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LAND USE CHANGE ANALYSIS IN A HIGHWAY CORRIDOR A MARKOV MODEL APPROACH

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INTRODUCTION

Major transportation corridors connecting growing urban centers are often characterized by significant changes in land use. In the rural-urban fringe areas, especially, such changes in the corridors are accompanied by frequent land ownership transfers and marked increases in land prices. There is direct competition between rural and urban land uses with the latter uses, commanding higher prices, usually replacing the former, if the land market is permitted to operate freely.

A consequence of this is that land speculators, land agents, land assemblers, builders, financial institutions, insurance companies, and above all, the buyers of residential property are engaged in changing land from some open or relatively less intensive state to an urbanized and more intensive use. The interactions among these different types of decision units usually create events which profoundly affect the probability of a change in the use of land. This makes it difficult to predict the future patterns of land use in the corridors. However, the use of a completely stochastic model in an analysis of land use change may help us in gaining insights into the behavior of such a system.

There are many forecasting problems in urban and regional studies which are essentially probabilistic. The Markov model provides an efficient framework for dealing with such problems. In this model, one introduces the notion of dependence of each trial on the results of its predecessors. The advantage of this method is that it helps in gaining insights about the system behavior which otherwise would have remained unnoticed. In the domain of land use planning, modelling of land use change as a Markov process has been attempted by a number of authors. Bourne (1969, 1976) utilized the Markov model to predict land use in the central city, and to address the questions of process stability and similarity. Bell (1975-79) used this model in order to evaluate the process of land use change while Robinson (1978) explored the utility of the model by examining the relationships between different types of land use environments. All these studies showed that the Markov model is capable of addressing several important issues concerning land use change.

In this paper, also, we look into the process of land use change as a Markov process. The paper examines the interrelatedness of land use types in the process of change.

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Although there are some studies concerned with the development of corridor system in Southern Ontario, these studies were motivated by more general considerations. Thus Whebel (1969) provided an historical account of corridor development in Southern Ontario while Russwurm (1964-1970) tested certain social, economic, demographic and interactional elements to see if any corridors developed in selected areas. The findings of these studies provide useful information on the general historical factors as well as trends of corridor development in the region in which the present corridor is located. But the findings are of limited applicability as far as local planning is concerned. None of these studies paid any attention to land use which is of major concern for local planning authorities. In contrast with these studies, the present study follows a more specific approach. It covers a single highway corridor and investigates its land use aspects in a much more detail in order to produce some pointed results which could be useful in formulating land use planning policies.

On the basis of broader administrative boundaries the whole study area can be divided into two regions: The Waterloo region includes the city of Kitchener while the Wellington region includes the city of Guelph. The corridor is about 20 kilometers long and approximately 7 kilometers wide centered on a highway linking the Kitchener-Waterloo urban area with a population of 200,000 and the Guelph urban area with a population of 80,000. The study area is located in the southwest part of the province of Ontario, Canada. The time span over which the land use change occurs is 1955 to 1980. Nineteen sixty-six was chosen as the intermediate year. In order to collect information for the study several sets of maps were prepared for 1955, 1966, and 1980 through the interpretation of air photos and the use of available land use and topographic maps.

DESCRIPTION OF LAND USE CHANGE AS A MARKOV PROCESS

In the core of our modelling exercise is the realization that a parcel of land in our area of interest could be in one of five mutually exclusive states of land use at any time instant. These five possible states are open-vacant use (OPV), residential use (RES), public service and recreational use (PSR), industrial use (IND) and commercial use (COM), in terms of which an entire ara could be described by an aggregate land use vector LU such that

$$LU = (LU_{opv}, LU_{res}, LU_{psr}, LU_{ind}, LU_{com})$$

$$= (LU_{1,}, LU_{2,} LU_{3,} LU_{4,} LU_{5} \qquad (1)$$

Each component LU_i in (1) represents the proportion of the area in the state of land use i, and thus

$$0.0 \leq LU_i \leq 1.0$$

$$\sum_i LU_i = 1.0$$

Let us assume that we observe the profile of land use patterns over a time period and notice that at time t the aggregate vector is given by LU_t, at time (t+1) the land use vector is LU_{t+1}, and so on for the same area. If the sequence of vectors LU_t, LU_{t+1}, ... remain the same for a sufficientlylong observation period we identify the system to be in a state of equilibrium as LU_t is invariant with respect to time. If the sequence is a string of different vectors we may concede the system to be in a transition state. In the latter case, two successive vectors in the sequence spanned by our five dimensional orthogonal basis set could be assumed related through a transition (transformation) matrix U such that

$$LU_{t+1} = (LU_t)\,U \qquad (2)$$

The first assumption our model suggests is that (2) is true for all subsequent values of t, in which case

$$LU_{t+1} = (LU_t)\,U$$

$$LU_{t+2} = (LU_{t+1})\,U$$

$$\vdots$$

$$LU_{t+p} = (LU_{t+p-1})\,U$$

The ramifications of our proposals are then: (a) whatever process is responsible for chaning the land use vector LU at each subsequent time point remains stationary throughout, and (b), the change to a new land use vector at a time t depends totally on the land use vector profile at a time (t-1), and not at all on the process by which the system did arrive at LU_{t-1} in the first plance. Thus the process is a stationary memoryless process. It should be noted that the transition matrix U is such that

$$0.0 \leq U_{ij} \leq 1.0$$

and $$\sum_i u_{ij} = 1.0 \qquad (4)$$

where i, j refer to indices associated with the components of the land use vector (basis set).

Let us now make an attempt to identify the matrix U in terms of observables. Since U transforms a vector of land use profile LU_t into a vector LU_{t+1} at time (t+1), U must be directly related to observed changes to amount of land allocation in use i at time t. Suppose, F is the matrix such that (f_{ij} is its (ij) element)

$\hat{F} = \sum_j \hat{f}_{ij}$ = amount of land in use i at time t

$\hat{F}_{tot.} = \Sigma \hat{F}_i$ = total amount of land in question

and, $\hat{f}_{ij}$ = amount of land originally in use i at time t, but changed to use j at time (t+1)

then U could be expressed in terms of F simply as

$$u_{ij} = \hat{f}_{ij} / \hat{F}_i \qquad (5)$$

Note that (5) satisfies the requirement in (4). Furthermore, if F is a diagonal matrix then U emerges as an identify matrix.

Now we may form successive powers of U and since U is a stochastic matrix so will be the the power of U, U^k, where k is a rational number. The element $(U^k)ij$ would then be the magnitude of the probability of transition from a state i to the j in k units of time.

The interesting part that now emerges is this: if we let k—> α then under certain conditions it could be shown (Kemeny and Snell, 1969) that the transition matrix U stabilizes to a matrix Q such that

$$\underset{k \to \alpha}{\text{Lt}}\, U = U^{k-1} = Q$$

or, equivalently, $QU = Q$ (6)

Further, when (6) does materialize, the matrix Q displays an important property that all its rows become identical to a vector, say π. The vector is then the limiting state probability vector or an equilibrium distribution vector which has the property that

$$\pi = \pi\, U$$

The equlibrium distribution vector shows the land use allocation at $t = \alpha$, if the system wer left to itself to evolve. Note that if U is stationary and irreducible (i.e. no uij = 1.0), once the system reaches its equilibrium it will remain there.

Given U, the transition matrix, we may obtain a number of interesting feature values characteristic of the process concerned. These are outlined below.

Mean Stay Time (MST)

If a land unit enters a use i now, the expected amount of time it is likely to spend there before making another transition to another use j is given by (MST)i where

$$(MST)_i = 1/(1-u_{ii}) \qquad (7)$$

Thus as Uii - 1.00, the mean stay time becomes infinitely large at the limit, as the diagonal of the transition matrix approaches unity, uses stay in the same state.

Mean First Passage Time (MFPT)

If land unit is in land use state i now, how long the process will take to arrive at the state j for the first time (or equivalently, how many transitions it will take to reach state j for the first time if the system is in state i now) is given by the measure (MFPT)ij. Note that, as in (7) we are concerned here with the expected time. The computation of (MFPTij) (for i = j, when indices are same we talk about mean recurrence time as detailed next) is somewhat involved as shown below.

Let us define

$$T = (I-U+Q)^{-1}-Q \quad (8a)$$

Where I is identity matrix, i.e., $I_{ij} = 1$ if $i = j$

= 0, otherwise.

Q is the limiting matrix as defined in (6).

Then in terms of T we define

$$(MFPT)_{ij} = (I_{ij} + T_{jj} - T_{ij})/ \pi_j \quad (8b)$$

Where π_j is the jth component of the equilibrium vector of the matrix U.

How long it will take on the average to re-enter into the state i if the system leaves that state now (or equivalently, how many transitions it will take, again on the average, between a departure from a state i and the first return to i) is given by the mean recurrence time (MRT) as shown below. It is simply

$$(MRT)_i = 1/ \pi_i \quad (9)$$

(MRT)i is thus (MFPT)ii, the first passage time from state i to state i.

Thus, in addition to the equilibrium distribution, a stable stationary Markov process could be characterized by various state occupancy statistics, namely (MST), (MFPT) and (MRT). These statistics enable us to identify specific relationships in the process of land use change. The mean stay times and the mean recurrence times indicate the ability of a land use environment to continue to exist or recur on the landscape while the mean first passage times indicate the relative ease with which land may change to certain alternative use given the one presently existing on that land. On the basis of these statistics, it is possible to evaluate a particular land use type in terms of its ability to exist or recur on land or the rigidity or flexibility of the relationships between different types of land use. In this way, it is possible to identity specific relationships in the change process which may be acting to produce undesirable mixes of land use or which may endanger the maintenance of an adequate amount of a desired type of use.

Empirical Analysis

Calculation of transition probability matrices has resulted in two transition probability matrices, one for the period 1955-1966 and the other for the period 1966-1980 for each of the two regions and two cities. Our analysis is, however, based on the matrices representing the period 1966-1980 since each of these matrices specifies the transition mechanism which will lead to a matrix with all its rows identical. The transition probability matrices for the earlier period do not show this property because these matrices are reducible (i.e., some of their elements are equal to unity).

Use Environment Relationships

In order to show the land use environment relationships, we have calculated the variables as defined earlier for each of the spatial units, that is, the Waterloo and Wellington regions and the cities of Kitchener and Guelph. Tables 1 and 2 provide the measures of mean stay times, mean recurrence times and mean first passage times of land use environments in Kitchener and Guelph. In Kitchener the mean stay time of the industrial use environment is least of all while its mean recurrence time is the highest of all. In Guelph, on the other hand, the mean stay time of the commercial use environment is the least of all while its mean recurrence time is the highest of all. Thus, the industrial land in Kitchener, once experiences a change to another use environment it is a very long time before such land will again host an industrial environment. In Guelph, on the other hand, commercial use environment does not easily recur on a parcel of land use once in that use. The mean stay time is the greatest for public service and recreational use in Kitchener while it is greatest for residential use in Guelph. This means that the public service and recreational environment in Kitcherner stays on land longer than any other use environment while in Guelph a residential environment stays on land longer than any other use once it is established. It is interesting to note that the staying power of these use environments are matched by their recurrence ability. Thus, in case of Kitchener public service and recreational environment has the lowest mean recurrence time while in case of Guelph residential environment has the lowest mean recurrence time.

The mean first passage times can be used as measures of interrelationships between use environments. Such measures indicate the rigidity or flexibility of land use environments. The rigidity of a land use environment is the relative ease with which land may change to certain alternate use environment given the one presently existing in that land.

Table 1 and 2 show mean first passage time in the cities of Kitchener and Guelph. It is observed from the tables that certain use environments are more flexible than others. In both Kitchener and Guelph open-vacant land appears most flexible, in general, than others while public service and recreational land is expectedly the most rigid.

When each use environment is considered in terms of its rigidity with respect to conversion to other uses it is observed that in Kitchener open vacant, residential, public service and recreational and commercial use environments are most rigid when considering their conversion to industrial use while industrial use environment is most rigid when considering its conversion to commercial use. In Guelph, on the other hand, open-vacant, residential, public service and recreational and industrial use environments are most rigid when considering their conversion to commercial use while commercial use environment is most rigid when considering its conversion to industrial use environment.

Table 3 and 4 provide the measures of mean stay times, mean recurrence times and mean first passage times of land use

TABLE - 1 KITCHENER CITY (1966-80)

CHARCTERISTICS OF LAND USE

(a) Mean First Passage Times (in years)

To / From	OPV	RES	PSR	IND	COM
OPV	25.65	184.00	319.08	1495.73	653.00
RES	950.84	2.91	341.46	1553.40	806.00
PSR	1306.55	355.71	1.96	1909.11	1161.61
IND	189.17	237.89	386.11	59.85	262.61
COM	262.20	232.49	388.33	1289.82	11.10

(b) Mean Stay Time (in years)

OPV	RES	PSR	IND	COM
31.90	156.07	355.71	23.20	60.61

(c) Mean Recurrence Times (in years)

OPV	RES	PSR	IND	COM
25.65	2.91	1.96	59.86	11.10

TABLE - 2

GUELPH CITY (1966-80) :

CHARACTERISTICS OF LAND USE

(a) Mean First Passage Times (in Years)

To From	OPV	RES	PSR	IND	COM
OPV	8.52	82.87	137.06	218.62	938.90
RES	198.36	1.58	154.35	413.79	1133.58
PSR	217.25	19.63	9.16	29.63	1148.97
IND	235.84	88.31	101.63	7.79	1007.07
COM	113.69	96.68	133.15	135.30	85.55

(b) Mean Stay Times (in Years)

OPV	RES	PSR	IND	COM
27.20	87.34	18.89	53.84	11.45

(c) Mean Recurrence Times (in Years)

OPV	RES	PSR	IND	COM
8.52	1.58	9.15	7.80	85.56

environments in the Waterloo and Wellington regions. It is observed from table 3 that in the Waterloo region the mean stay time is the highest for industrial use environment while in the Wellington region the mean stay time is the highest for residential use environment. The staying power of these use environments is again matched by their mean recurrence times. When the mean first passage time is considered it is observed that in both the Waterloo and Wellington regions public service and recreational use environments appear more rigid compared to other use environments. When directional biases are considered, it is observed that in the waterloo region open-vacant, residential, public service and recreational, and commercial use environments are most rigid when considering their conversion to industrial use. These results are more or less consistent with what we observed in case of the cities of Kitchener and Guelph.

It is, however, Important to observe that the results of our analysis indicate the influence of both urban and rural areas. While examining the regional processes we find that the intra- and inter-use environment relationships remain more or less the same as the intra- and inter-use environment relationships in the cities. At the same time we also observe that the mean stay times, mean recurrence times and mean first passage times in most cases are considerably higher in the regions than the mean stay times, mean recurrence times and mean first passage times in the cities. This reflects the influence of the rural areas where the process of land use change is much slower than the process in urban areas.

TABLE - 3

WATERLOO REGION (1966-80) :

CHARACTERISTICS OF LAND USE

(a) Mean First Passage Times (in Years)

To / From	OPV	RES	PSR	IND	COM
OPV	6.71	522.27	1080.51	2071.15	1211.17
RES	1190.54	4.13	851.40	2169.39	115.88
PSR	1563.40	372.85	3.28	2542.23	1488.73
IND	776.79	1299.06	1857.30	4.05	702.12
COM	74.66	596.93	1155.17	2145.81	17.22

(b) Mean Recurrence Times (in Years)

OPV	RES	PSR	IND	COM
191.60	191.80	372.86	702.13	74.66

(c) Mean Recurrence Times (in Years)

OPV	RES	PSR	IND	COM
6.71	4.14	3.28	4.06	17.22

TABLE - 4

WELLINGTON REGION (1966-80)
CHARACTERISTICS OF LAND USE

(a) Mean First Passage Times (in Years)

To / From	OPV	RES	PSR	IND	COM
OPV	5.01	184.18	253.76	608.98	2385.63
RES	485.74	1.53	193.60	1092.64	2869.99
PSR	30.06	19.48	10.98	1111.16	2887.38
IND	483.66	104.18	124.09	18.53	2451.77
COM	260.61	155.26	199.33	308.33	199.78

(b) Mean Stay Times (in Years)

OPV	RES	PSR	IND	COM
113.17	122.40	19.39	54.10	12.17

(c) Mean Recurrence Times (in Years)

OPV	RES	PSR	IND	COM
5.02	1.54	10.99	18.53	199.80

ASSESSMENT AND CONCLUSION

The Markov model analysis has afforded valuable information concerning the interrelationships between different types of land uses in the corridor under study. The model thus may be useful for planning purposes as it is capable of identitying specific relationships in the process of land use change which may act to produce undesirable mixes of land use or which may endanger the maintenance of a desirable land use pattern.

The study indicates that certain types of land uses in the corridor are more flexible than others when considering their conversion to other uses. In all the subareas (cities and regions) open-vacant land apppear most flexible, in general, than others while public service and recreational land is expectedly the most rigid. It is however observed that in Kitchener city and Waterloo region transition of land from any other use to industrial use for the first time takes longest average duration. In Guelph city and Wellington region, longest average duration is observed in case of transition of land from any other use to commercial use.

An important issue which has not been dealt with in this paper is the dynamic, nature of the concept of equilibrium in Markov chain theory (Robinson, 1980). A system may show quite large variations from one point in time to another while approaching towards its equilibrium vector. This may be a source of instability in the system. In our study, we have dealt with some system related issues such as use environment relationships and future patterns of land use. The results are likely to be more meaningful if one could know whether the process with which one is concerned is, indeed, a stable process. An approach towards this problem can be found elsewhere (Jahan, 1986).

Another problem which needs attention is the non-stationary character of the land use change process. In the present study stationary Markov chain model has been used to study the process of land use change. While such a model may provide useful information on the process dynamics, one may nevertheless feel uncomfortable when such a process is heavily influenced by planning and fiscal controls and thus become non-stationary. As a further research topic, one may extend the study to a non-stationary Markov chain model and attempt to observe the extent to which the process dynamics in the two models appear similar.

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