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02최운섭(325-335)2008.6.273:43PM페이지325

The Geographical Journal of Korea Vol. 39, No. 3, 2005 (325~335)

Calibration of Land Use Change Drivers in Support of Dynamic Urban Growth Modeling

Woonsup Choi* and Zhanli Sun**

Abstract : The Land use Evolution and impact Assessment Model (LEAM) is a cellular urban dynamics model designed to simulate changing landscapes over space and time. One of the challenging problems in the LEAM model is calibrating the model results, and this study presents a step to calibration. The probability of land use change in each cell is determined by various factors including a cell's proximity to development attractors, which are physical features that promote residential and commercial developments. This study presents a way to calculate a cell's proximity to development attractors and converting the proximity to relative probability to help with LEAM calibration. The ten-county area in Illinois and Missouri, USA, around the City of St. Louis, was chosen as a study area. The results show general patterns of distributions of existing urban cells in terms of travel time to attractors. Furthermore, existing residential and commercial land uses show distinct spatial patterns for development. The adoption of this method has contributed to more realistic simulation of new developments in the study area.

Key Words : spatial frequency analysis, GIS, land use change modeling, LEAM

I. Introduction

Urban sprawl has been a problematic issue in urban planning over the past half century in the United States, and will continue to be so in the future. Cities are developing open area outside of the municipality that once was used for agriculture, woodlands, or open space. Between 1970 and 1990, the Chicago region as a whole has been experiencing only modest population growth, a total of 4.1%, but the amount of developed, residential land has increased more than 11 times faster, by some 46% (Benfield *et al*., 1999). Unchecked urban growth is linked to many environmental problems, including increased automobile emissions, deterioration of air and water quality, loss of rural lands, and a declining sense of community (Schmidt, 1998).

Many cities develop their future growth plans to maintain sustainability and minimize negative environmental impacts. However, the reality does not follow the plans because the plans generally do not (or cannot) incorporate the dynamics of human dimensions and biophysical systems, which drive land use changes (Veldkamp and Verburg, 2004). Therefore, dynamic modeling of urban sprawl incorporating the spatial dynamics of human dimensions and biophysical systems can help with better understanding of the process of urban sprawl and pursuing alternative growth patterns. These days, more and more models are adopting cellular automata (CA) approaches for urban growth simulations (Chen *et al*., 2002). Land use Evolution and

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02최운섭(325-335)2008.6.273:43PM페이지326

impact Assessment Model, or LEAM, is one of those efforts developed at the University of Illinois at Urbana-Champaign. More information on LEAM is given later.

One of the key factors in dynamic urban growth modeling is drivers. There are socioeconomic factors such as economy, population growth and governmental policies as well as biophysical factors such as elevation, slope, or soil type (Veldkamp and Lambin, 2001) that drive land use change. Most cities may have common drivers, but each driver is not of equal importance. For example, slope factor may explain far more of the urbanization in San Francisco than in Washington/ Baltimore region (Clarke and Gaydos, 1998). Urbanization in Asian megalopolis is proceeding differently from that experienced in European or North American cities (Murakami *et al*., 2005). Therefore, it is important to select appropriate drivers in modeling and to calibrate them for the cities or regions of the model application.

Lo and Yang (2002) investigated several groups of land use change drivers (administrative/statistical boundaries, land-use/land-cover, landscaped ecological measures, topographic measures, population and income and location measures) for the Atlanta Metropolitan Area in Georgia, USA. Location measures include urban center proximity, highway proximity, node point proximity and shopping mall proximity. The objects of proximities are believed to encourage or discourage new development near them. Chen *at al*. (2002) also adopted similar location measures for modeling urban growth of Beijing, China. Both studies carried out buffer analysis with respect to those objects.

This study presents a more sophisticated way as a step to calibrating land use change drivers in LEAM. In LEAM, the objects which drive new development around them are called 'development attractors.' For example, main roads, existing developed areas, and utilities are development attractors in LEAM because new development is likely to occur in their vicinity. For each development attractor, a map is generated in which proximity is assigned to each cell in the region. This proximity is computed based on the cumulative travel time from the concerned cell to the nearest cell containing a development attractor. Then the frequency of developed cells residential and commercial for each proximity value and development scores are calculated. In this paper, the approach for computing development scores is introduced and the distributions of urban development with respect to development attractors are examined.

II. The Study Region

The study region consists of five counties (Clinton, Jersey, Madison, Monroe and St. Clair) in Illinois and five counties (City of St. Louis, St. Louis, St. Charles, Jefferson and Franklin) in Missouri and is shown in Figure 1. The main reason for the selection is that LEAM was applied for the region with extensive scenario analysis. This is the fourth application site of LEAM, and there was substantial improvement of the model in this application, especially in terms of calibration.

Total population of the region was 2,540,138 in 2000, of which about 14% live in St. Louis City and about 40% in St. Louis County (U.S. Census Bureau, 2004). The total land area is 13,818km^2. Therefore, population density of the whole region is 184/km^2. About 76% of the population is located in

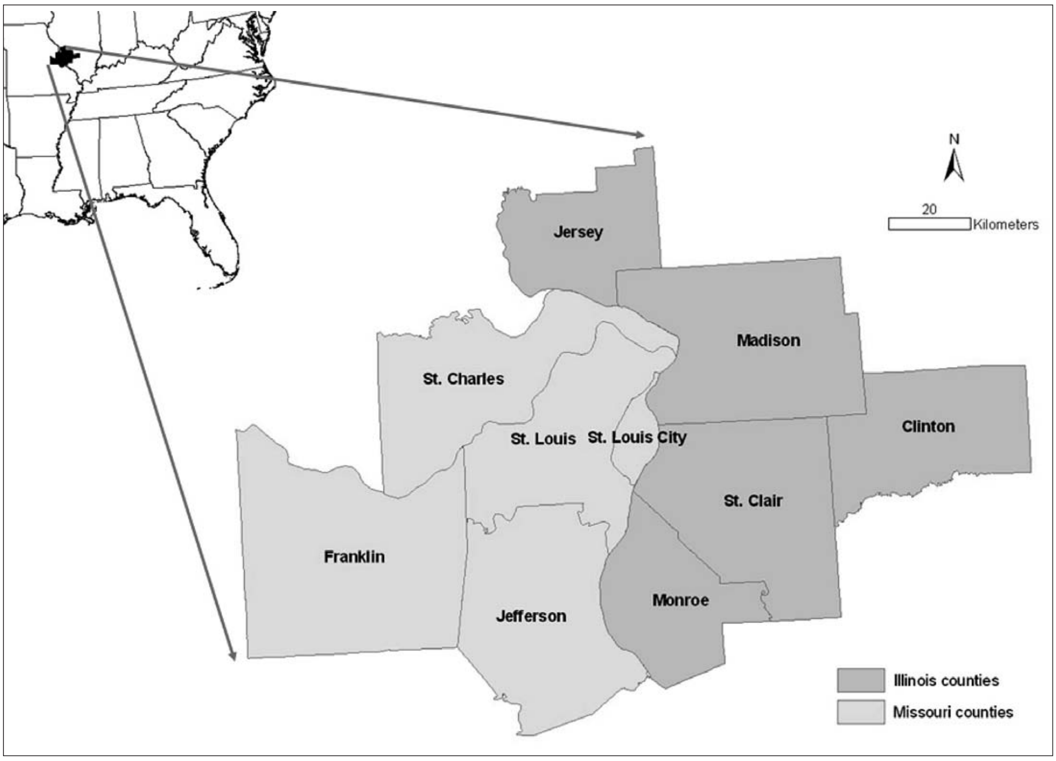

Figure 1. Study region

the Missouri side. The population of St. Louis City declined 12.2% between 1990 and 2000, and keeps declining. However, that of the State of Missouri has been increasing, which implies that people in the city are moving to suburbs. This is a common phenomenon in many cities in the Unites States.

III. LEAM

The Land use Evolution and impact Assessment Model (http://www.leam.uiuc.edu) is an ongoing research project at the University of Illinois at Urbana-Champaign. LEAM simulates land use change over space and time in order to support regional public land use policymaking. LEAM has been described in great detail elsewhere (Deal 2003; Deal, 2001) and will only be briefly reviewed here.

LEAM adopts a hybrid dynamic spatial modeling approach that combines regional drivers of land use change along with drivers that operate in 30m × 30m cells across the landscape. At each time step in a LEAM simulation, the probability of land use change for each cell is computed based on the combined probability associated with a number of drivers. Then, the regional demand for new land uses are spatially distributed to cells based on these probabilities.

The LEAM for a region is assembled using a software tool, STELLA®, and a spatial modeling environment, or SME. STELLA® is used to construct the mathematical formulation of local rules that drive cellular-level change. SME, developed at

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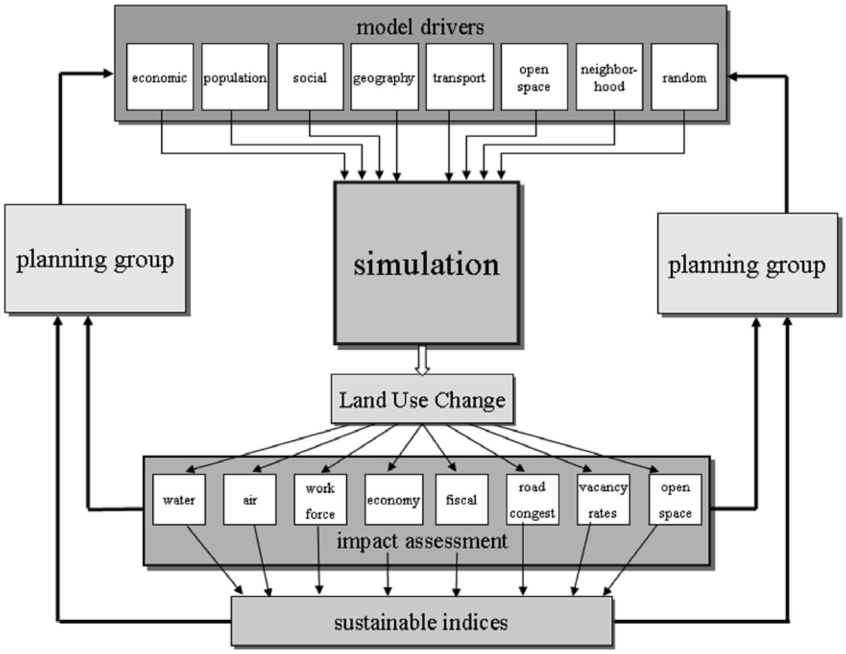

Figure 2. The LEAM spatial modeling environment (source: Deal, 2001)

the University of Maryland, spatializes the single-cell STELLA models, applying them to a geographic area (represented in this case as a matrix of cells), and simulating the changes that take place to the state of each cell over multiple time steps. SME automatically converts the STELLA models into computer code that can be run on multiple processors (and multiple computers) in parallel.

GIS data layers provide the spatial foundation and data used to initialize sub-models, and as the vehicle for graphic output. Results can be displayed in a number of ways, including a built-in mapping tool; the raw data can also be processed to create other representations such as map movies (that show change over space and time) and growth summary maps. SME imposes constraints of modularity and hierarchy in model design, and supports archiving of reusable model components (Voinov *et al*. 1999). In these ways, this approach eliminates 'black box' complexities and advances a disaggregated approach to spatial modeling.

The overall concept of LEAM is presented in Figure 2. As it shows, LEAM has a set of land use change drivers. All the drivers determine the development probability of each cell at each time step, which is the probability of a cell changing to an alternative land use. Of the drivers shown in Figure 2, 'Geography' drivers are about the relative and absolute locations of each cell. The elevation or slope is about the absolute location, and the proximity to highways or city centers is about the relative location.

In this study, two drivers are selected and analyzed for calibration. They are proximity to interstate highway ramps and proximity to state highways. Interstate highways have limited access and can be accessed only through ramps. Therefore, proximity to interstate highways should be calculated as proximity to ramps, which was not adopted by Lo and Yang (2002) or Chen *at al*. (2002). Proximity to state highways was selected since state highways are major roads that draw development around themselves.

IV. Procedure

Overall, there are three steps in this study. The first step is to develop a map, called an attractor map, for a particular type of attractor, containing proximity to each attractor. The second step is to evaluate the frequency of urban development that is found in cells within a given proximity (time) from an attractor. The third step is to estimate development score with regard to each attractor map.

1. Attractor maps

The first step of this study involves computing the proximity of each cell to the nearest attractor cell, and storing this information in a raster map, i.e., an attractor map. In many natural or biological phenomena, the proximity is just Euclidian distance to objects (e.g. Ali *et al*., 2002; Perotto-Baldiviezo *et al*., 2004). However, the movement of human beings is restricted by transportation infrastructure, i.e. roads. Therefore, computing of proximity requires preprocessing road data, merging it with land cover data, computing travel 'friction' in each cell, and then computing travel times. As in the work of Ward *et al*. (2000), friction-of-distance, which is another expression of proximity and associated with transportation, is one of constraints on urban growth.

Road data were obtained as Census 2000 TIGER/Line shapefile through ESRI (http://arcdata. esri.com/data/tiger2000/tiger_download.cfm).

Table 1. Travel speeds on different road and land cover types

Road category or land cover	Travel speed (mph)
Interstate highway (A1)	75
US route (A2)	60
State route (A3)	45
Ramp (A63)	40
Other road (A4 Rd)	25
Non-road land cover	0.5
Interstate 70m buffer	0.001
Open water and wetland	0.001

Roads are classified by census feature class code (CFCC) into primary highway with limited access (A1), primary highway without limited access (A2), secondary and connecting road including state highways (A3), local, neighborhood and rural road (A4), vehicular trail (A5), road with special characteristics including ramps (A6), and road as other thoroughfare (A7). A5 and A7 roads were considered unimportant and removed. Only ramps (A63) in A6 roads were used, and only roads of type "Rd" in A4 were used. Since people can access limited access interstate highways only through ramps, seventy-meter buffers were created along these highways (The distance 70m was chosen so that the buffer takes up at least two cells in terms of thickness when converted to a grid). The buffer shapefile and road cover were converted to separate grids with the buffer distance and the road class as cell values respectively.

The road grid and buffer grid were then superimposed on a land cover grid obtained from the U.S. Geological Survey (USGS) National Land Cover Dataset (NLCD) (USGS, 2003). The combined grid was then transformed into a travel friction or speed grid, in miles per hour. This speed is assumed as standard for different land uses as shown in Table 1 and Figure 3. For example, cells

02최운섭(325-335)2008.6.273:43PM페이지330

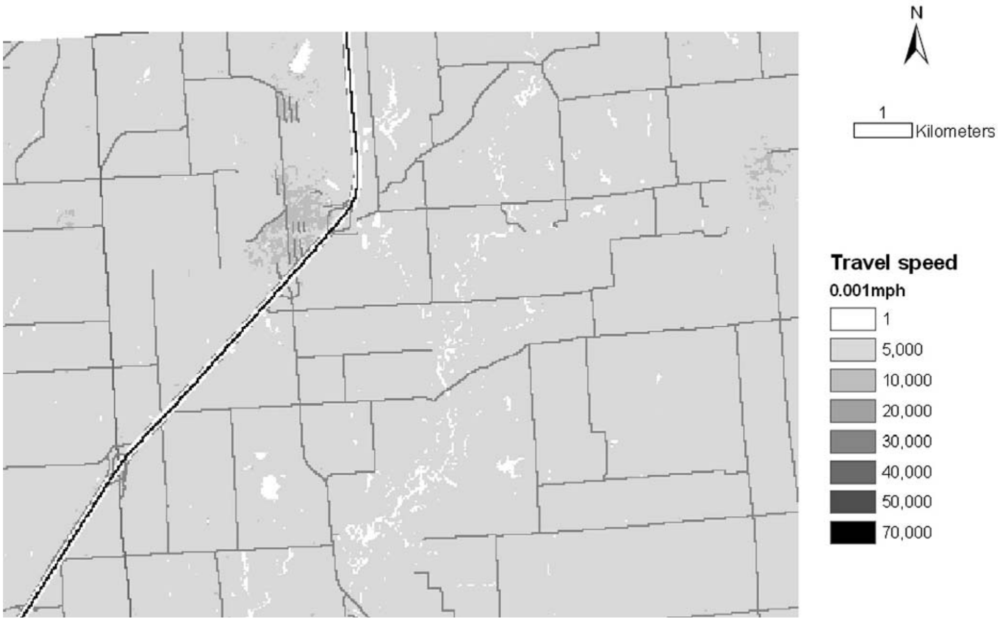

Figure 3. Travel speed in 1/1000 miles per hour (mph) (zoomed in around a corner of Madison County)

that represent a stretch of interstate highway have low travel friction and high travel speeds; a cell that is in a wetland, on the other hand, has a very high travel friction and low travel speed. Some of these values were determined based on common sense (e.g. 70 mph on interstate highways) while others were determined in a more arbitrary manner (e.g. non-road land cover). While generating the travel speed grid, care was taken so that limited access roads, namely, interstate highways, are not blocked by buffers created around ramps.

The travel speed grid was then used to generate a travel time grid. The values in the travel time grid represent the time, in minutes, taken to traverse that cell. Because the travel friction grid contains decimal numbers, the cell values were multiplied by 1000 to remove the decimal numbers. A travel-time grid was generated based on the travel friction grid according to the following logic:

1mile/hr = 1609.344m/hr = 26.8224m/min → (1/26.8224) min/m = 0.0373min/m

For example, if speed limit is 60mph, 1/(26.8224 × 60) min/m = 1min/mile. Taking the multiplication of 1000 into account, the values for the travel-time grid were computed as follows:

TRAVELTIME = 1000 / (26.8224 × TRAVELSPEED)

where TRAVELTIME denotes the values in the travel time grid, and TRAVELSPEED the values in the travel speed grid (Figure 3). Each value of the travel-minute grid denotes the time in minute required to pass through the cell.

Finally, the attractor maps were generated using the COSTDISTANCE command in ArcGrid®. These values represent proximity to the nearest attractors (Figures 4 and 5). A grid indicating the location of attractors (for instance, interstate ramps, state highways) was used as a source grid, and the travel time grid was used as a cost grid. The cell values were set to integers.

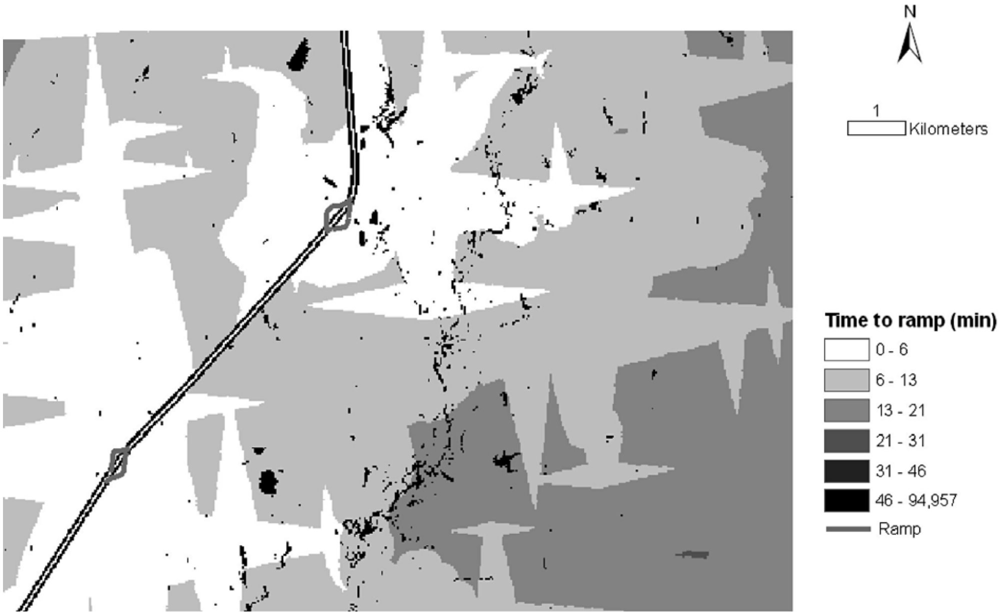

Figure 4. Ramp attractor map (zoomed in around a corner of Madison County)

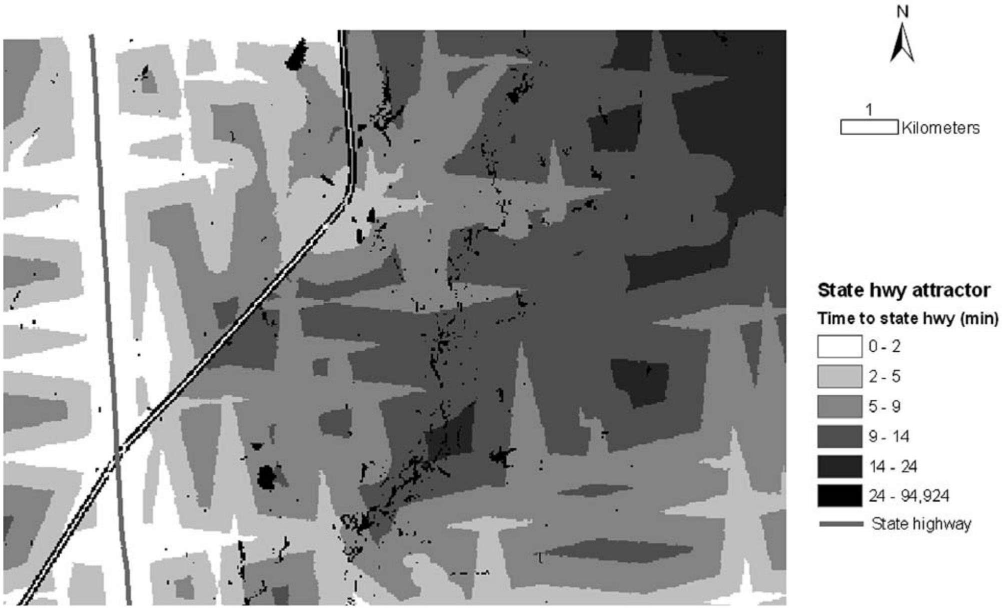

Figure 5. State highway attractor map (zoomed in around a corner of Madison County)

2. Spatial frequency analysis

After the attractor maps were generated, we computed the frequencies with which various types of urban development occur in cells whose travel time to the attractor is the same. This spatial frequency analysis (SFA) was conducted using grids

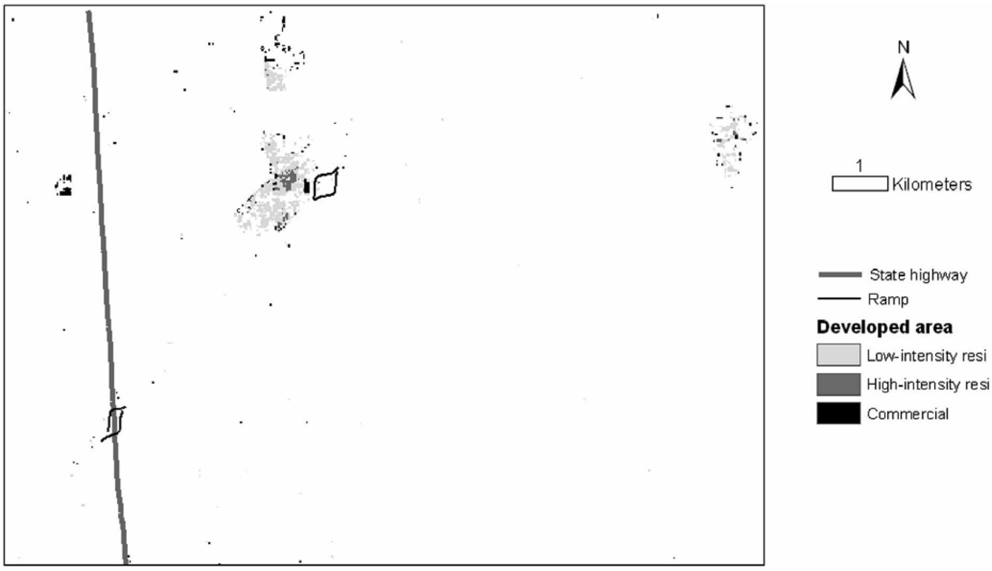

Figure 6. Location of residential and commercial cells along with ramps and state highways

indicating two types of urban development: residential and commercial development (Figure 6). Grid codes 21 (low intensity residential) and 22 (high intensity residential) were selected from NLCD to create the residential grid and code 23 (commercial, industrial and transportation) was selected for the commercial grid. Because major highways were classified as the grid code 23, the cells assumed to be major highways were removed from the grid so that the grid represents as pure commercial and industrial land use as possible.

The number of occurrences of cells of each development type was calculated for each value of travel time. The development grids were reclassified to unit values and multiplied by each attractor map using the 'Map calculator' menu in ArcView ® 3.3. The tables of the resulting grids were saved in a spreadsheet. Spatial frequencies for travel time larger than 60 minutes were aggregated into one category because the effects of attractors on the cells in that category are assumed negligible.

3. Development scores

Finally, the frequency for each development type was converted to development scores between 0 and 1. To allow comparisons between urban developments at different distances from attractors, the development score has to be an index. To arrive at such an index, we first divided the number of developed cells with a particular travel time by the total number of cells having the same travel time. To make these ratios comparable across travel times, we divided each ratio by the highest value computed. This produces a normalized score between 0 and 1. These scores are computed separately in this manner for residential and commercial development . The results of these computations are shown in Figures 7 and 8.

V. Conclusions

The development scores generated by our

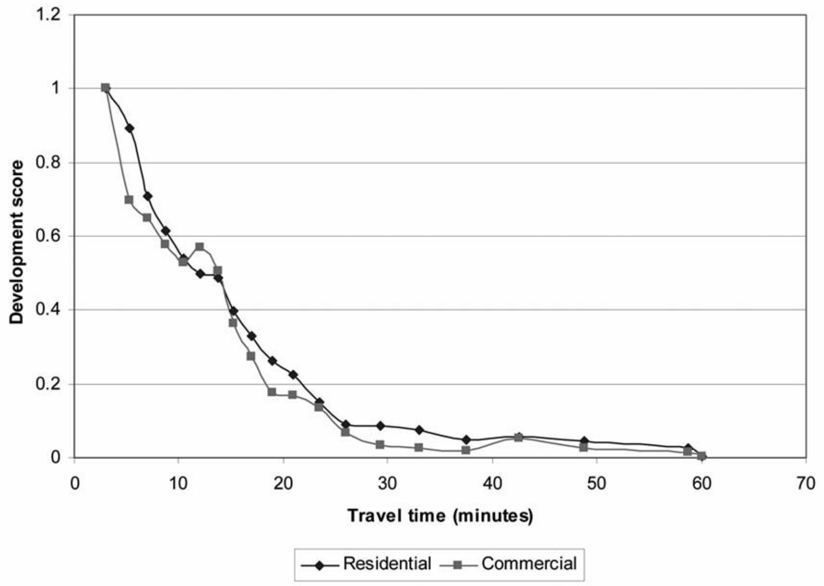

Figure 7. Development score with state highways

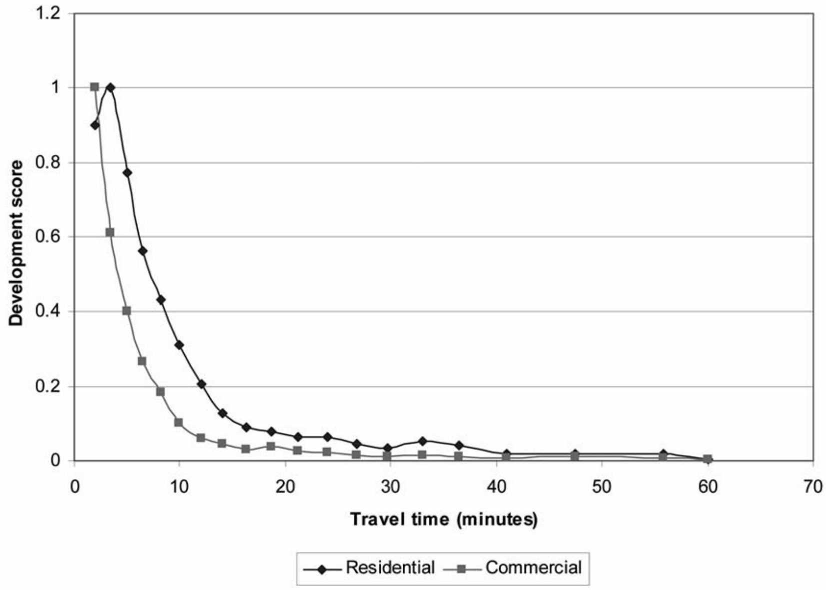

Figure 8. Development score with ramps

approach in this region for state highways and interstate ramps, displayed in Figures 7 and 8, demonstrate that these scores are intuitive and meaningful. Residential and commercial developments appear to display very different trends as the travel time to attractors increases. The attractiveness of cells for commercial development drops off more rapidly with increasing travel time from state highways than does the attractiveness for residential development (Figure 7). This trend holds with respect to interstate ramps as well but is further exaggerated (Figure 8); commercial land use appears more attracted to interstate ramps, while residential land use is less attracted initially, but it peaks later and then slows down. These differences between the two types of land uses and the two types of attractors are consistent with empirical observations. For example, people want to live close to transportation nodes such as ramps, but not too close to them.

The approach described in this paper reveals how urban developments are spatially distributed with respect to development attractors, and how they are different from each other in terms of distribution. This approach has contributed to more realistic simulations of new urban developments in the study area, since it provides insight for where new developments are likely to occur. It should be acknowledged that this analysis is only a step in calibrating LEAM simulation. Nevertheless, this analysis is more advanced than those mentioned in the introduction chapter.

There are some ways in which this approach could improve. First, we should better deal with grade-separated intersections where, for instance, a limited-access highway crosses over or below another road without a ramp. Since that information is lost in a 2-D map, a limited-access highway could, for instance, cut a road in a travel speed map. Second, the travel friction for non-road cells could be more sophisticated since it is too simplistic currently. Residential and commercial cells may have lower travel friction than agricultural or forest cells.

Acknowledgements

Development of LEAM was originally funded by the National Science Foundation. We would like to thank LEAM staff members Jeff Terstriep and Chris Johns, Professors Varkki George and Mu Lan at the University of Illinois, and anonymous reviewers.

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(Received 29 July 2005; Accepted 20 August 2005)