehicles has grown from 266,000 in 1980 to 500,000 in 1997 (Traffic and Transport Survey Division, 1998) representing an increase of 88% over the past 17 years or an average annual growth rate of 3.8%. With this growth, the transport authority is certainly faced with a great challenge to handle the increasing road traffic demand. Thus, there is a need to better understand the choice of car ownership and to forecast the car owning households by zone in Hong Kong for strategic planning purpose.

This chapter identifies factors that would affect the choices of car ownership in Hong Kong's households. In order to estimate the choice of owning a car in Hong Kong, a survey contains both revealed and stated preference questions were conducted to assess the willingness of people to own or dispose of a car. The influences of monthly household income, household size, accessibility to employment, residential car parking availability, monthly car ownership cost and monthly car usage cost are examined. Binary logit-type choice models (Ben-Akiva and Lerman, 1985) are calibrated for modelling car ownership choice-making behaviour. The number of non-car owning households, one-car owning households and multi-car owning households can be forecast for each zone by the developed models using RP data. SP technique was also used to assess the effects of economic changes and fiscal policies on car ownership choices. The SP-based results were mainly used to confirm the RP-based results.

4.2 THE SURVEY

The survey was designed to collect relevant data for analyzing car owning choices of Hong Kong residents. In order to identify the factors affecting car ownership and test the reasonableness of the values used in the design of hypothetical scenarios, a pilot survey was conducted. The pilot survey mainly studied the influence of personal income and parking rents on car ownership (Tam and Lam, 1997b). From the pilot survey, the information of sample frame, sample size required and factors were used for the design of the main survey. Car ownership and usage costs such as purchase cost of private cars, annual license fees, monthly fuel costs, insurance fee and others are also considered in the main survey.

The main survey was conducted in the four licensing offices of Transport Department in the Territory of Hong Kong, namely the Hong Kong, Kowloon, Kwun Tong and Shatin Licensing Offices (Figure 4.1) in the beginning of 1998. Survey targets are individuals who have entered the survey sites are over the age of 18 and can obtain valid driving licenses according to the laws in Hong Kong. The survey was conducted by 'face to face' interview at the licensing offices. In the main survey, all interviewers have been trained and participated in the pilot surveys. During the main survey, the area of each of the licensing offices was divided into different clusters and assigned to the interviewers. The interviewers based on their experiences to randomly select the individuals for answering the questionnaire in their assigned areas. Using the simple random sampling method can minimize the disturbances to persons in the licensing offices during the survey. This was one of the major constraints in the survey.

To suit the Hong Kong situation, the questionnaire contains RP and SP questions in both Chinese and English. RP questions are designed to collect valuable data relating to characteristics of the persons surveyed and their households. SP questions are designed to assess the effects of varying factors that contribute toward the decision of car owning. SP is a factorial design procedure in which hypothetical combinations of attributes are varied in order to reveal their role in influencing the individual's preferences for alternative attribute levels (Kroes and Sheldon, 1988). Data obtained was used for an empirical analysis of discrete choice models to quantify the respondents' behaviour. The English version of the questionnaire is shown in Appendix A.

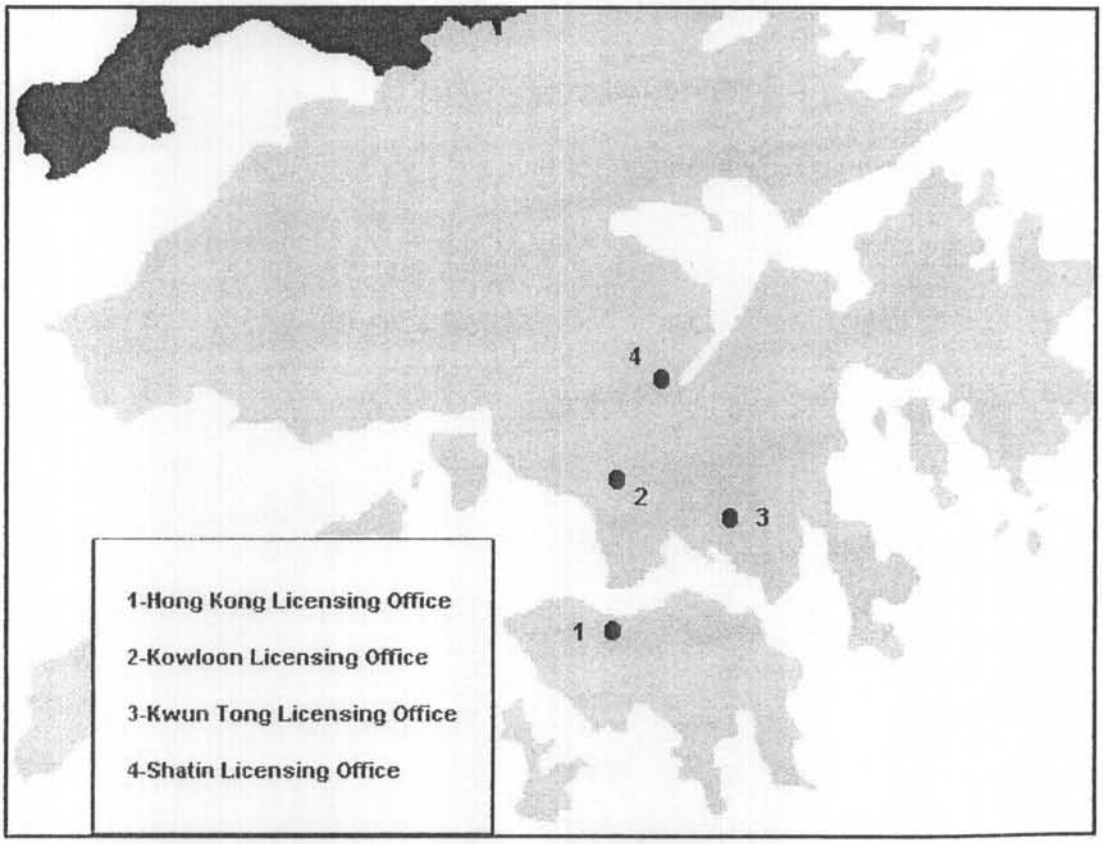


Figure 4.1 Locations of the Four Licensing Offices (Transport Department) in Hong Kong

When asking the SP questions, the samples are classified into car owning and non-car owning groups. The two groups are asked different SP questions. Car owning households are asked whether they are intended to buy another additional car(s) or dispose of their cars, under a set of hypothetical scenarios. Non-car owning households are asked to make their choices to own a car(s) under various hypothetical scenarios. Each scenario describes the hypothetical level (increasing or decreasing) of their monthly household income, car purchase cost (including first registration tax), annual vehicle license fee (ALF), home-end parking fee and car usage cost. The response bases themselves on a "trade-off" decision made between various attribute combinations. The attribute levels for alternatives are presented in Table 4.1.

For the car owning household group, the 'base' in Table 4.1 means the existing income, prices or costs that they have paid for owning and using their cars. For the non-car owning household group, the 'base' is referred to their existing income or the average estimated costs for car ownership and usage. These reference costs were estimated by the Second Comprehensive Transport Study (CTS-2) of the Government.

In order to avoid presentation bias, the placement of the order of attribute combinations are randomised. This procedure can avoid the order or learning effects that may occur when certain game sets are always asked in the same order.

Table 4.1 Attribute Levels for Alternatives

		Car Owning Households			Non-Car Owning Households	
Parameters	Attribute level	Those who asked to dispose of their car(s)	Those who asked to give up buying an additional car(s)	Those who asked to own an additional car(s)	Those who asked to give up buying a car(s)	Those who asked to own a car(s)
Monthly household income	1	Base	Base	Base	Base	Base
	2	Base*0.8	Base*0.8	Base*1.2	Base*0.8	Base*1.2
	3	Base*0.7	Base*0.7	Base*1.3	Base*0.7	Base*1.3
	4	Base*0.6	Base*0.6	Base*1.4	Base*0.6	Base*1.4
	5	Base*0.5	Base*0.5	Base*1.5	Base*0.5	Base*1.5
	6					Base*2.0
Car purchase cost	1	Base	Base	Base	Base	Base
	2	---	Base*1.2	Base*0.9	Base*1.2	Base*0.9
	3	---	Base*1.3	Base*0.8	Base*1.3	Base*0.8
	4	---	Base*1.4	Base*0.7	Base*1.4	Base*0.6
	5	---	Base*1.5	Base*0.6	Base*1.5	Base*0.5
ALF	1	Base	Base	Base	Base	Base
	2	Base*1.2	Base*1.2	Base*0.9	Base*1.2	Base*0.8
	3	Base*1.3	Base*1.5	Base*0.8	Base*1.3	Base*0.7
	4	Base*1.5	Base*1.7	Base*0.7	Base*1.5	Base*0.5
	5	Base*2		Base*0.5	Base*1.7	
Monthly home-end parking fee	1	Base	Base	Base	Base	Base
	2	Base*1.2	Base*1.2	Base*0.8	Base*1.2	Base*0.8
	3	Base*1.3	Base*1.3	Base*0.7	Base*1.3	Base*0.7
	4	Base*1.5	Base*1.5	Base*0.6	Base*1.4	Base*0.6
	5	Base*2	Base*2	Base*0.5	Base*1.5	Base*0.5
Monthly usage cost	1	Base	Base	Base	Base	Base
	2	Base*1.2	Base*1.2	Base*0.9	Base*1.2	Base*0.9
	3	Base*1.4	Base*1.4	Base*0.8	Base*1.3	Base*0.8
	4	Base*1.5	Base*1.5	Base*0.7	Base*1.4	Base*0.7
	5	Base*2	Base*2	Base*0.5	Base*1.5	Base*0.5

A sample consisted of 422 successfully interviewed on the four survey sites. The average response rate is 52%. However, about 9% of samples were eliminated because their questionnaires were incomplete. The remaining valid 384 samples were used for further analysis. The following information was collected in the RP questions of this survey:

- the number of private cars owned by a household;
- monthly household income;
- household size;
- household location;
- car ownership cost (including purchase cost, first registration tax, annual license fee, insurance and home-end parking fee); and
- car usage cost (including fuel cost, maintenance cost and attraction-end parking fee).

Household location is asked to relate the accessibility and parking availability information to the respondents' residential locations. In order to be compatible with the input data used in the CTS-2, the breakdown of the car ownership costs and usage costs are not considered in the revealed preference analysis.

In the SP questions of the survey, each respondent was asked for five to ten hypothetical scenarios. As a result, a database of 3,438 observations was created from the valid SP samples. The following attributes are considered in the SP survey:

- monthly household income;
- car purchase cost;
- annual vehicle license fee;
- home-end parking fee; and
- car usage cost.

Car purchase cost, annual vehicle license fee and home-end parking fee are broken down from the car ownership costs so as to assess the effect of each of the components of car ownership costs on car ownership choices.

4.3 SURVEY RESULTS

Among the 384 observations, there are 217 car owning households and 167 non-car owning households. The number of cars owned by households is shown in Table 4.2. From the selected samples, the average number of cars per household is 0.70.

Table 4.2 Number of Cars Owned by Households

Number of Cars	Number of Respondents	Proportion of Total (%)
0	167	43.49
1	178	46.36
2	30	7.81
3	4	1.04
4	5	1.30
Total	384	100.00

The monthly household income for car owning and non-car owning households is illustrated in Figure 4.2. There are about 72% of non-car owning households in the income ranges of less or equal to HK$40,000[1]. The percentage of car owning households in the high-income ranges (above HK$40,000) is about 63% which is comparatively higher than that of non-car owning households 28%. The average household income of the car owning households is about HK$59,100 per month, and HK$35,300 per month for the non-car owning households.

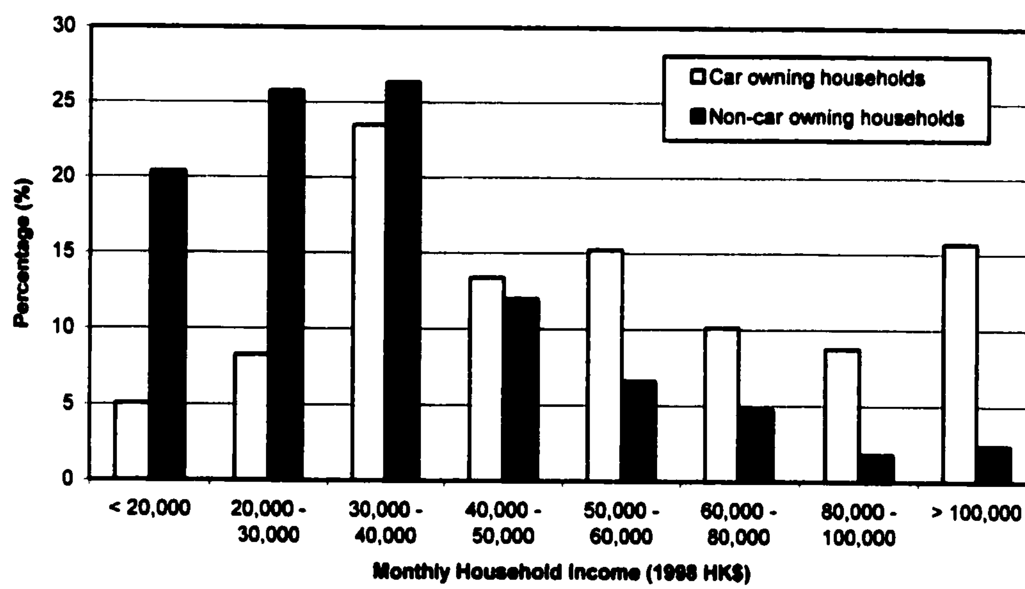


Figure 4.2 Monthly Household Income Distribution

A comparison of the average car ownership cost and usage cost in the survey and the CTS-2 is given in Table 4.3. CTS-2 used the data collected in a travel characteristics survey (TCS) in 1992, which has now been updated to 1998 prices by an inflation rate. However, annual license fees are more reasonable for using current values to compare

[1] Exchange rate in 1998: US$1.00 = HK$7.76

the fees obtained from the survey. This is because only about a 1.5% growth in annual license fees was found between 1992 to 1998, which is much lower than the inflation rate of 45% during this period. When compared to the results of CTS-2, it was found that the percentage of car purchase cost including the first registration tax of car ownership cost is reduced by 11.5%. However, the proportion of home-end parking fee to the ownership cost increases greatly by 12%. This shows that the parking rent becomes an important component of car ownership costs. With reference to the car usage costs, the proportion of the three components (i.e. fuel expenses, maintenance and attraction-end parking costs) found in the survey is similar to that in CTS-2.

It was also found in the survey that the average car ownership cost and usage cost is just 15.47% of the average monthly household income of car owning households, but it is 25.91% of the average monthly household income of non-car owning households.

As referring the valid samples mentioned in Table 4.2, the relative proportions of car owning and non-car owning households are 56.51% and 43.49%. The proportion of car owning households is higher than that of non-car owning households in the survey sample. When compared to the population, the proportions of car owning and non-car owning households are about 13.79% and 86.21%, respectively. There is a possibility of bias in those respondents from car owning households who might be over-represented in the licensing offices. Licensing offices were chosen for surveying is to easily control the survey samples so as to obtain a higher response rate. Therefore, adjustment on the sampling data has been made for model calibration on the basis of the distribution of car owning and non-car owning households by location in the Hong Kong Territory.

Table 4.3 Comparison of Average Car Ownership and Usage Costs in the 1998 Survey and in Hong Kong CTS-2

Cost Item	Survey in 1998 Monthly Cost (1998 HK$)	Survey in 1998 Percentage (%)	CTS-2* Monthly Cost (1998 HK$)	CTS-2* Percentage (%)
Ownership Costs				
Car purchase cost (including first registration tax (FRT))	3,584	59.89	5,795	71.46
Annual license fee (ALF)	475	7.94	473#	5.83
Insurance	339	5.67	679	8.37
Home-end parking fee	1,586	26.50	1,163	14.34
Sub-total	5,984	100.00	8,110	100.00
Usage Costs				
Fuel expenses	1,781	56.32	1,535	54.84
Maintenance and spares costs	354	11.20	414	14.79
Attraction-end parking fee	1,027	32.48	850	30.37
Sub-total	3,162	100.00	2,799	100.00
Total	9,146		10,909	

* CTS-2 was based on the data collected in a TCS in 1992.
\# Weighted average of current annual license fees.

4.4 PROPOSED CAR OWNERSHIP CHOICE MODEL

Discrete choice analysis was employed to develop car ownership choice models to examine the responses to various factors on car ownership. The basic form of car ownership choice model is a binary logit-type discrete choice equation. The logit-type model is a choice model that represents the behaviour of individuals trading off among the attributes of alternatives when selecting one alternative out of a set of available alternatives (McFadden, 1974). The form of the model is

$$P_i = \frac{1}{1+e^{-Z}} \qquad i = 1, \ldots, 5 \qquad (4.1)$$

where five binary logit-type choice models were formulated, in which

P_1 = probability of a household owning one-or-more cars;

P_2 = probability of a car owning household owning two-or-more cars;

P_3 = probability of a car owning household to retain his car(s);

P_4 = probability of a car owning household to own an additional car;

P_5 = probability of a non-car owning household to own a car;

$Z = C_0 + C_1X_1 + C_2X_2 + \cdots + C_iX_i$ is the utility function in a linear formulation;

C_0 = model constant;

$C_1, C_2, \ldots, C_i$ = model coefficients; and

$X_1, X_2, \ldots, X_i$ = model variables.

Car ownership can be obtained from the estimated probability given by Equation (4.1) with the number of households in Hong Kong. For examples,

Car owning households in Hong Kong = $P_1 \times$ the number of households; and

Multi-car owning households = $P_2 \times$ the number of car owning households.

However, the method of naïve aggregation adopted in this study would cause some problems. The total number of cars obtained by the above method may not be equivalent to that obtained by the territory-wide car ownership model (in Chapter 3). So adjustment should be made in order to integrate the results of the two different types of model. The total number of cars obtained by the logit-type car ownership choice models was adjusted to equal to the total obtained by the territory-wide model using the following two adjustment factors. The logit-type choice models are then more concerned with the distribution of zonal car ownership.

The estimated non-car owning households were multiplied by an adjustment factor (1-μ), where

$$\mu = \frac{(C - N_2 - mN_3)(N_2 + N_3)}{N_1(N_2 + mN_3)}; \qquad (4.2)$$

and the estimated car owning households were multiplied by an adjustment factor λ determined by

$$\lambda = 1 + \frac{\mu N_1}{N_2 + N_3} \qquad (4.3)$$

where C = the territory-wide car ownership estimated by the territory-wide model;

m = the number of cars owned by a multi-car owning household. It was assumed with an average of 2.2 cars in a multi-car owning household that was found in Travel Characteristics Survey (Transport Department and MVA Asia, 1993); and

N_1, N_2 and N_3 = the territory total number of households that are non-car owning, single-car owning and multi-car owning, respectively.

The model assumes that the utility of owning a car is a function of the following factors (or variables):

- monthly household income;
- household size;
- accessibility to employment;
- residential car parking availability;
- monthly car ownership cost; and
- monthly car usage cost.

Household income is an important element affecting the desire of owning cars. It may be the most important variable for explaining variation in car ownership levels. Most of the previous related studies, such as Lerman and Ben-Akiva (1976) and Bhat and Pulugurta (1998), included household income in their car ownership models.

The impact of household size on car ownership is twofold. On the one hand, a household with larger size implies higher trip frequency and thus has higher mobility expectation. On the other hand, household members may have greater expenditure on essentials such as food, clothing. Therefore, less income will be available for automobiles.

The influence of public transportation facilities on the level of car ownership can be assessed by the accessibility index of the residential location. In the CTS-2 study, accessibility is measured by the average public transport generalised cost to reach the closest 600,000 employment opportunities (Transport Department and Wilbur Smith Associates, 1995). On this basis, the accessibility was converted to a set of categories for use in the CTS-2 model and are shown in Table 4.4.

Table 4.4 Accessibility to Employment

Accessibility Category	Generalised Cost Range (minutes)
1 Very High	Less than 15
2 High	16 to 24
3 Medium	25 to 30
4 Low	31 to 40
5 Very Low	Over 40

Car parking availability is closely related to household location. It can also reflect the accessibility to public transport. Lower parking availability implies that households may be located in the centre of the city and thus have better access to public transport. In the CTS-2 study, residential car parking availability is expressed as car parking spaces per household and is converted into a set of categories in a similar manner to that of accessibility. The categories used are shown in Table 4.5.

Table 4.5 Residential Car Parking Availability

Residential Car Parking Category	Parking Space Range (spaces/household)
1 Low	Less than 0.09
2 Medium	0.10 to 0.29
3 High	0.30 to 0.99
4 Very High	Above 1.00

Vehicle costs are partitioned into fixed ownership costs and variable usage costs. Ownership costs include purchase cost, the first registration tax, the annual vehicle license fee, insurance and the home-end parking cost. Usage costs include gasoline, maintenance and spares, and attraction-end parking fees. All these costs are converted to a monthly basis in the study.

4.5 MODEL CALIBRATION USING REVEALED PREFERENCE DATA

In view of the limited size of the valid samples particularly for the multi-car owning households, a binary logit-type model was adopted for the calibration of the car ownership models. The model system developed in this study consists of two parts. The first part contains a binary logit-type model of car ownership, which predicts whether a household has zero or one-or-more cars. The second part is another binary logit-type model (multi-car ownership choices) for car owning households, which splits car owning households into one or two-or-more cars. The adjusted revealed preference data was used to calibrate these two binary logit-type choice models.

The calibration results of the car ownership choice models are presented in Tables 4.6 – 4.9 in terms of the estimated coefficients, t-statistics and overall model goodness-of-fit statistics. The model goodness-of-fit statistics were used to compare the observed probabilities with those predicted by the model. The statistic is defined as

$$Z^2 = \sum_{i=1}^{n} \frac{(P_i - Y_i)^2}{P_i(1 - P_i)} \qquad (4.4)$$

where P_i is the value predicted by the model, Y_i is the observed value and n is the number of observations. This statistic follows a chi-squared distribution with approximately $(n - p)$ degrees of freedom, and p is the number of predictors (including a constant term). If the goodness-of-fit statistic Z^2 is not significant, then it implies that the model does not fit well.

Another statistic 'Chi-square' given in the Tables 4.6 – 4.9 is defined as the difference between –2 times the log likelihood (-2 LL) for the model containing only a constant term and –2 LL for the developed model. Thus the chi-square statistic is used to test the null hypothesis that the coefficients for all of the terms in the current developed model, except the constant, are zero. This is comparable to the overall *F* test for regression.

The probability of a household owning one-or-more cars (P_1) has been obtained from the developed model presented in Table 4.6, in which the t-statistics of the variables indicate their statistical significance. In order to assess how well the model fits, the predicted outcomes are compared to the observed values. The above model gives about 88.54% of accuracy for predicting the number of car owning and non-car owning households.

It can be noted that monthly household income, accessibility, monthly car ownership cost and monthly car usage cost are significant to car ownership choices at the 1% level. As a result, car owning households increase with their monthly income. However, an increase in car ownership and usage costs would lead to a reduction in the willingness of car ownership. Household size is marginally significant to car ownership choices. Residential car parking availability (Category 2) has not been demonstrated with statistical significance.

As some of the variables are statistically insignificant or just marginally significant, it is reasonable to eliminate them from the model. The revised model is calibrated and presented in Table 4.7. The revised model gives an accuracy of 88.11% for predicting the non-car and car owning households. The four factors, monthly household income, accessibility, monthly car ownership cost and monthly car usage cost, included in the model are all statistically significant at a 5% level. The revised model is recommended for the estimation of car owning households in Hong Kong.

Table 4.6 Binary Logit-type Choice Model of Car Ownership (0 / 1-or-more)

Variable (X_i)	Coefficient (C_i)	t-statistics
Constant	-2.8411	-0.8589
Monthly household income (1998 HK$)	3.7900×10^{-5}	5.3403 **
Ln(Monthly household income)	0.2163	0.6476
Household size (number of persons)	-0.1154	-2.3599 ^
Accessibility index - category 2	0.6716	3.2873 **
Accessibility index - category 3	0.6741	2.8324 **
Accessibility index - category 4	0.9276	3.8236 **
Accessibility index - category 5	0.5505	1.9852 *
Residential car parking availability - category 2	-0.0827	-0.5188
Residential car parking availability - category 3	1.6099	3.5135 **
Residential car parking availability - category 4	-1.6331	-3.0378 **
Monthly car ownership cost (1998 HK$)	-0.0002	-4.7348 **
Monthly car usage cost (1998 HK$)	-0.0005	-5.6902 **
Chi-square	543.4790	
Goodness-of-fit	4,406.5570	
Number of samples	3,045	

Notes: Value marked with an asterisk, ^, is statistically significantly at a 10% level

Value marked with an asterisk, *, is statistically significantly at a 5% level

Values marked with an asterisk, **, are statistically significantly at a 1% level

Table 4.7 Revised Binary Logit-type Choice Model of Car Ownership

Variable (X_i)	Coefficient (C_i)	t-statistics
Constant	-1.1547	-3.1907 **
Monthly household income (1998 HK$)	4.1200×10^{-5}	18.4423 **
Accessibility index - category 2	0.6549	3.5631 **
Accessibility index - category 3	0.6561	3.1139 **
Accessibility index - category 4	0.8939	4.1346 **
Accessibility index - category 5	0.6249	2.5886 *
Monthly car ownership cost (1998 HK$)	-0.0002	-5.1546 **
Monthly car usage cost (1998 HK$)	-0.0006	-6.8752 **
Chi-square	507.2070	
Goodness-of-fit	4,317.1270	
Number of samples	3,045	

Notes: Value marked with an asterisk, *, is statistically significantly at a 5% level

Values marked with an asterisk, **, are statistically significantly at a 1% level

Similarly, the multi-car ownership choice model for car owning households is calibrated and the results are shown in Table 4.8. The probability of a car owning household owning two-or-more cars (P_2) can be determined by this model. The model gives overall accuracy of 83.33% to predict the one car or two-or-more car owning households. However, the accuracy of the estimation of multi-car owning households is poor. The low accuracy may be due to the insufficient sample sizes (only 86 samples) for multi-car owning households. More samples should be collected in a further study. The results found that household size, accessibility, monthly car ownership cost and monthly car usage cost did not contribute significantly to the accuracy of the model. Thus household size, accessibility, monthly car ownership and usage costs affect the initial decision to own a car, but once the appropriate conditions are met, the decision to have more than one car is solely related to affordability and car parking availability.

Table 4.8 Binary Logit-type Model for Multi-car Ownership Choices (1 / 2+)

Variable (X_i)	Coefficient (C_i)	t-statistics
Constant	7.6042	1.0605
Monthly household income (1998 HK$)	3.8800×10^{-5}	3.0455 **
Ln(Monthly household income)	-1.1945	1.6446
Household size (number of persons)	0.1334	1.3529
Accessibility index - category 2	-0.3859	-0.6625
Accessibility index - category 3	-0.5690	-0.8796
Accessibility index - category 4	0.0565	0.0859
Accessibility index - category 5	0.0130	0.0181
Residential car parking availability - category 2	0.9888	2.1641 ^
Residential car parking availability - category 3	2.5100	4.5176 **
Residential car parking availability - category 4	2.0333	2.3137 *
Monthly car ownership cost (1998 HK$)	-2.2000×10^{-5}	-0.4688
Monthly car usage cost (1998 HK$)	0.0001	1.1804
Chi-square	75.8530	
Goodness-of-fit	399.4230	
Number of samples	420	

Notes: Value marked with an asterisk, ^, is statistically significantly at a 10% level

Value marked with an asterisk, *, is statistically significantly at a 5% level

Values marked with an asterisk, **, are statistically significantly at a 1% level

The exclusion of the insignificant parameters produces a revised model presented in Table 4.9 with 81.43% of accuracy for predicting the multi-car owning households. It can be observed that eliminating the household size, accessibility, monthly car ownership cost and monthly car usage cost from the model made the remaining variables, monthly household income and residential car parking availability, more significant. The revised model is therefore recommended for modelling the multi-car ownership choices.

Table 4.9 Revised Binary Logit-type Model for Multi-car Ownership Choices

Variable (X_i)	Coefficient (C_i)	t-statistics
Constant	-3.6858	-7.9094 **
Monthly household income (1998 HK$)	1.9700×10^{-5}	5.0539 **
Residential car parking availability - category 2	0.9595	2.5724 *
Residential car parking availability - category 3	2.2140	4.7328 **
Residential car parking availability - category 4	1.8259	2.2609 *
Chi-square	69.8190	
Goodness-of-fit	395.1640	
Number of samples	420	

Notes: Values marked with an asterisk, *, are statistically significantly at a 5% level

Values marked with an asterisk, **, are statistically significantly at a 1% level

4.6 STATED PREFERENCE MODELLING

In order to assess the effects of economic changes and fiscal policies on car ownership choices, interviewers are asked to make a response to the changes of car owning attributes in the stated preference questions of the survey. The attributes are monthly household income, car purchase cost, vehicle license fee, parking fee and car usage cost. The respondents make decisions to own their cars, to own an additional car or to dispose of their cars in view of these given attributes.

The choice of car ownership is modelled based on the results of the stated preference questions of the survey (refer to Appendix A). For car owning households, the model is presented in Equation (4.5) with a 60% of accuracy for predicting the decision of retaining or disposing of their cars. The number of samples for calibration of this model is 1,438. It was found that monthly household income, car purchase cost per month, vehicle license fee per month and monthly home-end parking fee are statistically significant at the 1% level, while monthly car usage cost is statistically significant at the 5% level of car ownership choices. However, a positive effect of car purchase cost on car ownership is found. As cars are the assets of car owning households, an increase in car purchase cost would increase the probability of retaining their cars.

$$P_3 = \frac{1}{1+\exp(-0.35 - 9.31\times10^{-6} X_1 - 0.0001X_2 + 0.0009X_3 + 0.0003X_4 + 5.1\times10^{-5} X_5)}$$

$$\textit{t - stat.:} \quad (-1.68) \quad (-3.77) \quad (-4.65) \quad (3.00) \quad (6.82) \quad (1.75)$$

... (4.5)

where P_3 = probability of a car owning household to retain his car(s);

X_1 = monthly household income (1998 HK\$);

X_2 = car purchase cost per month (1998 HK\$);

X_3 = vehicle license fee per month (1998 HK\$);

X_4 = home-end parking fee per month (1998 HK\$); and

X_5 = car usage cost per month (1998 HK\$).

In order to calibrate the multi-car ownership choice model, car owning households are asked to own an additional car under various hypothetical scenarios. The multi-car ownership choice model is shown in Equation (4.6), which gives 65% accuracy for predicting the choices of multi-car ownership. The number of samples for calibration of the model is 305.

$$P_4 = \frac{1}{1+\exp(-0.27 - 2.12\times10^{-5}X_1 + 0.0001X_2 + 0.0023X_3 + 0.0003X_4 - 0.0002X_5)}$$

t - stat.: (-0.52) (-4.37) (3.00) (2.88) (3.00) (2.97)

... (4.6)

where P_4 = probability of a car owning household to own an additional car.

The results show that all the above five factors are statistically significant at the 1% level, whereas monthly household income is the most significant factor. The car purchase cost now negatively affects the choices of owning an additional car. However, the sign of car usage cost is incorrect. This may be due to the combined effects of fuel cost, maintenance fee and attraction-end parking fees. The sample sizes for owning an additional car may also be insufficient to calibrate the model. Therefore, further refinement of this model should be carried out with more representative survey samples. The revised model for deleting the incorrect sign variable X_5 is listed in the following Equation (4.7).

$$P_4 = \frac{1}{1+\exp(-0.92 - 2.09\times10^{-5}X_1 + 8.70\times10^{-5}X_2 + 0.0025X_3 + 0.0002X_4)} \quad (4.7)$$

t - stat.: (-1.94) (-4.40) (2.81) (3.13) (2.08)

For the non-car owning households, the model is calibrated for the choices of owning a car and is presented in Equation (4.8). The number of samples for calibration is 1473. 58% of accuracy is obtained from the model for predicting the choices of owning a car. Monthly household income, vehicle license fee per month, home-end parking fee per month and monthly car usage cost are found to be statistically significant at the 1%

level. However, car purchase cost is insignificant. This may be partially due to the fact that the non-car owning households are inexperienced in car purchasing and so the effect of changing the car purchase cost could not be perceived properly.

$$P_5 = \frac{1}{1 + \exp(-5.29 - 1.42 \times 10^{-5} X_1 + 4.10 \times 10^{-5} X_2 + 0.0020 X_3 + 0.0011 X_4 + 0.0007 X_5)}$$

t - stat.: *(-6.87)* *(-6.46)* *(0.88)* *(2.86)* *(5.50)* *(7.00)*

... (4.8)

where P_5 = probability of a non-car owning household to own a car.

The above three logit-type choice models investigate the effects of economic and fiscal changes on the choices of car ownership for a car owning and non-car owning household, respectively. It was found that the monthly household income is the key factor on the decision of car ownership for both car owning and non-car owning households. However, the effects of the fiscal factors (costs and fees of car ownership and usage) are varied for the choices made by car owning and non-car owning households.

4.7 SUMMARY

In this chapter, five disaggregate car ownership choice models are developed for Hong Kong using the results of a survey with both RP and SP questions. The car ownership choice (logit-type) models are calibrated to classify households into non-car owning and car owning households, and one-car owning and multi-car owning households using RP data. The values of P_1 and P_2 estimated from the RP models would be used in Chapter 6 for estimating the number of car owning and non-car owning households with the planning data in Hong Kong.

The logit-type choice models based on SP data are developed to assess the effects of fiscal factors on car ownership so as to confirm the results of RP models. The significance of the monthly household income, the breakdown of car ownership costs and car usage costs on the choices of car ownership are investigated.

The RP results show that on the one hand monthly household income, accessibility to employment, monthly car ownership and usage costs are statistically significant to car ownership choices. On the other hand, from the SP results, it was found that monthly household income, vehicle license fee, home-end parking fee and car usage costs are the key factors of owning cars in Hong Kong.

Refinement of the developed models by breaking down the components of the car ownership and usage costs in the RP analysis is recommended for further study. Another survey should be carried out so as to increase the sample sizes for both RP and SP modelling, particularly the sample sizes for multi-car owning households. A multinomial logit-type choice model can then be calibrated for estimating car ownership choices when more representative survey samples are collected.

5 CAR OWNERSHIP UNDER ROAD NETWORK SUPPLY CONSTRAINTS

As most of the American and European countries/cities are low densely development and private car is their major transport mode, the previous related studies have been mainly concerned with the demand for car ownership (e.g. Ben-Akiva *et al.*, 1981; Pendyala *et al.*, 1995). However, in the high densely development countries/cities such as Hong Kong, public transport is the major transport mode (over 90% of people used in Hong Kong). Private car is only an alternate transport mode. Also, due to the shortage of road space, both user demand and network supply conditions on car ownership should be studied. This chapter focuses the determination of maximum car ownership under road network supply constraints by a bilevel programming model. These supply constraints are referred to as the road capacity and the number of parking spaces in each traffic zone.

5.1 CONCEPT OF RESERVE CAPACITY FOR CAR OWNERSHIP

In the conventional approach of traffic management, road networks are improved to cater for traffic demand generated by car ownership growth. However, in real circumstances, there may not be enough resources for improving road networks. In order to distribute the resources effectively, the maximum zonal car ownership growth potential should be determined in advance of given network supply conditions.

The reserve capacity for car ownership is referred to as the greatest additional amount of car ownership that can be accommodated in a traffic zone, i.e. the potential maximum zonal car ownership growth that generates the road traffic within the network supply constraints. It can examine whether the existing transport network is capable of accommodating future car ownership growth and hence establishing efficient policies for controlling car ownership and improving road networks. The zonal reserve capacity for car ownership would provide important information for the planning of future transport infrastructure development and policies.

5.2 BACKGROUND

In the previous studies of bilevel programming problems, the lower-level problem has generally been a deterministic user-equilibrium assignment model (Sheffi, 1985), in which the assumption of perfect network information is adopted together with a fixed origin-destination (O-D) demand pattern. In general, the target O-D matrix should correspond to the future development of each urban area and the growth of car ownership in each traffic zone.

To overcome this shortcoming, a combined trip distribution/assignment (CDA) model (Evans, 1976; Lam and Huang, 1992a) can be adopted to incorporate both the destination and route choices of travellers. A model of Equilibrium Trip Distribution/Assignment with Variable Destination Costs (ETDA-VDC) (Sheffi, 1985; Oppenheim, 1993) is used as a lower-level problem for the analysis of zonal development potential from the perspective of an equilibrium network capacity (Yang *et al.*, 1996). This model calculates the destination cost or attractiveness as a function of the number of trips attracted to each destination. Given the growth in trip productions within various traffic zones, trip distributions among alternative destination zones and routes can be predicted by the ETDA-VDC model based on the destination attractiveness and user-equilibrium. The ETDA-VDC model assumes that a trip distribution is only constrained to the trip production ends and that trip production is insensitive to the zonal accessibility.

However, trip production rates for trip productions may vary due to the effect of accessibility measures on trip production rates. The availability of parking spaces may also influence the trip productions. Thus, constant and variable trip rates, and the model with and without parking constraints are both investigated in the sections of numerical examples. This study is believed to be the first bilevel programming model for modelling zonal car ownership under given network supply conditions. It combines the existing models to create a new model that includes car ownership, link-based traffic flow forecasting and parking space availability.

Although traffic congestion in a single time period is a short-term effect, the proposed model can be applied to a whole day split into several time periods, assuming that the system is in a steady state for each of these periods. For example, the time periods can be classified into the four conventional peak periods: morning peak, interpeak, evening peak and off peak. The most critical reserve capacity of zonal car ownership within a typical day can then be obtained from the results for the four study periods. For the long-term strategic planning purposes, the effects of different scenarios of zonal car ownership growth can be studied for alternative strategic networks using the proposed model. The level of car ownership demand by zones can then be assessed under the given supply conditions for different alternative networks.

5.3 ASSUMPTIONS

The proposed model is designed to determine the reserve capacity of zonal car ownership growth under network supply conditions for the purpose of strategic planning. The following assumptions are made throughout the study:

(a) A single user category is adopted to facilitate the presentation of the essential ideas without loss of accuracy or leading to an erroneous conclusion. However, the model can be extended to multi-user classes, such as classifying the population into different income groups (Lam and Huang, 1992a). The car ownership in each income groups can then be assessed.

(b) Travel times on road links are continuous and strictly increasing functions of link flows. The link travel time functions are assumed to be differentiable and separable. If one exists, these assumptions ensure the uniqueness of the solution to the network equilibrium problem (Sheffi, 1985).

(c) Drivers have sufficient and perfect network information to make routing decisions in a user equilibrium manner (Sheffi, 1985).

(d) The study period is assumed to be a one-hour (unit time) period, such as the morning peak hour period. However, the time of day element can be catered for in the model. For example, a typical whole day can be divided into several time periods, in which the system is assumed in a steady state and O-D demand is uniformly distributed. The model can be applied to each of the study periods to determine the zonal car ownership. As a result, there are differences in the reserve capacities of car ownership by different time periods. Trade-off should be made in order to optimize the resources such as introducing penalty for excess capacity, or using time-varying parking charges for balancing the car ownership demand and supply facilities.

(e) It is known that morning peak hour is usually the most critical period in a typical weekday and almost all car trips are home-based work trips to work. It is also assume that no round trips occur during the one-hour study periods. Thus, attention is focused on attraction-end parking. Linked trips are treated as a number of separate trips and presented in the O-D matrix.

(f) Steady state traffic flow is assumed in the model.

(g) The type of parking space is classified as public and private generally, and the total number of public and private parking spaces supplied in each traffic zone is given and fixed.

(h) The capacity of a road link in passenger car units per hour (pcu/hr) is fixed and known.

(i) Public transport network is assumed to be constant and fixed.

(j) For planning purposes, each car must occupy one parking space at the destination zone during the study period. Illegal parking is not allowed.

(k) When a car trip is generated by a traffic zone, it is assumed that a car leaves its parking space. However, only available public parking spaces can be competed for.

(l) When a car trip is attracted to a traffic zone, it represents a car entering the traffic zone and looking for a parking space. Thus, trip attraction is equivalent to the parking demand.

(m) The zonal trip production is assumed to be a function of the number of cars owned by the residents in the households in a zone, which reflects the number of households living in the zone. The relationship between trip production and the number of cars is established by a trip production rate (constant or elastic).

(n) The zonal trip attraction is assumed to be a function of the number of parking spaces in a zone, which, it is assumed, is related to the amount of employment in that zone. The proposed model can also be extended to other trip purposes (e.g. shopping). The relationship between trip attraction and the number of parking spaces is established by a trip attraction rate (constant or elastic).

Further assumptions are adopted for the elastic trip production and attraction rates:

(o) The trip production and attraction rates are sensitive to accessibility measured by generalized travel time and the size of activity (Ortúzar and Willumsen, 1994) which reflects the degree of ease or difficulty in making trips from/to each traffic zone.

(p) The accessibility measure for trip production is affected by the number of trips attracted, and the generalized travel time from an origin zone to a destination zone (Ortúzar and Willumsen, 1994). The accessibility measure for trip attraction is influenced by the number of trips produced and the generalized travel time by O-D pair. With reference to assumption (o), the number of trip production and attraction represents the size of activities in production zones and attraction zones, respectively.

5.4 MODEL FORMULATION

In order to obtain the reserve capacity of zonal car ownership under given network supply conditions, maximum car ownership is determined by a bilevel programming model to compare with the existing car ownership level in each of the traffic zones. The proposed bilevel programming model includes car ownership estimation, trip distribution and traffic assignment. The lower-level problem is a combined equilibrium trip distribution/assignment (CDA) model (Evans, 1976; Lam and Huang, 1992a), while the upper-level problem is to maximize the sum of the number of cars by traffic zone under the condition of road and parking capacities. Thus, maximum car ownership is determined by considering the route and destination choice behaviour of travellers and satisfying road capacity and parking space constraints.

Upper-level problem:

$$\underset{\mathbf{u}}{Maximize} \sum_{i \in I} u_i \tag{5.1}$$

subject to

$$v_a(\mathbf{u}) \le S_a, \quad a \in A \tag{5.2}$$

$$\sum_{i \in I} t_{ij}(\mathbf{u}) \le \phi_{1k} h_k - (1 - p_i(z_i))\phi_{2i} u_i, \quad when\, i = k, j = k,\ i \in I, j \in J \tag{5.3}$$

$$\phi_{2i} u_i \le \phi_{1k} h_k, \quad when\ i = k,\ i \in I \tag{5.4a}$$

$$(1 - \phi_{2i}) u_i \le (1 - \phi_{1k}) h_k, \quad when\ i = k,\ i \in I \tag{5.4b}$$

$$u_i \ge u_i^{\min},\ i \in I \tag{5.4c}$$

where the equilibrium flow $v_a(\mathbf{u})$, $a \in A$ and O-D demand $t_{ij}(\mathbf{u})$, $i \in I$, $j \in J$ is obtained by solving the following network equilibrium CDA problem.

Lower-level problem:

$$\underset{\mathbf{v}}{Minimize} \sum_a \int_0^{v_a} c_a(x)dx + \frac{1}{\alpha} \sum_i \sum_j t_{ij} (ln\, t_{ij} - 1) \tag{5.5}$$

subject to

$$\sum_{r \in R_w} f_r = t_{ij}, i \in I, j \in J \tag{5.6}$$

$$\sum_{j \in J} t_{ij} = O_i(u_i), i \in I \tag{5.7}$$

$$\sum_{i \in I} t_{ij} = \overline{D}_j, j \in J \tag{5.8}$$

$$v_a = \sum_{r \in R} f_r \delta_{ar}, a \in A \tag{5.9}$$

$$f_r \geq 0, r \in R \tag{5.10}$$

$$t_{ij} \geq 0, i \in I, j \in J \tag{5.11}$$

where

$$\overline{D}_j = \frac{\sum_{i \in I} O_i(u_i)}{\sum_{j \in J} D_j} D_j, j \in J \tag{5.12}$$

is the balanced trip attractions. The function of the balanced trip attractions is used to adjust the total trip attractions to be equal to the summation of trip productions. The trip productions and attractions would be expressed as different functions for constant or elastic trip rates, and would be presented in the sections of numerical examples.

As the model is aimed to be used for strategic planning, link flows can be greater than link capacities in the lower-level problem so as to assess the adequacy of the network supply to the travel demand.

Equation (5.2) is the link capacity constraint that requires that vehicular flow on each link does not exceed the link capacity. Equation (5.3) is the parking constraint, in which the total attraction trips (representing the number of cars entering a destination zone and searching for parking spaces) should be less than or equal to the spare public parking spaces so that the attraction-end parking demand is fulfilled by the available stock of public parking spaces. Equation (5.3) also allows for the pre-occupancy of public parking spaces in the beginning of the study period. A simple example is shown as below to illustrate the implication of Equation (5.3).

Consider a simple road network with 3 origins i and destinations j, as shown in Figure 5.1. The data for the number of parking spaces, cars and trip production rates in traffic zones are assumed and presented in Table 5.1. It can be observed that zone 1 is an origin for the car trips to zones 2 and 3, and it is also a destination for the trips from zones 2 and 3.

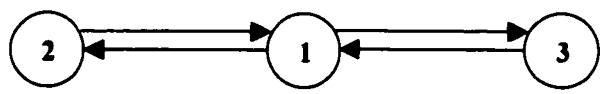


Figure 5.1 A Simple Road Network

Table 5.1 Data for the Simple Road Network

		$i/j/k$		
		1	2	3
The number of cars in origin zone	u_i	600	500	300
Average trip production rate	P_i	0.4	0.3	0.5
Total number of parking spaces in destination zone	h_k	800	600	500
Proportion of public parking spaces	ϕ_{1k}	0.5	0.2	0.3
Proportion of cars parked in public parking spaces (i.e. pre-occupancy of public parking spaces)	ϕ_{2i}	0.3	0.4	0.2

The number of public parking spaces in zone $k = 1$

= Total number of parking spaces in destination zone 1 × Proportion of public parking spaces

= 800 × 0.5

= 400 parking spaces

The number of cars parked in public parking spaces in zone $i = 1$

= Number of cars in origin 1 × Proportion of cars parked in public parking spaces

= 600 × 0.3

= 180 cars

The available stock of public parking spaces in zone 1 become

= The number of public parking spaces – The number of public parking spaces still be occupied

= 400 – (1–0.4) × 180

= 292 parking spaces

Therefore, i is equivalent to k that equals to 1. At the same time, car trips would be attracted to destination zone $j = 1$ from origin zones $i = 2$ and 3, which denote as t_{21} and t_{31}. In the parking constraint of Equation (5.3), the total trip attractions that represent attraction-end parking demand should not exceed the available public parking spaces, i.e. $t_{21}+t_{31} \leq 292$. Thus, it can be found that destination j is equivalent to zone k, where $j = k = 1$.

In general, the number of cars in each zone should be bounded by the lower and upper limits as expressed in Equations (5.4a-c). The lower boundary of car ownership is set to retain a certain mobility, other than via public transport, in that zone. The upper boundary of car ownership is due to the limited land supply and/or parking availability. Thus, it is set to be the number of parking spaces (public and private) in that zone.

The lower-level problem (5.5)-(5.12) is a standard CDA problem that can be solved by a convex-combination method for given car ownership, **u**, and zonal trip production/attraction rates, **p** and **q**, in the traffic zones. The CDA model is adopted to incorporate a destination attractiveness measure reflecting the activity opportunities available there, and to determine the destination and route choices of travellers simultaneously for any given number of trips originating from each origin. The Lagrangian of the lower-level problem of Equations (5.5)-(5.12) is described in the followings:

$$L(\mathbf{v},\mathbf{T},\mathbf{z},\mathbf{z}')=\sum_a\int_0^{v_a}c_a(x)dx+\frac{1}{\alpha}\sum_{ij}t_{ij}(\ln t_{ij}-1)+\sum_{ij}g_{ij}(t_{ij}-\sum_r f_r)+\sum_i\lambda_i(O_i-\sum_j t_{ij})$$
$$+\sum_j\gamma_j(\overline{D}_j-\sum_i t_{ij})$$

... (5.13)

where g_{ij}, λ_i and γ_j denote the Lagrange multipliers associated with the O-D demand constraint of Equation (5.6) and trip production constraint of Equation (5.7) and trip attraction constraint of Equation (5.8), respectively. The Lagrangian of Equation (5.13) is then differentiated and becomes

$$\frac{\partial L}{\partial f_r}=\sum_a c_a(v_a)\delta_{ar}-g_{ij}=c^+_{rij}-g_{ij},\quad i\in I, j\in J \tag{5.14}$$

$$\frac{\partial L}{\partial t_{ij}}=\frac{1}{\alpha}\ln t_{ij}+g_{ij}-\lambda_i-\gamma_j,\quad i\in I, j\in J \tag{5.15}$$

The first-order (Kuhn-Tucker) conditions are applied to Equation (5.14) and assuming $t_{ij}>0$,

$$f_{rij}(c^+_{rij}-g_{ij})=0,\quad i\in I, j\in J, r\in R_{ij} \tag{5.16}$$

$$c^+_{rij}-g_{ij}\geq 0,\quad i\in I, j\in J, r\in R_{ij} \tag{5.17}$$

$$f_{rij} \geq 0, \quad i \in I, j \in J, r \in R_{ij} \tag{5.18}$$

$$i.e. \quad c^{+}_{rij} = g_{ij} \quad if\ f_{rij} > 0 \tag{5.19}$$

$$c^{+}_{rij} \geq g_{ij} \quad if\ f_{rij} = 0 \tag{5.20}$$

It can be seen that the above conditions (5.16)-(5.20) define a user equilibrium flow pattern. Furthermore, from Equation (5.15),

$$\begin{aligned} t_{ij} &= \exp(-\alpha(g_{ij} - \lambda_i - \gamma_j)) \\ &= \exp(\alpha\lambda_i)\exp(\alpha\gamma_j)\exp(-\alpha g_{ij}) \\ &= \theta_i \tau_j \exp(-\alpha g_{ij}),\ where\ \theta_i = \exp(\alpha\lambda_i), \tau_j = \exp(\alpha\gamma_j) \end{aligned} \tag{5.21}$$

which is a gravity-type model for trip distribution. Therefore, the lower-level problem (5.5)-(5.12) is equivalent to the CDA problem when car ownership, trip production rate and trip attraction rate are given and constant.

The dispersion parameter α for trip distribution in Equation (5.5) is a measure to reflect the sensitivity of travel time from an origin to a destination. An increase in α would generate an O-D travel demand and/or trip length frequency with shorter O-D travel time.

The proposed bilevel car ownership problem can be described as a leader-follower or a Stackelberg game (Fisk, 1984), where the system manger (in upper-level problem) is the leader, and the network users (in lower-level problem) are the followers. The system manager can influence, but cannot control, the users' travel demand and route choice behaviour by constraining zonal car ownership subject to road and parking capacities. In view of given zonal car ownership, the road users will decide whether to make their trips and to make decisions on destination and route choice in a user-equilibrium manner.

It is assumed that the system manager selects feasible values for his decision variables (zonal car ownership), in an attempt to optimize his objective function (maximize car ownership). Subsequently, the network users, with complete knowledge of the system manager's decision, would make decisions on O-D travel and route choices so as to minimize their travel times. Furthermore, it is assumed that for any given zonal car ownership pattern, there is a unique equilibrium O-D travel demand and link flow distribution obtained from the lower-level problem. The O-D travel demand and link flows are also called the response or reaction functions. An efficient car ownership pattern by zones will greatly depend on how to evaluate the reaction functions, or, in other words, how to predict travel demand and route changes of users in response to the controlled zonal car ownership.

Based on the above ideas, the two constraints of Equations (5.2) and (5.3) are placed in the upper-level problem to determine the maximum number of cars by zones under constraints of the road capacities and parking spaces. That is to control car ownership in each of the traffic zones so as to avoid road congestion due to shortage of road spaces and parking facilities. However, in the lower-level problem, traffic congestion and shortage of parking spaces are still allowed. This is because, with reference to the above point of view, the link flows and O-D travel demand in the lower-level problem are dependent on the decision of zonal car ownership obtained in that of the upper-level. The congested road network and shortage of parking spaces are released by controlling zonal car ownership in the upper-level problem.

As the proposed model is designed for the strategic planning of car ownership, the road network is simplified to facilitate the presentation of the essential ideas and the mechanism of the model. Although modal choice decisions have not been explicitly considered in the model, they have been implicitly reflected by the elastic trip generation rates. This is because the travellers would switch to an alternative mode or not make a trip if the road congestion is getting worst. The elastic trip generation rates would then reflect the response of travellers to traffic congestion. In this model, public transport network is assumed to be constant and fixed.

Public transport network can be incorporated in the model explicitly. However, the mechanism of the proposed model would not be affected. For example, modal split can be incorporated into the lower-level model. Then the lower-level CDA model becomes a combined trip distribution, model split and assignment model, such as the one developed in Florian and Nguyen (1978); Tatineni *et al.* (1995).

5.5 SENSITIVITY ANALYSIS

The road and parking capacity constraints (5.2) and (5.3) in the upper-level problem involve the nonlinear and implicit functions of decision variable $\mathbf{u}$. Therefore, local linear approximations using Taylor's formula are implemented based on the derivatives of the link flows and O-D demand function with respect to the perturbation parameter in car ownership. The derivative information is used to evaluate the changes in equilibrium link flows and the corresponding O-D travel patterns caused by the changes in car ownership. The derivative information is obtained by implementing the method of sensitivity analysis (Tobin and Friesz, 1988; Yang *et al.*, 1994). The sensitivity analysis theory can then be applied to the development of the solution algorithm for the proposed car ownership model.

Yang *et al.* (1994) presented the fundamental ideas in the sensitivity analysis for the user equilibrium (UE) problem. In the proposed bilevel model, the lower-level problem is a CDA problem. The main difference is that the O-D demand is unconstrained in the UE model, while in the CDA problem, the O-D demand can be restrained to the trip production ends only or to both trip production and attraction ends. Thus, in the sensitivity analysis procedure of Yang *et al.*'s paper (1994), path flows and O-D demands are used to calibrate the derivative information. However, path flows, trip production and attraction ends, together with trip entropy are applied for determining the derivative information in the sensitivity analysis of this study. A detailed procedure for the computation based on the method of sensitivity analysis for equilibrium network flows is presented as follows.

Firstly, a general situation that perturbation parameters exist in the link travel time function $\mathbf{c}(\mathbf{v},\varepsilon)$, O-D demands $\mathbf{T}(\varepsilon)$, trip productions $\mathbf{O}(\varepsilon)$ and trip attractions $\mathbf{D}(\varepsilon)$ is considered. For convenience of exposition, the equations are used with vector and matrix notation, and $\sum_{i\in I} O_i = \sum_{j\in J} D_j$. The perturbed problem can be written as

$$\underset{\mathbf{v}}{Minimize} \sum_a \int_0^{v_a} c_a(x,\varepsilon)dx + \frac{1}{\alpha}\sum_i \sum_j t_{ij}(\varepsilon)(ln\, t_{ij}(\varepsilon) - 1) \tag{5.22}$$

subject to

$$\mathbf{\Lambda f} = \mathbf{T} \tag{5.23}$$

$$\mathbf{\Phi}_I \mathbf{T} = \mathbf{O}(\varepsilon) \tag{5.24}$$

$$\Phi_j \mathbf{T} = \mathbf{D}(\varepsilon) \tag{5.25}$$

$$\mathbf{v} = \Delta \mathbf{f} \tag{5.26}$$

$$\mathbf{f} \geq 0 \tag{5.27}$$

$$t_{ij}(\varepsilon) \geq 0 \tag{5.28}$$

where ε is a vector of the perturbation parameters, Φ_i and Φ_j are the trip production/ and attraction/O-D incidence matrices, that can be defined as below for a road network. m is the number of origin nodes and n is the number of destination nodes.

$$\Phi_i = \begin{bmatrix} \underbrace{1 \cdots 1}_{n} & 0 & \cdots & \cdots & \cdots & \cdots & 0 \\ 0 \cdots 0 & \underbrace{1 \cdots 1}_{n} & 0 & \cdots & \cdots & \cdots & 0 \\ 0 & \cdots & \cdots 0 & \underbrace{1 \cdots 1}_{n} & 0 & \cdots & \cdots 0 \\ \vdots & \cdots & \cdots & \cdots 0 & \ddots & & 0 \cdots 0 \\ 0 & \cdots & \cdots & \cdots & \cdots 0 & & \underbrace{1 \cdots 1}_{n} \end{bmatrix}_{m \times mn}, \tag{5.29}$$

$$\Phi_j = \begin{bmatrix} \underbrace{1\,0 \cdots 0}_{n} & \underbrace{1\,0 \cdots 0}_{n} & \cdots & \cdots & \underbrace{1\,0 \cdots 0}_{n} \\ \underbrace{0\,1\,0 \cdots 0}_{n} & \underbrace{0\,1\,0 \cdots 0}_{n} & \cdots & \cdots & \underbrace{0\,1\,0 \cdots 0}_{n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \underbrace{0 \cdots 0\,1\,0 \cdots 0}_{n} & \underbrace{0 \cdots 0\,1\,0 \cdots 0}_{n} & \cdots & \cdots & \underbrace{0 \cdots 0\,1\,0 \cdots 0}_{n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \underbrace{0 \cdots 0\,1}_{n} & \underbrace{0 \cdots 0\,1}_{n} & \cdots & \cdots & \underbrace{0 \cdots 0\,1}_{n} \end{bmatrix}_{n \times mn}, \tag{5.30}$$

and

$$\mathbf{O} = \begin{bmatrix} O_1(\varepsilon) \\ \vdots \\ O_i(\varepsilon) \\ \vdots \\ O_m(\varepsilon) \end{bmatrix}, \qquad \mathbf{D} = \begin{bmatrix} D_1(\varepsilon) \\ \vdots \\ D_j(\varepsilon) \\ \vdots \\ D_n(\varepsilon) \end{bmatrix}. \tag{5.31}$$

It is assumed that $c_a(v_a,\varepsilon)$, $t_{ij}(\varepsilon)$, $O_i(\varepsilon)$ and $D_j(\varepsilon)$ are once continuously differentiable in ε. The solution of the perturbed problem for $\varepsilon^* = 0$ is assumed to be $\mathbf{v}^*(0)$ and $\mathbf{f}^*(0)$ and that $c_a(v_a,\varepsilon)$ is strongly monotone in v_a so that the solution is unique.

However, the direct application of the standard sensitivity analysis (Fiacco, 1976) to the perturbed combined trip distribution and traffic assignment problem of Equations (5.22)-(5.28) is not feasible. This is because the path flow solution does not satisfy the unique condition even if the link flow solution, itself, is unique. In order to overcome the non-unique difficulty, the restricted network equilibrium approach proposed by Tobin and Friesz (1988) is adopted to derive the derivative expressions.

This approach is to select a nondegenerate extreme point in the feasible region of equilibrium path flows. An extreme point can be obtained easily if the convex combination method (Frank-Wolfe method) suggested by LeBlanc *et al.* (1975) is used to solve the equilibrium assignment problem. The Frank-Wolfe algorithm generates a unique set of minimum time paths by O-D pairs at each iteration. If the paths generated are saved from iteration to iteration, upon termination the Frank-Wolfe algorithm provides an equilibrium path flow pattern and a link/path incidence matrix for the paths used. An extreme point in the feasible region can then be identified from this set of equilibrium path flows (Yang and Yagar, 1994; Yang *et al.*, 1994).

Let $\mathbf{f}^* > 0$ be a nondegenerate extreme point in the region of equilibrium path flows. It is easily observed that the necessary conditions for the perturbed equilibrium assignment problem of Equations (5.22)-(5.28) at $\varepsilon = 0$ lead to a solution for the following system equations:

$$\mathbf{c}^{+}(\mathbf{f}^{*},0) + \frac{1}{\alpha}\Lambda^{T}\ln(\Lambda\mathbf{f}^{*}) - (\Phi_i\Lambda)^{T}\lambda - (\Phi_j\Lambda)^{T}\gamma - \pi = 0 \tag{5.32}$$

$$\pi^{T}\mathbf{f}^{*} = 0 \tag{5.33}$$

$$\Phi_i\Lambda\mathbf{f}^{*} - \mathbf{O}(0) = 0 \tag{5.34}$$

$$\Phi_j\Lambda\mathbf{f}^{*} - \mathbf{D}(0) = 0 \tag{5.35}$$

$$\pi \geq 0, \mathbf{f}^{*} \geq 0 \tag{5.36}$$

where λ, γ and π are the Lagrange multipliers of the Equations (5.24), (5.25) and (5.27) respectively.

Tobin and Friesz (1988) have shown that under the assumption of strictly positive link flows and strictly complementary slackness, Equations (5.33) and (5.36) can be eliminated without changing the solution near $\varepsilon = 0$. Therefore, only the nondegenerate extreme points of the positive path flow solutions are considered. The system of Equations (5.32)-(5.36) can then be reduced to

$$\mathbf{c}^{+}(\mathbf{f}^{0*},0) + \frac{1}{\alpha}\Lambda^{0T}\ln(\Lambda^{0}\mathbf{f}^{0*}) - (\Phi^{0}_i\Lambda^{0})^{T}\lambda - (\Phi^{0}_j\Lambda^{0})^{T}\gamma = 0 \tag{5.37}$$

$$\Phi^{0}_i\Lambda^{0}\mathbf{f}^{0*} - \mathbf{O}(0) = 0 \tag{5.38}$$

$$\Phi^{0}_j\Lambda^{0}\mathbf{f}^{0*} - \mathbf{D}(0) = 0 \tag{5.39}$$

where ^{0} represents the corresponding reduced vectors and matrices.

Let $$\mathbf{c}^{+}(\mathbf{f}^{0*},0) + \frac{1}{\alpha}\Lambda^{0T}\ln(\Lambda^{0}\mathbf{f}^{0*}) = \mathbf{c}'(\mathbf{f}^{0*},0), \tag{5.40}$$

$$\mathbf{h}=\begin{bmatrix}\lambda\\ \gamma\end{bmatrix},\ \mathbf{s}(\varepsilon)=\begin{bmatrix}\mathbf{O}(\varepsilon)\\ \mathbf{D}(\varepsilon)\end{bmatrix},\ \mathbf{M}=\begin{bmatrix}\Phi_i^0\Lambda^0\\ \Phi_j^0\Lambda^0\end{bmatrix}. \tag{5.41}$$

Then the system of Equations (5.37)-(5.39) can be written as

$$\mathbf{c}'(\mathbf{f}^{0*},0)-\mathbf{M}^{\mathrm{T}}\mathbf{h}=0 \tag{5.42}$$

$$\mathbf{M}\mathbf{f}^{0*}-\mathbf{s}(0)=0 \tag{5.43}$$

The Jacobian matrix of the system of Equations (5.42) and (5.43) with respect to (f^0, λ, γ) and evaluated at $\varepsilon = 0$ is

$$\mathbf{J}_{f^0,\lambda,\gamma}=\begin{bmatrix}\nabla_f\mathbf{c}'(\mathbf{f}^{0*},0) & -\mathbf{M}^{\mathrm{T}}\\ \mathbf{M} & 0\end{bmatrix}. \tag{5.44}$$

Suppose that

$$\left[\mathbf{J}_{f^0,\lambda,\gamma}\right]^{-1}=\begin{bmatrix}\mathbf{B}_{11} & \mathbf{B}_{12}\\ \mathbf{B}_{21} & \mathbf{B}_{22}\end{bmatrix} \tag{5.45}$$

The following can be obtained

$$\mathbf{B}_{11}=\nabla_f\mathbf{c}'(\mathbf{f}^{0*},0)^{-1}[\mathbf{E}-\mathbf{M}^{\mathrm{T}}[\mathbf{M}\nabla_f\mathbf{c}'(\mathbf{f}^{0*},0)^{-1}\mathbf{M}^{\mathrm{T}}]^{-1}\mathbf{M}\nabla_f\mathbf{c}'(\mathbf{f}^{0*},0)^{-1}] \tag{5.46}$$

$$\mathbf{B}_{12}=\nabla_f\mathbf{c}'(\mathbf{f}^{0*},0)^{-1}\mathbf{M}^{\mathrm{T}}[\mathbf{M}\nabla_f\mathbf{c}'(\mathbf{f}^{0*},0)^{-1}\mathbf{M}^{\mathrm{T}}]^{-1} \tag{5.47}$$

$$\mathbf{B}_{21}=-[\mathbf{M}\nabla_f\mathbf{c}'(\mathbf{f}^{0*},0)^{-1}\mathbf{M}^{\mathrm{T}}]^{-1}\mathbf{M}\nabla_f\mathbf{c}'(\mathbf{f}^{0*},0)^{-1} \tag{5.48}$$

$$\mathbf{B}_{22}=[\mathbf{M}\nabla_f\mathbf{c}'(\mathbf{f}^{0*},0)^{-1}\mathbf{M}^{\mathrm{T}}]^{-1} \tag{5.49}$$

where **E** is an identity matrix of appropriate dimension, and

$$\nabla_f\mathbf{c}'(\mathbf{f}^{0*},0)=\nabla_f\mathbf{c}^{+}(\mathbf{f}^{0*},0)+\frac{1}{\alpha}\Lambda^{0\mathrm{T}}(\Lambda^0\mathbf{f}^{0*})^{-1}\Lambda^0$$

$$=\Delta^{0\mathrm{T}}\nabla_v\mathbf{c}(\mathbf{v}^*,0)\,\Delta^0+\frac{1}{\alpha}\Lambda^{0\mathrm{T}}(\Lambda^0\mathbf{f}^{0*})^{-1}\Lambda^0 \tag{5.50}$$

The Jacobian matrix of the system of Equations (5.42) and (5.43) with respect to ε and evaluated at ε = 0 is

$$\mathbf{J}_\varepsilon = \begin{bmatrix} \nabla_\varepsilon \mathbf{c}'(\mathbf{f}^{0*},0) \\ -\nabla_\varepsilon \mathbf{s}(0) \end{bmatrix}. \tag{5.51}$$

It can be shown that the Jacobian matrix $\mathbf{J}_{f^0,\lambda,\gamma}$ is non-singular and the partial derivatives of $[\mathbf{f}^{0*},\lambda^*,\gamma^*]$ with respect to ε are given by

$$\begin{aligned} \begin{bmatrix} \nabla_\varepsilon \mathbf{f}^0 \\ \nabla_\varepsilon \mathbf{h} \end{bmatrix} &= \mathbf{J}^{-1}_{f^0,\lambda,\gamma} \cdot \mathbf{J}_\varepsilon \\ &= \begin{bmatrix} \mathbf{B}_{11} & \mathbf{B}_{12} \\ \mathbf{B}_{21} & \mathbf{B}_{22} \end{bmatrix} \begin{bmatrix} -\nabla_\varepsilon \mathbf{c}'(\mathbf{f}^{0*},0) \\ \nabla_\varepsilon \mathbf{s}(0) \end{bmatrix} \end{aligned} \tag{5.52}$$

Therefore, the derivatives of path flows and Lagrange multipliers with respect to ε at ε = 0 are

$$\nabla_\varepsilon \mathbf{f}^0 = -\mathbf{B}_{11} \nabla_\varepsilon \mathbf{c}'(\mathbf{f}^{0*},0) + \mathbf{B}_{12}\, \nabla_\varepsilon \mathbf{s}(0) \tag{5.53}$$

and

$$\nabla_\varepsilon \mathbf{h} = -\mathbf{B}_{21} \nabla_\varepsilon \mathbf{c}'(\mathbf{f}^{0*},0) + \mathbf{B}_{22}\, \nabla_\varepsilon \mathbf{s}(0) \tag{5.54}$$

Since

$$\nabla_\varepsilon \mathbf{v} = \Delta^0 \nabla_\varepsilon \mathbf{f}^0 \text{ and } \nabla_\varepsilon \mathbf{T} = \Lambda^0 \nabla_\varepsilon \mathbf{f}^0 \tag{5.55}$$

the derivatives of link flows and O-D demands with respect to ε at ε = 0 are obtained as

$$\nabla_\varepsilon \mathbf{v} = -\Delta^0 \mathbf{B}_{11} \nabla_\varepsilon \mathbf{c}'(\mathbf{f}^{0*},0) + \Delta^0 \mathbf{B}_{12}\, \nabla_\varepsilon \mathbf{s}(0) \tag{5.56}$$

and

$$\nabla_\varepsilon \mathbf{T} = -\Lambda^0 \mathbf{B}_{11} \nabla_\varepsilon \mathbf{c}'(\mathbf{f}^{0*},0) + \Lambda^0 \mathbf{B}_{12}\, \nabla_\varepsilon \mathbf{s}(0) \tag{5.57}$$

where $\mathbf{B}_{11}$, $\mathbf{B}_{12}$, $\mathbf{B}_{21}$, $\mathbf{B}_{22}$ are given in Equations (5.46)-(5.49).

Equations (5.54), (5.56) and (5.57) are the general expressions of the derivatives of the constraint multipliers and decision variables (link flows and O-D demands) with respect to a variety of perturbation parameters in the network equilibrium problem.

The explicit expressions for link flows with respect to the number of cars by zone can be derived in the following. Since the link travel time functions and entropy term are fixed in the problem,

$$\nabla_{\varepsilon}\mathbf{c}'(\mathbf{f}^{0*},0) = 0 \qquad \text{but} \qquad \nabla_{\mathbf{f}}\mathbf{c}'(\mathbf{f}^{0*},0) \neq 0 \tag{5.58}$$

From Equation (5.58), Equations (5.56) and (5.57) can be simplified into

$$\nabla_{\varepsilon}\mathbf{v} = \Delta^{0}\mathbf{B}_{12}\nabla_{\varepsilon}\mathbf{s}(0) \tag{5.59}$$

and

$$\nabla_{\varepsilon}\mathbf{T} = \Lambda^{0}\mathbf{B}_{12}\nabla_{\varepsilon}\mathbf{s}(0) \tag{5.60}$$

Let $\varepsilon = \delta\mathbf{u}$, which represents a small variation in the number of cars, then the derivatives of link flows and O-D demands with respect to the number of cars by zone can be obtained.

From Equation (5.59),

$$\nabla_{\mathbf{u}}\mathbf{v} = \nabla_{\varepsilon}\mathbf{v} = \Delta^{0}\mathbf{B}_{12}\nabla_{\varepsilon}\mathbf{s}(0)$$

$$= \Delta^{0}\mathbf{B}_{12}\begin{bmatrix}\nabla_{\varepsilon}\mathbf{O}(0)\\ \nabla_{\varepsilon}\mathbf{D}(0)\end{bmatrix}, \text{ from Equation (5.41)}$$

$$= \Delta^0 \mathbf{B}_{12} \begin{bmatrix} \nabla_u \mathbf{O} \\ \nabla_u \mathbf{D} \end{bmatrix}$$

$$= \Delta^0 \nabla_f \mathbf{c}'(\mathbf{f}^{0*}, 0)^{-1} \mathbf{M}^T \mathbf{B}_{22} \begin{bmatrix} \nabla_u \mathbf{O} \\ \nabla_u \mathbf{D} \end{bmatrix}, \text{ from Equations (5.47) and (5.49)}$$

$$= \Delta^0 \left[\Delta^{0T} \nabla_v \mathbf{c}(\mathbf{v}^*, 0) \Delta^0 + \frac{1}{\alpha} \Lambda^{0T} (\Lambda^0 \mathbf{f}^{0*})^{-1} \Lambda^0 \right]^{-1} \mathbf{M}^T \mathbf{B}_{22} \begin{bmatrix} \nabla_u \mathbf{O} \\ \nabla_u \mathbf{D} \end{bmatrix}, \text{ from Equation (5.50)}$$

... (5.61)

where $\mathbf{B}_{22}$ are given by Equation (5.49).

Similarly,

$$\nabla_u \mathbf{T} = \Lambda^0 \left[\Delta^{0T} \nabla_v \mathbf{c}(\mathbf{v}^*, 0) \Delta^0 + \frac{1}{\alpha} \Lambda^{0T} (\Lambda^0 \mathbf{f}^{0*})^{-1} \Lambda^0 \right]^{-1} \mathbf{M}^T \mathbf{B}_{22} \begin{bmatrix} \nabla_u \mathbf{O} \\ \nabla_u \mathbf{D} \end{bmatrix} \quad (5.62)$$

5.6 SOLUTION ALGORITHM

The derivatives of link flows and O-D demands with respect to the number of cars by zone were obtained from the theory of sensitivity analysis for a given solution of the network equilibrium problem. Local linear approximations of capacity and parking constraints based on these derivatives were formulated. The resulting linear programming problem can then be solved using the well-known simplex method.

The linear approximation of road and parking capacity constraints (5.2) and (5.3) can be derived as follows:

$$v_a(\mathbf{u}) \approx v_a(\mathbf{u}^{(n)}) + \sum_{i \in I} \left[\left. \frac{\partial v_a(\mathbf{u})}{\partial u_i} \right|_{\mathbf{u}=\mathbf{u}^{(n)}} \right] \left(u_i - u_i^{(n)} \right), a \in A \tag{5.63}$$

and

$$t_{ij}(\mathbf{u}) \approx t_{ij}(\mathbf{u}^{(n)}) + \sum_{k \in I} \left[\left. \frac{\partial t_{ij}(\mathbf{u})}{\partial u_k} \right|_{\mathbf{u}=\mathbf{u}^{(n)}} \right] \left(u_k - u_k^{(n)} \right), i \in I, j \in J \tag{5.64}$$

where $\partial v_a / \partial u_i, \partial t_{ij} / \partial u_k$ can be obtained by the method of sensitivity analysis. $\mathbf{u}^{(n)}$ is the solution at the current iteration n, $v_a(\mathbf{u}^{(n)})$ and $t_{ij}(\mathbf{u}^{(n)})$ are the corresponding equilibrium link flow pattern and O-D travel demand, respectively. Equations (5.63) and (5.64) are then applied to Equations (5.2) and (5.3) to form a set of simple linear constraints. Consequently, the upper-level problem reduces to a standard linear programming problem that can be easily solved by the simplex method.

The mechanism of the solution algorithm is an iterative process between the upper-level and the lower-level problems. Based on the above ideas, the proposed sensitivity analysis based (SAB) algorithm can be described as follows:

SAB Algorithm:

Step 0. Determine an initial car ownership value $\mathbf{u}^{(n)}$, trip production rate $\mathbf{p}^{(n)}$ and trip attraction rate $\mathbf{q}^{(n)}$. Set $n = 0$.

Step 1. Solve the lower-level combined trip distribution/assignment problem (5.5)-(5.12) for given $\mathbf{u}^{(n)}$, $\mathbf{p}^{(n)}$ and $\mathbf{q}^{(n)}$; and hence get $\mathbf{v}^{(n)}$, $\mathbf{T}^{(n)}$ and $\mathbf{g}^{(n)}$.

Step 2. Calculate the new trip production $\mathbf{p}^{(n+1)}$ and attraction $\mathbf{q}^{(n+1)}$ rates if elastic trip rates are used.

Step 3. Calculate the derivatives $\nabla_{\mathbf{u}}\mathbf{v}^{(n)}$ and $\nabla_{\mathbf{u}}\mathbf{T}^{(n)}$ using the sensitivity analysis method.

Step 4. Formulate local linear approximations of the upper-level capacity constraints (5.2) and (5.3) using the derivative information, and solve the resulting linear programming problem to obtain an auxiliary solution $\mathbf{y}$.

Step 5. Compute $\mathbf{u}^{(n+1)} = \mathbf{u}^{(n)} + \frac{1}{1+n}(\mathbf{y} - \mathbf{u}^{(n)})$ to obtain a new number of cars by method of successive averages (MSA).

Step 6. If $|u_i^{(n+1)} - u_i^{(n)}| \leq \omega$ for all $i \in I$ or $n = \eta$ then stop, where ω is a predetermined error tolerance and η is the maximum number of iterations. Otherwise let $n := n + 1$ and return to Step 1.

As referred to Step 0, the initial values of zonal car ownership $\mathbf{u}$, trip production/attraction rates $\mathbf{p}$ and $\mathbf{q}$ are given for solving the lower-level CDA problem. Using the results obtained in the CDA model in Step 1, the elastic trip production/attraction rates for the next iteration can be calibrated. The rates remain unchanged if constant trip rates were used.

Sensitivity analysis is then implemented to compute the derivatives of equilibrium link flows and O-D demands with respect to the number of cars by zones. The derivative information obtained from sensitivity analysis is used to formulate local linear approximations of the upper-level constraints.

After solving the upper-level problem, a new value of zonal car ownership can be obtained by MSA. There are conditions for guaranteeing the convergence. The above three new values $\mathbf{u}$, $\mathbf{p}$ and $\mathbf{q}$ can then be fed into the lower-level CDA problem again to obtain another set of new values. It is expected that this iteration process will converge to a stable point.

As refer to the procedure, the O-D travel time **g** obtained at iteration n is used to estimate the elastic trip production/attraction rates for iteration $n+1$. The O-D travel time at iteration n approaches to the value at iteration $n+1$ when the solution converges and hence for the trip production/attraction rates. The mechanism of the solution algorithm is presented in a flow chart, Figure 5.2.

The proposed sensitivity analysis algorithm is heuristic and cannot be guaranteed to converge to a global optimum, since local minimum points may exist due to nonconvexity of the bilevel programming problems (Friesz *et al.*, 1990). However, it appears that the algorithm is promising for solving the problems with user equilibrium as a constraint (Yang and Yagar, 1994) and could be expected to obtain a good sub-optimal solution. Furthermore, existence of local optima could be examined and identified by applying the algorithm at different starting points or by exploring the solution surface.

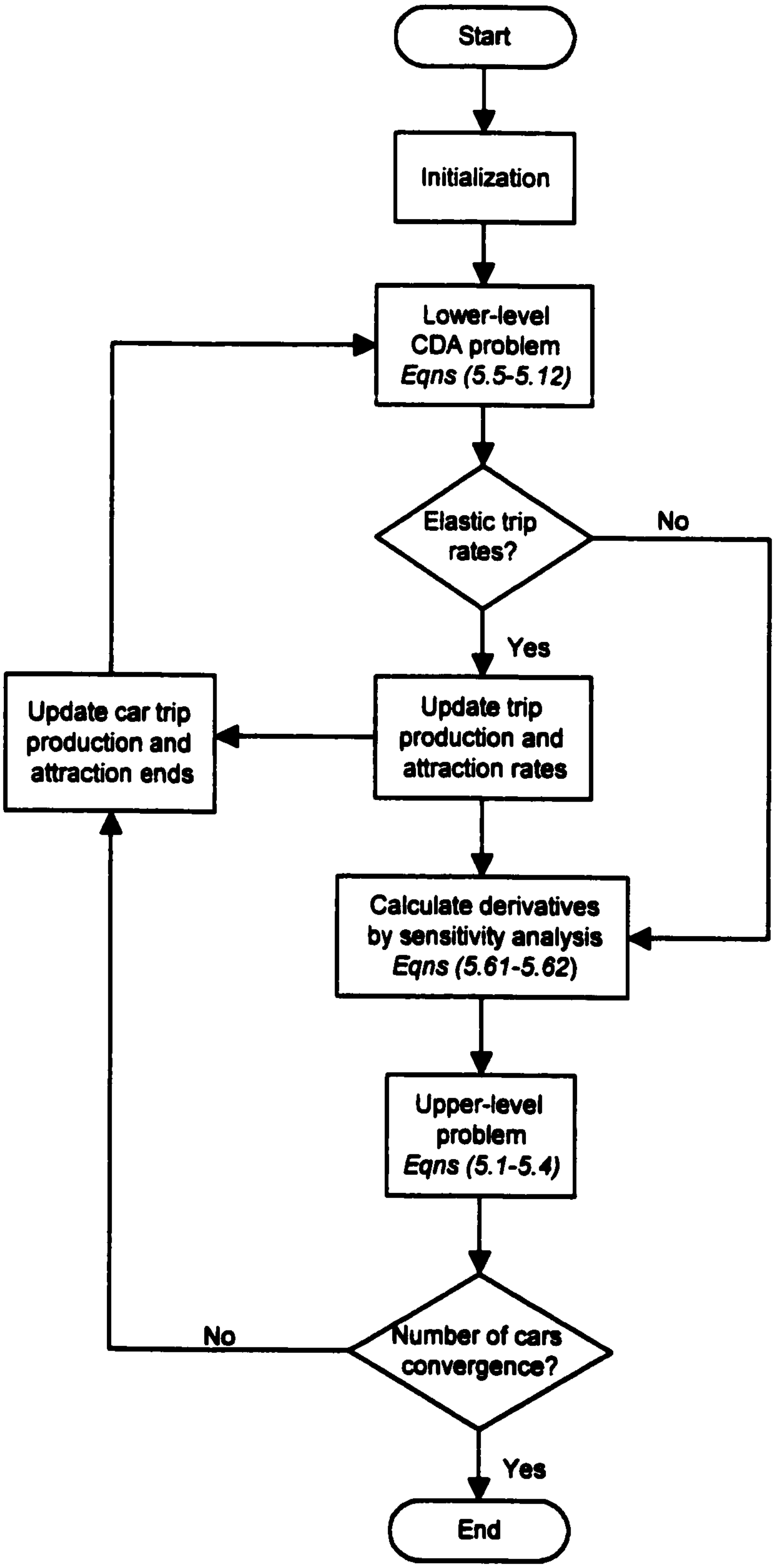


Figure 5.2 Mechanism of the SAB Solution Algorithm

5.7 NUMERICAL EXAMPLE 1: CONSTANT TRIP RATES

A numerical example is presented to illustrate how to use the proposed method to obtain the maximum number of cars under conditions of road capacities. The parking constraints are ignored in this example. For simplicity, ϕ_{1k} and ϕ_{2i} are assumed to be 1 for all parking spaces are public uses, and so all cars are parked in the public parking spaces at the beginning of the study period. Passenger car units (pcu) are used for the units of car ownership. The example road network shown in Figure 5.3, consists of 7 links, 6 nodes and 2 O-D pairs (of which 1 and 2 are origin nodes and 5 and 6 are destination nodes). The BPR (Bureau of Public Roads, 1964) link travel time function was used with associated input data given in Table 5.2. The BPR type function was used because the steady state traffic flow assumption (Ran *et al.*, 1997) was adopted in the model.

$$c_a(v_a) = c_a^0\{1.0 + 0.15(\frac{v_a}{S_a})^4\} \tag{5.65}$$

The function of trip productions (5.7) is assumed as the multiplication of constant trip production rate per car and the number of cars in each zone; i.e.

$$O_i(u_i) = p_i u_i, i \in I \tag{5.66}$$

while the trip attractions are assumed as constant.

The trip production rate in origin node 1 is assumed to be 2 pcu/hr and in origin node 2 is 3 pcu/hr. So, there are two times and three times travels during one hour for each car in origins 1 and 2, respectively. The trip attractions are given as **D** = [120, 90], which is the total number of parking spaces in each destination node. The lower and upper bounds of car ownership are assumed to be [10, 100] in origin node 1 and [10, 80] in origin node 2. The lower boundary is set to retain at least 10 pcu mobility on private vehicles for travelling and goods transportation, rather than only depends on public transport. The upper boundary is set for considering the amount of vacant land that is suitable and available for residential use. The value of dispersion parameter α is assumed to be 0.1 for the gravity-type trip distribution model in this example.

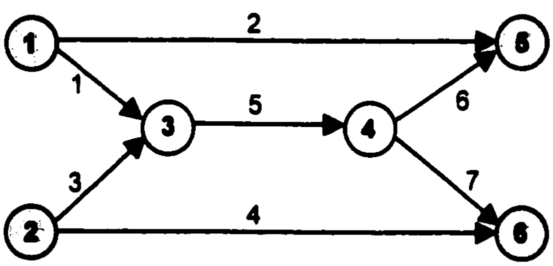


Figure 5.3 Example Road Network 1

Table 5.2 Link Travel Time Data for the Network 1

Link Number a	Free-flow Travel Time c_a^0 (minutes)	Capacity S_a (pcu/hr)
1	4	60
2	10	80
3	4	70
4	10	80
5	5	110
6	4	70
7	4	60

The initial number of cars is set to be $\mathbf{u}^{(0)} = [30, 50]$ and the resultant link flows are $\mathbf{v}^{(0)} = [25.71, 34.29, 85.71, 64.29, 111.43, 85.71, 25.71]$. It can be seen that the traffic flows on links 3, 5 and 6 are greater than their road capacities, while the remaining link flows are satisfied the road capacity constraints. Therefore, it is a potential to accommodate future growth on car ownership and in turn an increase in traffic flows. However, the number of cars at origin zone(s) should be suppressed to a certain level due to the violation of the road capacity constraints (Links 3, 5 and 6). Hence, the proposed model can be applied to obtain the balance on both sides.

The numerical results of the proposed model with different error tolerances are summarized in Table 5.3. The convergence was achieved in 230 iterations at the error tolerance $\omega = 1.0\times10^{-4}$. Figure 5.4 shows the changes of optimal car ownership versus the number of iterations. The optimal number of cars was found in each origin node. The maximum number of cars in the study area is 93.33 pcu which is greater than the initial figure 80 pcu. The number of cars owned by residents in zone 1 is increased from 30 pcu to 69.98 pcu, while that in zone 2 is reduced from 50 pcu to 23.35 pcu. Hence, the traffic congestion made by the initial case was due to the exceeding number of cars owned by residents in zone 2.

The corresponding link flows and O-D demand matrix are given in Tables 5.4 and 5.5. As shown in Table 5.4, links 1, 2 and 7 are identified to become saturated when car ownership equals to the estimated maximum value in each of the two origin zones. Thus capacity improvement is required in these links if more cars are to be owned by residents in the origin traffic zones.

Table 5.3 Numerical Results obtained by the SAB Algorithm

Error Tolerance ω	Number of Iterations	Final Solution u_1	Final Solution u_2
1.0×10^{-1}	8	69.40	23.73
1.0×10^{-2}	23	69.78	23.48
1.0×10^{-3}	72	69.93	23.38
1.0×10^{-4}	230	69.98	23.35

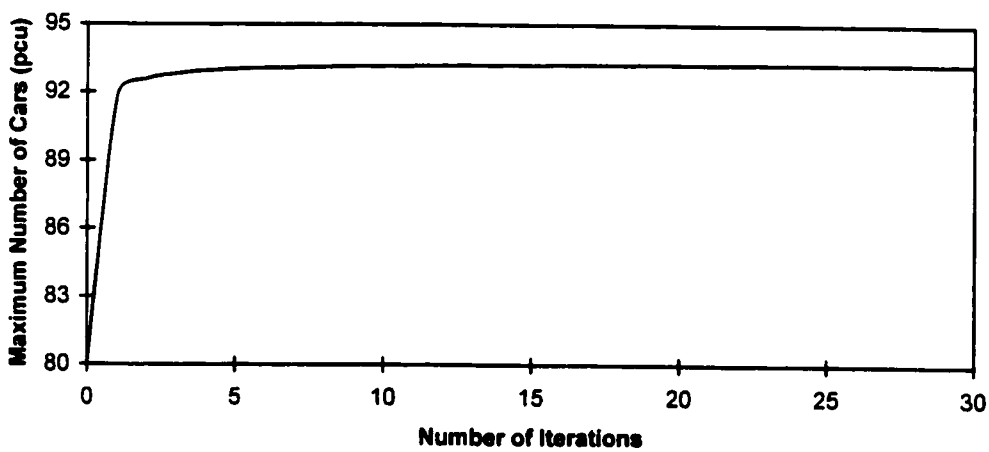


Figure 5.4 Convergence of Optimal Car Ownership at the Error Tolerance $\omega = 1.0\times10^{-4}$

Table 5.4 Corresponding Equilibrium Link Flow Pattern

Link Number a	Equilibrium Link Flow v_a(pcu/hr)	Flow/Capacity Ratio v_a/S_a
1	59.98	1.00
2	79.97	1.00
3	40.03	0.57
4	30.02	0.38
5	100.01	0.91
6	40.03	0.57
7	59.98	1.00

Table 5.5 Estimated Origin-Destination (O-D) Matrix

		Destination nodes		
		5	6	O_i
Origin Nodes	1	79.97	59.98	139.95
	2	40.03	30.02	70.05
	D_j	120.00	90.00	210.00

The predicted maximum number of cars indicates to what extent zonal car ownership growth could be accommodated or suppressed by the existing transportation facilities. In this example, positive car ownership growth potential of 69.98 pcu exists in zone 1; while negative potential of 23.35 pcu occurs in zone 2. The reserve capacity of car ownership at traffic zone 1 is 39.98 pcu, while 26.65 pcu should be reduced in traffic zone 2. In terms of percentage, 133.27% of existing cars (in pcu) can be accommodated by the reserve capacity in zone 1. However, 53.30% of the existing amount (in pcu) should be suppressed in zone 2. Totally 13.33 pcu can gain in the two origin zones. Figure 5.5 shows the existing number of cars and the maximum number of cars in the two origin zones estimated by the model.

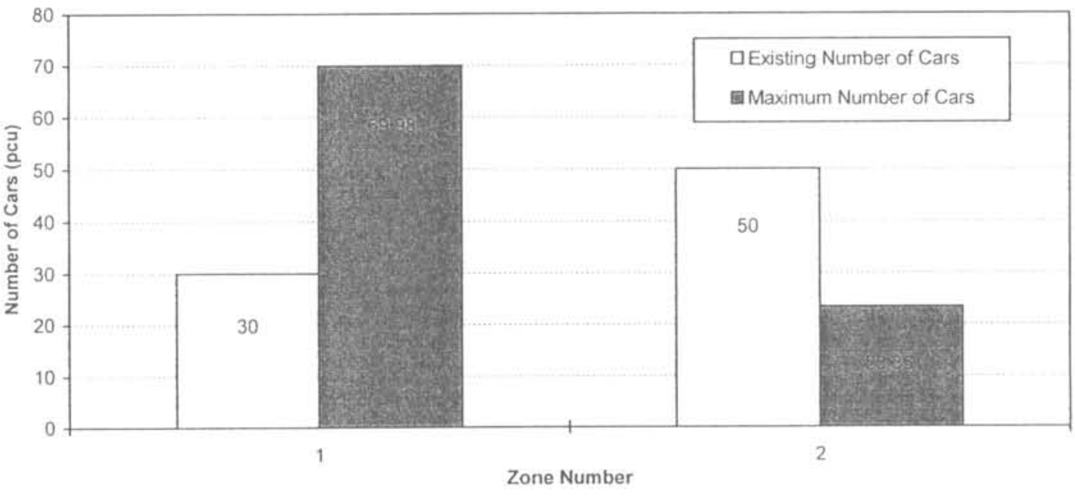


Figure 5.5 Existing and Maximum Number of Cars in Origin Zones

5.8 NUMERICAL EXAMPLE 2: ELASTIC TRIP RATES

A numerical example is presented to illustrate how to use the proposed method to obtain the maximum total number of cars under conditions of road capacity and parking constraints. This example is designed for two purposes, namely (1) to demonstrate the effectiveness of the proposed model for determining the maximum zonal car ownership, and (2) to test the sensitivity of accessibility measures on trip rates (i.e. car usage) and in turn on car ownership.

The merit of incorporating accessibility to elastic trip rates is that the model then reflects the response of road users to traffic congestion, which includes changing the time of day at which a journey is made, switching to an alternative mode or not making the journey at all. Hence, the number of trip productions should be formulated as a function of trip production rates, while the trip rate is a function of accessibility measures (Ortúzar and Willumsen, 1994). A similar relationship should be established for the trip attractions.

There are some car ownership models that include accessibility measures. In the study of Train (1986), public transport accessibility was approximated through the number of transit trips per capita and population density in the residence zone. Bunch and Kitamura (1989) introduced a logsum value derived from a destination choice model. Han (1997) has estimated car ownership models for Sweden in which accessibility variables were introduced as logsum variables from nested logit models of trip frequency, mode and destination choice for work trips and other trip purposes.

The main difference between this study and previous related works is that the proposed model includes the relationship between traffic assignment and car ownership. Furthermore, most of the previous car ownership models are household-basis, whereas the proposed model is a zonal-basis model for the purposes of strategic planning.

The functions of trip productions and attractions (5.7) - (5.8) are defined as follows:

$$O_i(u_i) = u_i p_i(z_i) \tag{5.67}$$

$$D_j = (\phi_{1k} h_k - (1 - p_i(z_i))\phi_{2i} u_i) q_j(z'_j) = \bar{h}_j q_j(z'_j), \quad when\, i = k\ and\ j = k \tag{5.68}$$

where

$$p_i(z_i) = \beta\left(\frac{z_i}{\text{households}_i} \times 100\right)^e, \quad 0 \le e < 1 \tag{5.69}$$

$$q_j(z'_j) = \eta\left(\frac{z'_j}{\text{employment}_j} \times 100\right)^e, \quad 0 \le e < 1 \tag{5.70}$$

and

$$z_i = \sum_{j \in J} \bar{D}_j \exp(-\delta g_{ij}) \tag{5.71}$$

$$z'_j = \sum_{i \in I} O_i \exp(-\delta g_{ij}) \tag{5.72}$$

As the objective of the proposed model is to determine the maximum number of cars by traffic zones, the decision variable is the number of cars in each zone. On the other hand, in order to take into account the accessibility of the road network, elastic trip production rate per car has been incorporated in the model. By making a simple relationship that the total number of trips generated is equal to the number of cars times the elastic trip production rate per car, the formulation of Equation (5.67) was applied. Similar formulation of Equation (5.68) for trip attraction was built with the relationship between available parking spaces and elastic trip attraction rate per parking space.

Equations (5.69) and (5.70) are the relationships between the elastic trip production/ attraction rates and the accessibility measures. In Equations (5.69) and (5.70), β and η are constants for trip production and attraction, respectively. e is a parameter to reflect the effect of accessibility measures on the trip production and attraction rates. That is, the ratio of the percentage change in trip rates to the percentage change in accessibility per 100 households or employment (Wohl and Martin, 1967). Therefore, a small value of e would be used for home-based work trips, while a larger value of e would be provided for home-based other and/or non-home based trips. Some socio-economic characteristics (e.g. household income) can be incorporated in the model by considering the parameter e as a function of household income. The effect of socio-economic characteristics between zones on car ownership, trip production rates and link demand can then be assessed.

The general form of accessibility measures can be expressed as a function of the generalized travel time between zones i and j, and the size of activity in zone i or j, such as population and number of jobs, etc. (Leake and Huzayyin, 1979; Ortúzar and Willumsen, 1994). In Equations (5.71) and (5.72), the size of activity in zones i and j are defined as the trip productions and attractions, respectively. δ is a constant to reflect the sensitivity to O-D travel time of the zonal accessibility. An increase in accessibility would generate higher demand for travel.

The example road network shown in Figure 5.6 consists of 4 zone centroids (represented by dotted line circles and connected to road nodes by artificial two-way links), 6 road nodes and 10 one-way links. The BPR link travel time functions were also used with associated input data given in Table 5.6.

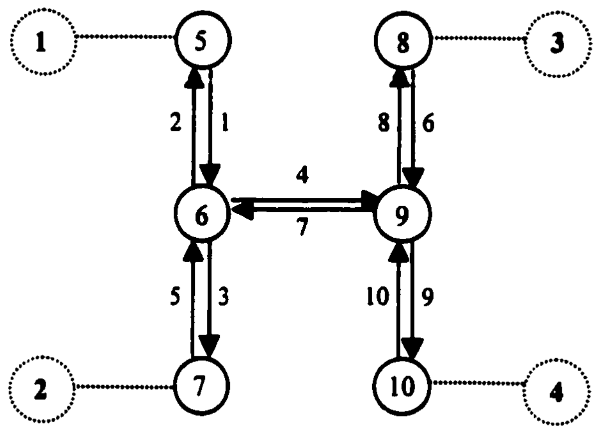


Figure 5.6 Example Road Network 2

Table 5.6 Link Travel Time Data for the Network 2

Link Number a	Free-flow travel time c_a^0 (hrs)	Capacity S_a (pcu/hr)
1	0.0900	1,800
2	0.0900	1,800
3	0.0943	1,800
4	0.0093	1,500
5	0.0943	1,800
6	0.0500	1,800
7	0.0093	1,500
8	0.0500	1,800
9	0.0833	1,800
10	0.0833	1,800

Parking charge is assumed to be constant for each traffic zone and expressed in terms of equivalent travel time on the artificial link, in the direction to the zone centroid using a pre-determined value of time. The parking data adopted for the example is presented in Table 5.7. For simplicity, the units of car ownership are defined in terms of pcu.

Table 5.7 Parking Data for the Network 2

Zone	Total Parking Space	Parking Charge (hrs)
1	3,500	0.02
2	3,700	0.02
3	4,000	0.05
4	3,800	0.04
Total	15,000	

The lower boundary of car ownership is assumed to be 20% of the existing number of cars (in terms of pcu) in all zones. In fact, the lower boundary can be predicted from the historical trend of car ownership. Using the regression analysis, the future level of car ownership can be forecast together with the confidence interval. The difference between the lower and the upper bounds is dependent on the level of confidence selected for forecasting. The upper boundary of car ownership is the total number of parking spaces, which fulfils the home-end parking demand.

The value of dispersion parameter α is assumed to be 0.1 for the gravity-type trip distribution model in this example. The constants β and η for trip production and attraction rates are assumed to be 0.3 and 0.45 respectively, and δ (parameter for reflecting the sensitivity to O-D travel time of accessibility measures) is assumed to be 2.0. The number of households and employment in each traffic zone are all assumed to be 100,000 units. Both ϕ_{1k} and ϕ_{2i} are equal to 1 assuming all parking spaces are for public users in the traffic zones. The sensitivity tests for the various parameters will be discussed later.

In order to assess the effect of the accessibility on trip production and attraction rates, different values of parameter e = [0.0, 0.05, 0.1, 0.3] are chosen for sensitivity testing. From Equations (5.69) and (5.70), the greater the parameter value, the greater the sensitivity of the trip production and attraction rates to accessibility. In the case of the parameter value equal to zero, both trip production and attraction rates are insensitive to the accessibility measures.

It is assumed that the existing number of cars in each zone is 3,500, 3,700, 3,900 and 3,800 pcu, i.e. the total number of cars is 14,900 (in pcu) in the four traffic zones. If the demand for travel is continuously increased, the potential for future growth of car ownership would be high. However, when traffic congestion occurs, the desire to make trips may be reduced and the potential growth of car ownership would be suppressed. Thus, using the proposed model, the maximum reserve capacity for accommodation of cars in the study network can be determined. The numerical results of the proposed model with various parameter values for e are summarized in Table 5.8. The convergence of the solutions at the error tolerance ω = 0.005 is shown in Figure 5.7.

Table 5.8 Maximum Number of Cars obtained by the SAB Algorithm

Parameter e	Number of Iterations	No. of cars in zone 1 u_1	No. of cars in zone 2 u_2	No. of cars in zone 3 u_3	No. of cars in zone 4 u_4	Total max. no. of cars $\sum_{i=1}^{4} u_i$
0.00	186	3,500.00	3,699.38	3,999.08	3,800.00	14,998.46
0.05	37	3,500.00	3,428.70	3,700.71	3,800.00	14,429.41
0.10	2,142	3,500.00	3,192.89	3,438.15	3,800.00	13,931.04
0.30	9,276	2,077.47	3,665.24	2,368.76	3,797.52	11,908.99

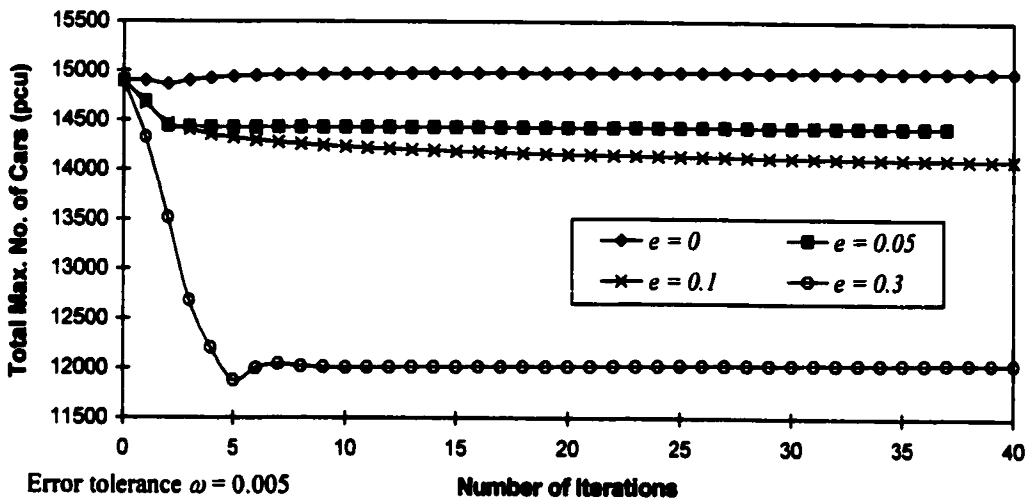


Figure 5.7 Convergence of Maximum Car Ownership at Various Values of Parameter *e*

The fluctuation of the upper-level objective value (the maximum total number of cars in the four traffic zones) became small as iterations increased, which has demonstrated that the proposed algorithm leads to a converged solution for this example. It can be seen in Table 5.8 that the number of iterations required increased with the value of parameter *e*. For larger *e* values, more iterations were needed because the trip rates were more sensitive to the measure of accessibility. If the link flows increased, the O-D travel time would increase. When the road users perceived the increase in the O-D travel time, their desire for trip making would reduce. The variation of the O-D travel time would also affect trip attractions. Thus, the response of the O-D demand and link flows would be larger with large e values, which resulted in a significant change in the value of the upper-level objective function.

From the overall results, the larger the e value, the greater reduction in the number of cars as the link capacity constraints cannot be satisfied. In Table 5.8, when e was increased from 0.0 to 0.1, the total number of cars was reduced by 1,000 pcu, and if e was increased from 0.1 to 0.3, the reduction in the total number of cars was about 2,000 pcu.

Reserve capacity of zonal car ownership has been defined as the additional number of cars that can be accommodated in road networks when comparing with the existing number of cars in each of the traffic zones. In the above example of $e = 0.3$, both traffic zones have negative car ownership reserve capacities. It shows that the study road network cannot cater for the existing car ownership demand due to road congestion caused by a shortage of road spaces and parking facilities. Therefore, zonal car ownership should be suppressed by the existing transportation facilities (road spaces and parking facilities).

5.8.1 Discussion of Results ($e = 0.3$)

When the parameter e was set to be 0.3, the computational link flows and flow/capacity ratios associated with the original and maximum car ownership can be obtained by the proposed model and were given in Table 5.9. As the congestion occurred at links 4 and 7 that are the main connections between zones 1, 2 and zones 3, 4, the number of cars was greatly suppressed so that all the link flows can fulfil the link capacity constraints. The flow/capacity ratios of links 4 and 7 were reduced by 24% and 20% respectively. The resultant maximum total number of cars in the study area was found to be 11,909 pcu at e = 0.3, which was smaller than the initial figure 14,900 pcu.

Table 5.9 Equilibrium Link Flow and Flow/Capacity Ratio at $e = 0.3$

Total no. of cars $\sum_{i=1}^{4} u_i$	*Original* 14,900		*Maximum* 11,909	
Link a	v_a (pcu/hr)	v_a/S_a	v_a (pcu/hr)	v_a/S_a
1	1,292.70	0.72	776.43	0.43
2	1,269.63	0.71	1,349.15	0.75
3	1,342.18	0.75	850.74	0.47
4	1,853.65	**1.24**	1,500.00	**1.00**
5	1,366.57	0.76	1,423.46	0.79
6	1,440.44	0.80	891.72	0.50
7	1,806.19	**1.20**	1,500.00	**1.00**
8	1,512.95	0.84	1,528.86	0.85
9	1,378.46	0.77	854.21	0.47
10	1,403.50	0.78	1,491.35	0.83

The estimated O-D matrices associated with the corresponding number of trip productions and attractions at each traffic zone and the turnover of attraction-end parking are shown in Tables 5.10 and 5.11 for the cases with 14,900 and 11,900 pcu in total, respectively. As the road users are sensitive to zonal accessibility, their desire for trips making is reduced or they may change their destinations. The total travel demand was decreased from 5,503.21 trips to 4,582.96 trips. As the number of cars was greatly suppressed in zones 1 and 3, the utilization of spare public parking spaces ($\bar{D}_j / \bar{h}_j$) dropped about 40% as shown in Tables 5.10 and 5.11. In order to full occupy the parking spaces in the four zones, the road network should be improved by enhancing the road capacity on links 4 and 7 so that the travel demand can be increased, and hence more cars can be accommodated in the traffic zones. Further study will be required on this issue.

Table 5.10 Estimated Origin-Destination (O-D) Matrix when $e = 0.3$ and $\sum_{i=1}^{4} u_i = 14,900$

		Destination zones				
		1	2	3	4	O_i
Origin Zones	1	0	402.88	471.10	418.72	1,292.70
	2	402.74	0	510.29	453.54	1,366.57
	3	448.39	485.85	0	506.20	1,440.44
	4	418.49	453.45	531.56	0	1,403.50
	$\bar{D}_j$	1,269.62	1,342.18	1,512.95	1,378.46	**5,503.21**
	$\bar{h}_j$	1,292.70	1,366.57	1,540.44	1,403.50	
	$\bar{D}_j / \bar{h}_j$	**0.98**	**0.98**	**0.98**	**0.98**	

Table 5.11 Estimated Origin-Destination (O-D) Matrix when $e = 0.3$ and $\sum_{i=1}^{4} u_i = 11{,}909$

Destination zones

		1	2	3	4	O_i
Origin zones	1	0	214.38	344.01	218.04	776.43
	2	485.51	0	574.08	363.87	1,423.46
	3	356.63	262.78	0	272.31	891.72
	4	507.00	373.58	610.77	0	1,491.35
	$\bar{D}_j$	1,349.14	850.74	1,528.86	854.22	**4,582.96**
	$\bar{h}_j$	2,198.96	1,458.22	2,522.96	1,493.83	
	$\bar{D}_j / \bar{h}_j$	**0.61**	**0.58**	**0.61**	**0.57**	

5.8.2 Sensitivity Tests for Various Parameters

Sensitivity tests have been conducted to investigate the effect of different parameter values on the example when determining the total maximum number of cars. The positive and negative effects of road capacity and parking space constraints on the maximum car ownership are to be illustrated. In total, ten cases (including the Core Case) were examined. Cases 1 to 5 indicated the negative effects on the total maximum number of cars with the results shown in Table 5.12. The positive effects on the total maximum car ownership were presented in Cases 6 to 9 and the results were given in Table 5.13. The value of parameter e was fixed at 0.3 in all the ten sensitivity tests.

Table 5.12 Results of Sensitivity Tests – Reduction in Total Maximum Car Ownership

	Case 1	Case 2	**Core Case**	Case 3	Case 4	Case 5
β for trip generation rate	0.20	0.30	**0.30**	0.30	0.30	0.40
η for trip attraction rate	0.30	0.45	**0.45**	0.45	0.45	0.60
δ for accessibility	1.00	2.00	**2.00**	2.00	3.00	2.00
Public parking spaces	- 500 in each zone	-1,000 in zone 3	**no change**	+ 500 in each zone	no change	no change
Total maximum number of cars	**13,000**	**11,775**	**11,909**	**12,489**	**12,723**	**9,718**
Constrained by	Parking capacity at all zones	Parking capacity at zone 3, and road capacity on links 4 and 7	**road capacity on links 4 and 7**	road capacity on links 4 and 7	road capacity on links 4 and 7	road capacity on links 4 and 7

Table 5.13 Results of Sensitivity Tests – Increase in Total Maximum Car Ownership

	Case 6	Case 7	Case 8	Case 9
β for trip generation rate	0.20	0.20	0.20	0.20
η for trip attraction rate	0.30	0.30	0.30	0.45
δ for accessibility	2.00	2.00	2.00	1.00
Public parking spaces	no change	+ 500 in each zone	+ 700 in each zone	+ 500 in each zone
Total maximum number of cars	**15,000**	**17,000**	**17,182**	**15,786**
Constrained by	Parking capacity at all zones	parking capacity at all zones	road capacity on links 4 and 7	road capacity on links 4 and 7

In Tables 5.12 and 5.13, parking capacity constraint means that the parking spaces were fully utilized by the home- and/or attraction-ends parking. Therefore, the road network cannot accommodate further increase of the number of cars due to a shortage of parking spaces. It indicates that more parking spaces should be provided if more cars are to be owned by households in the four traffic zones. However, if the road network is not improved, the number of cars cannot grow further due to the link capacity constraints despite some of the parking spaces being vacant. Therefore, it is required to investigate the balance of the supply and demand of parking spaces.

Case 1. The values of parameters β, η and δ were reduced from 0.3, 0.45 and 2.0 to 0.2, 0.3 and 1.0, respectively. The number of parking spaces reduced by 500 units in each traffic zone. The results, compared with the Core Case, show that the link flows would not exceed the link capacities as the O-D demand becomes smaller. However, the number of parking spaces were greatly reduced. As a result, the total number of cars was suppressed from 14,900 to 13,000 pcu.

Case 2. The number of parking spaces in zone 3 reduced by 1,000 units when comparing with that in the Core Case. As a result, the total maximum car ownership was restrained to 11,775 pcu by both the capacities of parking space at zone 3 and of road links 4 and 7. However, the results of Case 2 indicated that the negative effect on the total number of cars was not very significant. Compared with the results in the Core Case, a reduction of only 134 pcu resulted from the reduction in parking spaces at zone 3.

Case 3. The number of parking spaces was increased in 500 units in each zone, while the other parameters remained unchanged. It is known that increasing the number of parking spaces would stimulate the desire for car ownership. However, the link flows were constrained by the road capacity on links 4 and 7 as in the Core Case. Therefore, there was only a small growth in car ownership.

Case 4. The parameter δ, which represents the sensitivity to O-D travel time of accessibility measures, was increased from 2.0 to 3.0. Therefore, the trip rates would decrease due to more sensitive to traffic congestion, and hence the reserve capacity of car ownership was greater than that in the Core Case.

Case 5. The parameters for trip production and attraction rates were increased from 0.3 to 0.4 and from 0.45 to 0.6, respectively. As the total number of cars was constrained by road capacity on links 4 and 7 in the Core Case, increasing the trip rates in Case 5 results in the number of cars being greatly reduced under the condition of road capacity constraint. The number of empty parking spaces was 5,282.

Case 6. The parameters for trip production and attraction rates were decreased from 0.3 to 0.2 and from 0.45 to 0.3, respectively. By decreasing values of parameter β and η, a small O-D travel demand was obtained. As a result, the flow generated from the total number of cars was increased to the number of parking spaces (15,000 pcu) from the original (14,900 pcu).

Case 7. 500 parking spaces were added to each traffic zone compared with Case 6. It was found that the total maximum number of cars reached the total number of parking spaces without being constrained by the road capacity.

Case 8. 200 more parking spaces were added to each traffic zone compared with Case 7. However, the total maximum number of cars was only 182 more than that in Case 7. As links 4 and 7 have already been saturated, the number of cars cannot increase although there are a lot of spare parking spaces.

Case 9. The parameter for trip attraction rate was increased to 0.45, the accessibility was less sensitive to the O-D travel time (δ was decreased from 2.0 to 1.0) and 500 additional parking spaces were added to each traffic zone. It was found that the number of cars was constrained by road capacity rather than being constrained by parking spaces such as in Case 7. This is because the O-D demand would increase with the elastic trip rates and so the road links 4 and 7 cannot cater for the additional link flows.

Sensitivity tests were given to assess the impacts of different degrees of accessibility and sensitivity on the trip productions and attractions. If the measure of accessibility is sensitive, the trip production and attraction rates fluctuate more and the response of O-D demands and link flows is larger. The results of the example showed that the road users' route and destination choices would change due to traffic congestion. However, changing their route and destination choices may not solve the traffic congestion problem and the potential growth of household car ownership in the traffic zones should be suppressed. Hence, the results of negative reserve capacity of zonal car ownership indicated the importance of further study on road network improvement taking into account car ownership demand and parking supply. The provision of alternative and efficient modes, investment of public transport, better traffic management and land use planning, or 'do nothing' can also be considered.

5.9 SUMMARY

This chapter proposes a bilevel programming model to maximize the number of cars by traffic zones, subject to network capacity and parking constraints. The maximum number of cars by zones indicates to what extent zonal car ownership growth could be accommodated or suppressed by the existing transportation facilities (i.e. road spaces and parking supply). The proposed model takes into account the route and destination choices of travellers, the effects of the number of cars and the constant or elastic trip production and attraction rates. The demand of attraction-end parking has also been investigated. A sensitivity analysis based algorithm has been developed for determining the maximum number of cars in the study area. Two numerical examples were presented to test the proposed model and the solution algorithm under different scenarios. A case study will be presented in the next chapter to illustrate the proposed car ownership model in practice.

6 CASE STUDY

In Chapter 3, the territory-wide car ownership in Hong Kong was estimated based on the developed aggregate car ownership model (3.1). In Chapter 4, disaggregate car ownership models (listed in Tables 4.7 and 4.9) were calibrated to forecast the probability of car owning and non-car owning households from the view of user demand. And hence, the zonal car ownership distribution in Hong Kong could be obtained provided that the number of households by zone is given. In Chapter 5, a bilevel programming model (Equations (5.1)-(5.12)) was proposed to determine the reserve capacity of car ownership constrained by the road network supply conditions.

In this Chapter 6, a case study was carried out for a selected region in Hong Kong to illustrate the application of the proposed models in practice. The steps in the case study are as follows:

i. selection of study area;

ii. collection of planning data and road network data;

iii. estimation of the number of car owning and non-car owning households in the selected study area using the developed disaggregate car ownership models (Tables 4.7 and 4.9) and hence obtaining the zonal car ownership distribution;

iv. adjustment of the zonal car ownership to agree with the total car ownership obtained from the territory-wide model (Equation (3.1));

v. calibration of the parameters used in the proposed bilevel programming model (Equations (5.1)-(5.12));

vi. determination of the maximum car ownership in each of traffic zone in the study area under the network supply conditions;

vii. comparison between car ownership obtained from user demand (iv) and network supply (vi); and

viii. assessment the degree of satisfaction of the user demand under the network supply conditions.

In the following sections, the results of the case study will be presented and discussed.

6.1 SELECTION OF STUDY AREA

A study road network in the Tuen Mun and Yuen Long Corridor of Hong Kong, as shown in Figure 6.1, is used for demonstrating the concept of balancing car ownership from user demand and road network supply conditions. This study area was chosen because Tuen Mun and Yuen Long are the new towns being developed. A larger population will be taken in when the West Rail is introduced in the year of 2004. The study road network consists of 115 nodes, 290 links and 36 traffic zones in which five zones are connected to external areas. The five external zones represent the remaining areas of the Hong Kong territory. The layout of the captioned network is shown in Figure 6.2.

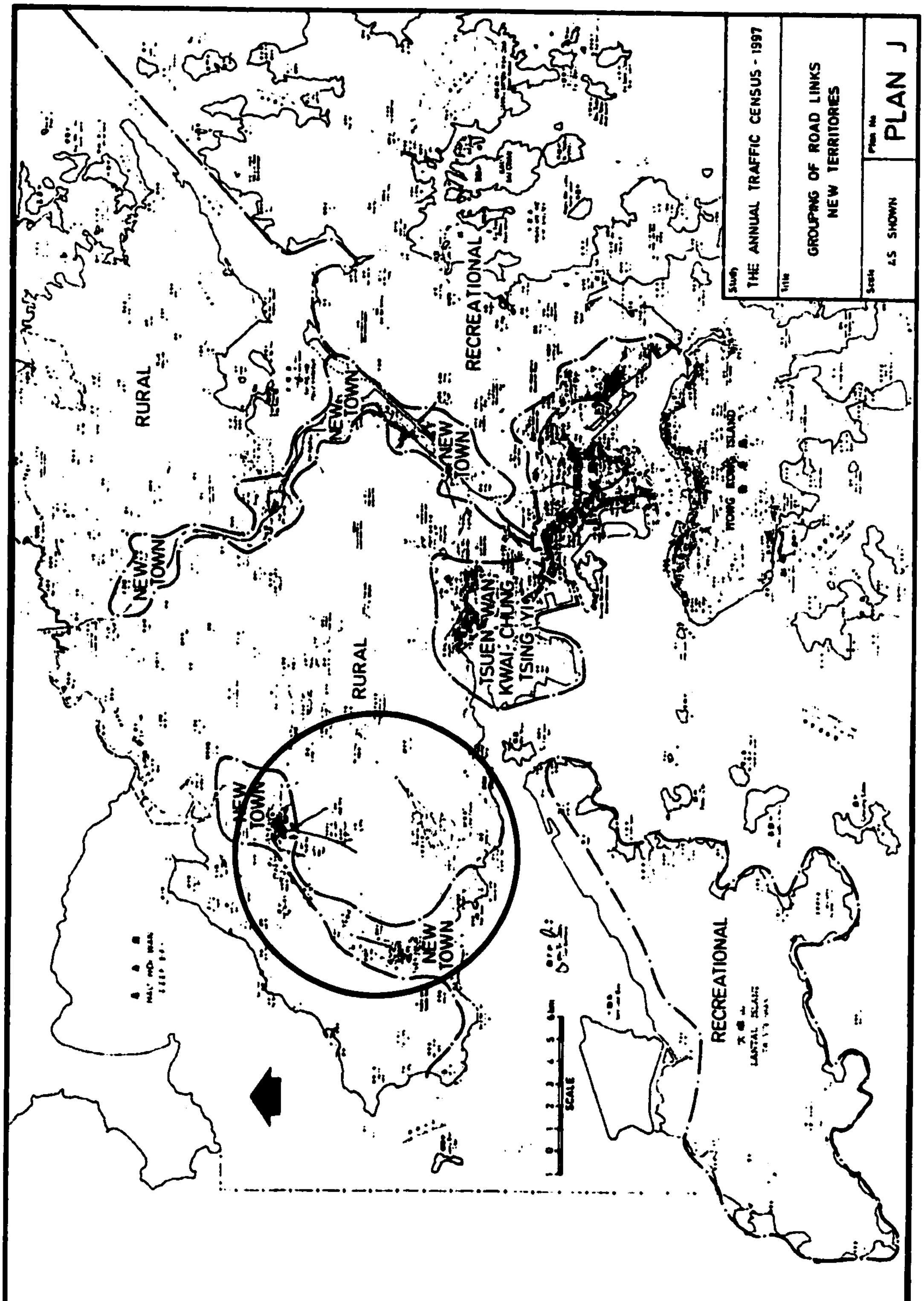


Figure 6.1 Location of the Selected Study Area

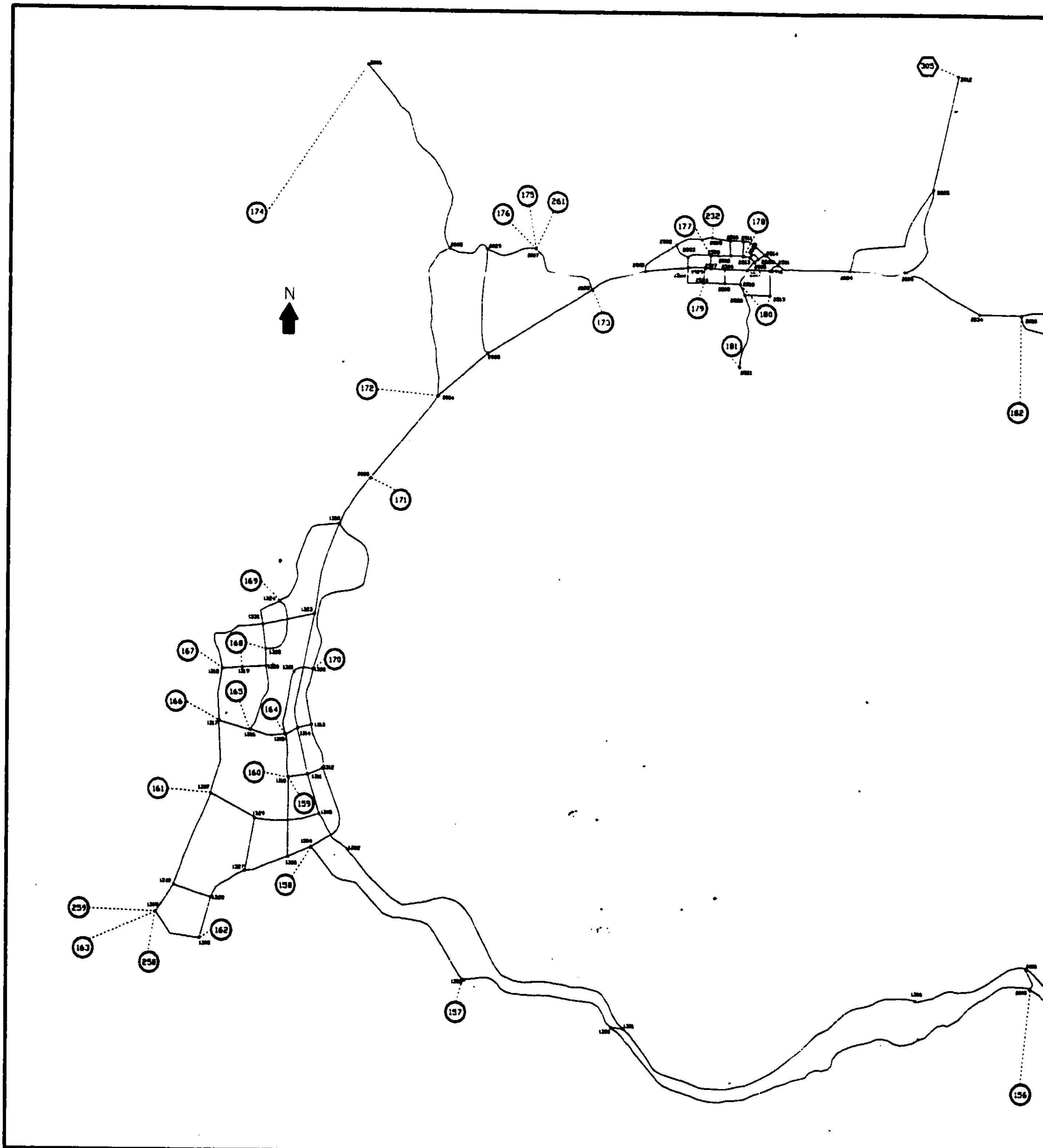
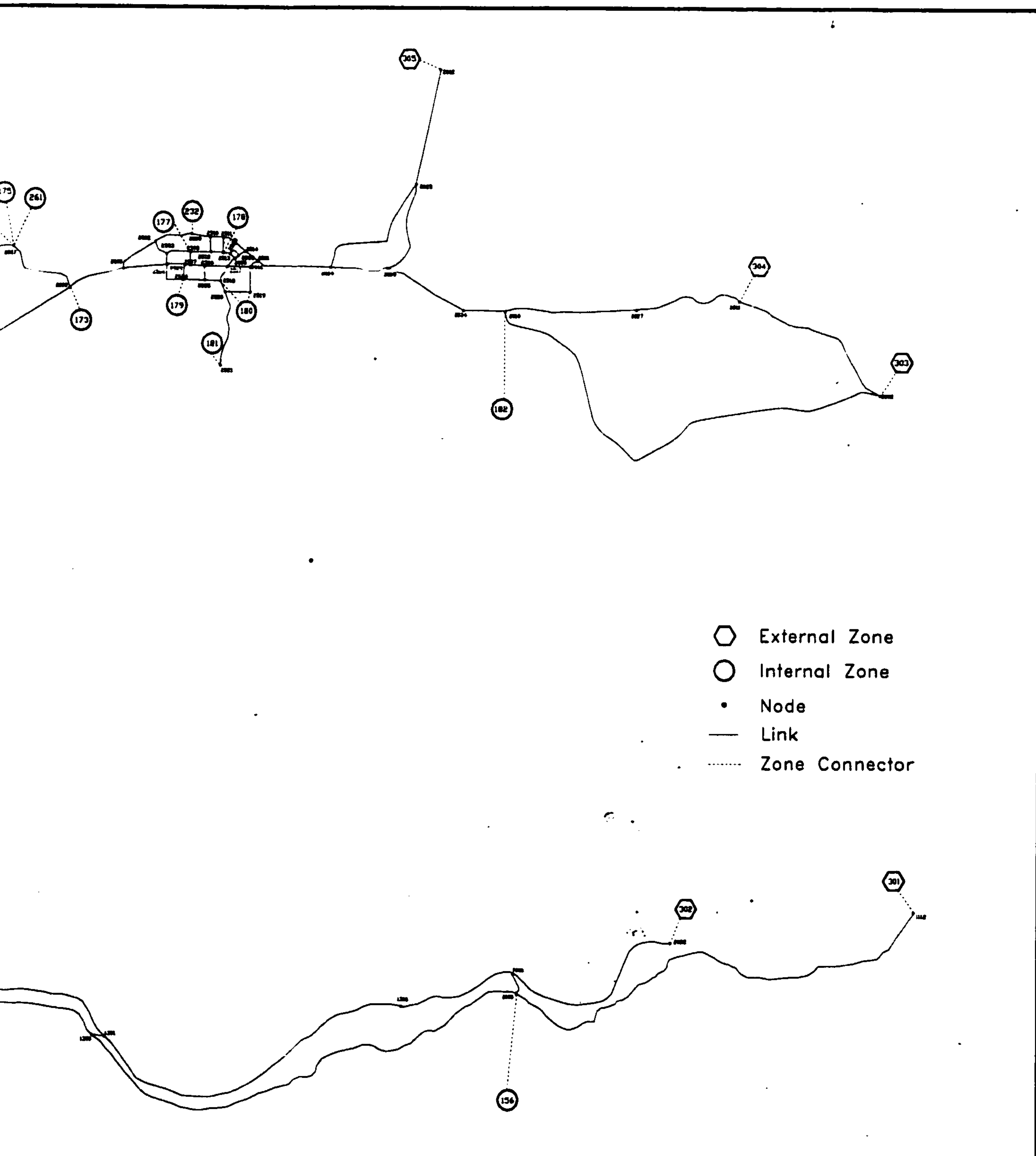


Figure 6.2 Road Network within Tuen Mun and Yuen Long Corridor



ad Network within Tuen Mun and Yuen Long Corridor of Hong Kong

Two transport modes were considered in the study network to facilitate the presentation of the main idea of the study. Private car (including motorcycle) is the decision transport mode in this study. For all other types of vehicles (e.g. taxis, goods vehicle, public light bus and franchised bus, etc.) are converted into their equivalent number of pcu, and are fixed and pre-loaded onto the study network. The normal weekday morning peak hour period (8:00 am - 9:00 am) was chosen as it is believed that morning peak hour is the most critical period in a typical weekday.

6.2 DATA COLLECTION

Planning data and road network data in 1997 were collected to estimate the number of cars owned by households living in the study area and to calibrate the parameters for the proposed bilevel car ownership model. The relevant data collected consists of:

i. Planning data - population, employment, the number of households, average monthly household income, resident workers, the number of off-street residential (private) parking spaces in each traffic zone, zonal accessibility index, average car ownership cost and average car usage cost.

ii. Road network data - link free flow speed, link speed at capacity, link distance, link capacity, pre-loaded vehicle flows and observed origin-destination matrix in morning peak hour.

The collected data was given in Appendices B, C and D.

Planning data was used to determine the zonal car ownership distribution and the functions of trip production and attraction as well as calibration of parameter α in the CDA model. Road network data was adopted in the bilevel car ownership model to determine the reserve capacity of zonal car ownership within the study area.

6.3 ESTIMATION OF CAR OWNERSHIP FROM USER DEMAND

From the results of the car ownership choice models in Chapter 4, the logit-type choice models based on the revealed preference data were developed for forecasting the number of cars owned by households. Planning data of the average monthly household income, zonal accessibility index, average monthly car ownership cost and usage cost were used to determine the probability of car owning and non-car owning households. The probability of multi-car owning households was obtained by using the planning data of average monthly household income and residential parking availability. The latter was converted from the number of residential parking space in each traffic zone using the four categories scheme mentioned in Table 4.5 of Chapter 4.

These probabilities were multiplied with the number of households by zone to obtain the number of non-car owning, single-car owning and multi-car owning households in each of the traffic zones (excluding external zones). An average of 2.2 cars owned by a multi-car household was assumed as reported from the 1992 travel characteristics survey (TCS) (Transport Department and MVA Asia, 1993).

It is necessary to estimate the parameters of each traffic zone so as to apply the logit-type car ownership choice model for prediction, while it is only required to estimate the territory-wide model parameters in the territory-wide car ownership model. The number of parameters estimated in the territory-wide car ownership model is much less than that of the logit-type car ownership choice model. So the compounded error of the territory-wide model would be much less than the car ownership choice model's. Hence, it is believed that the total number of cars is more accurately estimated by the territory-wide model (i.e. Equation (3.1)) than the logit-type car ownership choice models (Tables 4.7 and 4.9). Therefore, it is decided to adjust the total number of cars obtained by the logit-type choice models so that it is equal to the total obtained by the territory-wide model. The logit-type choice models are more concerned with the distribution of zonal car ownership among the study area.

Thus, in order to agree with the territory-wide car ownership estimated by Equation (3.1), the estimated non-car owning households were multiplied by an adjustment factor ($1-\mu$) calculated by the following Equation (6.1).

$$\mu = \frac{(C - N_2 - mN_3)(N_2 + N_3)}{N_1(N_2 + mN_3)} \tag{6.1}$$

The estimated car owning households including single-car owning and multi-car owning households were multiplied by an adjustment factor λ determined by

$$\lambda = 1 + \frac{\mu N_1}{N_2 + N_3} \tag{6.2}$$

where C = the territory-wide car ownership estimated by Equation (3.1);

m = the number of cars owned by a multi-car owning household and is taken as an average of 2.2 that found in TCS;

N_1, N_2 and N_3 = the territory total number of households that are non-car owning, single-car owning and multi-car owning, respectively.

Table 6.1 shows the resultant number of non-car, single- and multi-car owning households together with the number of cars (i.e. user demand) obtained for each traffic zone.

6.4 CALIBRATION OF PARAMETERS IN THE PROPOSED BILEVEL CAR OWNERSHIP MODEL

With reference to the formulation of the proposed car ownership model in Chapter 5, it can be found that the following parameters in the lower-level CDA problem (5.5)-(5.12) needed to be calibrated:

(i) the dispersion parameter (α) in Equation (5.5) for a gravity-type trip distribution model; and

(ii) the parameters (β, η and e), in Equations (5.69) and (5.70), for the functions of trip productions and attractions.

In this Chapter, the link travel time function is generally expressed as

$$c_a(v_a) = c_a^0 \left\{ 1.0 + \mu_a \left(\frac{v_a}{S_a} \right)^{\lambda_a} \right\} \tag{6.3}$$

in order to incorporate the road network data of the study area, where μ_a can be obtained by

Table 6.1 Car Ownership Distribution by Zone

CTS-2 Zone number	Number of non-car owning Households	Number of single-car owning households	Number of multi-car owning households	Zonal car ownership demand (number of cars)
156	6,551	1,303	745	2,942
157	2,314	404	250	955
158	4,478	764	400	1,644
159	13,723	1,466	151	1,797
160	10,979	1,044	101	1,266
161	3,116	267	110	510
162	21,689	1,833	192	2,254
163	0	0	0	0
164	9,668	947	93	1,152
165	19	1	0	1
166	7,712	520	163	879
167	19,427	1,348	48	1,453
168	11,568	847	82	1,029
169	6,954	547	55	669
170	5,037	442	160	794
171	3,118	203	19	244
172	1,965	129	12	155
173	3,900	239	83	421
174	1,683	108	4	116
175	23,233	1,879	72	2,037
176	22	1	0	1
177	12,863	1,131	39	1,218
178	8,838	858	31	927
179	3,354	380	40	468
180	9,509	1,004	38	1,088
181	4,733	351	13	379
182	6,096	633	24	685
232	1,805	136	13	166
258	0	0	0	0
259	135	13	1	15
261	2,732	312	38	396
External zones	1,463,299	175,897	51,126	288,373
Total	1,670,520	195,007	54,103	314,034

$$\mu_a = \frac{c_a(S_a)}{c_a^0} - 1.0 \tag{6.4}$$

and the relevant parameters of the link travel time function can be extracted from the CTS-2 road network data as shown in Appendix C.

In response to the change of number of cars in each traffic zone, the functions of trip productions and attractions can be used to estimate the number of trips produced by origin zones and attracted to destination zones. However, external trips cannot be estimated on the basis of the relative time and distance perceived by the selected study network. Also, the gravity model cannot give the reliable O-D estimates, particularly for external zone pairs (Lam and Huang, 1994). Therefore, the O-D demand for external zone pairs (i.e. external – external travel) is fixed throughout the analysis.

The calibration method developed by Lam and Huang (1992b) was adopted for determining the parameter of the CDA model. The entropy information in the objective function was found to be the best measure for calibrating the CDA model. After completing the calibration process of the model, the parameter α = 4.5290 of the CDA model was obtained for the study area.

In order to incorporate the planning data of the study area in the model, the proposed functions of trip productions and attractions should be modified. A widely used multiple linear regression technique was adopted to derive the estimates of future trip productions and attractions. The following factors that have been proposed for consideration in many practical studies (Bruton, 1985; Ortúzar and Willumsen,

1994) and were considered in the regression analysis. They are referred to each traffic zone of the study area:

- Population;
- Employment;
- Number of households;
- Number of resident workers;
- Average monthly household income;
- Number of cars;
- Number of off-street residential (private) parking spaces; and
- Zonal accessibility.

Multiple linear regression models were applied using the above factors in the set of planning data with the number of observed trips produced from origins and attracted to destinations, respectively. The zonal car ownership demand obtained in Section 6.3 was used to represent the number of cars by zone for the calibration of the regression models. Zonal accessibility was defined in the Equations (5.71) and (5.72) by origin zone and destination zone respectively in Chapter 5. It was assumed that the parameter (δ) for reflecting the sensitivity of O-D travel time to accessibility is equal to the calibration parameter (α) of the gravity model in this case study (Ortúzar and Willumsen, 1994). By solving the lower-level CDA problem with the observed O-D demand, the zonal accessibility could be obtained.

From the correlation analysis, it was found that population, the number of households, the number of resident workers and the number of cars are highly correlated. The correlation coefficients among these four factors were greater then 0.75, which were statistically significant at the 0.01 level. The correlation of car ownership and the number of off-street residential (private) parking spaces by traffic zone was also found to be statistically significant at the 0.01 level. Therefore, in order to avoid the problem of multicollinearity, some of the factors would be excluded from the regression models.

It was found from the planning data that it is more appropriate to calibrate the trip production and attraction functions by land-use type. However, due to only 31 sets of planning data (for 31 internal zones), two land-use types were classified. One is for residential or mixed land use development, while the other one is for industrial or commercial purposes.

The results of the calibrated trip production and attraction functions are listed as below.

Residential or mixed development:

$$O_i = 0.128u_i + 21.346 ln(z_i) \qquad Adj.\ R^2 = 0.840 \qquad (6.5)$$
$$t-stat. \quad (3.666) \quad (4.245)$$

$$D_j = 1.543\times10^{-2}e_j + 18.611 ln(z'_j) \qquad Adj.\ R^2 = 0.791 \qquad (6.6)$$
$$t-stat. \quad (2.816) \quad (3.712)$$

Industrial or commercial development:

$$O_i = 3.599\times10^{-3}e_i + 0.417 ln(z_i) \qquad Adj.\ R^2 = 1.000 \qquad (6.7)$$
$$t-stat. \quad (278.215) \quad (22.579)$$

$$D_j = 1.757\times10^{-2}e_j + 15.816 ln(z'_j) \qquad Adj.\ R^2 = 0.853 \qquad (6.8)$$
$$t-stat. \quad (2.196) \quad (1.417)$$

where O_i = trip productions;

D_j = trip attractions;

u_i = car ownership in zone i;

e_i or e_j = employment in zone i or j;

z_i = zonal accessibility in zone i;

z'_j = zonal accessibility in zone j; and

$Adj.\ R^2$ = adjusted coefficient of determination.

The two zonal accessibility measures (z_i and z'_j) were taken a logarithmic transformation for improving the fitness of the models. For the zones with residential or mixed land use development, the two factors included in the functions (6.5) and (6.6) were found to be statistically significant at the 0.05 level. The calibrated models can explain the observed number of production and attraction trip ends by 80% and 79%, respectively. However, the zonal car ownership (u_i) could not give a great impact on both zonal trip productions. This means that a large number of cars (u_i) would not lead to a significant change in the number of trip produced in the traffic zones due to the small magnitudes of their coefficients.

For the industrial or commercial zones, employment and zonal accessibility were found to be the key factors for trip production and attraction. As no household or only a few households was found in these traffic zones, car ownership is not significant to affect the number of trips produced and attracted at these zones. Therefore, only accessibility measures affect the variation of trip production and attraction during the iteration. Note that employment data at these zones are given and fixed for the study year.

6.5 Determination of Maximum Car Ownership from Road Network Supply Conditions

The bilevel car ownership model that proposed in Section 4 of Chapter 5 can be used to determine the maximum car ownership by traffic zone under road network supply conditions. However, in this case study, some additional assumptions are made as the planning data on parking spaces by traffic zone is not available.

(a) The planning data only includes the number of off-street residential (private) parking spaces in each zone, while the number of on-street residential (private) parking spaces is not available. However, the total provision of on-street parking spaces in the Tuen Mun and Yuen Long areas can be collected by the Parking Demand Study in 1994 (Ove Arup & Partners, 1995). Assuming the on-street residential (private) parking spaces are proportional to the population in the traffic zones of the study area, the total number of residential parking spaces (off-street and on-street) can be obtained.

(b) Since the proportion of private and public parking spaces in each traffic zone is not available, it is assumed that public parking spaces are proportional to employment in all traffic zones of the study area.

(c) As the proportion of car owners who have their own private parking spaces is not known, the following assumptions are made. If the zonal car ownership demand (shown in Section 6.3) is less then the number of private parking spaces available in a particular zone, then it is assumed that all the cars are parked in the private parking spaces. Otherwise, the excess zonal demand is fulfilled by the public parking spaces within the traffic zone. Therefore, ϕ_{2i} can be expressed as

$$\phi_{2i} = \begin{cases} \dfrac{u_i - (1-\phi_{1k})h_j}{u_i}, & if \;\; u_i > (1-\phi_{1k})h_j \\ 0 & , if \;\; u_i \le (1-\phi_{1k})h_j \end{cases} \quad , for \;\; i = j = k \tag{6.9}$$

Apart from the parking data, the trip production rate by traffic zone is also not available in the planning data set. However, it is unreasonable to follow the assumption in the Chapter 5 that

$$p_i = \frac{O_i}{u_i}, \; i \in I \tag{6.10}$$

especially for the industrial or commercial zones. It is because there are only small proportion or even none of cars owned by residents in these zones, and the car trips produced by these zones are mainly made by company cars. Therefore, the formulation of the attraction-end parking constraint (5.3) in Chapter 5 is inappropriate in this case study and hence the constraint is not considered.

In this case study, the maximum number of cars is constrained by the link capacities and the boundaries of car ownership (parking spaces availability). Three link types, namely rural trunk road, urban primary distributor and urban trunk road, are chosen for case study in order to determine the maximum number of cars by zone when the traffic flows are restrained to the capacities of these links within the study area.

With the use of the proposed bilevel model under these assumptions, the maximum number of cars by zone and the reserve capacity of car ownership in the study area can be obtained by the SAB solution algorithm. However, due to the large consumption of computational time required (about 3 CPU-hours per iteration on a PII 450 machine with 256 RAM capability), ten iterations were carried out to obtain reasonable solutions. The results of the case study are presented in the next section together with discussion of the findings.

6.5.1 Results and Findings

Zonal car ownership demand obtained in Section 6.3 was used as the initial values of the number of cars in each internal zone for the bilevel car ownership problem. It should be noted that the car ownership for external zones is fixed as the external network is not taken into account explicitly. After solving the bilevel car ownership model, the maximum number of cars in each internal zone was found and shown in Table 6.2 and Figure 6.3.

It was found that some of the internal zones have positive reserve capacities of car ownership, which means that these zones can accommodate further car ownership potential growth. However, negative reserve capacities of car ownership were also found in the other internal zones. The zones with negative reserve capacities of car ownership imply that there are traffic congestion on the road network and shortage of parking space. Note that illegal parking is not considered in the proposed model. In fact, illegal parking usually occurs on roadside while traffic congestion always exists in the peak hours. Therefore, under the constraints of link capacities and parking spaces, negative reserve capacity of car ownership would exist.

Table 6.2 Car Ownership in the Internal Zones of the Study Area

CTS-2 Zone	Car ownership demand (pcu)	Maximum number of cars (pcu)	Reserve capacity* (pcu)
156	2,942	2,707.67	-234.33
157	955	1,832.00	877.00
158	1,644	2,639.00	995.00
159	1,797	1,112.85	-684.15
160	1,266	1,178.33	-87.67
161	510	743.00	233.00
162	2,254	1,281.67	-972.33
163	0	0.00	0.00
164	1,152	1,253.00	101.00
165	1	105.83	104.83
166	879	1,415.50	536.50
167	1,453	832.88	-620.12
168	1,029	1,112.20	83.20
169	669	871.06	202.06
170	794	239.81	-554.19
171	244	43.53	-200.47
172	155	185.14	30.14
173	421	1,277.85	856.85
174	116	58.10	-57.90
175	2,037	1,357.91	-679.09
176	1	460.54	458.54
177	1,218	737.03	-480.97
178	927	618.20	-308.80
179	468	312.13	-155.87
180	1,088	725.53	-362.47
181	379	252.52	-126.48
182	685	456.92	-228.08
232	166	335.00	169.00
258	0	0.00	0.00
259	15	11.73	-2.27
261	396	443.33	47.33

* Reserve capacity = Maximum number of cars – Car ownership demand

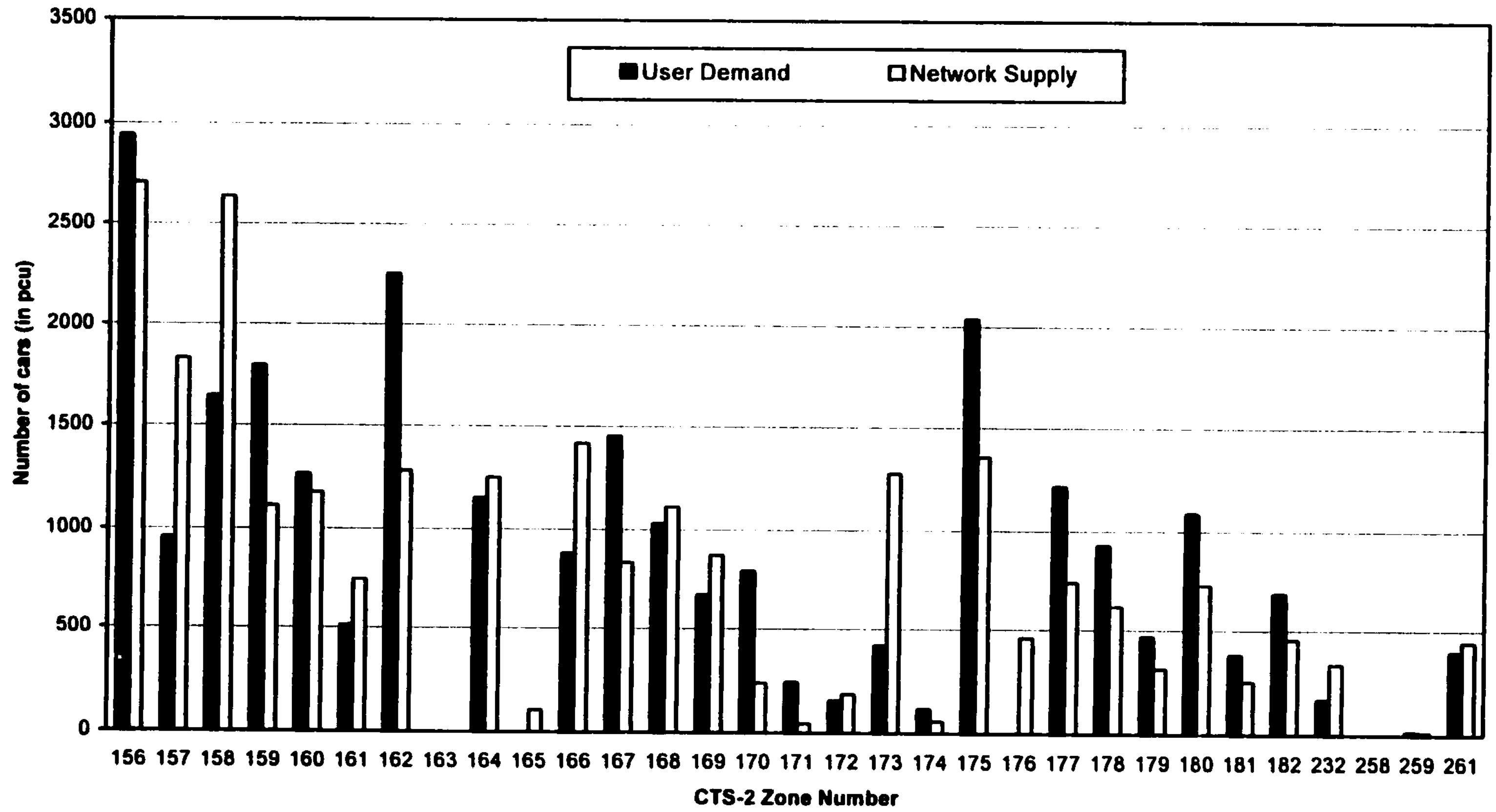


Figure 6.3 Zonal Car Ownership from the Views of User Demand and Network Supply

Thus, parking regulations should be applied to discourage illegal parking activities. Differential penalties for parking offences at congested roads or areas can be enforced to further optimize the utilization of the existing parking spaces. On the other hand, parking supply should also be increased or reallocated in order to satisfy the parking demand. As the main purpose of the study is to balance car ownership under the user demand and network supply conditions for strategic planning purposes, the parking behaviour problem is not considered in this research. However, it is worthwhile for further study particularly in view of the findings in Chapter 7.

From the above results, zonal car ownership growth should be suppressed in these zones, or the network should be expanded in order to fulfill the car ownership demand. The total user demand for car ownership is 25,661.00 pcu in the internal zones, however, car ownership under network supply constraints is reduced to 24,600.25 pcu. The results show that the study road network cannot cater for the car ownership demand by the existing supply conditions although the total reduction of car ownership is 4.13%.

Table 6.3 compares the flows and flow/capacity (V/C) ratios on the most congested links without (i.e. the initial condition) and with network supply constraint (i.e. the maximum solution). The computational V/C ratios indicate the degree of saturation on these links. Some of the links shown in the Table 6.3 are over-saturated at the initial condition, while the link capacity constraints are fulfilled in the maximum solution under the network supply conditions.

Table 6.3 Comparison of the Congested Links

Link		Initial condition (without network constraint)		Maximum solution (with network constraint)	
From	To	Link flow (v_a)	V/C ratio ($\frac{v_a}{S_a}$)	Link flow (v_a)	V/C ratio ($\frac{v_a}{S_a}$)
1302	1323	3,911.22	**1.03**	3,451.12	0.91
1305	1332	5,627.88	0.99	5,387.78	0.95
1314	1311	3,486.04	1.00	3.215.23	0.92
1314	1323	4,006.96	**1.05**	3,678.51	0.97
1323	1314	4,060.56	**1.07**	3,800.00	**1.00**
1332	1301	5,627.88	0.99	5,387.78	0.95
2001	2022	6,738.02	**1.01**	6,419.07	0.96
2003	1302	4,288.88	**1.07**	3,765.19	0.94
2004	2003	4,241.68	**1.06**	3,734.50	0.93
2008	2035	3,867.10	0.99	3,306.57	0.85
2035	2004	3,987.40	**1.02**	3,538.34	0.91
2500	2008	4,419.16	**1.00**	3,923.19	0.89

The total O-D demand is found to be reduced from 12,983.21 to 12,730.29 pcu/hr. The total reduction of trips is about 1.95%. The total network travel time is reduced from 13,383.98 hours to 13,104.76 hours. Thus, the total network travel time is reduced by 2.09% after maximization of the number of cars that constrained by the link capacities. As the degree of over saturation on links is not great, small suppression on the number of cars is required in the study area so as to satisfy the link capacity constraints, and so leads to small reductions on the total O-D demand and the network travel time.

The parking demand and supply required for the maximum number of cars by traffic zone are also presented in Table 6.4. The home-end parking demand is equivalent to the maximum number of cars obtained in the bilevel car ownership model. If the private parking spaces cannot cater for this demand, excess parking demand is fulfilled by the public parking spaces. The attraction-end parking demand is equivalent to the number of trips attracted to the zone. Since the attraction-end parking demand is not restrained, extra parking spaces are required to alleviate the illegal parking problem.

6.6 TERRITORY-WIDE CAR OWNERSHIP FROM USER DEMAND AND NETWORK SUPPLY

In the previous sections of this Chapter, the zonal car ownership in the study area was obtained with taking into account both the user demand and network supply aspects. This section is to determine the proportion of the territory-wide car ownership demand that would be fulfilled by the existing network supply conditions in the study area. Assuming that car ownership demand is restrained pro-rata in the external zones, the total maximum number of cars in the Hong Kong territory could be found on the basis of the results of the case study. The total maximum number of cars in the internal zones is 24,600.25 pcu, and the number of cars in the external zones is reduced from 288,373.00 pcu to 276,452.56 pcu proportionally. Thus, the number of cars is 301,052.82 pcu in the Hong Kong territory under the network supply conditions in the study area. The total number of cars in the Hong Kong is reduced from 314,034.00 pcu to 301,052.82 pcu and is suppressed by 4.13%.

Table 6.4 Parking Demand and Supply

	Parking Demand*		Parking Supply*		
CTS-2 Zone	Home-end (*a*)	Attraction-end (*b*)	Private spaces (*c*)	Public spaces (*d*)	Shortage of parking spaces#
156	2,708	214	8,123	509	0
157	1,832	197	1,832	385	0
158	2,639	199	2,639	324	0
159	1,113	246	3,074	623	0
160	1,179	212	1,414	406	0
161	743	243	2,229	610	0
162	1,282	288	3,845	917	0
163	0	156	0	211	0
164	1,253	402	1,253	1,640	0
165	106	473	127	1,967	0
166	1,416	194	2,831	292	0
167	833	248	333	642	106
168	1,113	392	1,580	1,573	0
169	872	263	1,226	747	0
170	240	206	2,279	366	0
171	44	189	801	259	0
172	186	178	433	196	0
173	1,278	240	1,763	602	0
174	59	178	70	260	0
175	1,358	253	1,485	715	0
176	461	150	1,417	31	119
177	738	256	1,020	686	0
178	619	400	447	1,636	0
179	313	206	456	357	0
180	726	347	545	1,274	0
181	253	175	250	196	0
182	457	214	481	504	0
232	335	276	402	864	0
258	0	125	0	16	109
259	12	155	3	59	105
261	444	150	665	45	105

* All figures are rounded-up to integer.

$$\text{\# } \textit{Shortage of parking spaces} = \begin{cases} 0, & \textit{if } (c) \geq (a) \textit{ and } (d) \geq (b) \\ 0, & \textit{if } (c) < (a) \textit{ but } (c)+(d) \geq (a)+(b) \\ (b)-(d), & \textit{if } (c) \geq (a) \textit{ but } (d) < (b) \\ (a)+(b)-(c)-(d), & \textit{if } (c) < (a) \textit{ and } (c)+(d) < (a)+(b) \end{cases}$$

By applying the results of the car ownership reliability analysis presented in Chapter 3, the probability of territory-wide car ownership estimated by user demand and network supply were obtained and the results are shown in Figure 6.4. It was found that the probability for estimating the car ownership demand is 53.69%, while for car ownership under network supply conditions is 36.85%. In other words, 36.85% of car ownership demand can be met by the existing network facilities.

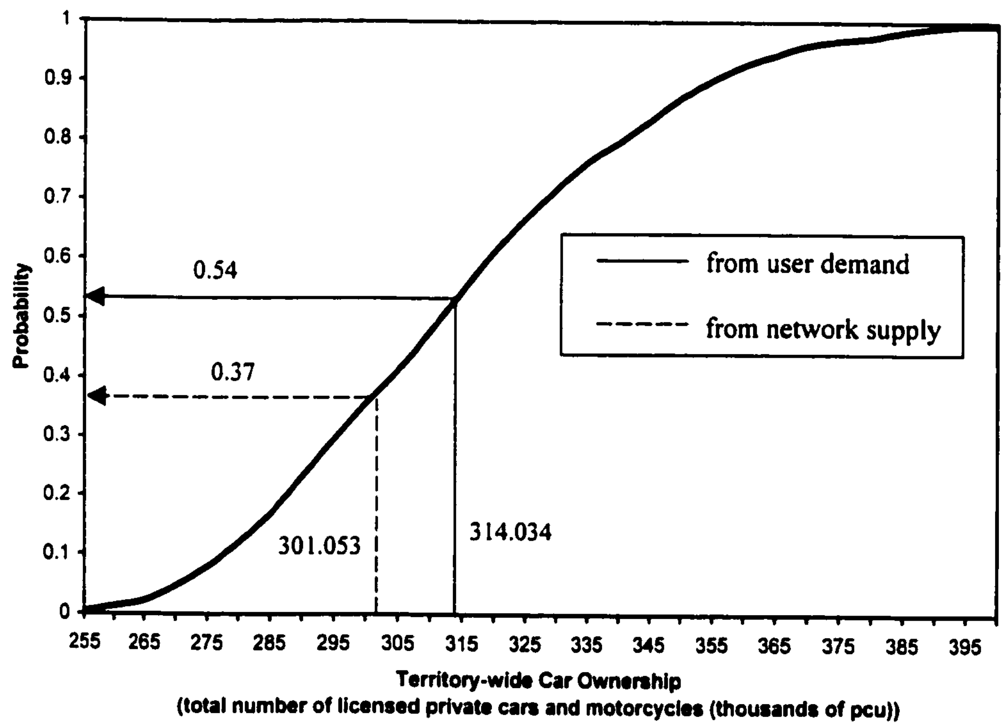


Figure 6.4 Territory-wide Car Ownership under User Demand and Network Supply Conditions

The balanced car ownership is an indicator for road expansion, reallocation of parking spaces, land use planning or suppression of car ownership demand. A high demand for car ownership leads to a great pressure on road network expansion and better traffic management. If the network is not expanded, the car ownership demand should be suppressed in order to alleviate traffic congestion. Based on the probability of car ownership demand that can be accommodated by the network supply conditions, an acceptance level for car ownership suppression or tolerance for car ownership demand can be determined. As a result, improvement of road network should be carried out when car ownership demand is beyond the acceptance level.

The effects of balancing car ownership can be examined by the total network travel time and the results are presented in Figure 6.5. Three scenarios including: (1) "unconstrained"; (2) "balanced" and (3) "redistributed" scenarios were studied. The unconstrained scenario is referred to the scenario that the car ownership demand is not constrained by the network supply conditions and the distribution of car ownership demand is estimated by the logit-type choice models (Tables 4.7 and 4.9). The balanced scenario implies that the demand is equal to supply. In other words, the car ownership is determined under both user demand and network supply conditions, i.e. the results obtained in the case study. The redistributed scenario is the scenario that the distribution of the car ownership demand is adjusted on pro-rata basis by the distribution of balanced car ownership.

The results show that the total network travel times in the unconstrained scenario are greater than that in the balanced car ownership even in the case with 10% of car ownership demand. Thus, balanced scenario gives a better distribution of cars among the traffic zones.

In the redistributed scenario, it is found that the total network travel time increases when the probability of car ownership demand is greater than the balanced one. This is because travel time is increased due to over-saturation of flows on links. Although the total network travel time decreases when the probability of car ownership demand in the redistributed scenario is less than that in the balanced scenario, over provision of link capacities means inefficiency and the social costs should be paid for. Hence, the balanced car ownership seems to be most efficient in utilization of existing resources.

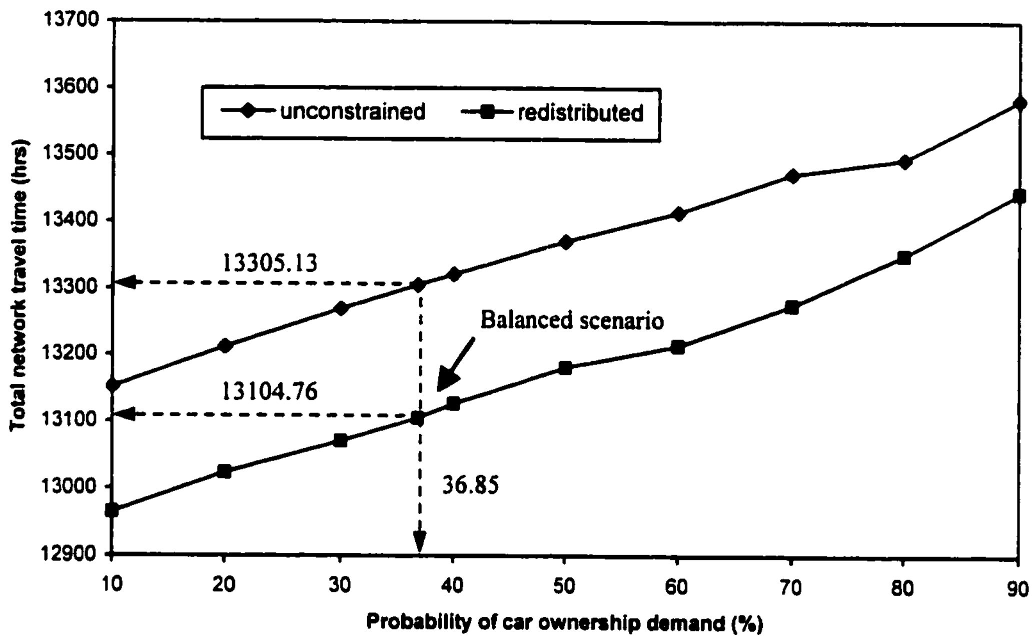


Figure 6.5 Total Network Travel Time for Various Car Ownership Demand

6.7 SUMMARY

This chapter integrates the models that presented in Chapters 3 to 5 using a case study at a selected study area in Hong Kong. The case study demonstrates that the maximum car ownership obtained from both views of user demand and network supply. Based on the results of aggregate and disaggregate car ownership models in Chapters 3 and 4, the zonal car ownership demand in the study area could be calculated. The maximum number of cars that was constrained by the link capacities and parking spaces has been determined by the proposed bilevel model in Chapter 5 under the network supply conditions.

It was found in the case study that some of the internal zones have negatively potential growth for car ownership. Thus, the car ownership demand should be suppressed under the condition of the existing network supply in the study area. If more car ownership demands need to be satisfied, the road network should be expanded. The balanced car ownership can act as an indicator for network expansion, reallocation of parking spaces, land use planning and establishment of efficient policies for controlling car ownership demand.

The effects of balancing car ownership were investigated by the total network travel times in the unconstrained and redistributed scenarios. It was found that, on the one hand, the balanced car ownership gives the least total network travel time when compared with various probabilities of car ownership demand in the unconstrained scenario. On the other hand, the balanced car ownership seems to be most efficient in utilization of existing resources in the redistributed scenario.

7 BALANCE OF DEMAND AND SUPPLY OF PARKING SPACES

There is always a controversy on whether the demand and supply of parking spaces should be balanced. This chapter extends the concept of balancing car ownership to investigate the effects of balancing the parking demand and supply. A bilevel programming model is proposed to determine the minimum supply of parking space required so as to take into account the elasticity effects of road congestion and parking delays on parking demands.

7.1 BACKGROUND OF PARKING PROBLEM

Parking is a common problem for most motorists in urban areas. Due to the inherent uncertainty associated with many of the attributes of public car parks (Saloman, 1986; Polak and Axhausen, 1990), a high proportion of motorists travelling within central city areas must search for a car park. A shortage of parking space increases the searching time for an available parking space and hence induces traffic congestion and environmental pollution problems. It also causes illegal roadside parking and traffic accidents. As a result, there may be a reduction of road space. However, excess parking spaces in some areas may represent a waste of resources and also induce traffic on the roads. Over-provision of parking spaces means inefficiencies, which need to be paid for, both in financial terms and in social costs. Such parking problems are caused by inaccurate prediction of car ownership/usage and parking supply. Parking controls are seen importantly to regulate and restrain car use, and develop parking facilities according to the estimated level of car ownership and parking demand (Coombe *et al.*, 1997).

Car parking is an issue of significance both at the local and at the strategic level of planning. Parking policy and supply play a major role in the management of transportation systems in urban areas. Although the policies that govern the provision and operation of parking facilities are recognised to have an important bearing on the operation of urban transport systems, decisions have often not been properly integrated with other elements of transport system analysis.

7.2 Review of Parking Models

A comprehensive review of parking models (Young *et al.*, 1991) identified a number of modelling approaches that have been used to understand and replicate parking choice behaviour. These choice models are used to investigate the demand for parking within a given supply situation. The models mainly concentrate on the choice of parking location (Ergun, 1971; Hunt, 1988) and the impact of parking on mode choice (Feeney, 1989). The effects of parking cost and access time and a number of socio-economic variables on parking location behaviour are studied in their models. Thompson and Richardson (1998) developed a parking search model to better understand the parking choice behaviour.

The second approach is to formulate the parking problem as an allocation problem, in which a fixed number of arrivals is allocated onto the parking lots on the basis of a measure of the relative attractiveness of each element of the parking lots. Optimisation models are developed to determine the optimal location of parking spaces in a way that minimizes the total walking distance for all parkers (Oppenlander and Dawson, 1988). The constraint models adopt the principle that parkers will look for a satisfactory parking space rather than an optimal one (Young, 1982). Gravity models for parking allocation (Bullen, 1982) provide estimates of the interchange of trips between particular origins and destinations. Their behavioural basis offers a number of advantages over the optimisation and constraint models, particularly for those trips where the parking location decision would affect the choice of destination. However, the vehicle trip production and attraction (i.e. parking demand) may not be fixed if the effects of road congestion and accessibility on trip production and attraction are taken into account.

Nour Eldin *et al.* (1981) developed a model different to the traditional assignment model by considering interaction between parking supply and vehicular traffic assigned to urban streets. The links included all parking facilities in the road network and a capacity correction factor was incorporated to take into account the illegal parking. Gur and Beimborn (1984) developed an equilibrium assignment model for analysis of parking process in dense urban areas. The model could provide estimates of parking impedance for each destination zone in the study area and the level of use of each parking location in the area. It was nevertheless assumed that the parking demand is constant and fixed in their models.

Bifulco (1993) studied a model, which consists of a supply model, a demand model and a supply/demand model. On the supply side, network-based and proper functions are introduced to simulate the attributes (e.g. parking access time, searching time) related to parking choices. The demand side of the model consists of a stochastic choice model in which a steady-state parking demand by time period is allocated onto the network and parking spaces. The connection between two successive time periods is mainly the parking occupancies carried over to the next period.

The traffic assignment/allocation models proposed by Nour Eldin model (1981) and Gur-Beimborn model (1984) both adopt the traditional deterministic user equilibrium (UE) conditions; while Bifilco's model (1993) uses stochastic user equilibrium (SUE) assignment. However, they all assumed a fixed origin-destination (O-D) demand. In general, the target O-D matrix should be varied and dependent on the future development of each urban area and the traffic conditions of the study network. To overcome this shortcoming, a combined trip distribution/assignment (CDA) model (Evans, 1976; Lam and Huang, 1992a) can be adopted to incorporate both destination and route choices of motorists.

Lam *et al.* (1998) evaluated the parking demand in Hong Kong using a stated preference survey and examined the influence of parking space availability on mode choice. A parking demand model has also been developed to forecast the future demand for parking facilities in different districts of Hong Kong. It was found that there was a shortfall in parking facilities provision, which are compatible with the results obtained by Lam and Tam (1997). Lam and Tam (1997) pointed out that an underestimation of parking demand would be obtained if the standard transport model was used to predict car ownership in Hong Kong. In order to assess maximum car ownership under network constraints, a bilevel programming model has been developed and presented in the previous chapters. The growth potential of car ownership can be determined by the bilevel programming model under the constraints of road capacities and parking supply.

7.3 EXTENSIONS OF THE STUDY

It is found that the previous work mainly concentrates on parking behaviour and deals with the allocation of parking demand for a fixed parking supply. In strategic transport planning, the number of parking spaces should however be supplied in response to elastic parking demand. A balance of demand and supply of parking spaces seems to be important for strategic transport planning. The balance of demand and supply of parking spaces can reduce the searching time for an available parking space, and hence reduce the total network travel time. Although increasing the number of parking spaces can reduce parking search-time, it would induce traffic and decrease the utilization rate of a parking space. Thus, a balance of demand and supply of parking spaces would lead to a reduction in total network travel time and full utilization of parking space.

This chapter makes three extensions of the existing parking models. Firstly, it is the first bilevel programming model that balances the parking demand and supply coherently. Secondly, the CDA model is adopted to incorporate the destination and route choices of motorists simultaneously. Thus, the O-D travel demand is not fixed. Finally, the vehicle trip production and attraction ends are elastic to traffic congestion and availability of parking spaces.

7.4 ASSUMPTIONS

Generally, the type of parking space can be classified as private or public. Home-end parking demand is assumed to be catered by the private parking spaces that are known and fixed. Otherwise, the excess home-end parking demand is presumed as the pre-occupancy of the public parking spaces. However, the public users normally cannot use the private car parks. In this study, attention is given to the attraction-end parking. Thus, the public parking space is the key decision variable in the proposed model. In the following sections, parking spaces (demand and supply) are referred to the public parking spaces only. In addition, further assumptions are also used to facilitate the presentation of the essential ideas without loss of accuracy or leading to an erroneous conclusion.

As the proposed model is aimed to be used for strategic planning of parking supply, the following assumptions are made throughout the study:

(a) A single user class is adopted. However, the model can be extended to multi-user classes (Lam and Huang, 1992a).

(b) Travel times on road links are continuous and strictly increasing functions of link flows. The link travel time functions are assumed to be differentiable and separable. These assumptions will ensure the uniqueness of the solution to the network equilibrium problem if it exists (Sheffi, 1985). Capacity constraint effect is not considered in this study but the overflow delay is incorporated into the link travel time function (Bell and Iida, 1997).

(c) Drivers have sufficient and perfect network information to make routing decisions in a user equilibrium manner (Sheffi, 1985).

(d) The study period is assumed to be a one-hour (unit time) period, such as the morning peak hour period. However, the proposed model can cater for the time of day element by splitting a typical day into several time periods. It is known that the morning peak hour is usually the most critical period in a typical weekday and all car trips are home-based work trips to work. It is also assumed that no round trips occur during the one-hour study period. Linked trips are treated as a number of separate trips.

(e) The network is assumed to be fixed with constant road capacity in terms of passenger car units per hour (pcu/hr).

(f) Public transport network is assumed to be constant and fixed.

(g) The population, number of job places and cars in each traffic zone is given and fixed.

(h) As the study period is a one-hour time-slice of a weekday, parking space is allowed to be occupied at the beginning of the study period. It should be noted that the proposed model could be extended to time-dependent dimension. This is because the model allows for the parking spaces to be occupied at the beginning of the one-hour study period and to be carried over to the next hour period (Bifulco, 1993).

(i) As the proposed model is for planning purposes, each car must occupy one parking space at the destination during the study period, i.e. no illegal parking is allowed.

(j) When a car trip is attracted to a traffic zone, it represents a car entering the traffic zone and looking for a parking space. Thus, trip attraction is equivalent to the parking demand.

(k) The zonal trip production by car is assumed to be a function of the number of people living in a zone, the number of cars owned by the residents in the zone, and an accessibility measure for producing car trips. The accessibility measure reflects the degree of ease or difficulty in making trips from each production zone (Leake and Huzayyin, 1980; Bruton, 1985).

(l) The zonal trip attraction by car is assumed to be a function of the number of job places in a zone, the number of parking spaces available in that zone and an accessibility measure for attracting car trips (i.e. ease or difficulty of making trips to each attraction zone).

(m) The accessibility measure for trip production is affected by the number of car trips attracted and the generalised travel time from an origin zone to a destination zone (Leake and Huzayyin, 1980; Ortúzar and Willumsen, 1994). The accessibility measure for trip attraction is influenced by the number of car trips produced and the generalised travel time by O-D pair.

7.5 NETWORK EQUILIBRIUM PROBLEM WITH ELASTIC TRIP PRODUCTION AND ATTRACTION ENDS

The problem of minimizing the total supply of parking spaces for satisfying the elastic parking demand, can be formulated as the following bilevel programming problem:

(Upper-level)

$$\underset{\mathbf{h}}{Minimize} \sum_{j \in J} h_j \tag{7.1}$$

subject to

$$\sum_{i \in I} t_{ij}(\mathbf{h}) \leq h_j - h_j^{occ}, \quad j \in J \tag{7.2}$$

$$h_j^{occ} < h_j \leq h_j^{max}, \quad j \in J \tag{7.3}$$

where the equilibrium O-D demand $t_{ij}(\mathbf{h})$, $i \in I, j \in J$ is obtained by solving the following network equilibrium trip distribution/assignment problem:

(Lower-level) $\underset{v}{Minimize} \sum_{a} \int_{0}^{v_a} c_a(x)dx + \frac{1}{\alpha} \sum_{i} \sum_{j} t_{ij}(\ln t_{ij} - 1) + \sum_{j} \int_{0}^{\sum_i t_{ij}} d_j(y)dy$ (7.4)

subject to

$$\sum_{r \in R_w} f_r = t_{ij}, i \in I, j \in J \tag{7.5}$$

$$\sum_{j \in J} t_{ij} = O_i, \ i \in I \tag{7.6}$$

$$\sum_{i \in I} t_{ij} = \overline{D}_j, j \in J \tag{7.7}$$

$$v_a = \sum_{r \in R} f_r \delta_{ar}, \ a \in A \tag{7.8}$$

$$f_r \geq 0, \ r \in R \tag{7.9}$$

$$t_{ij} \geq 0, \ i \in I, j \in J \tag{7.10}$$

As the proposed model is aimed for long-term strategic planning, the drivers are assumed to be familiar with the road network. Thus, the user equilibrium (UE) conditions are adopted in the model in which drivers have complete information to the road network and parking availability. Steady state traffic flow is also assumed in the model and therefore the vehicle trips would be completed in the one-hour study period. The proposed model can be extended to time-dependent dimension because the model allows for parking spaces to be occupied at the beginning of the one-hour study period and to be carried over to the next hour period and so the parking duration could be considered.

The trip production and attraction in Equations (7.6) and (7.7) are defined as below:

$$O_i = \beta_0 \ z_i + \beta_1 q_i + \beta_2 u_i, i \in I \tag{7.11}$$

$$\overline{D}_j = \frac{\sum_{i \in I} O_i}{\sum_{j \in J} D_j} D_j = \frac{\sum_{i \in I} \beta_0 z_i + \beta_1 q_i + \beta_2 u_i}{\sum_{j \in J} \gamma_0 z'_j + \gamma_1 e_j + \gamma_2 (h_j - h_j^{occ})} (\gamma_0 z'_j + \gamma_1 e_j + \gamma_2 (h_j - h_j^{occ})), \ j \in J \tag{7.12}$$

and the accessibility measures are defined as follows (Safwat and Magnanti, 1988):

$$z_i = \max\{0, \ln \sum_{j \in J} \overline{D}_j \exp(-\theta(g_{ij} + d_j))\} \tag{7.13}$$

$$z'_j = \max\{0, \ln \sum_{i \in I} O_i \exp(-\theta(g_{ij} + d_j))\} \tag{7.14}$$

The BPR (Bureau of Public Roads, 1964) link travel time function is used.

$$c_a(v_a) = c_a^0 \{1.0 + 0.15(\frac{v_a}{S_a})^4\}, \ a \in A \tag{7.15}$$

It is noted in Equations (7.11) and (7.12) that the sensitivity of accessibility measures (Ortúzar and Willumsen, 1994) and the effect of social factors on trip production and attraction are incorporated in the proposed model. The merit of elastic trip production and attraction ends is the capability of reflecting the responses of motorists to traffic congestion and availability of parking facilities. These include changing the time of day at which a journey is made and switching to an alternative mode or not making the journey.

As more car trips attracted to a destination would increase the parking demand at that destination, the time required to search for a parking space would become longer. Hence, the parking delay is not fixed, but follows a function, $d_j = d_j(\overline{D}_j)$, of the number of car trips attracted to destination j. The parking delay function is strictly increasing with trip attraction.

The generalised cost for parking delay can be considered as the free-flow parking access time, d_{0j}, plus the searching time for an available parking space plus the parking fee. The equivalent time of the parking fee, F_j, can be calculated using a pre-determined value of time. The free-flow access time is the minimum time taken to reach the parking facilities in a given zone under free-flow conditions. A complicated searching time function for an available parking space was adopted by Bifulco (1993). In this study, a simplified searching time function (7.16) is adopted. In order to calibrate the parameter of Equation (7.16), the searching time was calculated by Bifulco's search-time cost function with various parameter values. The value of the parameters in Equation (7.16) were then obtained by regression analysis based on the calculated data.

$$searching\ time = \mu\left(\frac{\overline{D}_j}{h_j - h_j^{occ}}\right)^{\lambda},\ j \in J \tag{7.16}$$

Hence, the parking delay function (in hrs) becomes:

$$d_j(\overline{D}_j) = d_{0j} + 0.31\left(\frac{\overline{D}_j}{h_j - h_j^{occ}}\right)^{4.03} + F_j,\ j \in J \tag{7.17}$$

The lower-level problem (7.4)-(7.10) is a CDA problem that can be solved by a convex-combination method for given $\mathbf{h}$ and trip production and attraction ends. The traffic flow v_a obtained in the lower-level problem represents the equilibrium flow on link $a \in A$ when the number of parking spaces in the zone j is h_j. The function of the balanced trip attractions ($\overline{D}_j$) is used to adjust the total trip attractions to be equal to the summation of trip productions. By solving the CDA problem, the equilibrium link flows, path flows, O-D travel patterns, journey times and parking delays will be obtained. The resultant journey time g_{ij} and parking delay d_j are used to update the accessibility measures using Equations (7.13) and (7.14). These results will then be fed into the upper-level problem (7.1)-(7.3) to determine the minimum total number of parking spaces required subject to the parking demand constraints.

A new set of parking spaces h_j by traffic zone j will be obtained by solving the upper-level problem. This set of values will then be applied to the Equation (7.12) and the parking delay function (7.17) for solving the lower-level problem again. This process will be repeated until a desirable convergence is achieved (see the proposed algorithm below). Figure 7.1 shows the flow chart of the mechanism of the proposed model.

The attraction trips (representing the number of cars entering a destination zone) should be less than or equal to the number of parking spaces so that the attraction-end parking demand is fulfilled. It is assumed that the illegal parking is restricted. As it is further assumed that no round trips is made during the one-hour peak period, the cars entering a destination zone are classified as visitors and cannot occupy the parking spaces owned by the residents in that zone. In general, the number of parking spaces built in each traffic zone should be bounded by an upper limit due to the limited land supply and/or parking standard.

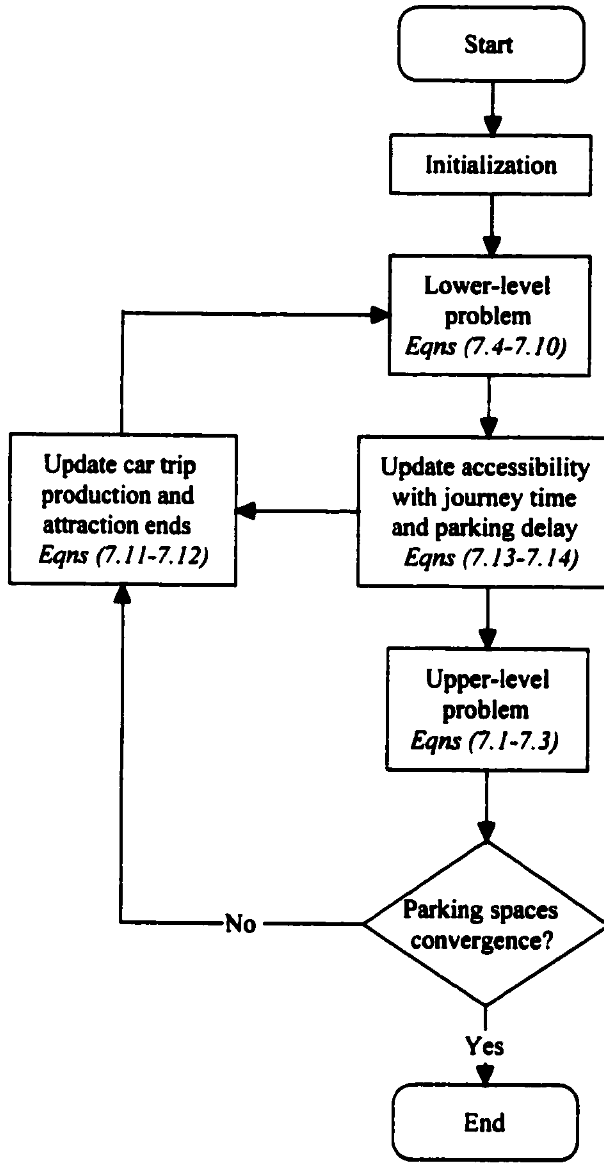


Figure 7.1 Flowchart of the Proposed Parking Model

The parameters in Equations (7.11) and (7.12) are to be estimated for trip production and attraction, respectively. The general form of accessibility measures can be expressed as a function of the generalised travel time between zones i and j, and the size of activity in zone i or j (Leake and Huzayyin, 1979; Ortúzar and Willumsen, 1994). In Equations (7.13) and (7.14), the size of activity in zones i and j are defined as the trip production and attraction in the last iteration respectively. θ is a parameter to reflect the sensitivity of journey time on the accessibility. An increase in accessibility would generate higher demand for travel. As accessibility is expressed as a negative exponential function with parameter θ, an increase in θ will decrease the accessibility. Thus accessibility is, by definition, inversely related to the parameter θ. In general, changes in θ tend to have greater effect on accessibility to non-work activities than on work activities. It is because work trips are less sensitive to travel time/cost than non-work trips. Thus, a small value should be adopted for work journeys. Sensitivity tests for various θ are to be carried out in the numerical example.

The dispersion parameter α for trip distribution in Equation (7.4) is a measure to reflect the sensitivity of journey time from an origin to a destination. An increase in α would generate an O-D travel demand and/or trip length frequency with shorter journey times. The effect of α is to be examined together with the sensitivity tests on parameter θ.

7.6 SENSITIVITY ANALYSIS BASED ALGORITHM

The parking demand constraint (7.2) in the upper-level problem involves the nonlinear and implicit function of the decision variable **h**. Therefore, local linear approximations using Taylor's formula are implemented based on the derivatives of the O-D demands with respect to the number of parking spaces by traffic zone. The derivative information is obtained by implementing the method of sensitivity analysis

(Tobin and Friesz, 1988; Yang and Yagar, 1994), which is similar to the procedure mentioned in Chapter 5. The resulting linear programming problem can then be solved using the well-known simplex method.

The linear approximation of parking demand constraint (7.2) can be derived as below:

$$t_{ij}(\mathbf{h}) \approx t_{ij}(\mathbf{h}^*) + \nabla_{\mathbf{h}} t_{ij}(\mathbf{h}^*)(\mathbf{h} - \mathbf{h}^*),\ i \in I, j \in J \tag{7.18}$$

where $\nabla_{\mathbf{h}} t_{ij}$ can be obtained by the method of sensitivity analysis for the network equilibrium problem. $\mathbf{h}^*$ is the solution at the current iteration and $t_{ij}(\mathbf{h}^*)$ is the corresponding equilibrium O-D travel demand. Equation (7.18) is then applied to Equation (7.2) to form a set of simple linear constraints.

The mechanism of the solution algorithm is an iterative process between the upper-level and the lower-level problems. The proposed sensitivity analysis based (SAB) algorithm can be described as follows:

SAB Algorithm:

Step 0. Determine an initial number of parking spaces $\mathbf{h}^{(n)}$ and trip productions and attractions by cars. Set $n = 0$.

Step 1. Solve the lower-level combined trip distribution/assignment problem (7.4)-(7.10) for given $\mathbf{h}^{(n)}$; and hence get $\mathbf{v}^{(n)}$, $\mathbf{T}^{(n)}$ $\mathbf{g}^{(n)}$ and $\mathbf{d}^{(n)}$.

Step 2. Calculate the accessibility measures using Equations (7.13) and (7.14), and hence find the new trip productions and attractions by Equations (7.11) and (7.12).

Step 3. Calculate the derivative $\nabla_{\mathbf{h}}\mathbf{T}^{(n)}$ using sensitivity analysis method.

Step 4. Formulate local linear approximations of the upper-level parking constraint (7.2) using the derivative information, and solve the resulting linear programming problem to obtain an auxiliary solution $\mathbf{y}$.

Step5. Use the method of successive averages (MSA) to compute the new number of parking spaces, $\mathbf{h}^{(n+1)} = \mathbf{h}^{(n)} + \frac{1}{n+1}(\mathbf{y} - \mathbf{h}^{(n)})$.

Step 6. If $|h_j^{(n+1)} - h_j^{(n)}| \le \omega$ for all $j \in J$ then stop, where ω is a pre-determined error tolerance and is set to be 0.0001 in the numerical example. Otherwise let $n := n+1$ and return to Step 1.

7.7 NUMERICAL EXAMPLE

A numerical example is presented to illustrate how to use the proposed model to minimize the supply of parking spaces for satisfying the elastic parking demand. The example is designed to demonstrate the advantages of the balance of demand and supply of parking spaces using the proposed model. Three scenarios: (1) "Demand" = "Supply"; (2) "Demand" > "Supply"; and (3) "Demand" < "Supply", are studied. The effects of sensitivity of accessibility measures (parameter θ) on the total network travel time defined by Equation (7.19) and the supply of parking spaces are investigated together with various values of dispersion parameter α.

$$Total\ network\ travel\ time = \sum_{a \in A} c_a(v_a) \times v_a + \sum_{j \in J} d_j(\overline{D}_j) \times \overline{D}_j \qquad (7.19)$$

The example road network shown in Figure 7.2 consists of 4 zone centroids (represented by dotted line circles and connected to road nodes by parking links), 6 road nodes and 14 one-way links. The link travel time data is presented in Table 7.1 and the data for parking, trip production and attraction and the parameter values are given in Table 7.2. The value of dispersion parameter α is assumed to be 0.1 for the gravity-type trip distribution model in this example. It should be borne in mind that the parking spaces (demand and supply) used in this example are referred to the public parking spaces.

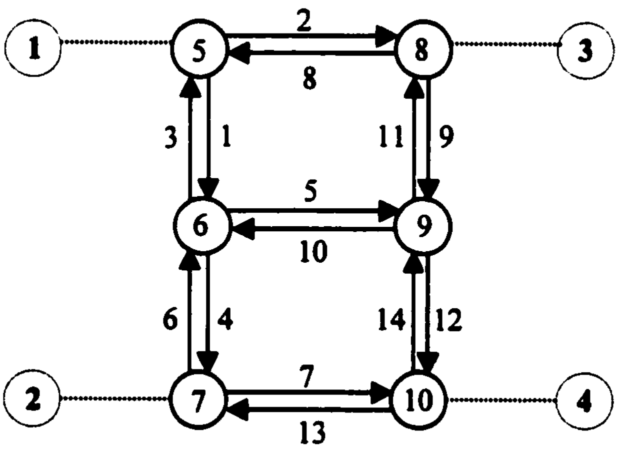


Figure 7.2 Example Network

Table 7.1 Link Travel Time Data for the Example Network

Link Number a	Free-flow travel time c_a^0 (hrs)	Capacity S_a (pcu/hr)
1, 3	0.15	1,500
2, 8	0.15	800
4, 6	0.15	1,500
5, 10	0.10	1,500
7, 13	0.15	800
9, 11	0.15	1,500
12, 14	0.15	1,500

Table 7.2 Trip Production, Attraction and Parking Data for the Network

	Zone 1	Zone 2	Zone 3	Zone 4
Population, q_i (10^3)	35	52	48	30
Employment, e_j (10^3)	32	21	27	20
Number of cars, u_i (10^3)	1.8	2.5	2.2	1.6
Free-flow parking access time, d_{0j} (hrs)	0.020	0.035	0.030	0.025
Parking charge, F_j (hrs)	0.080	0.065	0.053	0.086
Upper limit of parking spaces supplied, h_j^{max}	5,000	5,000	5,000	5,000
Pre-occupied parking spaces, h_j^{occ}	80	120	75	50
Parameter, β_0, for trip production	125.60	125.60	125.60	125.60
Parameter, β_1, for trip production	0.0063	0.0063	0.0063	0.0063
Parameter, β_2, for trip production	0.46	0.46	0.46	0.46
Parameter, γ_0, for trip attraction	122.40	122.40	122.40	122.40
Parameter, γ_1, for trip attraction	0.0072	0.0072	0.0072	0.0072
Parameter, γ_2, for trip attraction	0.53	0.53	0.53	0.53
Parameter, θ, for accessibility	0.50	0.50	0.50	0.50

7.7.1 Scenario (1): Parking Demand = Parking Supply

Firstly, the balance of parking demand and supply is studied using the proposed bilevel model. In the formulation of the model, parking supply is minimized but still ensure that it can cater for parking demand. Thus, parking supply is minimized to parking demand and so an equality of parking demand and supply reaches.

As the number of parking spaces supplied would affect the searching time for an available parking space, which influences the desire for trip making and the distribution of travel patterns, parking demand at each traffic zone would then be changed. Subsequently, the change of zonal accessibility would lead to a change in trip production and attraction. Tables 7.3 and 7.4 show the demand and supply of parking spaces and the total network travel time of the example network under the initial and balanced scenarios, respectively. Since the balance of parking demand and supply is obtained, the utilization of parking spaces is 100%. The resultant link flows are compared in Table 7.5 for the cases with initial and optimum solutions.

Table 7.3 Results at Initial Conditions

	Zone 1	Zone 2	Zone 3	Zone 4	Total
(a) Parking demand *, $\overline{D}_j$	2,360.10	2,284.74	2,335.07	2,307.19	9,287.10
(b) Total parking supply, h_j	3,500	3,500	3,500	3,500	14,000
(c) Pre-occupied parking spaces, h_j^{occ}	80	120	75	50	325
(d) Available parking spaces, $h_j - h_j^{occ}$	3,420	3,380	3,425	3,450	13,675
(a)/(d)	**0.69**	**0.68**	**0.68**	**0.67**	**0.68**
(e) Total network travel time (hrs)			**4,585.11 (100%)**		
- Total link travel time			**3,064.70 (66.8%)**		
- Total parking delays			**1,520.41 (33.2%)**		

* Parking demand was calculated by Equation (7.12).

Table 7.4 Results of Scenario 1

	Zone 1	Zone 2	Zone 3	Zone 4	Total
(a) Parking demand, $\overline{D}_j$	2,351.55	2,189.47	2,276.31	2,195.29	9,012.62
(b) Total parking supply, h_j	2,431.55	2,309.47	2,351.32	2,245.28	9,337.62
(c) Pre-occupied parking spaces, h_j^{occ}	80	120	75	50	325
(d) Available parking spaces, $h_j - h_j^{occ}$	2,351.55	2,189.47	2,276.32	2,195.28	9,012.62
(a)/(d)	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
(e) Total network travel time (hrs)			**6,609.15 (100%)**		
- Total link travel time			**2,928.53 (44.3%)**		
- Total parking delays			**3,680.62 (55.7%)**		

Table 7.5 Equilibrium Link Flow and Flow/Capacity Ratio

Objective function $\sum_{j=1}^{4} h_j$	*Initial solution* 14,000.00		*Optimum solution* 9,337.62	
Link a	v_a (pcu/hr)	v_a/S_a	v_a (pcu/hr)	v_a/S_a
1	1,423.40	0.95	1,366.99	0.91
2	755.50	0.94	742.09	0.93
3	1,530.51	**1.02**	1,521.07	**1.01**
4	1,579.81	**1.05**	1,520.96	**1.01**
5	1,568.19	**1.04**	1,516.00	**1.01**
6	1,759.60	**1.17**	1,735.37	**1.16**
7	848.40	**1.06**	804.18	**1.01**
8	829.59	**1.04**	830.48	**1.04**
9	1,615.21	**1.08**	1,545.07	**1.03**
10	1,495.51	1.00	1,455.67	0.97
11	1,579.56	**1.05**	1,534.22	**1.02**
12	1,458.79	0.97	1,391.10	0.93
13	704.93	0.88	668.51	0.84
14	1,350.47	0.90	1,319.92	0.88

7.7.2 Scenario (2): Parking Demand > Parking Supply

In the second scenario, the parking supply is reduced from 3,500 to 2,000 parking spaces for each traffic zone. By solving the lower-level problem with the fixed parking supply, the parking demand and the total network travel time was obtained. If parking demand is greater than the number of parking spaces available, the parking delay would be increased. Thus, the journey time would also increase. The accessibility measures would reflect the increase of travel time. The desire of trip making would then be reduced and car traffic suppressed. However, the parking demand would not be reduced significantly in the morning peak hours.

The resulting parking demand and supply are shown in Table 7.6 together with the total network travel time. It is found that the overall parking demand exceeds the available parking spaces by 17% and the total network travel time is increased significantly by 35% as compared to the balanced scenario i.e. Scenario (1).

Since illegal parking is not allowed in the model for the planning purpose, an artificial shadow link (Lam and Zhang, 1999) can be introduced to each zone centroid so as to store the excess demand vehicles. The excess demand vehicles then cruise around in the shadow links until parking spaces are available in the next time slice. The volumes on the shadow links would affect the travel parameters (e.g. vehicle-hours of travel) but they have been considered in the parking delays. The waiting time on the shadow links can be referred to the parking delay that included in the model.

Table 7.6 Results of Scenario 2

	Zone 1	Zone 2	Zone 3	Zone 4	Total
(a) Parking demand, $\overline{D}_j$	2,286.78	2,180.81	2,251.13	2,223.76	8,942.48
(b) Total parking supply, h_j	2,000	2,000	2,000	2,000	8,000
(c) Pre-occupied parking spaces, h_j^{occ}	80	120	75	50	325
(d) Available parking spaces, $h_j - h_j^{occ}$	1,920	1,880	1,925	1,950	7,675
(a)/(d)	**1.19**	**1.16**	**1.17**	**1.14**	**1.17**
(e) Total network travel time (hrs)			**8,918.26 (100%)**		
- Total link travel time			**2,892.55 (32.4%)**		
- Total parking delays			**6,025.71 (67.6%)**		

7.7.3 Scenario (3): Parking Demand < Parking Supply

In the third scenario, the parking supply is increased from 2,000 to 2,500 parking spaces in each traffic zone. Parking demand is then obtained by solving the lower-level problem again. When the motorists can easily find a parking space at their destination zones, the parking delay is reduced. As the travel time is decreased, the change of zonal accessibility measures would lead to a change in trip production and attraction. As a result, car traffic is induced and the parking demand increases correspondingly. In this scenario, the available parking spaces can still cater for the increase in parking demand. The results of parking demand and supply, and total network travel time are shown in Table 7.7. It is found that the available parking supply exceeds the total parking demand by 7% and the total network travel time is reduced by 10% when compared with the one in Scenario (1).

Table 7.7 Results of Scenario 3

	Zone 1	Zone 2	Zone 3	Zone 4	Total
(a) Parking demand, $\bar{D}_j$	2,305.62	2,208.85	2,271.24	2,245.70	9,031.41
(b) Total parking supply, h_j	2,500	2,500	2,500	2,500	10,000
(c) Pre-occupied parking spaces, h_j^{occ}	80	120	75	50	325
(d) Available parking spaces, $h_j - h_j^{occ}$	2,420	2,380	2,425	2,450	9,675
(a)/(d)	**0.95**	**0.93**	**0.94**	**0.92**	**0.93**
(e) Total network travel time (hrs)			**5,952.68 (100%)**		
- Total link travel time			**2,936.37 (49.3%)**		
- Total parking delays			**3,016.31 (50.7%)**		

7.7.4 Overall Results

The overall results of the three scenarios show that the total network travel times decrease with an increased supply of parking spaces. The total network travel time is the greatest in the scenario of parking demand being greater than parking supply. Followed by the total network travel time in the scenario with equal parking demand and supply (i.e. balanced scenario). Moreover, the parking spaces are fully utilized. The least total network travel time is found in the scenario where parking demand is less than parking supply. However, in this scenario the excess parking spaces represents a waste of resources.

Figure 7.3 shows the total network travel time during the 1-hour study period for various combinations of parking demand and supply. The dotted diagonal shown in Figure 7.3 represents the balanced scenario (i.e. parking demand = parking supply), and the iso curves represent the equivalent of total network travel time. The results can be classified into three categories and discussed as follows.

In the study, one-hour morning peak period (8:00 – 9:00 am) was studied, as it is believed that the traffic condition in the morning peak is the worst in a typical weekday. If different length of the study interval is considered, dynamic traffic assignment should be carried out. The excess traffic flow in this one-hour study period would be carried over to the next one-hour period. However, dynamic traffic assignment is not considered in this research as this study is aimed for long-term strategic planning.

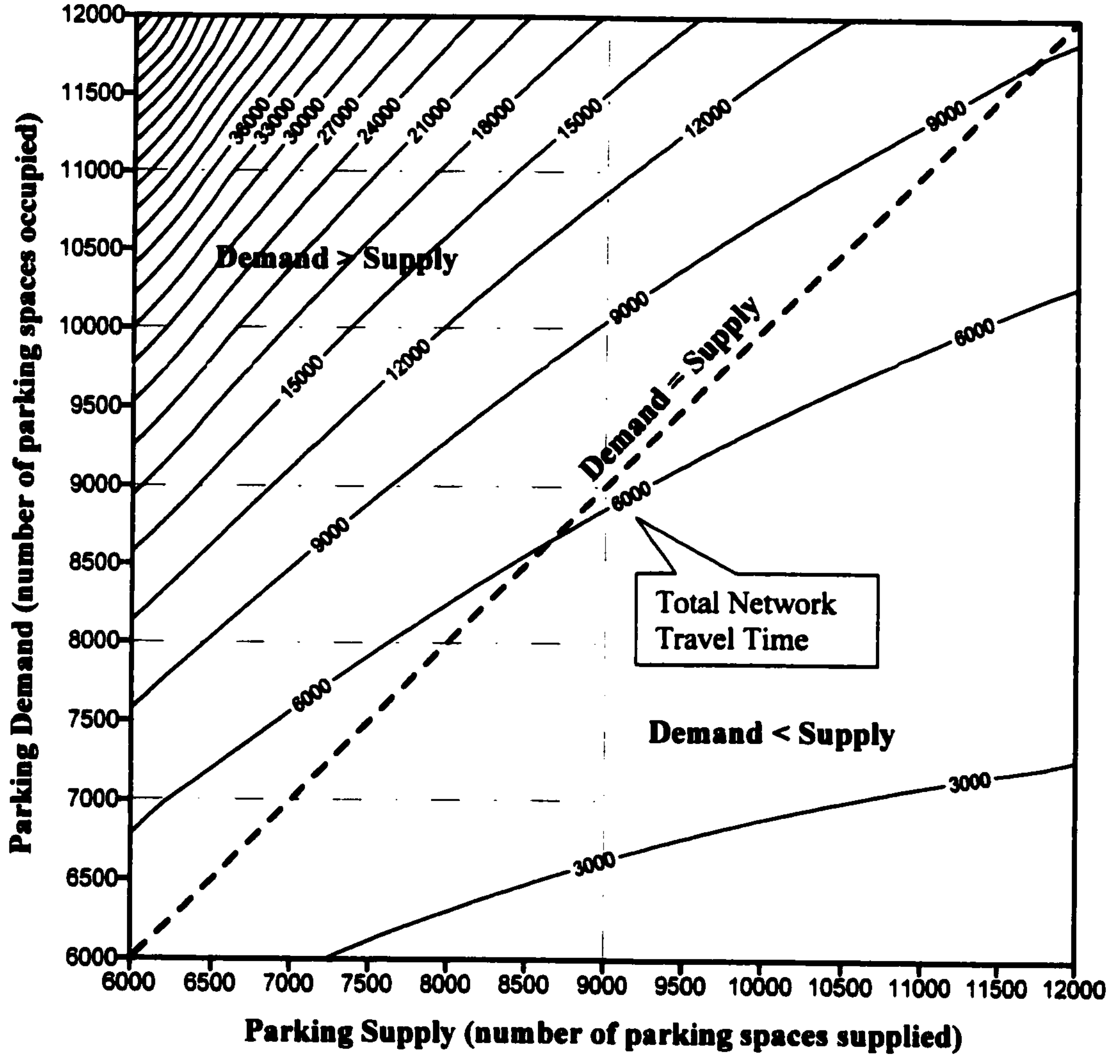


Figure 7.3 Total Network Travel Time (veh-hr) during the 1-hour Study Period for Various Parking Demand and Supply

Category 1. Parking demand = Parking supply

This category is a reference point for comparing the total network travel time with the following two categories. In the case of parking demand and supply are equal to

9,000 parking spaces (i.e. the balanced scenario), it is observed that the total network travel time is 6,300 veh-hrs.

Category 2. Parking demand > Parking supply

In this category, it is found that the total network travel time increases sharply when parking demand is greater than supply. This is because the parking delay is greatly increased due to a shortage of parking spaces. Considering the scenario that the total supply of parking spaces is 9,000 and the total parking demand is 10,000, the rate of change in total network travel time from the balanced scenario is increased by 40.75%. If the parking demand increases to 11,000, the total network travel time is increased by 99.35%. Moreover, if the parking demand increases to 12,000, there is a 181.95% increase in the total network travel time. The rate of change in total network travel time increases dramatically with the parking demand.

Category 3. Parking demand < Parking supply

In this category, there is only a small reduction in the total network travel time when the parking demand is less than supply. By comparing the balanced scenario with 9,000 parking spaces, the decrease of parking demand to 8,000 leads to 27.89% reduction in total network travel time. If the parking demand is decreased to 7,000 parking spaces, 46.88% of total network travel time is reduced. If the parking demand is decreased to 6,000 parking spaces, 60.03% reduction in total network travel time is obtained. The rate of reduction in total network travel time is gradually decreased with the reduction of the parking demand.

The results of the above three categories show that the excess parking spaces supplied cannot reduce the total network travel time efficiently. However, a shortage of parking spaces would increase the total network travel time significantly. Thus, the balanced parking demand/supply seems to be most effective.

7.7.5 Sensitivity Tests on Parameter θ

In order to assess the impact of the journey time variation to accessibility measures on the minimum parking supply and total network travel time, a set of sensitivity tests have been carried out with different values of parameter θ. For varying values of θ, the total network travel time and the optimum total number of parking spaces supplied is plotted in Figures 7.4 and 7.5 respectively together with different values of α (dispersion parameter for trip distribution).

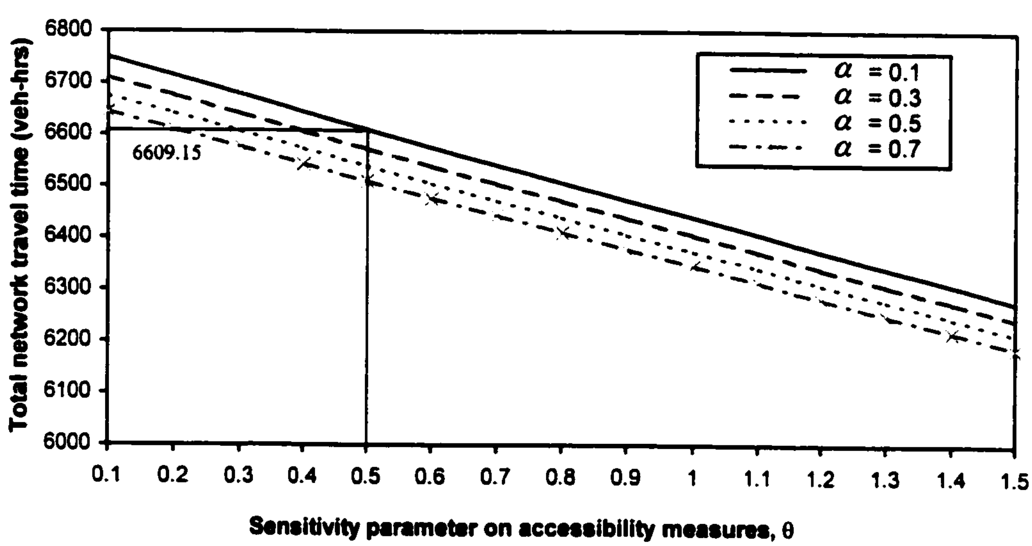


Figure 7.4 Sensitivity of Accessibility Parameter on Total Network Travel Time

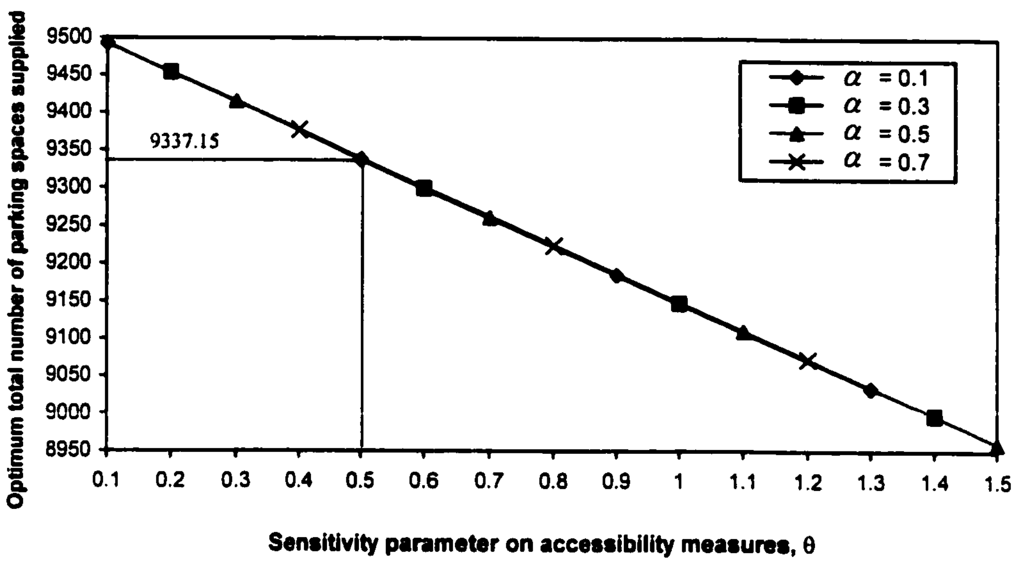


Figure 7.5 Sensitivity of Accessibility Parameter on Optimum Total Number of Parking Spaces Supplied

It can be seen in Figures 7.4 and 7.5 that an increase in the value of θ results in a decrease in both total network travel time and an optimum total number of parking spaces supplied. This is because the sensitivity of journey time is increased with θ and hence there is a reduction in the accessibility of trip production and attraction. Thus, the number of car trips made decreases as does the parking demand. Therefore, the corresponding parking supply can be reduced. Since the travel demand decreases, there is less traffic on the roads and leads to a reduction in the total network travel time.

It can be found in Figure 7.4 that the total network travel time decreases with the value of parameter α. This is because when α increases, the distribution of trips from an origin shifts to a destination with shorter journey time. Hence, the total network travel time decreases. Figure 7.5 shows that the optimum number of parking spaces supplied is independent of the values of parameter α. Although the distribution of trips is changed, the total number of car trips attracted to a destination is almost unchanged in this example (with symmetric characteristics). Thus, the parking demand and so the supply of parking spaces is more or less the same for various values of α.

7.7.6 Effectiveness

A cost analysis should be made to demonstrate the trade-off between the reduction in total network travel time and the amount of parking spaces supplied. It was assumed that the cost for parking supply is proportional to the number of parking spaces for which parking demand is required. Based on this assumption, a measure of effectiveness of one additional parking supply can be defined as below:

$$\textit{Measure of Effectiveness} = \frac{\textit{Percentage reduction in total network travel time}}{\textit{Number of additional parking spaces supplied}} \quad (7.20)$$

It is expected that the measure of effectiveness would decrease with the increasing number of parking spaces supplied. Suppose that parking demand is 11,000 and parking supply is referred to 6,000, Figure 7.6 shows the variation of the percentage reduction in total network travel time against the increasing additional parking spaces supplied.

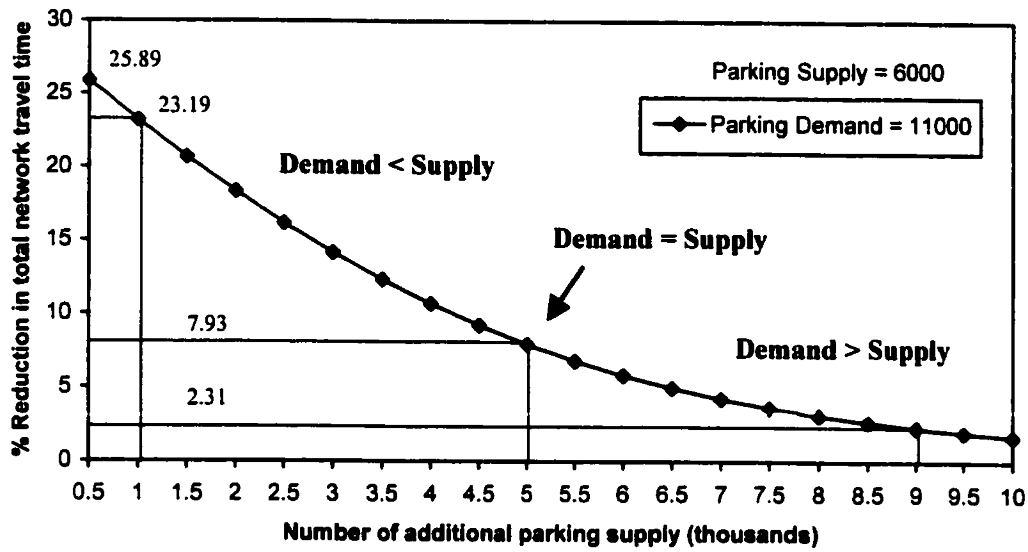


Figure 7.6 Percentage Reduction in Total Network Travel Time by Every 500 Additional Parking Spaces Supplied

Figure 7.6 shows that the impact of additional parking space on reduction of travel time is decreased with the further increment of the number of parking spaces. The relative reduction in travel time is due to the increment of 500 additional parking spaces. For example, when parking supply is increased from 6,00 to 6,500 (i.e. 500 additional parking spaces), the travel time is reduced by 25.89%. If additional parking supply is increased to 1,000, the travel time reduction due to the next 500 additional spaces (i.e. from 6,500 to 7,000 spaces) is 23.19%. The effectiveness of the next 500 additional parking spaces to the reduction in travel time is reduced when comparing with that of the first 500 additional parking spaces.

The results shown in Figure 7.6 also indicate that the percentage reduction in total network travel time decreases from 23.19 to 7.93 (about 192%) when the additional parking spaces are increased from 1,000 to 5,000 at the destination zones (i.e.

reaching to the balanced scenario). However, the percentage reduction in total network travel time only reduces from 7.93 to 2.31 (about 71%) if the parking spaces are further increased from 5,000 to 9,000. It can be seen in Table 7.8 that the measure of effectiveness is decreasing with the increasing number of parking spaces. The highest percentage of effectiveness (0.052 per parking space) was found with the first 500 additional parking spaces.

Table 7.8 Measure of Effectiveness of Parking Spaces

Number of additional parking spaces	Percentage reduction in Total network travel time	Measure of Effectiveness	
500	25.89	0.052	
1,000	23.19	0.046	
1,500	20.68	0.041	
2,000	18.33	0.037	
2,500	16.16	0.032	Demand < Supply
3,000	14.15	0.028	
3,500	12.33	0.025	
4,000	10.68	0.021	
4,500	9.22	0.018	
5,000	7.93	0.016	Demand = Supply
5,500	6.80	0.014	
6,000	5.82	0.012	
6,500	4.98	0.010	
7,000	4.26	0.009	
7,500	3.65	0.007	Demand > Supply
8,000	3.13	0.006	
8,500	2.69	0.005	
9,000	2.31	0.005	
9,500	1.99	0.004	
10,000	1.72	0.003	

7.8 SUMMARY

This chapter proposes a bilevel programming model to balance the demand and supply of parking spaces. The proposed model takes into account the route and destination choices of motorists simultaneously, in which the O-D travel demand is not fixed. The vehicle trip production and attraction ends are elastic to traffic congestion, availability of parking spaces and variable parking delays. A sensitivity analysis based algorithm has been developed for determining the total minimum number of parking spaces required to cater for the elastic parking demand in the study area.

The numerical example is presented to illustrate the application of the proposed model. The effects of balanced and unbalanced parking demand/supply are investigated in the three scenarios. The results show that the total network travel time is greatest when parking demand is greater than parking supply. The least total network travel time is obtained in the scenario that parking demand is less than parking supply, but the parking resource becomes inefficient. The total network travel time in the balanced scenario lies in between, and the parking space is fully utilized. The results also show that excess parking spaces supplied cannot reduce the total network travel time efficiently. However, a shortage of parking spaces would increase the total network travel time dramatically. Thus, a balance of parking demand and supply leads to the most effective result on reduction of the total network travel time. The sensitivity tests of the two parameters for the accessibility measures and trip distribution are also carried out to examine their effects on the number of parking spaces supplied and the total network travel time.

As the degree of sensitivity of journey time on accessibility measures should be different for different trip purposes, further study is required to extend the proposed model to multi-user classes. Various types of parking spaces such as off-street and on-street for private cars and goods vehicles can also be considered in the model. The proposed model can also be extended to time-dependent dimension because the model allows for parking spaces to be occupied at the beginning of the one-hour study period and to be carried over to the next hour period. The number of parking spaces supplied can then be determined at the most critical period with the greatest parking demand, although parking demand may be less than parking supply in the other periods throughout the day.

8 SUMMARY AND CONCLUSIONS

Prior to the implementation of road infrastructure projects and transport policies, an evaluation of the car ownership on traffic impacts is often required, particularly in countries or cities with high density development. This is because car ownership is one of the key factors in affecting road usage. Under this perspective, the forecasting of car ownership is a significant research topic in the field of transport planning.

This study introduces a new approach for estimating car ownership, while taking into account both user demand and the conditions of the road network supply. Most of the previous car ownership estimation studies have analyzed the determinants of total or household car ownership demand. They usually estimated car ownership as a function of household characteristics, demographic, geographic and socio-economic factors. These functions are mainly based on the view of user demand. The constraints of road network supply have not been addressed in the previous related studies. This research brings a new concept of balancing car ownership from the views of user demand and network supply. It is hoped that the concept proposed could provide better insights for future transport planning and car ownership growth.

In the aspect of user demand, the territory-wide car ownership that is defined as the total number of licensed private cars and motorcycles (converted to passenger car units), has been estimated by an aggregate car ownership model. Gross domestic products per capita, average first registration taxes per private car and annual passenger trips on public transport have been found to be significant to the territory-wide car ownership in Hong Kong. The reliability of the estimated car ownership has been assessed through the simulated probability distribution of the territory-wide car ownership.

Zonal car ownership has been estimated by the calibrated disaggregate car ownership choice (logit-type) models. The logit-type choice models were calibrated using the revealed preference data obtained in a survey. Monthly household income, accessibility to employment, monthly car ownership and usage costs were statistically significant to the choice of household car ownership. By means of the stated preference data, the effects of the change of economic and fiscal factors on the choice of car ownership were investigated. The probabilities of car owning (single and multiple) and non-car owning households in Hong Kong have been obtained from the developed models. A high demand for car ownership in Hong Kong was found from the survey results.

In view of the road network supply conditions, a bilevel programming model for car ownership has been proposed. The proposed model extends the concept of reserve capacity to car ownership. The reserve capacity of car ownership is referred to as the greatest additional amount of car ownership that can be accommodated in a traffic zone. The lower-level problem is an equivalent combined distribution and assignment model, while the upper-level problem is to maximize car ownership under network supply constraints. These constraints are related to road capacities and parking facilities.

The contributions of the study are summarized as follows. Firstly, it is the first bilevel programming model for modelling zonal car ownership under the given network supply conditions. The relationship between traffic assignment, car ownership and parking availability were studied. Secondly, the CDA model was adopted to incorporate the destination and route choices of travellers simultaneously. Thus, the O-D travel demand is not fixed. Finally, the vehicle trip production and attraction ends were formulated as functional forms so that they can be elastic to traffic congestion on network and the number of cars in each zone. As a result, the proposed bilevel car ownership model combines the existing models to create a new model that incorporates car ownership, link-based traffic flow forecasting, trip distribution and parking space availability together.

A sensitivity based solution algorithm has been derived for solving the proposed bilevel car ownership model. Numerical examples have demonstrated the applicability of the proposed car ownership model and the solution algorithm.

The concept of balancing car ownership from the viewpoints of user demand and road network supply has been demonstrated and investigated with a case study. The case study illustrated the application of the proposed bilevel car ownership in practice. The effects of balancing car ownership have been examined by comparing the total network travel times. It was found that balanced car ownership gives the least network travel time when compared with that in unconstrained scenarios. It is also efficient for the utilization of link capacities and parking spaces. With the use of the simulated probability distribution of the territory-wide car ownership, the proportion of car ownership demand that can be accommodated by the network condition in Hong Kong could be obtained. The higher the proportion, the greater is the car ownership demand that can be met and vice versa.

It is believed that car ownership and availability of parking spaces have strong correlation. Thus, the concept of balancing car ownership has been extended to the problem of balancing parking demand and supply. In this study, attention was paid to public parking spaces so as to fulfill the attraction-end parking demand. A bilevel model for balancing of parking demand and supply has been proposed together with solution algorithm. The effects of balancing the demand and supply of parking spaces have also been investigated. It was found that balanced parking spaces optimize journey time (including parking delay) and increase utilization of parking spaces.

Based on this research work, several directions may merit further study:

1. In the estimation of car ownership, other statistical and econometric models can be applied to incorporate dynamic behaviour, such as taste changes, transaction costs and brand loyalty.
2. Car ownership and usage can be considered simultaneously to assess their interaction effects on the decisions of choices of car ownership and usage.
3. The proposed bilevel car ownership model includes two transport modes, private cars and pre-loaded vehicles (other than private cars). Its extension to multi-vehicle types is required for wider applications in practice.
4. The assumption of trip purposes (work trips) during the morning peak hour has limited the application of the proposed model. The extension of the

proposed model to multi-purposes such as work trips, school trips and other trips is desirable.

5. In the proposed bilevel car ownership model, public transport network is assumed to be constant and fixed. In order to consider modal choice decisions, public transport should be incorporated in the model. For example, modal split is incorporated into the lower-level of the proposed bilevel model.

6. Parking spaces should be more generally divided into various types, such as on-street and off-street public and private parking spaces for private cars and goods vehicles respectively, so as to represent the road network more realistically.

7. The proposed bilevel car ownership model applies to a one-hour study period. It can be extended to a time-dependent model for long term strategic transport planning purposes.

8. A sensitivity based solution algorithm has been derived for solving the proposed model in this study. Some other approaches such as a genetic algorithm, recently widely used for optimization problems can also be considered.

9. Network design models can be developed to investigate the road network expansions for satisfying the car ownership demand.

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APPENDIX A SURVEY QUESTIONNAIRE

The Hong Kong Polytechnic University
Department of Civil and Structural Engineering
Car Ownership Questionnaire Interview

This questionnaire contains four parts for concerning car ownership in Hong Kong.

Part 1

The following questions concern:

- Your car owning and usage information.
- The ownership and usage costs for your private car.

1) Do you have a driving license?
   A. Yes B. No

2) How many private cars do your household have?
   A. 0 B. 1 C. 2 D. 3 E. ________

3) Residential location (district):
   A. Hong Kong Island ( ) B. Kowloon ( ) C. N.T. ( )

4) Working location (district):
   A. Hong Kong Island ( ) B. Kowloon ( ) C. N.T. ( )

Questions 5 to 13 only for car owners

5) Do you drive your private car in the weekdays (Mon. to Fri.)?
   A. Yes (how many days?) B. No

6) When did you buy your private car(s), what was/were the price(s)?
   Year: ________
   A. Below 50,000 B. 50,001-100,000 C. 100,001-200,000
   D. 200,001-300,000 E. 300,001-400,000 F. Above 400,000

7) How much is your annual license fee (ALF)?

		A	B	C	D
		Annual	4 months	Annual	4 months
	Engine size	Gasoline ($)		Light Diesel ($)	
1	Below 1,500 c.c.	3,929	1,404	5,389	1,915
2	1,500-2,500 c.c.	5,794	2,056	7,254	2,567
3	2,500-3,500 c.c.	7,664	2,711	9,124	3,222
4	3,500-4,500 c.c.	9,534	3,365	10,994	3,876
5	Above 4,500 c.c.	11,329	3,994	12,789	4,505

8) How much is your monthly home-end parking fee?
   A. Below 1,000 B. 1,000-1,999 C. 2,000-2,999
   D. 3,000-3,999 E. Above 4,000 F. No need to pay

9) How much is your monthly attraction-end parking fee?

A. Below 200 B. 200-399 C. 400-599
D. 600-799 E. 800-999 F. 1,00-1,299
G. 1,300-1,499 H. 1,500-1,999 I. 2,000-2,499
J. 2,500-2,999 K. Above 3,000

10) How much is your monthly fuel expense?

A. Below 600 B. 600-999 C. 1,000-1,199
D. 1,200-1,399 E. 1,400-1,999 F. 2,000-2,499
G. 2,500-2,999 H. 3,000-3,499 I. Above 3,500

11) How much is your annual vehicle insurance fee?

A. Below 1,500 B. 1,500-1,999 C. 2,000-2,499
D. 2,500-2,999 E. 3,000-3,499 F. 3,500-3,999
G. 4,000-4,999 H. 4,500-4,999 I. 5,000-6,000
J. Above 6,000

12) How much are the annual maintenance fee and other minor fees for your private car?

A. Below 1,000 B. 1,000-1,499 C. 1,500-1,999
D. 2,000-2,499 E. 2,500-2,999 F. 3,000-3,499
G. 3,500-3,999 H. 4,000-4,499 I. 4,500-4,999
J. 5,000-7,999 K Above 8,000

13) Have you decided to purchase another private car or change your private car?

A. Yes (Answer Question 18) B. No

__**Questions 14 to 17 only for non-car owners**__

14) How much is your monthly transportation fee?

A. Below 400 B. 400-599 C. 600-999
D. 1,000-1,199 E. 1,200-1,599 F. 1,600-1,999
G. Above 2,000

15) Have you decided to purchase a private car?

A. Yes (Answer Question 18) B. No

16) In which level of your household income, you will decide to purchase a private car?

A. Below 30,000 B. 30,000-39,999 C. 40,000-44,999
D. 45,000-49,999 E. 50,000-54,999 F. 55,000-59,999
G. 60,000-64.000 H. 65,000-69,999 I. 70,000-79,999
J. Above 80,000 K Not decide to purchase

17) If the parking fee reduces, in what level of reduction of parking fee that you will decide to purchase a private car?

A. Below 500 B. 500-999 C. 1,000-1,499
D. 1,500-1,999 E. 2,000-2,499 F. Above 2,500
G. Not decide to purchase (Answer Question 19)

18) Which type of car (new or second hand) do you want to purchase? What is the expected car price?

(New)---c

A. Below 50,000 B. 50,000-100,000 C. 100,001-200,000
D. 200,001-300,000 E. 300,001-400,000 F. Above 400,000

(Second hand)---n

A. Below 20,000 B. 20,000-30,000 C. 30,001-40,000
D.40,001-50,000 E. 50,001-60,000 F. Above 60,000

Part 2

This part is the description of car ownership and usage costs of a private car in Hong Kong, which give a reference to non-car owning people.

Car owning costs include:

- Car price with first registration fee (FRT)
- Annual license fee (ALF)
- Home-end Parking Fee
- Car Insurance

Car usage costs include:

- Fuel Fee
- Attraction-end Parking Fee
- Car Maintenance Fee and Other Minor Cost

Estimated Car Ownership and Usage Costs for a Private Car

Item	Average Cost (HK$)
(1) Base vehicle price	217,500
(2) First Registration Tax (FRT)	97,875
(a) Sub-total = (1)+(2)	315,375
(3) Annual license fee (ALF)	5,670
(4) Monthly Home-end parking fee	1,800
(5) Annual insurance	8,000
(6) Monthly fuel expenses	1,500
(7) Monthly maintenance and spares costs	400
(8) Monthly attraction-end parking fee	850
(b) Monthly car usage cost = (6)+(7)+(8)	2,750

Part 3 (Stated Preference questions)

This part describes 10 different scenarios related to monthly household income, car ownership and usage costs. Please consider the costs as described in Part 2 for non-car owners and answer the following questions:

For car owners:

If you decided to purchase another private car(s), please answer Question 21. Otherwise, please answer Question 19 or Question 20.

For non-car owners:

If you decided to purchase a private car, please answer Question 22. Otherwise, please answer Question 23.

19) Please answer 19)-1 to 19)-10 and show that at which scenarios you will continue to own your car and which scenarios that you will dispose of your car.

19)-1
ALF unchanged
Monthly home parking fee unchanged
Monthly usage cost increased by _____%

19)-2
ALF unchanged
Monthly home parking fee decreased by _____%
Monthly usage cost increased by _____%

19)-3
ALF increased by _____%
Monthly home parking fee unchanged
Monthly usage cost unchanged

19)-4
ALF increased by _____%
Monthly home parking fee decreased by _____%
Monthly usage cost unchanged

19)-5
ALF unchanged
Monthly home parking fee increased by _____%
Monthly usage cost unchanged

19)-6
ALF unchanged
Monthly home parking fee increased by _____%
Monthly usage cost decreased by _____%

19)-7
ALF decreased by _____%
Monthly home parking fee increased by _____%
Monthly usage cost unchanged

19)-8
ALF increased by _____%
Monthly home parking fee unchanged
Monthly usage cost decreased by _____%

19)-9
ALF decreased by _____%
Monthly home parking fee unchanged
Monthly usage cost increased by _____%

19)-10
Household income decreased by _____%
ALF unchanged
Monthly home parking fee decreased by _____%
Monthly usage cost unchanged

20) Please answer 20)-1 to 20)-10 and show that at which scenarios you will or will not purchase an additional private car.

20)-1
Purchase price of a private car unchanged
ALF unchanged
Monthly home parking fee unchanged
Monthly usage cost decreased by _____%

20)-2
Purchase price of a private car unchanged
ALF increased by _____%
Monthly home parking fee unchanged
Monthly usage cost decreased by _____%

20)-3
Purchase price of a private car unchanged
ALF unchanged
Monthly home parking fee decreased by _____%
Monthly usage cost unchanged

20)-4
Purchase price of a private car unchanged
ALF unchanged
Monthly home parking fee decreased by _____%
Monthly usage cost increased by _____%

20)-5
Purchase price of a private car unchanged
ALF decreased by _____%
Monthly home parking fee unchanged
Monthly usage cost unchanged

20)-6
Purchase price of a private car unchanged
ALF decreased by _____%
Monthly home parking fee unchanged
Monthly usage cost increased by _____%

20)-7
Purchase price of a private car decreased by _____%
ALF unchanged
Monthly home parking fee unchanged
Monthly usage cost unchanged

20)-8
Purchase price of a private car decreased by _____%
ALF increased by _____%
Monthly home parking fee unchanged
Monthly usage cost unchanged

20)-9
Purchase price of a private car decreased by _____%
ALF unchanged
Monthly home parking fee unchanged
Monthly usage cost increased by _____%

20)-10
Purchase price of a private car decreased by _____%
ALF unchanged
Monthly home parking fee increased by _____%
Monthly usage cost unchanged

21) Please answer 21)-1 to 21)-10 and show that at which scenarios you will or will not give up purchasing a private car.

21)-1
Purchase price of a private car increased by _____%
ALF unchanged
Monthly home parking fee unchanged
Monthly usage cost unchanged

21)-2
Purchase price of a private car increased by _____%
ALF unchanged
Monthly home parking fee unchanged
Monthly usage cost decreased by _____%

21)-3
Purchase price of a private car unchanged
ALF unchanged
Monthly home parking fee increased by _____%
Monthly usage cost unchanged

21)-4
Purchase price of a private car unchanged
ALF decreased by _____%
Monthly home parking fee increased by _____%
Monthly usage cost unchanged

21)-5
Purchase price of a private car unchanged
ALF increased by _____%
Monthly home parking fee unchanged
Monthly usage cost unchanged

21)-6
Purchase price of a private car unchanged
ALF increased by _____%
Monthly home parking fee decreased by _____%
Monthly usage cost unchanged

21)-7
Purchase price of a private car unchanged
ALF unchanged
Monthly home parking fee unchanged
Monthly usage cost increased by _____%

21)-8
Purchase price of a private car decreased by _____%
ALF increased by _____%
Monthly home parking fee unchanged
Monthly usage cost unchanged

21)-9
Purchase price of a private car unchanged
ALF increased by _____%
Monthly home parking fee unchanged
Monthly usage cost decreased by _____%

21)-10
Purchase price of a private car decreased by _____%
ALF unchanged
Monthly home parking fee unchanged
Monthly usage cost increased by _____%

22) Please answer 22)-1 to 22)-10 and show that at which scenarios you will or will not give up purchasing a private car.

22)-1
Purchase price of a private car increased by _____%
ALF unchanged
Monthly home parking fee unchanged
Monthly usage cost unchanged

22)-2
Purchase price of a private car unchanged
ALF increased by _____%
Monthly home parking fee unchanged
Monthly usage cost unchanged

22)-3
Purchase price of a private car unchanged
ALF decreased by _____%
Monthly home parking fee increased by _____%
Monthly usage cost unchanged

22)-4
Purchase price of a private car unchanged
ALF increased by _____%
Monthly home parking fee decreased by _____%
Monthly usage cost unchanged

22)-5
Purchase price of a private car increased by _____%
ALF decreased by _____%
Monthly home parking fee unchanged
Monthly usage cost unchanged

22)-6
Purchase price of a private car decreased by _____%
ALF increased by _____%
Monthly home parking fee unchanged
Monthly usage cost unchanged

22)-7
Purchase price of a private car unchanged
ALF decreased by _____%
Monthly home parking fee unchanged
Monthly usage cost increased by _____%

22)-8
Purchase price of a private car unchanged
ALF increased by _____%
Monthly home parking fee unchanged
Monthly usage cost decreased by _____%

22)-9
Purchase price of a private car unchanged
ALF unchanged
Monthly home parking fee increased by _____%
Monthly usage cost decreased by _____%

22)-10
Purchase price of a private car unchanged
ALF unchanged
Monthly home parking fee decreased by _____%
Monthly usage cost increased by _____%

23) Please answer 23)-1 to 23)-10 and show that at which scenarios you will or will not purchase a private car.

23)-1
Purchase price of a private car decreased by _____%
ALF unchanged
Monthly home parking fee unchanged
Monthly usage cost is HK$_______

23)-2
Purchase price of a private car unchanged
ALF unchanged
Monthly home parking fee decreased by _____%
Monthly usage cost is HK$_______

23)-3
Purchase price of a private car unchanged
ALF decreased by _____%
Monthly home parking fee increased by _____%
Monthly usage cost is HK$_______

23)-4
Purchase price of a private car unchanged
ALF increased by _____%
Monthly home parking fee decreased by _____%
Monthly usage cost is HK$_______

23)-5
Purchase price of a private car unchanged
ALF decrease by _____%
Monthly home parking fee unchanged
Monthly usage cost is $_______

23)-6
Purchase price of a private car decreased by _____%
ALF unchanged
Monthly home parking fee unchanged
Monthly usage cost is HK$_______

23)-7
Household income increased by _____%
Purchase price of a private car unchanged
ALF unchanged
Monthly home parking fee increased by _____%
Monthly usage cost is HK$_______

23)-8
Household income increased by _____%
Purchase price of a private car unchanged
ALF unchanged
Monthly home parking fee increased by _____%
Monthly usage cost is HK$_______

23)-9
Household income increased by _____%
Purchase price of a private car increased by _____%
ALF unchanged
Monthly home parking fee unchanged
Monthly usage cost is HK$_______

23)-10
Household income increased by _____%
Purchase price of a private car unchanged
ALF increased by _____%
Monthly home parking fee unchanged
Monthly usage cost is HK$_______

Part 4
This part concerns your personal information and all the information will be kept confidential.

24) What is your age?

A. 18-24 B. 25-34 C. 35-44
D. 45-54 E. Above 55

25) How many members in your family (including yourself)?

____

26) How much is your monthly household income?

A. Below 20,000 B. 20,000-29,999 C. 30,000-39,999
D. 40,000-49,999 E. 50,000-59,999 F. 60,000-79,999
G. 80,000-99,999 H. Above 100,000

The End

Thank you for your co-operation!

APPENDIX B 1997 BASE YEAR PLANNING DATA

The planning data for the selected Tuen Mun and Yuen Long study areas shown in Chapter 6 is listed as below.

CTS-2 zone number	Population	Households	Monthly household income (HK$)	Resident workers	Employment	Off-street residential parking spaces	Acc. Index
156	24030	8071	45803	14713	5090	8025	4
157	10261	2816	49794	4945	3852	1790	5
158	18477	5397	41435	10212	3233	2564	4
159	53480	15552	22738	26603	6225	2857	4
160	47251	12367	19854	23674	4053	1223	4
161	10944	3537	29746	6125	6102	2184	5
162	84698	24310	23591	41895	9166	3502	5
163	0	0	0	0	2111	0	5
164	33285	10906	20588	17165	16408	1118	4
165	28	21	8975	21	19681	126	5
166	32127	8626	16016	13827	2917	2701	4
167	78486	21564	17409	32295	6416	15	5
168	40540	12890	20056	21635	15739	1416	5
169	29432	7771	21825	12596	7473	1107	5
170	18692	5713	23081	9118	3660	2203	4
171	10856	3460	17150	5357	2589	757	5
172	7405	2181	17334	3111	1953	403	5
173	11327	4350	20691	5747	6021	1717	5
174	6367	1863	15558	2615	2594	44	5
175	91758	25931	21093	40358	7151	1114	5
176	149	25	19386	75	304	1416	5
177	54979	14402	16642	21838	6858	797	4
178	29385	9939	19024	14117	16368	328	4
179	11314	3814	24178	5723	3564	410	4
180	33147	10737	21038	15367	12738	411	4
181	16313	5265	18981	7606	1955	184	5
182	22549	6877	20627	11223	5037	389	4
232	6376	2014	20818	3162	8637	376	5
258	0	0	0	0	151	0	5
259	534	152	25057	294	586	0	5
261	7793	3110	31089	4422	447	633	5
External zones	5633217	1684727	21870	2909686	2898932	262357	--
Total	6425200	1918388	21919	3285525	3088011	302167	--

APPENDIX C ROAD NETWORK DATA

The road network data for the selected Tuen Mun and Yuen Long study areas shown in Chapter 6 is listed as follows:

FROM NODE	TO NODE	FREE-FLOW SPEED(kph)	SPEED AT CAPACITY(kph)	CAPACITY (pcu/hr)	DISTANCE (m)	POWER IN LINK COST FUNCTION	PRELOADED VEH.FLOW	ROAD* TYPE
156	2000	15	15	10000	1800	0.5	272.00	0
157	1303	15	15	10000	1850	0.5	356.25	0
158	1304	15	15	10000	220	0.5	288.00	0
159	1310	15	15	10000	280	0.5	795.75	0
160	1310	15	15	10000	250	0.5	788.00	0
161	1307	15	15	10000	200	0.5	524.75	0
162	1308	15	15	10000	280	0.5	1009.25	0
163	1309	15	15	10000	1800	0.5	229.00	0
164	1315	15	15	10000	320	0.5	643.50	0
165	1316	15	15	10000	200	0.5	809.25	0
166	1317	15	15	10000	310	0.5	681.25	0
167	1318	15	15	10000	200	0.5	783.25	0
168	1319	15	15	10000	160	0.5	367.50	0
168	1325	15	15	10000	190	0.5	463.50	0
169	1324	15	15	10000	500	0.5	504.00	0
170	1322	15	15	10000	350	0.5	357.25	0
171	2003	15	15	10000	500	0.5	67.50	0
172	2004	15	15	10000	800	0.5	108.25	0
173	2008	15	15	10000	1000	0.5	133.25	0
174	2006	15	15	10000	1800	0.5	152.50	0
175	2007	15	15	10000	1700	0.5	633.25	0
176	2007	15	15	10000	1200	0.5	110.50	0
177	2508	15	15	10000	300	0.5	782.75	0
178	2513	15	15	10000	680	0.5	678.25	0
179	2524	15	15	10000	80	0.5	367.75	0
180	2518	15	15	10000	180	0.5	177.25	0
180	2519	15	15	10000	200	0.5	466.75	0
181	2521	15	15	10000	1000	0.5	156.00	0
182	2010	15	15	10000	2000	0.5	320.00	0
232	2509	15	15	10000	1800	0.5	0.00	0
258	1309	15	15	10000	1000	0.5	72.50	0
259	1309	15	15	10000	500	0.5	132.50	0
261	2007	15	15	10000	1700	0.5	558.75	0
301	1112	15	15	10000	200	0.5	1866.00	0
302	2022	15	15	10000	150	0.5	3615.50	0
303	2002	15	15	10000	190	0.5	2201.50	0
304	2011	15	15	10000	120	0.5	296.50	0
305	2012	15	15	10000	180	0.5	1913.50	0
1112	301	15	15	10000	200	0.5	1938.75	0
1112	2000	60	35	3200	4600	3.6	963.25	2
1300	1301	50	22	2880	10	3.6	781.50	2
1300	1303	50	35	2000	1620	3.6	920.00	2
1300	2000	45	22	2800	5530	3.6	879.50	2
1301	1300	50	22	2492	10	3.6	640.75	2
1301	1332	66	30	5700	4330	3.9	3271.00	7
1301	2001	65	30	6700	5850	3.5	3806.25	3
1302	1322	50	11	3600	2430	3.2	577.00	5
1302	1323	65	30	3800	1100	3.8	2440.00	7
1302	1324	50	11	3200	1400	3.2	562.00	5
1302	2003	65	30	4100	700	3.5	1869.75	3
1303	157	15	15	10000	1850	0.5	353.00	0
1303	1300	45	22	1825	1620	3.6	1372.75	2

1303	1304	50	35	1800	3300	3.6	911.75	2
1304	158	15	15	10000	220	0.5	254.25	0
1304	1303	45	22	3150	3300	3.4	1361.25	2
1304	1312	50	11	3600	1020	3.2	614.25	5
1304	1326	50	11	3600	280	3.2	488.00	5
1305	1311	65	30	4900	500	3.8	2711.75	7
1305	1329	50	16	3700	820	2.9	1148.50	6
1305	1332	66	30	5700	700	3.9	3378.50	7
1307	161	15	15	10000	200	0.5	482.00	0
1307	1317	40	11	3600	880	2.8	1013.00	5
1307	1329	50	16	3700	530	2.9	1089.25	6
1307	1330	40	11	3600	1080	2.8	675.75	5
1308	162	15	15	10000	280	0.5	819.75	0
1308	1309	40	5	3200	450	4.7	523.50	4
1308	1328	45	11	3600	500	3.0	654.75	5
1309	163	15	15	10000	1800	0.5	323.50	0
1309	258	15	15	10000	1000	0.5	95.25	0
1309	259	15	15	10000	500	0.5	120.75	0
1309	1308	40	5	3100	450	4.7	444.00	4
1309	1330	40	11	3600	410	2.8	798.75	5
1310	159	15	15	10000	280	0.5	843.25	0
1310	160	15	15	10000	250	0.5	747.50	0
1310	1311	45	11	4500	310	3.0	1451.00	5
1310	1315	50	11	3800	500	3.2	931.50	5
1310	1326	40	11	3100	820	2.8	587.00	5
1311	1305	65	30	4900	500	3.8	2875.25	7
1311	1310	45	11	4500	310	3.0	1247.75	5
1311	1312	45	11	4500	250	3.0	259.50	5
1311	1314	65	30	3500	500	3.8	2313.50	7
1312	1304	50	11	3600	1020	3.2	776.50	5
1312	1311	45	11	4200	250	3.0	182.25	5
1312	1313	50	11	3600	530	3.2	695.50	5
1313	1312	50	11	3600	530	3.2	782.25	5
1313	1314	50	11	3200	150	3.2	321.25	5
1313	1322	50	11	3600	640	3.2	524.25	5
1314	1311	65	30	3500	500	3.8	2349.50	7
1314	1313	50	11	3200	150	3.2	210.00	5
1314	1315	50	11	4200	220	3.2	529.75	5
1314	1323	65	30	3800	1100	3.8	2811.50	7
1315	164	15	15	10000	320	0.5	681.75	0
1315	1310	50	11	3800	500	3.2	1143.25	5
1315	1314	50	11	4200	220	3.2	359.00	5
1315	1316	50	11	4200	370	3.2	1011.50	5
1315	1321	50	11	1800	630	3.2	213.75	5
1316	165	15	15	10000	200	0.5	902.25	0
1316	1315	50	11	4200	370	3.2	1178.50	5
1316	1317	50	11	4200	430	3.2	898.00	5
1316	1320	40	11	3100	1220	2.8	104.50	5
1317	166	15	15	10000	310	0.5	532.75	0
1317	1307	40	11	3800	880	2.8	1084.50	5
1317	1316	50	11	4200	430	3.2	871.75	5
1317	1318	40	11	3600	1030	2.8	949.00	5
1318	167	15	15	10000	200	0.5	673.25	0
1318	1317	40	11	3600	1030	2.8	844.25	5
1318	1319	50	11	3600	160	3.2	373.25	5
1318	1331	50	11	5700	1000	3.2	704.00	5
1319	168	15	15	10000	160	0.5	241.75	0
1319	1318	50	11	4200	160	3.2	516.75	5
1319	1320	50	11	3600	300	3.2	131.50	5
1320	1316	40	11	3100	1220	2.8	390.75	5
1320	1319	50	11	3600	300	3.2	151.00	5
1320	1325	40	11	2900	150	2.8	291.50	5
1321	1315	50	11	1800	630	3.2	122.50	5
1321	1322	50	11	1950	350	3.2	213.75	5
1322	170	15	15	10000	350	0.5	390.75	0
1322	1302	50	11	1950	2430	3.2	437.00	5
1322	1313	50	11	3600	640	3.2	723.75	5
1322	1321	50	11	1950	350	3.2	122.50	5

1323	1302	65	30	4100	1100	3.8	2768.75	7
1323	1314	65	30	3800	1100	3.8	2905.50	7
1323	1331	40	11	5000	550	2.8	925.00	5
1324	169	15	15	10000	500	0.5	536.75	0
1324	1302	50	11	800	1400	3.2	148.50	5
1324	1325	40	11	2900	680	2.8	499.50	5
1324	1331	45	5	3600	560	5.0	401.75	4
1325	168	15	15	10000	190	0.5	472.75	0
1325	1320	40	11	2900	150	2.8	528.00	5
1325	1324	40	11	2900	680	2.8	100.50	5
1325	1331	45	11	4200	260	3.0	545.50	5
1326	1304	50	11	3600	280	3.2	739.25	5
1326	1310	40	11	3100	820	2.8	590.50	5
1326	1327	50	11	3600	600	3.2	332.75	5
1327	1326	50	11	3600	600	3.2	589.75	5
1327	1328	50	11	3600	500	3.2	695.00	5
1327	1329	50	11	3600	620	3.2	337.50	5
1328	1308	45	11	3600	500	3.0	544.75	5
1328	1327	50	11	3600	500	3.2	700.50	5
1328	1330	45	11	3600	440	3.0	161.75	5
1329	1305	50	16	3700	820	2.9	1092.25	6
1329	1307	50	16	3700	530	2.9	898.25	6
1329	1327	45	11	3600	620	3.0	586.25	5
1330	1307	40	11	3600	1080	2.8	754.75	5
1330	1309	40	11	3600	410	2.8	823.25	5
1330	1328	45	11	3600	440	3.0	58.25	5
1331	1318	50	11	5000	1000	3.2	345.75	5
1331	1323	40	11	4500	550	2.8	1348.50	5
1331	1324	45	5	3600	560	5.0	422.00	4
1331	1325	45	11	3800	260	3.0	462.50	5
1332	1301	66	30	5700	4330	3.9	3378.50	7
1332	1305	66	30	5700	700	3.9	3271.00	7
2000	156	15	15	10000	1800	0.5	258.00	0
2000	1112	45	22	2300	4600	3.6	1037.00	2
2000	1300	50	35	2000	5530	3.6	567.50	2
2000	2001	50	22	3000	280	3.6	830.00	2
2001	1301	65	30	6000	5850	3.5	3557.25	3
2001	2000	50	22	1060	280	3.6	577.75	2
2001	2022	65	30	6700	1830	3.6	4108.75	3
2002	303	15	15	10000	190	0.5	2172.75	0
2002	2010	60	30	3100	5540	3.0	688.75	3
2002	2011	65	30	1700	1970	3.5	437.50	3
2003	171	15	15	10000	500	0.5	79.50	0
2003	1302	65	30	4000	700	3.5	1710.00	3
2003	2004	65	30	4100	1000	3.5	1842.00	3
2004	172	15	15	10000	800	0.5	105.50	0
2004	2003	65	30	4000	1000	3.5	1695.25	3
2004	2005	50	22	750	2000	3.6	65.00	2
2004	2035	65	30	3800	960	3.5	1830.25	3
2005	2004	50	22	720	2000	3.6	95.75	2
2005	2006	50	22	750	2000	3.6	226.25	2
2005	2029	50	22	1500	750	3.6	134.75	2
2006	174	15	15	10000	1800	0.5	173.25	0
2006	2005	50	22	750	2000	3.6	205.50	2
2007	175	15	15	10000	1700	0.5	501.00	0
2007	176	15	15	10000	1200	0.5	0.00	0
2007	261	15	15	10000	1700	0.5	777.75	0
2007	2008	50	22	1000	920	3.6	420.75	2
2007	2029	50	22	1700	1130	3.6	566.50	2
2008	173	15	15	10000	1000	0.5	108.00	0
2008	2007	50	22	4000	920	3.6	1021.25	2
2008	2035	65	30	3900	1320	3.5	1646.25	3
2008	2500	65	30	4000	670	3.5	1644.25	3
2009	2024	65	45	5700	680	3.5	2624.25	3
2009	2025	60	30	4900	1350	3.5	1738.75	3
2009	2034	60	22	1950	1390	3.7	1169.00	2
2010	182	15	15	10000	2000	0.5	333.00	0
2010	2002	50	30	3100	5540	3.0	582.75	3

2010	2027	60	22	3100	910	3.6	613.50	2
2010	2034	60	35	2150	240	3.7	1228.00	2
2011	304	15	15	10000	120	0.5	255.00	0
2011	2002	65	30	1700	1970	3.5	511.25	3
2011	2027	60	22	3050	1970	3.6	580.00	2
2012	305	15	15	10000	180	0.5	2142.75	0
2012	2025	50	30	5700	2360	3.5	1507.50	3
2022	302	15	15	10000	150	0.5	4115.00	0
2022	2001	65	30	6000	1830	3.6	3608.50	3
2024	2009	45	30	4100	680	3.5	2795.75	3
2024	2025	45	30	2300	1750	3.5	0.00	3
2024	2501	65	35	6000	700	3.5	1515.50	3
2025	2009	60	30	4500	1350	3.5	1507.50	3
2025	2012	50	30	4800	2360	3.5	1738.75	3
2025	2024	65	35	5100	1750	3.5	0.00	3
2027	2010	60	35	3050	910	3.6	580.00	2
2027	2011	60	22	3100	1970	3.6	613.50	2
2029	2005	50	22	1250	750	3.6	186.50	2
2029	2007	50	22	3300	1130	3.6	197.75	2
2029	2035	50	22	700	1300	3.6	0.00	2
2034	2009	60	35	2150	1390	3.6	1228.00	2
2034	2010	60	35	1850	240	3.6	1169.00	2
2035	2004	65	30	3900	960	3.5	1646.25	3
2035	2008	65	30	3700	1320	3.5	1830.25	3
2035	2029	50	22	1300	1300	3.6	0.00	2
2500	2008	65	30	4400	670	3.5	2026.50	3
2500	2502	50	16	3700	560	2.9	986.25	6
2500	2504	65	11	1700	520	3.8	1095.75	5
2501	2024	45	30	3800	700	3.5	1795.50	3
2501	2514	50	16	4900	170	2.9	1031.25	6
2501	2516	40	11	3600	40	2.8	798.50	5
2502	2500	50	16	3700	560	2.9	639.50	6
2502	2503	48	11	3100	200	3.1	497.75	5
2502	2509	50	16	3500	450	2.9	681.50	6
2503	2502	48	11	3100	200	3.1	73.50	5
2503	2504	48	11	1300	140	3.1	629.75	5
2503	2508	48	11	900	290	3.1	328.75	5
2504	2500	65	11	2650	520	3.8	1588.75	5
2504	2503	48	11	1450	140	3.1	101.00	5
2504	2524	55	30	1700	390	3.1	563.50	5
2504	2525	48	11	2650	230	3.1	677.75	5
2505	2506	40	5	1200	130	4.7	511.00	4
2505	2518	55	30	1300	460	3.1	22.00	5
2505	2524	55	30	1700	290	3.1	121.00	5
2506	2507	48	11	3600	230	3.1	858.25	5
2506	2517	48	11	3600	220	3.1	847.25	5
2507	2506	48	11	4200	230	3.1	727.25	5
2507	2508	40	5	900	150	4.7	341.00	4
2507	2525	48	11	2650	70	3.1	823.25	5
2508	177	15	15	10000	300	0.5	597.50	0
2508	2503	48	11	900	290	3.1	433.25	5
2508	2507	40	5	1200	150	4.7	354.00	4
2508	2512	48	11	900	230	3.1	354.00	5
2509	232	15	15	10000	1800	0.5	0.00	0
2509	2502	50	16	3500	450	2.9	759.25	6
2509	2510	50	16	3700	200	2.9	686.50	6
2510	2509	50	16	3700	200	2.9	764.25	6
2510	2511	50	16	3700	160	2.9	678.75	6
2510	2512	40	11	900	150	2.8	219.00	5
2511	2510	50	16	4900	160	2.9	970.50	6
2511	2514	50	16	3700	290	2.9	678.75	6
2512	2508	48	11	900	230	3.1	286.25	5
2512	2510	40	11	900	150	2.8	5.00	5
2512	2513	48	11	800	150	3.1	377.25	5
2513	178	15	15	10000	680	0.5	565.25	0
2513	2511	50	16	1250	150	2.8	335.25	5
2513	2512	48	11	800	150	3.1	96.50	5
2513	2523	48	11	1300	90	3.1	384.00	5

2514	2501	50	16	3500	170	2.9	644.75	6
2514	2511	50	16	4100	290	2.9	635.25	6
2514	2522	40	11	900	80	2.8	430.25	5
2515	2517	40	11	3100	120	2.8	492.00	5
2515	2523	48	11	1300	90	3.1	322.25	5
2516	2501	40	11	3600	40	2.8	1463.50	5
2516	2517	48	11	3600	240	3.1	787.25	5
2516	2519	40	11	1200	270	2.8	240.50	5
2517	2506	48	11	3600	220	3.1	467.25	5
2517	2516	48	11	3600	240	3.1	1134.50	5
2517	2518	50	22	2800	190	2.8	570.25	5
2518	180	15	15	10000	180	0.5	393.00	0
2518	2505	55	30	1700	460	3.1	219.00	5
2518	2517	40	40	1300	190	0.5	47.00	1
2518	2520	50	22	1200	150	2.8	254.50	5
2519	180	15	15	10000	200	0.5	217.00	0
2519	2516	40	11	1200	270	2.8	561.75	5
2519	2520	40	11	1200	300	2.8	35.25	5
2520	2518	50	22	1200	150	2.8	145.75	5
2520	2519	40	11	1450	300	2.8	106.75	5
2520	2521	50	22	750	840	3.6	219.50	2
2521	181	15	15	10000	1000	0.5	142.50	0
2521	2520	50	22	750	840	3.6	182.25	2
2522	2514	40	11	900	80	2.8	0.00	5
2522	2515	40	11	2950	90	2.8	430.25	5
2523	2513	48	11	1300	90	3.1	322.25	5
2523	2515	48	11	1300	90	3.1	384.00	5
2523	2522	48	11	900	170	3.1	0.00	5
2524	179	15	15	10000	80	0.5	289.50	0
2524	2504	55	11	2650	390	3.1	382.25	5
2524	2505	55	30	1300	290	3.1	382.00	5
2524	2525	40	5	1200	160	4.7	0.00	4
2525	2504	48	11	2650	230	3.1	823.25	5
2525	2507	48	11	2650	70	3.1	677.75	5

* Note:

No.	Road Type
0	Zone Centroid
1	Bus Only
2	Rural Road A
3	Rural Trunk Road
4	Urban Local Distributor
5	Urban District Distributor
6	Urban Primary Distributor
7	Urban Trunk Road

APPENDIX D OBSERVED ORIGIN-DESTINATION MATRIX

The observed origin-destination (O-D) matrix of the selected study area presented in Chapter 6 is tabulated in the next two pages. The O-D demand by car and motorcycles (in pcu/hr) was derived for the morning peak hour period (8:00 am – 9:00 am) in a typical weekday in 1997.

	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173
156	1.3684	0.1139	0.0	0.3032	0.5112	1.0708	1.8668	2.0487	0.4795	0.6425	0.0	0.3544	0.6946	0.4275	0.0	0.0550	0.0	1.2967
157	0.0826	11.905	1.6575	1.8001	0.7323	4.9761	3.8937	7.9859	2.4639	5.1242	2.3226	0.6011	1.1781	2.5092	0.3887	0.3697	1.2058	1.9809
158	0.0449	1.6248	1.3738	3.9911	4.7235	2.8218	6.1359	1.7476	3.1317	5.2624	2.0060	2.2869	3.0277	1.7738	1.0567	0.2283	1.2101	0.9530
159	0.0991	1.8732	3.1673	12.499	13.807	8.8250	24.398	2.4917	14.654	23.289	13.703	18.925	20.748	9.1239	7.9199	1.2052	1.9435	2.6141
160	0.1302	2.1587	2.9563	11.736	21.584	10.745	24.716	3.2442	12.802	21.191	16.175	16.720	18.176	9.3449	10.579	1.0378	2.6940	2.8957
161	0.3984	1.0945	0.9125	5.1030	6.9925	14.779	9.9653	4.3802	4.1009	10.744	5.2246	6.3493	5.3389	2.6025	1.9961	0.2396	1.0986	0.6002
162	0.1450	2.6833	4.3791	26.057	25.269	14.901	28.370	7.8734	13.920	25.589	16.070	18.342	19.909	5.7269	8.8429	0.8341	2.0127	1.8253
163	0.0019	0.1561	0.0440	0.0676	0.2536	0.2119	0.3435	0.4199	0.0739	0.3003	0.0120	0.0351	0.0243	0.0670	0.0	0.0256	0.0592	0.0751
164	0.1132	1.3889	1.5898	12.681	13.449	7.3783	12.306	2.0648	9.4141	19.629	9.7849	13.601	16.121	7.9894	5.0575	1.1014	1.7629	1.4288
165	0.0092	0.4386	0.1208	1.7487	3.8077	2.1092	2.3552	1.2430	1.5013	11.556	1.6222	1.5897	1.2409	1.6952	0.6586	0.0943	0.6480	0.3508
166	0.0570	0.6660	2.3654	17.022	15.650	11.683	20.928	2.5286	13.387	20.622	5.2927	24.865	23.015	7.9999	6.4336	0.9009	1.0311	0.9448
167	0.1051	0.8600	2.5452	18.316	17.780	12.919	19.377	1.7208	19.008	29.048	21.903	14.311	30.946	16.601	8.4060	2.0945	1.9020	1.8516
168	0.0893	0.7302	1.8525	16.766	18.375	9.7737	14.243	2.4994	14.761	17.663	14.946	23.727	14.556	13.386	6.7181	1.6592	2.8233	1.7573
169	0.0969	1.6167	0.9547	7.8318	6.4325	4.2488	4.4373	1.6015	7.0599	11.973	4.6829	11.265	13.340	9.9386	5.0094	1.1536	2.2192	1.8347
170	0.0587	0.8237	2.5124	10.963	12.062	4.8189	7.2834	0.7691	7.9870	16.823	6.5553	11.958	13.393	8.2440	5.1715	0.9285	1.3661	1.8927
171	0.0134	0.2791	0.1543	0.7497	1.3044	1.1817	1.3201	0.5028	1.4862	2.3090	0.7969	1.3628	2.2260	1.1744	1.1334	0.3302	0.9260	0.7446
172	0.1871	0.8441	0.3278	0.9184	2.9646	1.3543	2.0172	1.5681	1.5891	3.5390	0.9735	1.6984	1.8649	0.7542	2.1973	0.2955	2.5681	1.2749
173	0.0769	0.8389	0.3031	0.9455	0.8506	1.7962	1.7121	1.8764	1.0764	1.7971	1.1306	0.7076	1.1354	2.2539	0.1526	0.3085	1.1681	2.6740
174	0.0207	1.1920	0.5204	0.5143	0.5829	0.8897	0.8824	2.5509	0.8487	1.7290	0.0	0.9015	0.9817	1.4692	0.0	0.3930	1.3857	1.4738
175	0.3921	3.2554	0.0	0.0	0.0	0.0	2.1141	13.680	2.4238	10.040	0.0	0.0	5.5885	0.0	0.0	3.0641	4.0537	12.123
176	0.0	0.0	0.0	0.0	0.0	0.0	1.8524	1.1248	0.0	0.7112	0.0	0.0	1.6323	0.0	0.0	0.1940	0.8880	0.7119
177	0.0528	0.8649	0.4875	7.2365	10.523	4.3642	5.4156	0.6923	5.7185	9.6131	1.9668	7.2730	11.672	6.4928	3.4811	1.7483	4.0520	6.0451
178	0.1088	0.5699	0.4741	4.9909	3.9817	3.3177	4.0727	2.0306	3.7213	8.1619	1.0053	1.6436	5.6073	1.7518	1.5747	0.7493	2.9472	4.0426
179	0.0	0.0	0.1500	2.6520	3.6694	0.9418	0.7014	0.9694	1.8094	3.2814	0.0	2.3650	2.4723	1.1413	0.0	0.3672	0.5044	1.3479
180	0.0985	0.6392	0.6814	5.6860	7.4631	4.7169	3.7459	1.0566	4.8996	8.9408	1.4660	3.2235	5.8502	3.4570	2.7801	1.2192	3.3936	4.9663
181	0.0887	0.3838	0.1364	0.5522	1.8341	0.5711	0.7974	0.4408	1.0970	1.6371	0.4402	0.6452	1.2647	1.1335	0.5565	0.3006	0.5150	1.6338
182	0.0166	0.0695	0.3653	0.5551	0.8872	0.3984	0.3649	0.7313	0.8488	1.1598	0.5939	0.4723	0.6747	0.2609	0.0	0.2734	0.7837	0.6980
232	0.0337	0.0395	0.2694	0.2101	0.9799	0.3559	0.6875	0.6443	0.5836	1.5709	0.6281	0.6590	0.8822	0.5925	0.1588	0.1143	0.6752	0.9262
258	0.0007	0.0568	0.0160	0.0245	0.0922	0.0771	0.1249	0.1527	0.0269	0.1092	0.0043	0.0128	0.0089	0.0243	0.0	0.0093	0.0215	0.0274
259	0.0007	0.0568	0.0160	0.0245	0.0922	0.0771	0.1249	0.1527	0.0269	0.1092	0.0043	0.0128	0.0089	0.0243	0.0	0.0093	0.0215	0.0274
261	0.0	3.0912	0.0	0.0	3.2982	0.0	12.784	4.3300	9.5381	0.0	0.0	2.7074	1.7689	0.0	3.5025	1.9913	1.9247	5.9688
301	144.43	101.98	31.133	20.257	0.0	4.9320	49.922	45.363	3.1583	9.2484	0.0	14.876	4.8548	0.0	9.6128	15.041	5.7733	0.0
302	16.022	43.606	13.297	59.586	108.34	85.672	88.641	103.01	38.953	123.50	38.250	27.118	47.918	65.156	28.859	9.9302	37.224	36.216
303	0.0	0.4869	5.4764	20.356	27.574	9.2700	38.924	13.123	12.687	43.104	13.688	19.426	15.825	8.2317	5.2223	3.1453	9.5631	23.801
304	0.0	0.0520	0.4443	1.5272	1.9675	0.5859	3.0177	1.0406	0.9681	3.3377	0.9862	1.4177	1.2166	0.5452	0.4037	0.2415	0.7394	1.7922
305	0.2388	5.3999	2.1110	14.090	27.672	14.603	19.183	14.769	7.9476	29.276	10.618	9.0478	12.796	12.066	2.3786	2.8701	10.971	13.570

	174	175	176	177	178	179	180	181	182	232	258	259	261	301	302	303	304	305
156	0.1759	0.0	0.0	0.0	0.2412	0.0	2.7143	0.3477	0.1054	0.4656	0.4343	0.7785	0.0	51.530	179.36	0.0	0.0	4.0999
157	4.1313	4.1123	0.0	2.7180	0.2045	1.5031	1.3305	1.2882	1.8143	1.0372	1.6930	3.0346	12.201	46.346	159.78	3.7663	0.3187	18.660
158	0.8859	0.6292	0.0	1.3304	1.6385	0.6128	1.2655	0.3206	0.3834	0.1965	0.3705	0.6641	1.8670	13.722	46.964	2.4311	0.2874	6.2511
159	1.6753	2.7744	0.0	12.905	8.0047	3.6023	10.363	4.1472	3.4419	1.7160	0.5282	0.9469	4.1158	48.019	154.33	19.886	1.0631	16.907
160	2.7662	0.0	0.0	16.687	5.1364	5.2732	7.3966	2.1670	1.9192	0.6043	0.6878	1.2328	17.077	35.295	123.56	17.495	0.9603	15.238
161	0.6275	0.7430	0.0	0.9424	2.0900	0.7235	2.2525	2.3953	0.8548	0.1374	0.9286	1.6645	0.0	25.796	90.068	10.931	0.5963	11.649
162	2.3950	11.841	29.894	6.9518	4.7660	4.0175	7.0048	1.8113	2.4350	1.6031	1.6691	2.9918	32.119	49.724	168.08	20.267	1.4010	21.148
163	0.1516	0.1070	0.0	0.1583	0.1119	0.0	0.0768	0.0523	0.0489	0.0084	0.0890	0.1596	0.7932	1.4120	4.4939	0.4916	0.0262	0.7583
164	1.6725	0.7925	0.0	10.055	4.8648	4.4005	8.0123	2.4228	1.9666	1.5440	0.4377	0.7846	0.0	30.257	106.26	8.6963	0.6205	10.622
165	0.4605	2.3220	0.0	0.7467	0.9989	0.2252	1.0774	0.8996	0.3808	0.4307	0.2635	0.4724	6.8892	6.4795	21.611	3.3751	0.2491	6.1787
166	1.3106	0.0	0.0	13.501	5.2331	2.5909	5.5041	1.2200	0.9725	0.7480	0.5361	0.9609	11.217	32.767	116.94	7.4204	0.7699	12.780
167	1.3287	4.4170	0.0	9.9614	5.7236	5.2572	8.8837	5.2900	1.5698	1.2344	0.3648	0.6540	0.0	32.572	113.37	7.4127	0.5768	10.939
168	1.2895	3.7507	0.0	17.446	5.3427	4.0583	8.9805	1.2739	1.9044	0.7810	0.5298	0.9498	11.128	34.018	120.55	7.4282	0.6596	10.616
169	2.2908	1.3560	0.0	10.321	4.2056	2.6409	6.6233	0.6908	1.4458	0.4236	0.3395	0.6085	0.0	31.954	93.514	19.775	1.0339	13.920
170	1.0604	0.0	0.0	11.130	4.3603	4.8060	9.4157	1.2571	1.5036	0.5139	0.1630	0.2923	4.8809	29.196	100.63	9.1320	0.5198	9.5167
171	0.4045	0.7499	0.0	3.0127	2.0906	0.7303	2.9288	0.3821	0.7846	0.9062	0.1066	0.1911	1.1125	5.5782	19.792	2.1883	0.1129	2.5433
172	1.9250	0.0	0.0	6.1541	3.4519	1.8681	4.1075	2.5229	0.8859	1.0146	0.3325	0.5959	5.7511	10.212	35.718	6.5298	0.5420	14.672
173	2.3147	4.6741	0.0	5.2776	3.6375	2.0257	5.2244	1.2638	0.7684	0.7169	0.3978	0.7131	6.1360	8.7333	33.885	17.272	0.5884	13.838
174	6.7516	5.9552	0.0	2.9370	1.9351	2.0517	2.9496	1.5713	1.0835	0.6256	0.5408	0.9693	6.1003	14.091	49.095	16.065	0.6378	13.725
175	6.4456	85.673	0.0	23.221	9.7035	3.5651	16.359	0.0	3.3469	0.0	2.9002	5.1985	0.0	41.750	141.19	61.013	0.8031	34.977
176	1.2407	9.6237	0.0	2.0346	1.7004	9.3714	4.1476	0.0	1.4663	0.0	0.2385	0.4274	0.0	8.8123	26.256	7.7685	0.2790	6.3788
177	3.2451	14.808	0.0	36.142	23.651	18.138	45.455	14.333	14.703	3.0490	0.1468	0.2631	4.3933	22.549	89.429	106.98	4.3922	84.302
178	2.0895	10.044	7.4930	25.010	29.171	10.893	28.037	10.186	8.8973	4.2933	0.4305	0.7716	22.243	18.207	60.180	95.713	5.4999	80.750
179	1.4094	0.0	0.0	11.212	9.3108	5.5359	17.950	4.6413	2.4978	0.5691	0.2055	0.3683	0.0	6.0044	26.390	36.863	1.2411	27.149
180	2.5556	9.6579	0.0	41.114	26.367	17.713	59.369	18.571	15.823	4.0374	0.2240	0.4015	8.1871	20.410	70.352	134.68	7.5827	99.618
181	1.7790	6.5620	13.727	13.663	9.4266	9.5114	18.548	6.2555	2.7432	1.2122	0.0934	0.1675	0.0	7.9457	28.145	37.830	2.0386	28.325
182	0.3518	1.2494	0.0	8.4711	4.7984	2.7036	8.8574	1.6498	6.4973	0.8233	0.1550	0.2780	2.9261	0.0	0.0	255.08	4.9086	8.2306
232	0.4605	0.9458	0.0	7.2933	3.5864	2.7912	6.6469	1.2046	1.9468	1.2674	0.1366	0.2448	0.0	4.4330	17.529	21.310	0.9423	16.210
258	0.0551	0.0389	0.0	0.0576	0.0407	0.0	0.0280	0.0191	0.0178	0.0030	0.0324	0.0580	0.2885	0.5135	1.6342	0.1788	0.0095	0.2757
259	0.0551	0.0389	0.0	0.0576	0.0407	0.0	0.0280	0.0191	0.0178	0.0030	0.0324	0.0580	0.2885	0.5135	1.6342	0.1788	0.0095	0.2757
261	17.017	0.0	0.0	17.640	7.3712	16.926	6.5445	7.9699	0.0	1.6288	0.9180	1.6454	0.0	36.645	125.59	73.585	3.4477	57.374
301	3.6899	0.0	0.0	0.0	5.0576	0.0	16.464	0.0	0.0	4.4704	9.6170	17.238	0.0	0.0	0.0	0.0	0.0	0.0
302	55.670	113.43	0.0	45.808	42.090	13.376	34.547	39.686	0.0	18.607	21.837	39.142	113.44	0.0	0.0	0.0	0.0	0.0
303	20.415	42.459	5.8408	147.54	179.52	78.217	209.41	89.813	249.15	40.574	2.7820	4.9867	0.0	0.0	0.0	0.0	0.0	261.25
304	1.4353	3.3109	0.0	11.364	15.063	5.6388	16.435	7.2686	29.010	3.0613	0.2206	0.3954	0.0	0.0	0.0	0.0	0.0	27.914
305	19.107	25.459	22.810	91.031	59.777	34.879	93.581	24.531	22.290	11.750	3.1310	5.6123	68.120	0.0	0.0	315.00	20.483	0.0