CHAPTER 12

PAVING NEW GROUND: A MARKOV CHAIN MODEL OF THE CHANGE IN TRANSPORTATION NETWORKS AND LAND USE

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INTRODUCTION

It has long been a mantra among planners that transportation policies and networks drive land use and it has also been a mantra among civil engineers that networks are built where the people are. Can it be that both are right?

Since the widespread introduction of paved roads early in the twentieth century, more and more roads, of higher and higher quality and capacity have been constructed. However, despite the growth in transportation networks, there has been even more growth in the demand for transportation networks. Vehicle kilometers traveled has outpaced lane kilometers in most cities (e.g. the Twin Cities of Minneapolis and St. Paul (Levinson and Karamalaputi, 2003)). This has led to significant increases in congestion, and over time, falling speeds on many links (TTI, 2002). This leads many in the engineering community to believe that when they are building roads, they are simply responding to existing needs.

Similarly with the growth of population and of cities, more and more land has been devoted to developed uses (commercial, employment, and residential) and less to "undeveloped" uses (agricultural and recreational). These trends are especially visible in growing metropolitan areas that have steadily added to their spatial extent. Of course, that development would be impossible with concurrent construction of infrastructure such as streets and highways. The phenomenon of induced demand, whereby an addition 1% roadways leads to some increase (typically 0.2%–0.8% (Parthasarathi *et al.*, 2003)) in travel demand leads many in the planning community to conclude that it is transportation capacity driving travel demand. While the length and number of trips per person may change (and has been increasing), transportation surely cannot be directly blamed for the increasing number of people that is the dominant part of the increase in travel demand.

In this paper we explore the inter-connectedness of the evolution of transportation networks and land use through the application of a Markov Chain model. This model investigates how individual cells, with both land use and transportation network attributes, change over time. We can see whether cells with more transportation network available are more likely to develop, and whether cells that are developed are more likely to attract additional highway investment. While this paper does not consider land use density directly, it does consider land use type, and as cells change type, we can conclude that some form of development is likely to be occurring.

The next section of this paper outlines the Markov Chain model. This is followed by a discussion of the Twin Cities data used in the study. The subsequent section develops the transition probability matrices used by the Markov Chain in our case. Those matrices are analyzed to understand the empirical regularities that appear in the data. They are then applied to both assess the predictive ability of the Markov Chain model (comparing what the model would predict with what actually happened), and then applying the model to forecast future changes in the Twin Cities area. The paper concludes with some suggestions for future research.

THE MARKOV CHAIN MODEL

It is fair to say that the co-evolution of urban highway network and land use is a complicated stochastic process; therefore, it is more appropriate to analyze the co-evolution with a probabilistic rather than a deterministic model. Among probabilistic processes, the Markov Chain Model, employed in this paper, provides a powerful tool for analyzing the system evolution through time series, and it has been applied in many fields of research.

The Markov Chain Model has a *discrete-time* version and a *continuous-time* version. In this study, we concentrate on the discrete-time version. A discrete-time Markov Chain Model describes the evolution of a process through a sequence of states S with equal time intervals, such as $S(0)$ --> $S(1)$ --> $S(2)$ -->…… $S(t)$, where $S(t)$ indicates the state of the system at time t. $S(t)$ controls $S(t+1)$ through transition probability p_{ij}, where p_{ij} is given by

$$p_{ij} = P(S(t+1) = j \mid S(t) = i)$$

We can describe the transition probabilities in a more compact way by arraying them into a square matrix P, called the transition matrix. The transition matrix looks like this:

$$\boldsymbol{P} = \begin{bmatrix} p_{00} & p_{01} & p_{02} & \cdots & p_{0n} \\ p_{10} & p_{11} & p_{12} & \cdots & p_{1n} \\ p_{20} & p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ p_{n0} & p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix}$$

Given the present state of the system $S(t)$, matrix P provides the probability to go in one step from state $S(t)$ to state $S(t+1)$, that is

$$S(t+1)= P\times S(t)$$

For a system with an initial state $S(0)$ and transition matrix P, the consecutive states in equal time intervals are estimated in the following succession:

$$S(1)= P\times S(0),\ S(2)= P\times S(1),\ S(3)= P\times S(2)\ \ldots\ldots$$

A generalized expression can be that given the current state $S(t)$, the kth power of the transition matrix P provides the conditional probability that after k steps' evolution the system becomes state $S(t+k)$, that is

$$S(t+k)= P^k\times S(t), \quad t,k=0,1,\ldots\ldots$$

This indicates that we can predict the future evolution of a system by determining the transition matrix P.

Of the few applications of Markov Chain Model in spatial social-economics and geography, land-use, and transportation research, Lever (1972) used a four-zone Markov Chain Model to predict the probable future distribution of manufacturing establishments. The transition matrix was estimated by counting the probability of the movements of firms from Zone i to Zone j,($i,j = 1,2,3,4$) throughout 1959 to 1969. Clark (1965) studied the movement of rental housing areas and divided the central city tracts into ten classes with $10 intervals in rents and each of the classes represented a state of the Markov Chain Model. Two decades of data, from 1940 (starting state) to 1950 (destination state) and from 1950 (starting state) to 1960 (destination state), were pooled in the same matrix to calculate the probability of the movements of tracts from class i to class j. Zhang and Li, (2005) used a two-dimensional Markov chain model to simulate multinomial land-cover classes and to estimate occurrence probability vectors for spatial uncertainty representation. Zhang, and Cho (2001) presented an evolutionary Markov chain Monte Carlo method to identify the functional structure of a target system that underlies the observed data. Janssens *et al.* (2005) developed and evaluated the implementation of an adapted Markov Chain modelling heuristic and simulation framework in the context of transportation research. Yin *et al.* (2003) simulated certain types of population dynamics using continuous-time finite-state Markov chains, and presented two case studies.

One was a process of drug delivery for which a closed-form solution of the forward equation can also be obtained; the other one simulated the birth, death, and growth of cell population dynamics using a Markovian model. Goulias (1999) used generalized mixed Markov latent class models to study the dynamics of travel patterns. The repeated nature of travelers' behavior "allows to distinguish units that over time change their behavior from those that are not and to uncover the underlying stochastic behavior generating the data… Travel pattern change is best explained by a single path of change with stationary day-to-day pattern transition probabilities that are different from their year-to-year counterparts."

In this paper, a Markov Chain Model is developed to analyze and predict the co-development of the highway network and land use. The sources of data and the Markov Chain Model are presented in the ensuing sections.

DATA

High-quality GIS land use and highway network maps for the Twin Cities Metropolitan Area from 1958 to 1990 were developed from paper maps (Table 1). Then a lattice layer is created which is composed of 188×188 m square cells. This lattice layer was transformed into polygon coverage which shares the same corridor system with the land use and highway network layers. The land use layer and highway layer were merged into the lattice layer, the cells of the lattice layer then contain the spatial information of land use and highways.

Note: Figures and Tables are located at the end of this chapter.

Figure 1 displays the gridded maps of land use for 1958, 1968, 1978, and 1990 wherein each cell is classified into one of five types of zones E, R, M, A, and W, based on land use:

- E (Employment zone), which contains Commercial areas, Industrial areas, Institutional and Office areas, and Airports;
- R (Residential zone), which contains both Single Family Residential and Multi-Family Residential areas;
- M (Mixed use), which contains both Employment and Residential areas;
- A (Agricultural and Recreational zones), which contains Agricultural, Recreational and also vacant areas; and
- W (Water zone), which is predominantly water covered.

Each of the cells is classified into one of the five types of zones based on the following rules: Firstly, for all the cells that are within or intersect Employment zones, they belong to E or M; a cell is classified as M if it intersects Employment zones and also contains Residential areas and a cell is classified as E if it is within or intersects Employment zones but does not contain Residential areas. Secondly, for the remaining cells, they belong to R if they are within or intersect Residential zones. Thirdly, for the cells not belonging to E, M, or R, they belong to

W if they are within or intersect Water zones. Finally, the cells belong to A if they do not belong to E, M, R, or W.

The highways are classified into two levels, the upper level highways composed of Interstates and Divided Highways and the lower level highways composed of Undivided Highways and County Highways. Each of the cells has one of the four attributes: U (the cell only contains upper level highways), L (the cell only contains lower level highways), B (the cell contains both upper and lower level highways), and N (the cell does not contain either upper or lower level highways).

Combining the 5 land use and 4 highway classifications, we can get the 20 types of cells: EU, EL, EB, EN, MU, ML, MB, MN, RU, RL, RB, RN, WU, WL, WB, WN, AU, AL, AB, and AN, which represent the 20 classes of the Markov Chain Model.

TRANSITION MATRIX

A Markov Chain Model moves from one state to the next controlled by the transition matrix. In this study Years 1958, 1968, 1978 and 1990 are the successive states[1]. A transition probability matrix can be derived from each pair of the successive states.

S(1958) → S(1968) → S(1978) → S(1990) ……

For instance, let $P_{EU,EU}$ denote the probability that a cell being EU in one state continues to be EU in the next state, and let $P_{EU,MB}$ denote the probability that a cell being EU in one state changes to be MB in the next state. Using this procedure, we can get 20×20 transition probabilities that are assembled into a transition matrix *P*.

$$
\boldsymbol{P} = \begin{bmatrix}
P_{EU,EU} & P_{EU,MU} & P_{EU,RU} & P_{EU,WU} & P_{EU,AU} & P_{EU,EL} & P_{EU,ML} & P_{EU,RL} & \cdots & P_{EU,MN} & P_{EU,RN} & P_{EU,WN} & P_{EU,AN} \\
P_{MU,EU} & P_{MU,MU} & P_{MU,RU} & P_{MU,WU} & P_{MU,AU} & P_{MU,EL} & P_{MU,ML} & P_{MU,RL} & \cdots & P_{MU,MN} & P_{MU,RN} & P_{MU,WN} & P_{MU,AN} \\
P_{RU,EU} & P_{RU,MU} & P_{RU,RU} & P_{RU,WU} & P_{RU,AU} & P_{RU,EL} & P_{RU,ML} & P_{RU,RL} & \cdots & P_{RU,MN} & P_{RU,RN} & P_{RU,WN} & P_{RU,AN} \\
P_{WU,EU} & P_{WU,MU} & P_{WU,RU} & P_{WU,WU} & P_{WU,AU} & P_{WU,EL} & P_{WU,ML} & P_{WU,RL} & \cdots & P_{WU,MN} & P_{WU,RN} & P_{WU,WN} & P_{WU,AN} \\
P_{AU,EU} & P_{AU,MU} & P_{AU,RU} & P_{AU,WU} & P_{AU,AU} & P_{AU,EL} & P_{AU,ML} & P_{AU,RL} & \cdots & P_{AU,MN} & P_{AU,RN} & P_{AU,WN} & P_{AU,AN} \\
P_{EL,EU} & P_{EL,MU} & P_{EL,RU} & P_{EL,WU} & P_{EL,AU} & P_{EL,EL} & P_{EL,ML} & P_{EL,RL} & \cdots & P_{EL,MN} & P_{EL,RN} & P_{EL,WN} & P_{EL,AN} \\
P_{ML,EU} & P_{ML,MU} & P_{ML,RU} & P_{ML,WU} & P_{ML,AU} & P_{ML,EL} & P_{ML,ML} & P_{ML,RL} & \cdots & P_{ML,MN} & P_{ML,RN} & P_{ML,WN} & P_{ML,AN} \\
P_{WL,EU} & P_{WL,MU} & P_{WL,RU} & P_{WL,WU} & P_{WL,AU} & P_{WL,EL} & P_{WL,ML} & P_{WL,RL} & \cdots & P_{WL,MN} & P_{WL,RN} & P_{WL,WN} & P_{WL,AN} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\
P_{MN,EU} & P_{MN,MU} & P_{MN,RU} & P_{MN,WU} & P_{MN,AU} & P_{MN,EL} & P_{MN,ML} & P_{MN,RL} & \cdots & P_{MN,MN} & P_{MN,RN} & P_{MN,WN} & P_{MN,AN} \\
P_{RN,EU} & P_{RN,MU} & P_{RN,RU} & P_{RN,WU} & P_{RN,AU} & P_{RN,EL} & P_{RN,ML} & P_{RN,RL} & \cdots & P_{RN,MN} & P_{RN,RN} & P_{RN,WN} & P_{RN,AN} \\
P_{WN,EU} & P_{WN,MU} & P_{WN,RU} & P_{WN,WU} & P_{WN,AU} & P_{WN,EL} & P_{WN,ML} & P_{WN,RL} & \cdots & P_{WN,MN} & P_{WN,RN} & P_{WN,WN} & P_{WN,AN} \\
P_{AN,EU} & P_{AN,MU} & P_{AN,RU} & P_{AN,WU} & P_{AN,AU} & P_{AN,EL} & P_{AN,ML} & P_{AN,RL} & \cdots & P_{AN,MN} & P_{AN,RN} & P_{AN,WN} & P_{AN,AN}
\end{bmatrix}
$$

The changes of the cells between different classes are summarized in three two-way tables for the 1958–1968 period, 1968–1978 period, and 1978–1990 period respectively (Table 2). A transition matrix can be derived from each of the two-way tables and each of the transition probabilities is calculated by its corresponding cell entry divided by the row total, for example,

$$P_{EU,MB} = \frac{EU,MB}{EU,EU + EU,MU + EU,RU + EU,WU + EU,AU + EU,EL + \cdots + EU,WN + EU,AN}$$

Clearly, the sums of the rows of a transition matrix are always equal to 1.

For the 1958 – 1968 period, 1968 - 1978 period, and 1978 - 1990 period respectively, we get three transition matrices $P_{1958\text{-}1968}$, $P_{1968\text{-}1978}$ and $P_{1978\text{-}1990}$ (Appendix: Table 3). The highlighted cells indicate the maximum of each row.

From Tables 2 and 3, we can derive some important evolution tendencies of highways and land use.

The percentage of land use distribution in different zones is shown in Figure 2. From 1958 to 1990, there was a significant increase (from 9% to 30%) of the proportion occupied by Zone E and M (Employment zones and the mixed Employment and Residential Zones), and also a significant increase (from 21% to 43%) of the proportion occupied by Zone R (Residential zones). Meanwhile, there was a significant decrease (from 62% to 20%) of the proportion occupied by Zone A (Agricultural and Recreational zones). These changes display a clear tendency toward urbanization over the last four decades of the twentieth century.

Accompanying the urbanization of land use, upper level highways (Interstates and Divided Highways) experienced a tremendous growth from 1958 to 1990, which was measured by the number of cells containing the upper level highways (Figure 3). Meanwhile, the proportions of the upper level highways within Zone E, M, and R increased significantly (from 43% to 83%), while the proportions of the upper level highways within Zone A decreased significantly (from 55% to 14%) (Figure 4). This was caused by the expansion of Employment and Residential zones and the contraction of Agricultural and Recreational zones (Figure 2), and also caused by transportation and land use interactions. Transportation and land use interactions can be simplified as follows: land development generates travel demand, which in turn leads to the development of new transportation infrastructure in the urbanized areas; the developed transportation infrastructure improves accessibility and mobility, which attracts further land development.

Compared with upper level highways, the lower level highways had moderate development and seemed to be close to a saturation state after 1978 (Figure 3). Furthermore, the proportions of lower level highways within Zone E, M, and R increased significantly (from 47% to 86%) while decreasing significantly within Zone A (from 51% to 12%) (Figure 4), similar to the upper level highways. This was partially caused by the expansion of

Employment and Residential zones and the contraction of Agricultural and Recreational zones (Figure 2), and partially due to the fact that lower level highways are the connecting links among urban settlement and the upper level highways, so their growth tends to accompany the development of Zone E, M, and R and the upper level highways. The share of cells with lower level highways also declines if those roads are upgraded.

Next, we will discuss the effects of transportation on land development. Figure 5 shows the development of Agricultural and Recreational zones. It is obvious that highways do affect the development of Agricultural and Recreational zones. Agricultural and Recreational zones without highways (AN) have the lowest probability to convert to urbanized land use (E, M, and R), while Agricultural and Recreational zones that contain both upper and lower level highways (AB) have the highest probability to convert to urbanized land use. These facts indicate that the construction of highways contributes to the urbanization of land development. Figure 6 shows the development of urbanized land use (E, R, M). Compared with Agricultural, the development of urbanized zones is less influenced by highways. Independent of whether the zone contains highways, Employment zones are most likely to continue being Employment zones, and next most likely to change to the Mixed zones. Highways do not obviously influence the development of Mixed zones either. Independent of their highways, Mixed zones are most likely to keep their land use attributes unchanged, and next most likely to change to Employment or Residential zones. Residential zones, however, are more likely to change to Mixed zones if they contain highways. Residential zones without highways (RN) have the highest probability of remaining unchanged, while Residential zones that contain both upper and lower level highways (RB) have the highest probability of converting to Mixed use zones.

The effect of land use on transportation growth is an equally important topic, addressed in Levinson and Chen (2004), which demonstrates that an area's land use attributes and population density level do have significant relationships with the area's likelihood of highway development.

PREDICTION

Section four presented the Markov Chain Model and transition matrices, some important evolution rules of highways and land use were summarized. Markov Chain Models also allow us to predict the future development of a system. To do this, we use one state as well as the transition matrix obtained from this state and its immediately preceding state to predict the next state, such as, $\widehat{\boldsymbol{S}}(\boldsymbol{t}) = \boldsymbol{P}_{t-2,t-1} \times \boldsymbol{S}(\boldsymbol{t}-\mathbf{1})$ and $\widehat{\boldsymbol{S}}(\boldsymbol{t}+\mathbf{1}) = \boldsymbol{P}_{t-1,t} \times \boldsymbol{S}(\boldsymbol{t})$. Furthermore, if we assume $P_{t-2,t-1} \approx P_{t-1,t}$ we obtain $\widehat{\boldsymbol{S}}(\boldsymbol{t}+\mathbf{1}) = \boldsymbol{P}^{\mathbf{2}}_{t-2,t-1} \times \boldsymbol{S}(\boldsymbol{t}-\mathbf{1})$.

Table 4 presents the observed and predicted *S(1978)* and *S(1990)*, where the predicted *S(1978)* and *S(1990)* are obtained through $\hat{S}(1978) = P_{1958\text{-}1968} \times S(1968)$, $\hat{S}(1990) = P^2_{1958\text{-}1968} \times S(1968)$, and $\hat{S}(1990) = P_{1968\text{-}1978} \times S(1978)$.

Chi-square tests of goodness-of-fit are conducted for the three pairs of predicted and observed percentage distribution in Table 4, the null hypothesis is that the differences between the predicted and observed distribution is due to chance only. All the four p values for the calculated chi-squares are much larger than 0.1, so the null hypothesis is not rejected, that means the difference between predicted and observed distribution under the null hypothesis is the result of chance, and therefore negligible. The predicted distribution is acceptable.

The quality of the predictions using Markov Chain Model depends on the constancy of the transition matrices. We can get good prediction results if the successive transition matrices are approximately constant, for example, the predicted distributions of *S(1978)* and *S(1990)* are close to their observed distributions, which indicates that the transition matrix of 1958-1968 period is similar to that of 1968-1978 period, and the transition matrix of 1968-1978 period is similar to that of 1978-1990 period. Since the transition matrix of 1978-1990 period is the most recent one we have in the database, we use this transition matrix to predict the future development of the system as below, assuming that this transition matrix is approximately constant for these years.

$$\hat{S}(2000) = P_{78\text{-}90} \times S(90),\ \hat{S}(2010) = P_{78\text{-}90}{}^2 \times S(90) \ldots \hat{S}(2050) = P_{78\text{-}90}{}^6 \times S(90).$$

Another commonly used prediction method is to pool the data of different periods into the same two-way table and derive a single transition matrix from the table, and use this transition matrix to predict the ensuing states, such as,

$$\left.\begin{array}{l} S(58) \rightarrow S(68) \\ S(68) \rightarrow S(78) \\ S(78) \rightarrow S(90) \end{array}\right\} \rightarrow \cdots\cdots S(t)$$

The matrix obtained from the pooled data may be rational for some other cases, but we do not think it would work better than the matrix of the 1978-1990 period in predicting the future development of the urban system. The growth pattern of the urban system in the 1978-1990 period should be more similar to the future development than that in the 1958-1968 and 1968-1978 periods. Clearly the closer the prediction the more accurate the results (assuming, as here, the transition matrices are based on a substantially long period of time that smoothes out the development cycle).

Figure 7 presents the predicted development of land use and highways in the next half century base on the transition matrix of the 1978-1990 period. It is expected that, from 1990 to 2050, the Employment zones keep stationary, while the Mixed use zones increase from 16% to 22%

and Residential zones increase from 43% to 48%. The Agricultural and Recreational zones decrease from 20% to 9%. The predicted results indicate that if the development pattern of 1978-1990 period is continued, we would expect to have a highly urbanized region in 2050, where more than 80% of land is used for commercial, industrial, institutional, office and residential purposes and only less than 10% of land in the currently designed metro area is left for agricultural and recreational purposes. Meanwhile, it is expected that the upper level highways continue to increase from 1990 to 2050 (measured by the number of the cells that contain the highways), and in 2050 about 15 percent of the cells contain upper level highways; the lower level highways, however, seem to have reached the stationary state and remain in about 16 percentage of cells. It is also expected that (Figure 8), in 2050, 86 percentage of the upper level highways and 91 percentage of the lower level highways are within the urbanized zones (Zones E, M, and R).

CONCLUSION

This paper employs a Markov Chain Model to analyze the spatial co-evolution of transportation and land use. A transition matrix records the interaction between transportation and land use and it is used to predict the future development of transportation and land use.

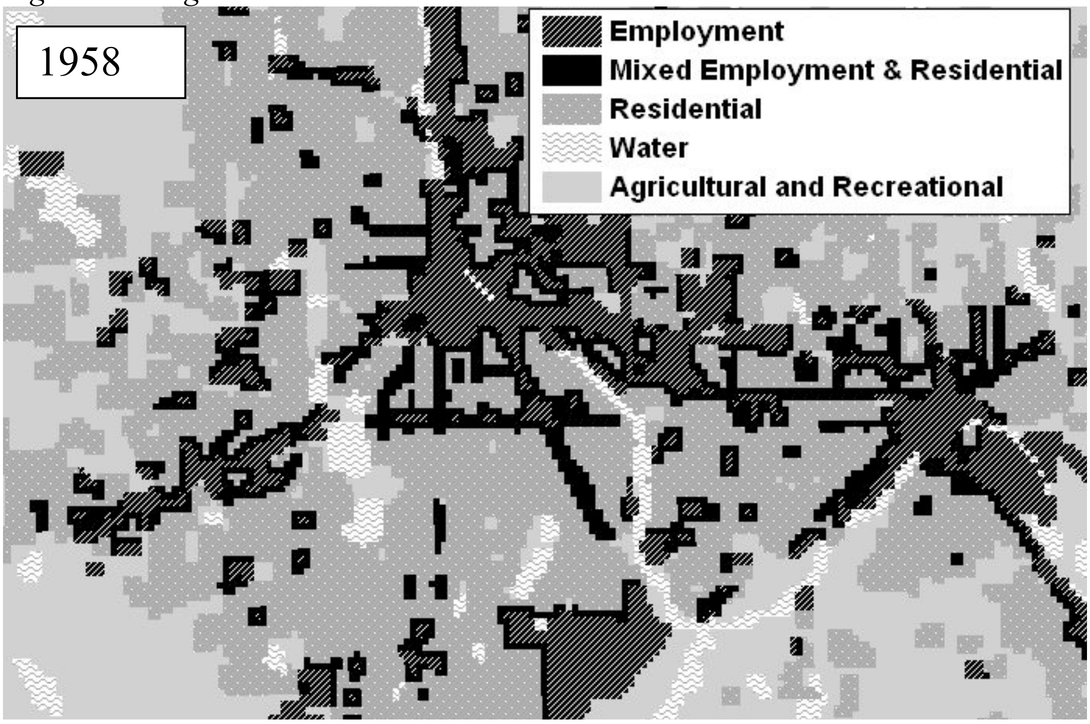
The study is based on the highway network and land use of the Twin Cities Metropolitan Area from 1958 to 1990. Through the Markov Chain Model we find that highways do affect the development of Agricultural and Recreational zones. The Agricultural and Recreational zones that contain highways are much more likely to convert to Employment and Residential zones than the Agricultural and Recreational zones without highways. Compared with Agricultural and Recreational zones, the development of urbanized zones is less influenced by highways. Employment zones are least likely to change their land use attributes. Residential zones, however, are more likely to change to Mixed use zones if they contain highways.

The prediction function of the Markov Chain Model has been performed and Chi-square tests tell that the predicted distributions of S(1978) and S(1990) are close to their observed distributions, which indicates that the Markov Chain Model works well to predict the future system development at least for the next decade. We also use the transition matrix of the 1978-1990 period to predict the future development of the system in the next half century assuming that this transition matrix is approximately constant during these years, and the predicted results show that if the future development of the system follows the same growth pattern of 1978-1990 period, we will expect to see a highly urbanized Metropolitan Area in the next half century.

Markov Chain Model allows us to describe, analyze and predict the development of complicated dynamic systems. Further improvements of the Markov Chain Model presented in this paper will result in a greater understanding of the dynamics of urban highway networks and land use.

FIGURES

Figure 1. The gridded land use zones



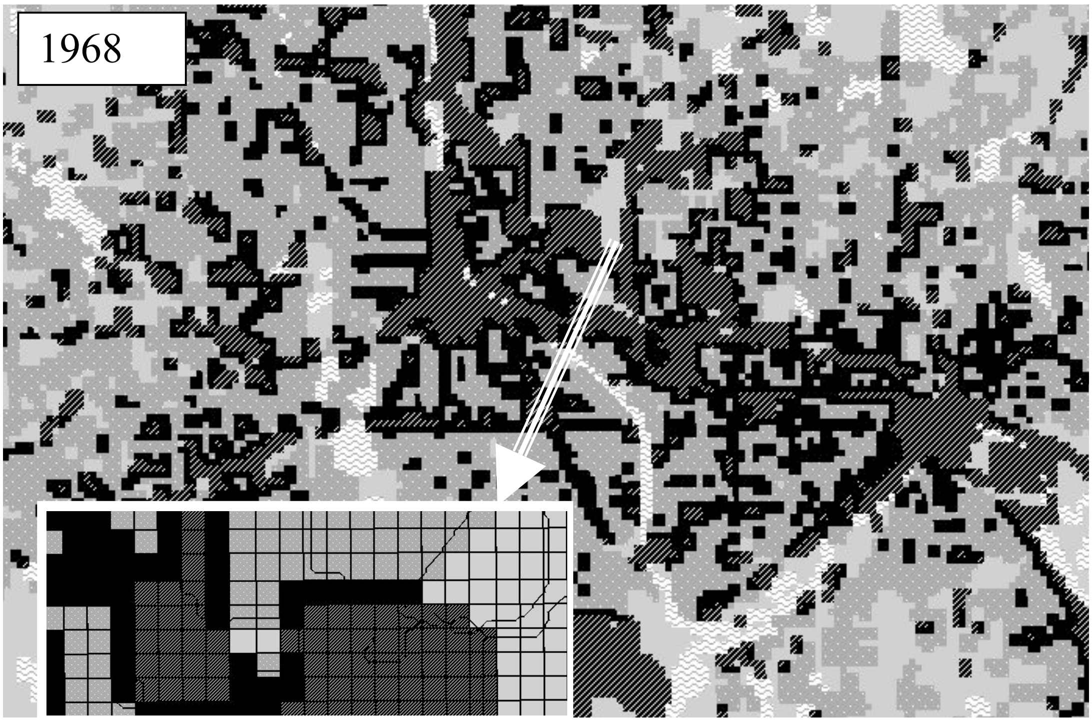
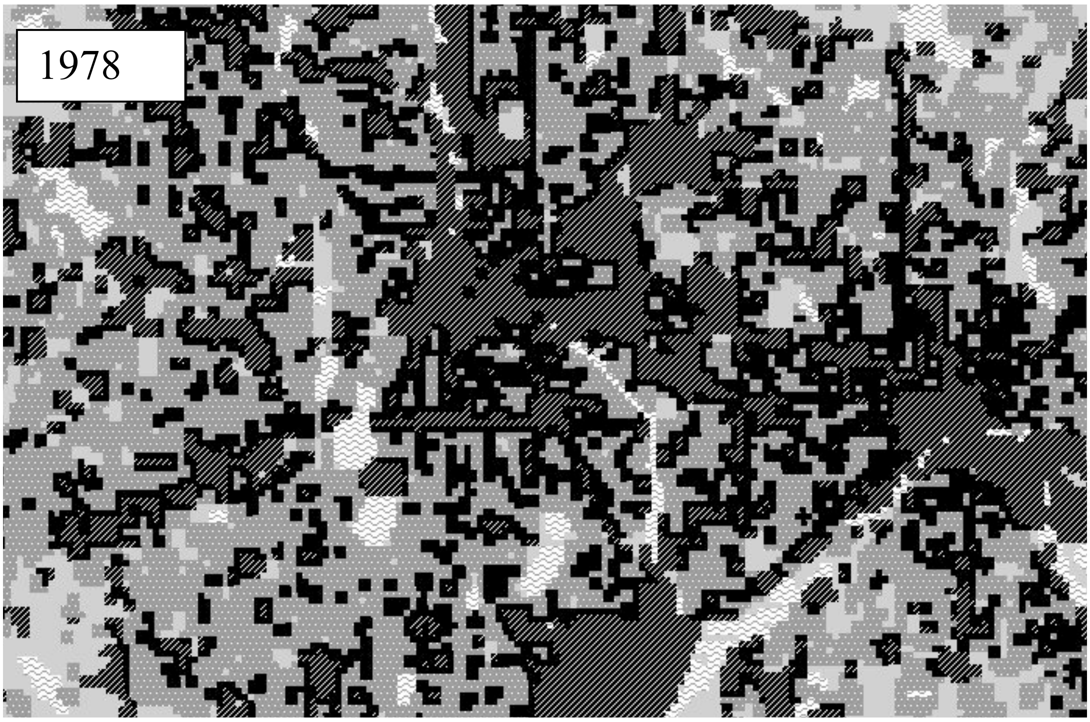


Figure 1. (cont'd)


1978

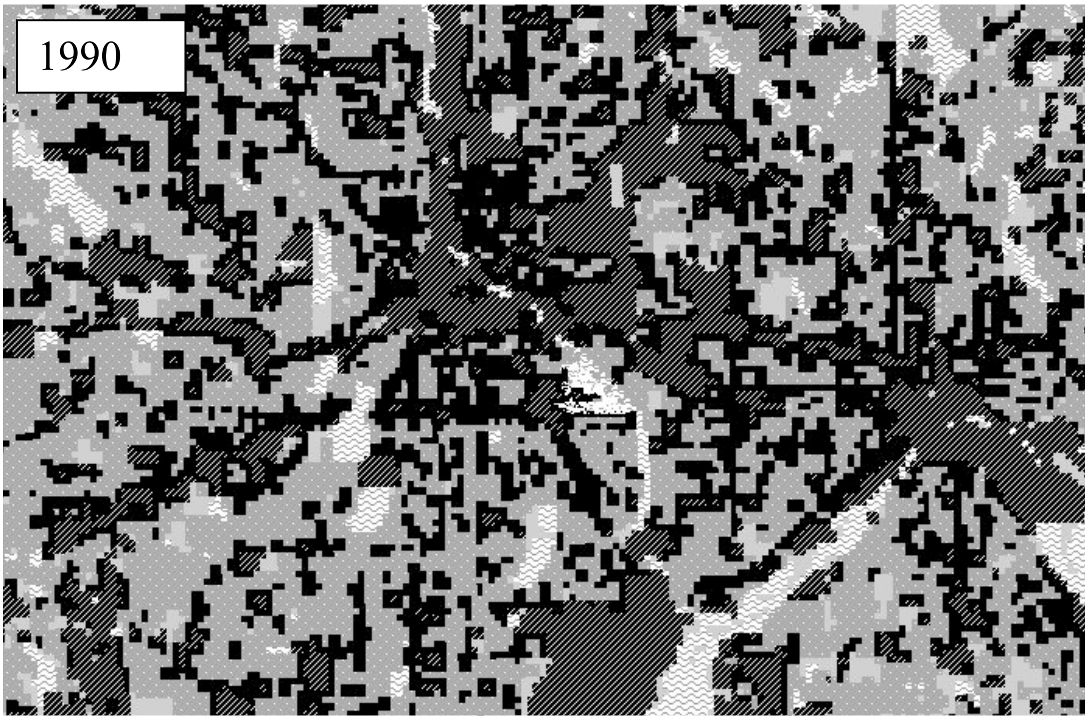

1990

Figure 2. The Percentage of Land use Distribution

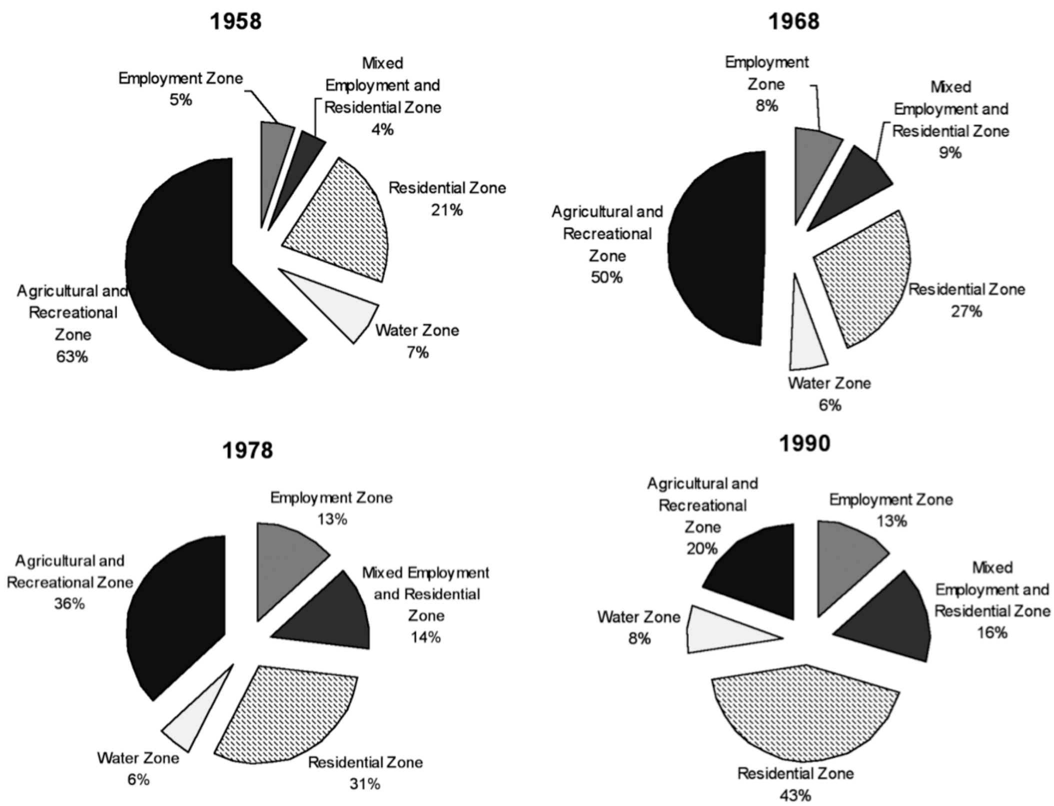
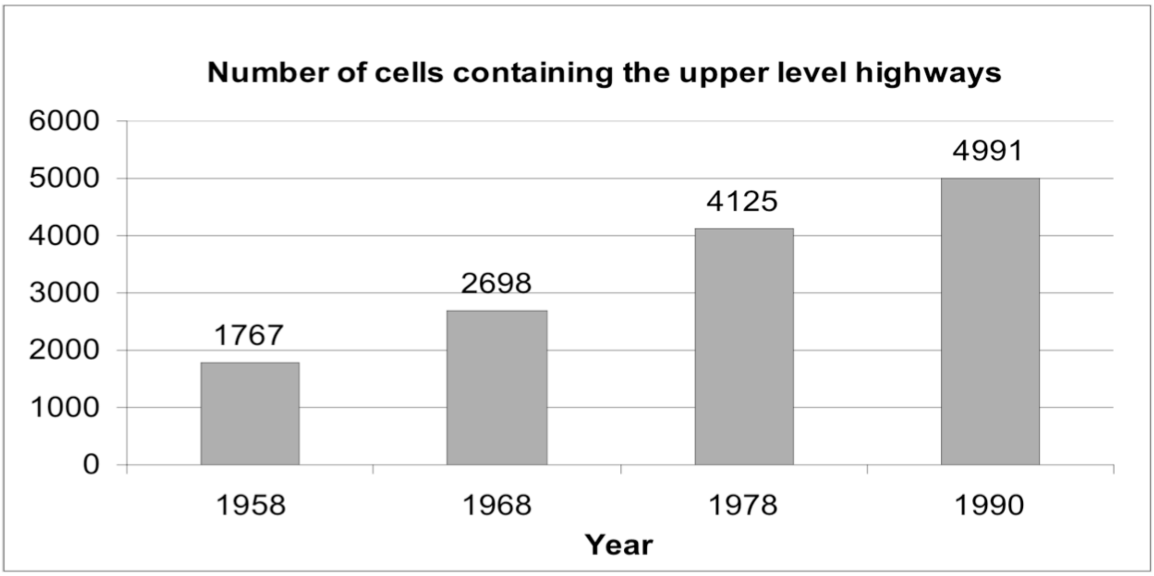


Figure 3. The growth of upper and lower level highways.



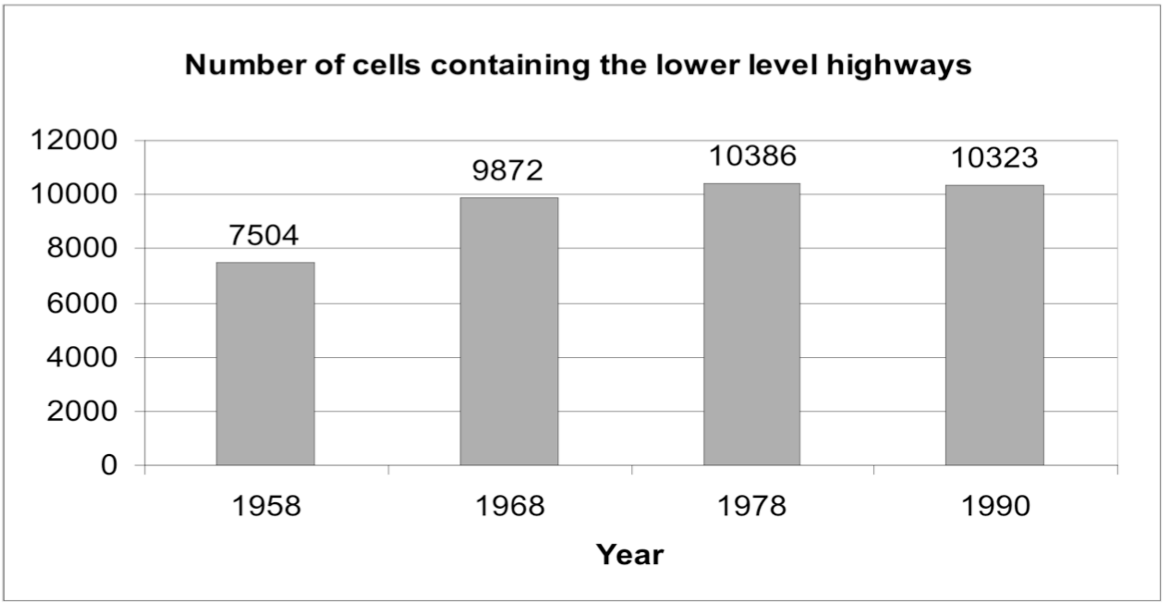
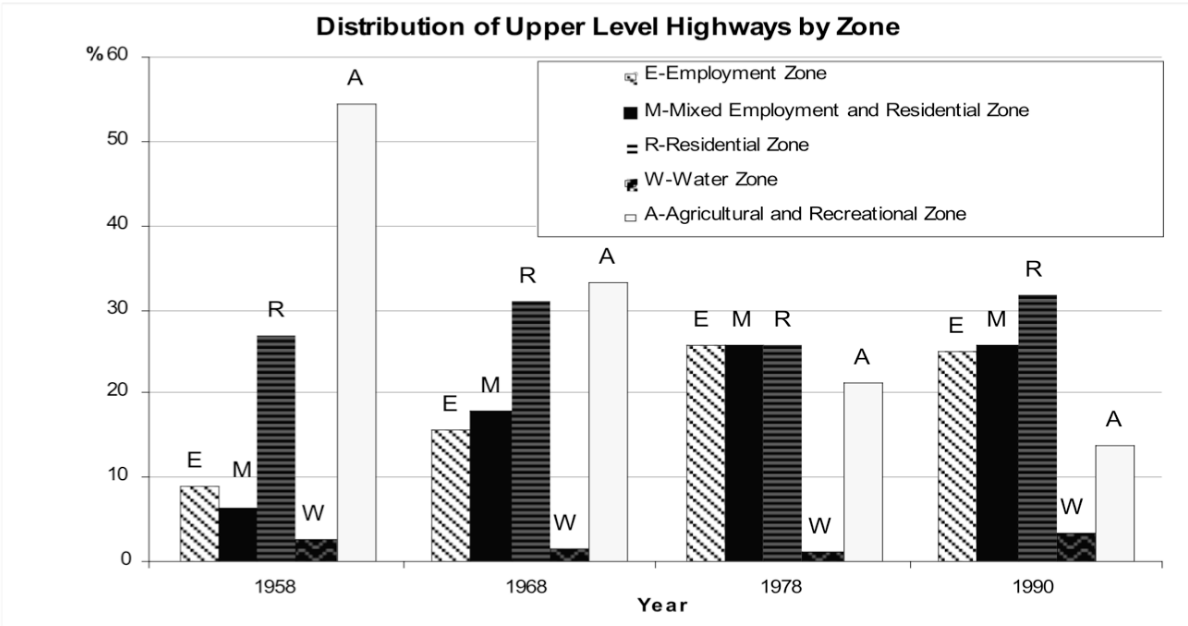


Figure 4. Distribution of upper and lower level highways by zone.



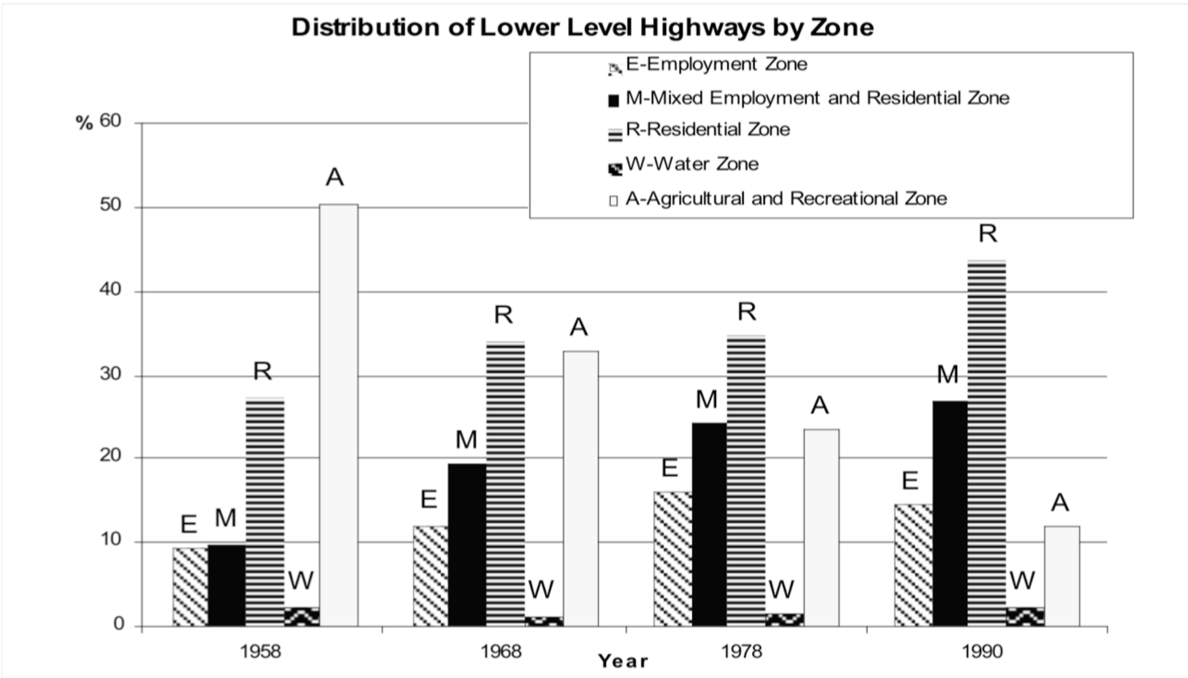
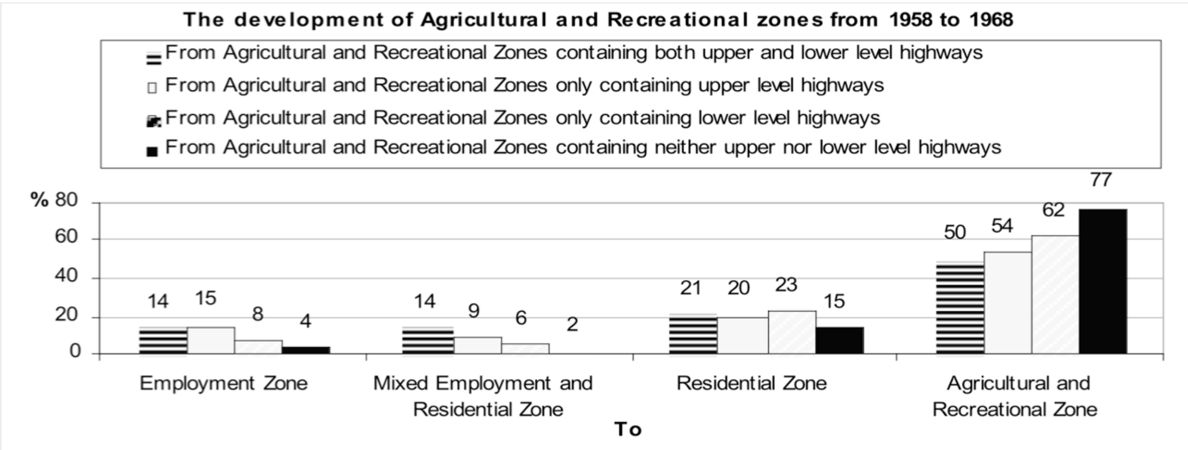
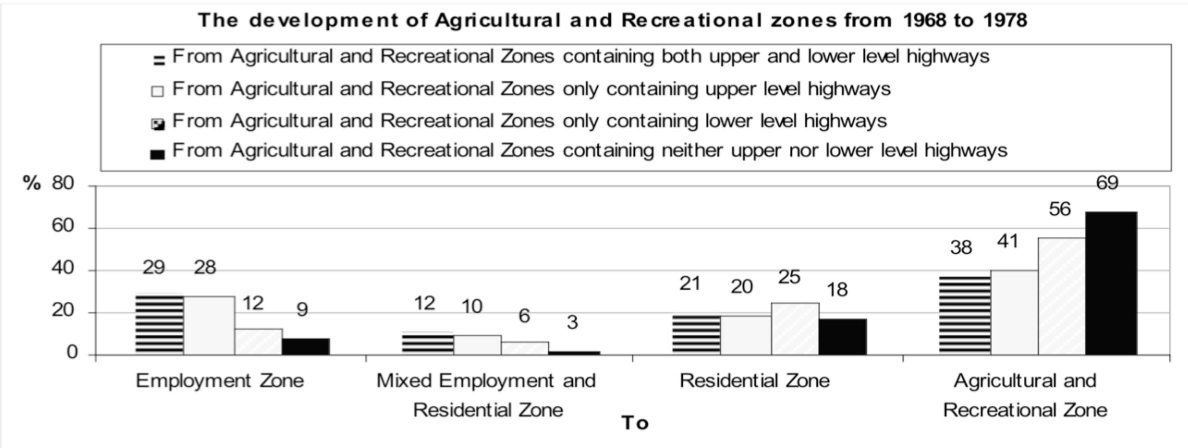


Figure 5. The development of Agricultural and Recreational zones.





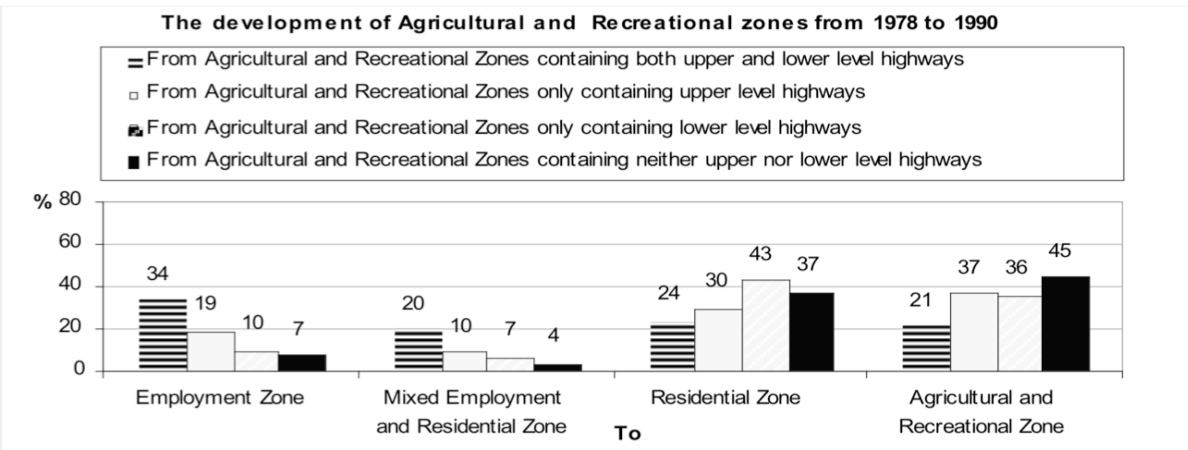
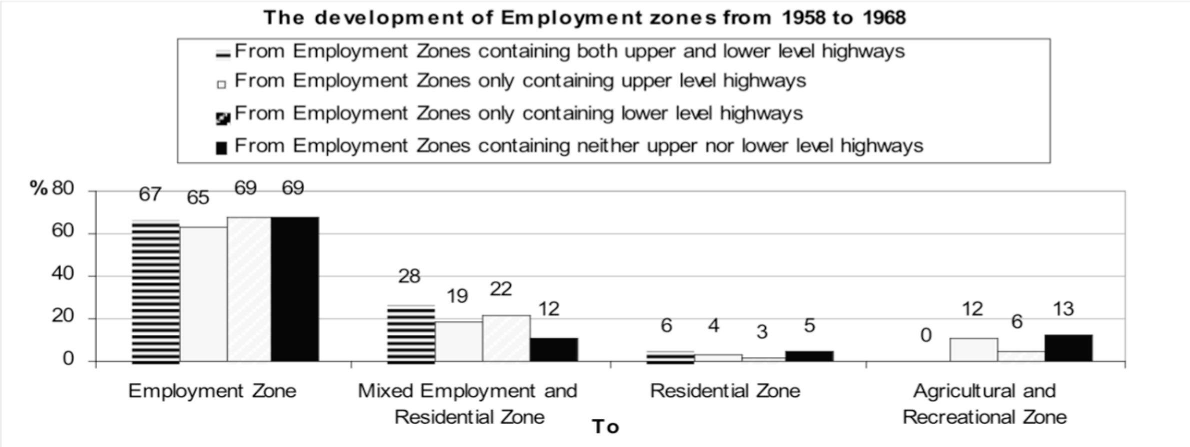
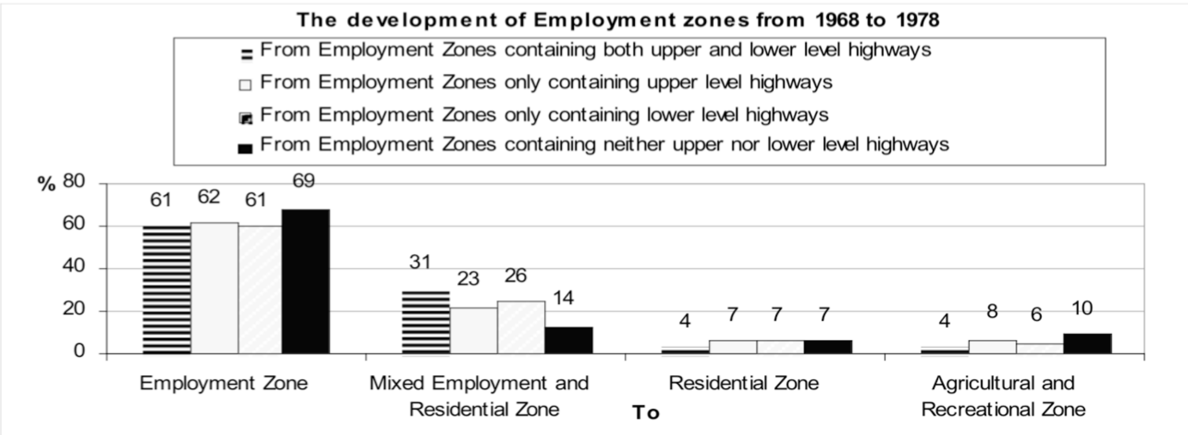


Figure 6. The development of urbanized land use – Employment zones, Residential zones, and the mixed Employment and Residential zones.





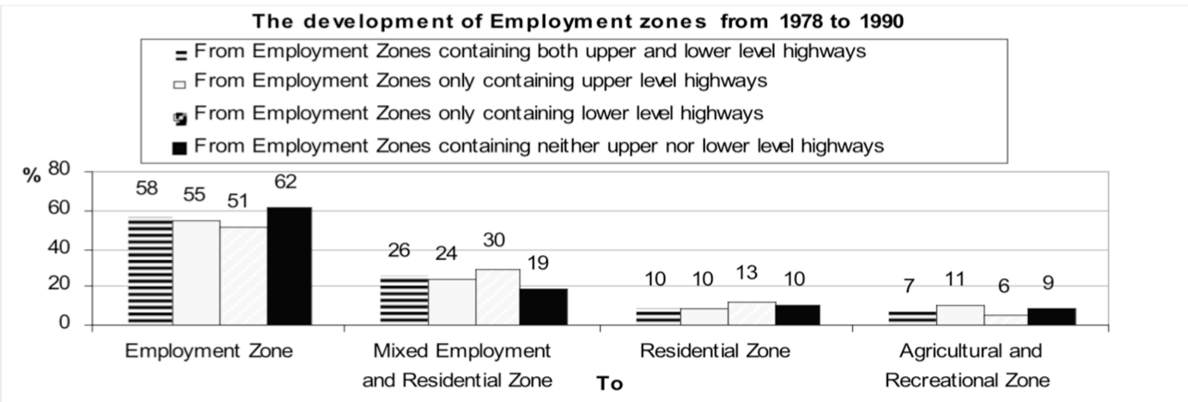
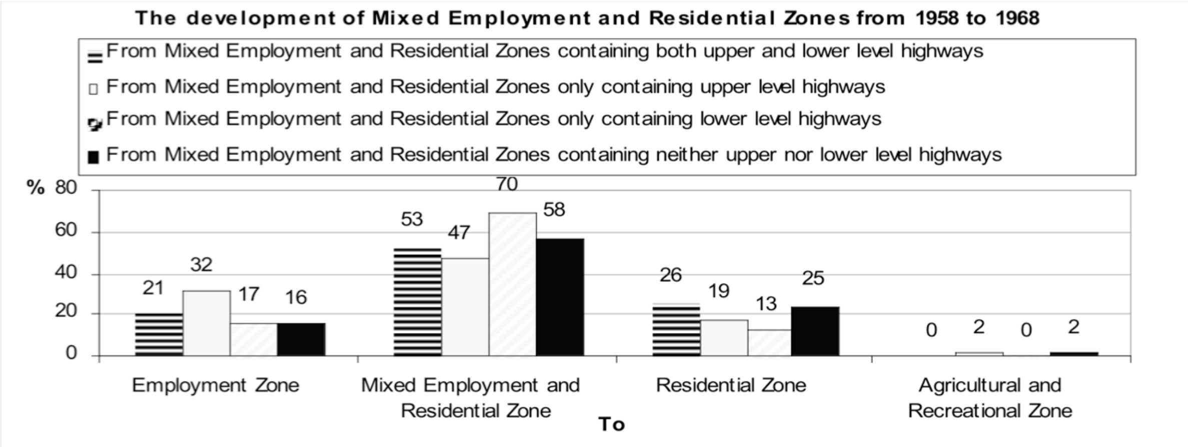
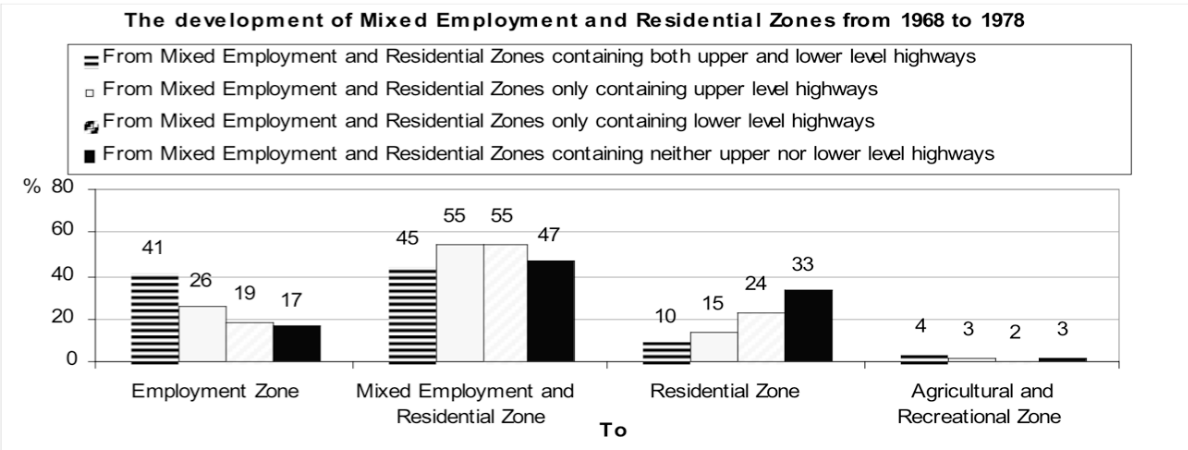


Figure 6. (cont'd)





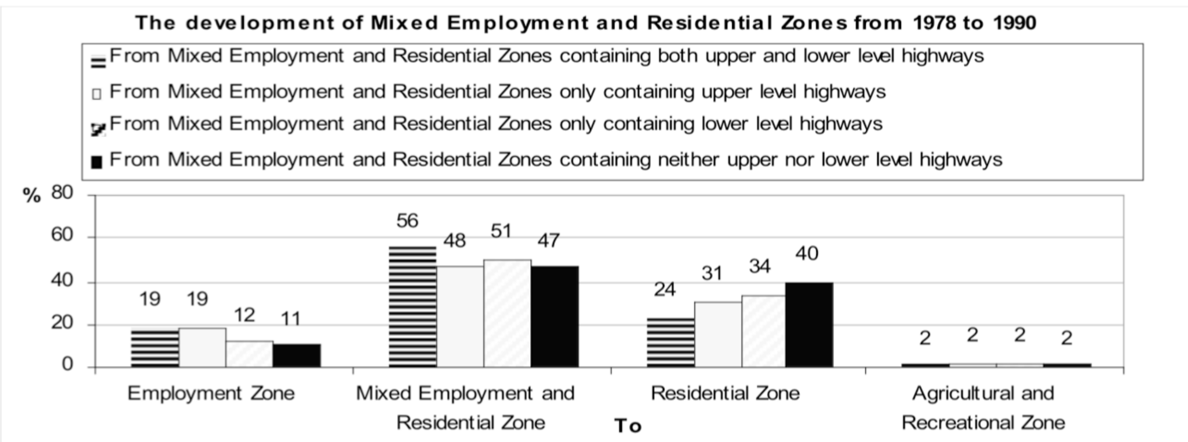
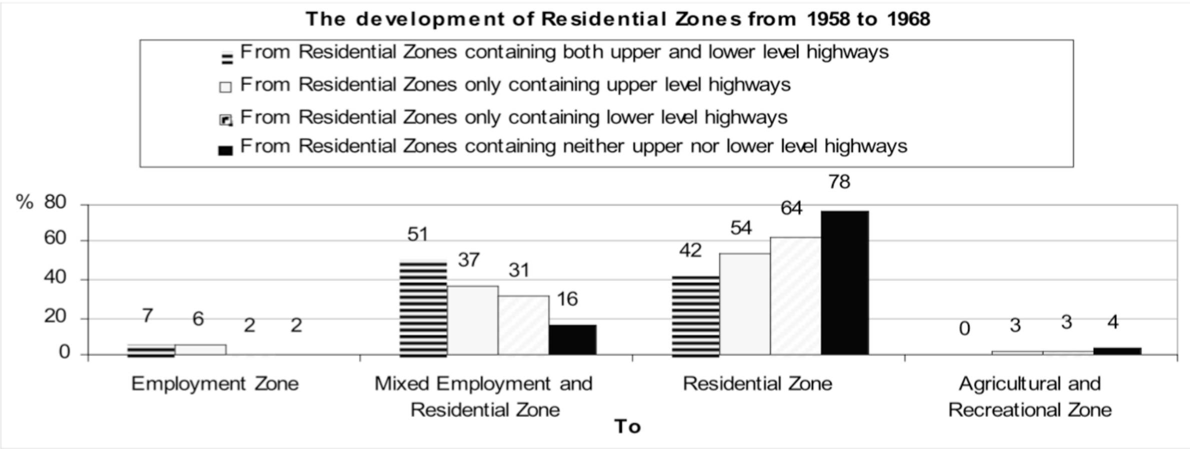
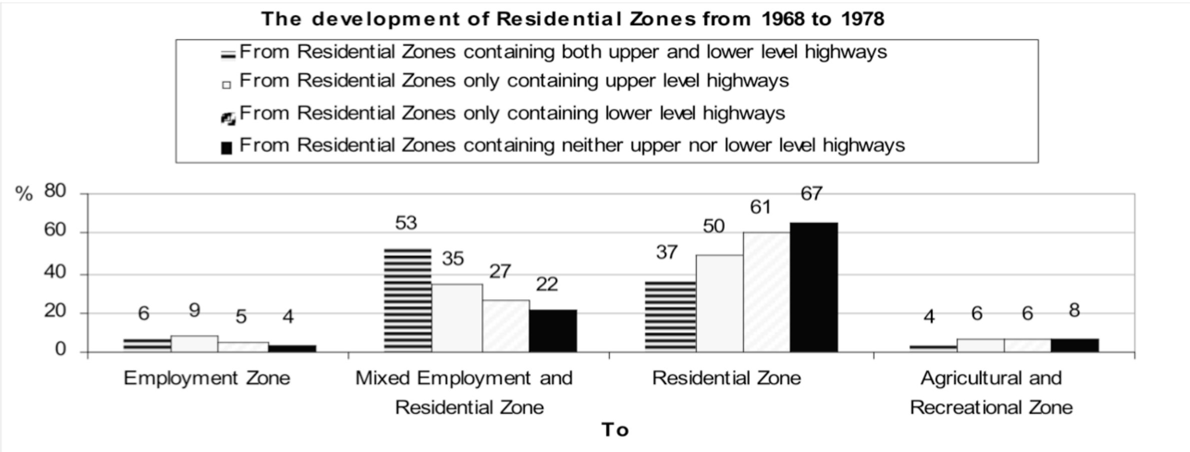


Figure 6. (cont'd)





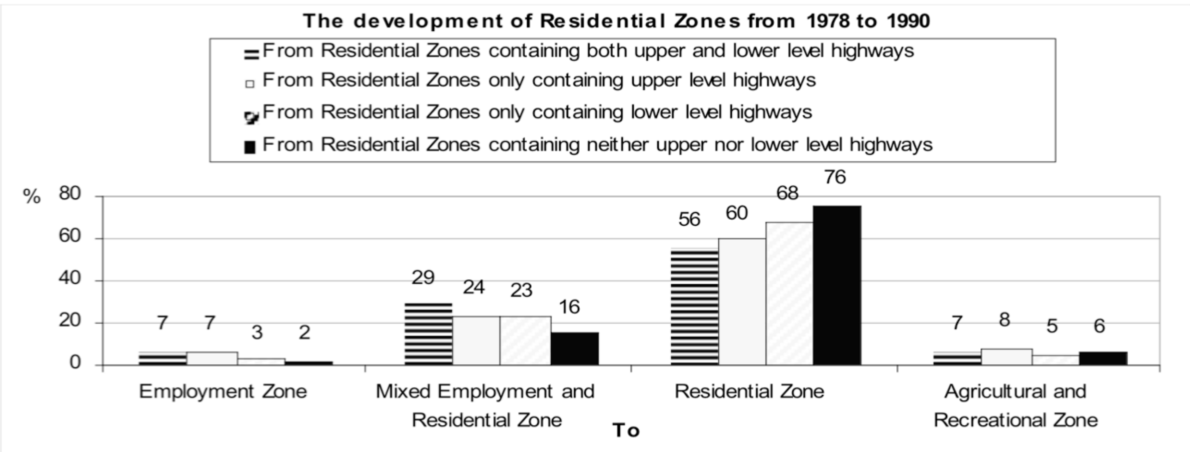
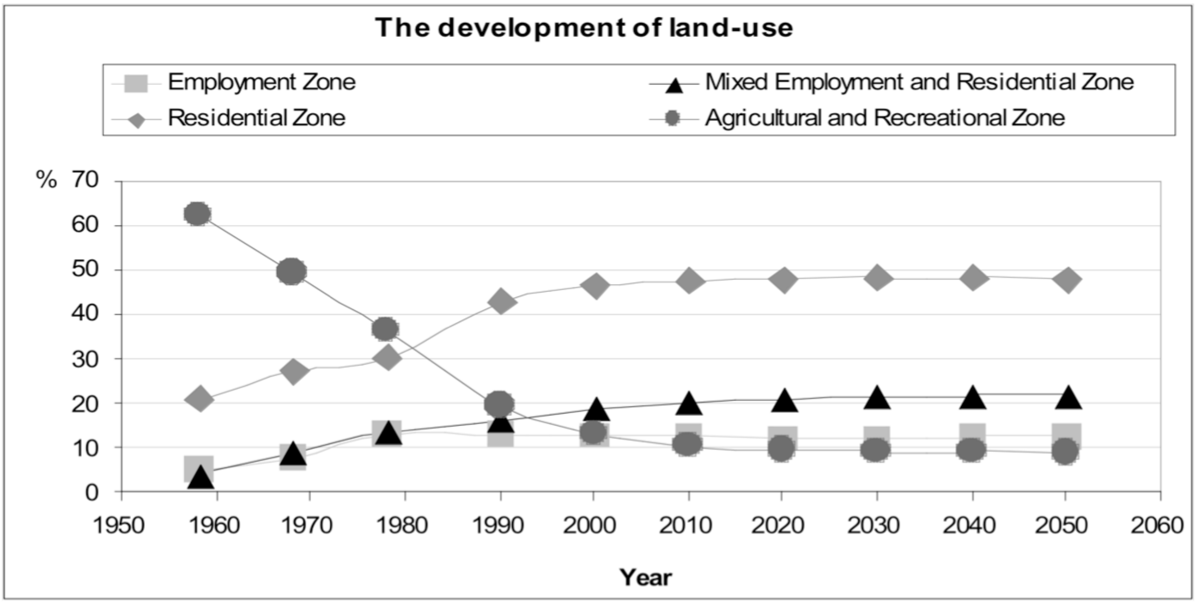


Figure 7. The development of land use and highways.



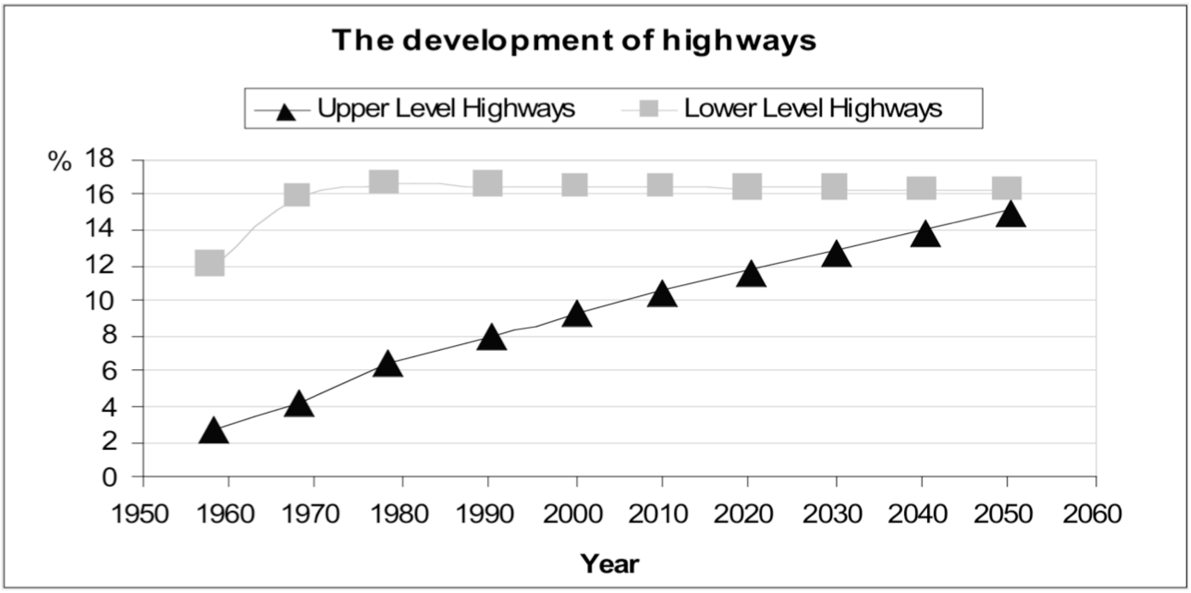
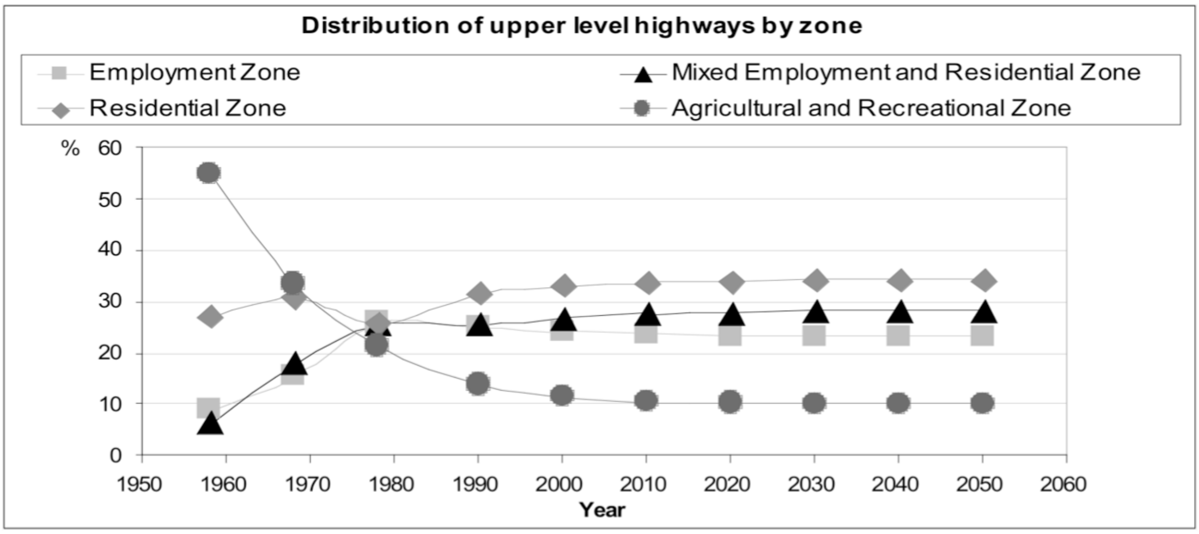
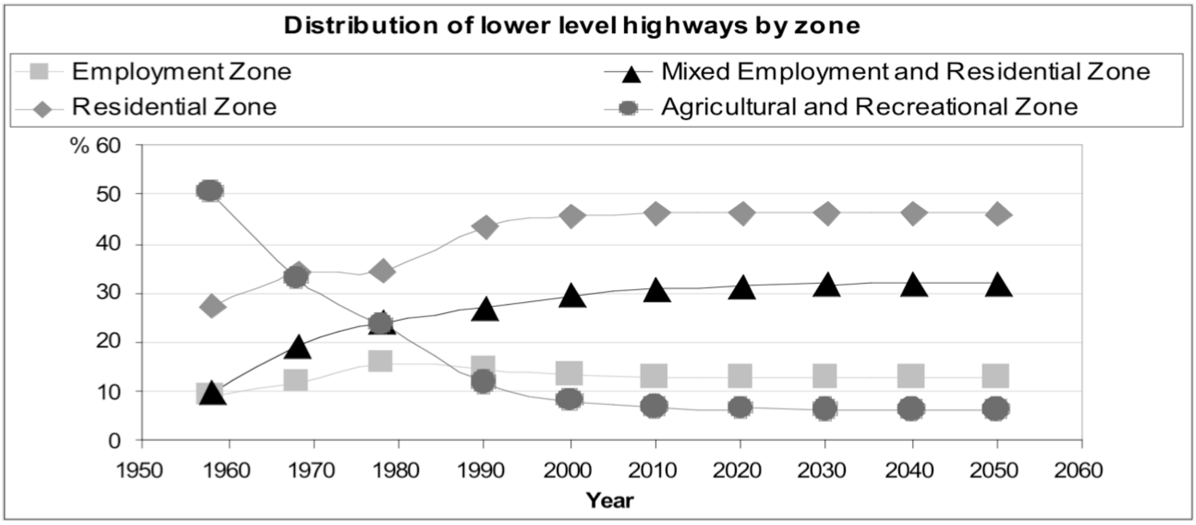


Figure 8. Distribution of upper and lower level highways by zone.





TABLES

Table 1. GIS data summary.

GIS Map	Source
Twin Cities Metropolitan Area Land use Distribution 1958, 1968, 1978 and 1990.	Generalized Land Use maps (paper copy) for 1958, 1968 and 1978 issued by Twin Cities Metropolitan Council. (* 1990 land use map can be downloaded at http://www.datafinder.org/).
Twin Cities Metropolitan Area Highway Network 1968, 1971, 1975, 1978, 1981, 1985, and1990.	Minnesota Official Transportation Maps, issued by Minnesota Department of Transportation *(* before 1978, it was called 'Minnesota Official Highway Maps' and 'Minnesota Department of Highway').*

Table 2. The changes of the cells between different classes.

1958 \ 1968	EU	MU	RU	WU	AU	EL	ML	RL	WL	AL	EB	MB	RB	WB	AB	EN	MN	RN	WN	AN	row sum
EU	78	18	6	0	16	5	7	0	0	0	4	2	0	0	1	4	0	0	0	0	141
MU	22	41	15	0	2	2	2	1	0	0	6	2	1	0	0	0	0	1	0	0	95
RU	26	151	206	1	9	0	1	6	0	0	0	6	19	0	3	1	3	3	0	0	435
WU	8	2	9	16	3	0	0	0	0	0	1	0	0	0	1	0	0	0	2	0	42
AU	127	71	167	8	434	0	3	0	0	0	6	4	9	0	27	2	3	4	0	14	879
EL	11	6	0	0	5	426	140	17	0	28	16	2	0	1	0	20	4	1	1	7	685
ML	2	15	5	0	0	115	465	81	0	3	3	15	3	0	0	3	15	5	0	0	730
RL	2	21	52	0	4	31	571	1150	5	53	2	14	22	0	3	0	27	58	0	3	2018
WL	2	0	4	2	0	10	6	53	54	37	0	1	1	0	1	0	0	1	9	3	184
AL	18	20	27	0	42	259	179	791	25	2179	4	2	13	0	17	18	8	31	0	79	3712
EB	3	1	0	0	0	1	1	0	0	0	8	3	1	0	0	0	0	0	0	0	18
MB	1	0	1	0	0	0	0	0	0	0	3	10	4	0	0	0	0	0	0	0	19
RB	0	3	2	0	0	1	0	1	0	0	2	20	16	0	0	0	0	0	0	0	45
WB	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
AB	2	3	3	0	6	1	0	0	0	1	10	9	16	0	37	0	1	0	0	1	90
EN	25	4	0	2	12	103	32	17	5	23	4	0	0	0	2	1517	248	111	91	281	2477
MN	2	9	14	0	0	25	115	48	2	4	1	1	4	0	0	229	801	329	5	28	1617
RN	1	26	123	0	8	20	223	680	8	33	0	2	17	0	1	161	1454	7312	274	390	10733
WN	4	0	10	7	11	17	3	35	18	16	0	0	0	2	1	98	15	471	2979	432	4119
AN	17	7	61	2	240	104	75	376	8	760	2	0	4	0	19	1400	576	4661	439	25351	34102
column sum	351	398	707	39	792	1120	1823	3256	125	3137	72	93	130	3	113	3453	3155	12988	3800	26589	62144

1978 \ 1990	EU	MU	RU	WU	AU	EL	ML	RL	WL	AL	EB	MB	RB	WB	AB	EN	MN	RN	WN	AN	row sum
EU	458	201	80	41	89	0	0	0	0	0	9	4	1	0	0	2	1	0	0	1	887
MU	158	393	262	9	21	0	3	0	0	0	3	8	4	0	0	0	3	0	0	0	864
RU	62	212	532	20	75	0	0	3	0	0	2	3	4	0	0	0	2	1	0	0	916
WU	10	2	5	16	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	41
AU	153	74	239	30	293	0	0	0	0	0	0	2	0	0	3	0	0	0	0	0	794
EL	41	13	6	0	9	628	396	164	27	71	10	15	5	0	2	70	16	10	1	2	1486
ML	17	21	7	0	1	239	1123	751	11	47	6	10	7	0	0	23	35	25	0	1	2324
RL	9	16	24	0	2	90	727	2178	76	168	1	13	15	0	2	8	29	79	6	6	3449
WL	2	0	0	1	0	15	23	47	28	6	0	0	2	0	0	6	1	4	9	0	144
AL	14	2	10	2	11	199	144	962	82	810	7	5	11	0	10	10	9	40	13	19	2360
EB	21	8	1	0	0	0	0	0	0	0	81	38	16	2	12	0	0	0	0	0	179
MB	2	13	5	0	0	0	0	1	0	0	35	97	41	3	3	0	1	0	0	0	201
RB	0	8	12	0	0	0	0	3	0	0	11	36	68	3	11	0	0	2	0	0	154
WB	0	0	0	0	0	0	0	0	0	0	0	1	2	1	0	0	0	0	0	0	4
AB	11	4	2	1	0	0	0	0	0	0	18	13	18	0	18	0	0	0	0	0	85
EN	37	11	10	3	3	92	21	9	1	11	3	2	1	0	1	3235	995	535	236	474	5680
MN	16	16	21	1	2	10	47	32	1	2	0	1	0	0	0	520	2371	2003	45	87	5175
RN	6	25	77	8	15	5	52	90	5	6	0	0	4	0	2	291	2086	10391	573	862	14498
WN	2	0	0	9	4	2	0	1	4	0	0	0	1	3	1	196	37	608	2228	286	3382
AN	53	17	90	18	89	35	21	86	8	41	1	1	3	0	3	1341	701	7107	1350	8556	19521
column sum	1072	1036	1383	159	622	1315	2557	4327	243	1162	187	249	203	12	68	5702	6287	20805	4461	10294	62144

1968 \ 1978	EU	MU	RU	WU	AU	EL	ML	RL	WL	AL	EB	MB	RB	WB	AB	EN	MN	RN	WN	AN	row sum
EU	211	77	23	1	28	0	0	0	0	0	5	4	0	0	0	2	0	0	0	0	351
MU	97	212	57	3	13	0	0	0	0	0	4	5	1	0	0	3	2	1	0	0	398
RU	59	234	336	8	44	0	1	0	0	0	1	9	4	0	1	0	1	9	0	0	707
WU	12	2	2	12	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	39
AU	218	77	148	7	317	0	0	1	0	0	5	3	4	0	6	2	0	2	1	1	792
EL	84	28	6	2	3	527	226	68	18	66	28	18	4	0	2	30	10	0	0	0	1120
ML	32	61	35	0	4	284	884	383	15	27	20	28	10	0	2	9	21	8	0	0	1823
RL	16	63	109	1	13	141	768	1777	49	179	2	11	37	1	8	7	30	36	0	8	3256
WL	6	0	0	0	0	11	17	35	30	24	0	0	0	0	0	0	0	0	1	1	125
AL	39	15	21	1	26	326	169	727	22	1682	5	3	10	0	14	13	5	13	1	45	3137
EB	6	3	1	0	0	0	1	0	0	0	38	18	2	0	3	0	0	0	0	0	72
MB	5	9	4	0	1	1	4	0	0	0	32	28	5	1	3	0	0	0	0	0	93
RB	1	11	5	0	4	0	0	0	0	0	7	57	41	2	1	0	0	1	0	0	130
WB	0	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	3
AB	4	3	2	0	4	1	0	0	0	1	28	10	22	0	38	0	0	0	0	0	113
EN	33	7	3	0	8	85	19	11	0	14	2	1	0	0	0	2201	448	219	92	310	3453
MN	7	17	17	0	2	24	56	47	0	5	0	4	1	0	0	502	1393	983	20	77	3155
RN	8	31	94	2	30	23	136	235	3	22	2	2	8	0	0	458	2568	8074	366	926	12988
WN	1	0	0	4	7	0	0	3	4	3	0	0	0	0	0	277	44	595	2459	403	3800
AN	48	13	53	0	279	63	43	162	3	337	0	0	3	0	7	2176	653	4557	442	17750	26589
column sum	887	864	916	41	794	1486	2324	3449	144	2360	179	201	154	4	85	5680	5175	14498	3382	19521	62144

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NOTES

[1] Since Year 1988 land-use map is not available, Year 1990 map is used as a substitute. Years 1958, 1968, 1978 and 1990 are considered the time points of equal intervals.