Spatial Frequency Analysis (SFA) of urban land cover in dynamic spatial modeling of urban development

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Introduction

The Land use Evolution and impact Assessment Model (LEAM; http://www.leam.uiuc.edu) is an ongoing research project at the University of Illinois at Urbana-Champaign (Deal 2003; Deal and George, 2001). LEAM simulates land-use change over space and time in order to support regional public land-use policymaking. In LEAM, land-use change can be modeled in large areas (10,000 km^2) at a very fine resolution (30m x 30m).

LEAM adopts a hybrid dynamic spatial modeling approach that combines regional drivers of land-use change along with drivers that operate in 30m x 30m cells across the landscape. At each time step in a LEAM simulation, the probability of land-use change in a cell is computed based on the combined probability associated with a number of factors. Then, the regional demand for new land uses are assigned to cells based on these probabilities. To capture the randomness of some land-use change, LEAM also produces land-use changes in a few cells in which the probability of change may not be high.

One set of factors driving land-use change include what can be called 'development attractors.' These are physical features that promote new residential and commercial development. 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 a score is assigned to each cell in the region. This 'development score' is a function of proximity and is computed based on the cumulative travel time from the concerned cell to the nearest cell containing a development attractor.

As part of the LEAM research, I developed an approach for computing development scores. Using a series of GIS spatial analysis functions, I was able to automate and speed up the process of assigning a development score to a cell. The first step is to develop a map, called an attractor map, for a particular type of attractor; this is based on travel time to the nearest attractor cell. The second step is to evaluate the frequency of urban development that is found in cells within a given time from an attractor. The third step is to estimate development score with regard to each attractor map.

In this paper, I describe our approach for computing development scores. I first provide some background information about LEAM and one region to which it was applied, the tri-county region around Peoria, Illinois. I then elaborate on the approach summarized above. I describe two sets of development scores I computed for the Peoria region: one associated with state highways and another with interstate highway ramps. I conclude with some discussion of the insights provided by this analysis, as well as some of its limitations.

Background

LEAM

LEAM has been described in great detail elsewhere (Deal 2003) and will only be briefly reviewed here. The LEAM for a region is assembled using a software tool, STELLA®, and a spatial modeling environment, SME. STELLA® is used to construct the mathematical formulation of local rules that drive cellular-level change. SME, developed at 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 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

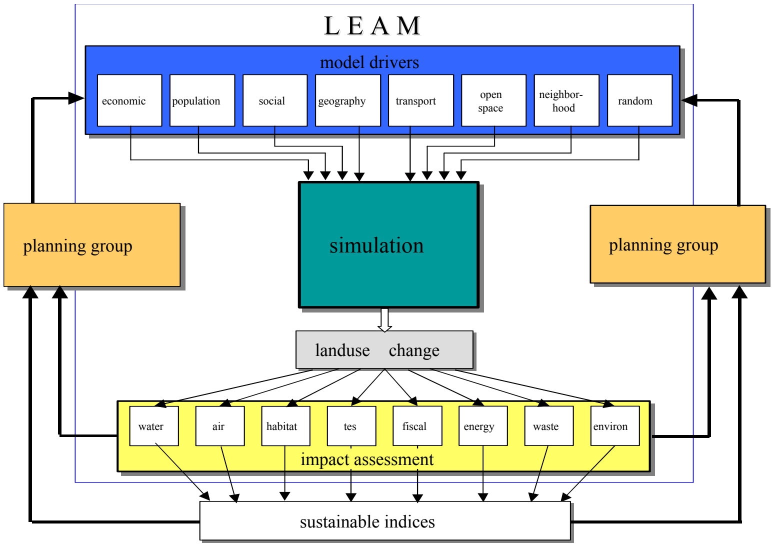

Figure 1 Overview of LEAM

eliminates ‘black box’ complexities and advances a disaggregated approach to spatial modeling.

The Peoria Region

One region where LEAM has been applied is around Peoria in central Illinois and comprises of Peoria, Tazewell, and Woodford counties (figure 2). This was the third application of LEAM, and the first one in which the methods described in this paper were applied. The population of the tri-county area was 347,387 in 2000, and the area is about 4,654km^2 (U.S. Census Bureau). The Illinois River separates Peoria County from other two counties, and the city of Peoria (2000 population 112,936) is right off the river. I will illustrate application of our approach for computing development scores by applying it to the Peoria region.

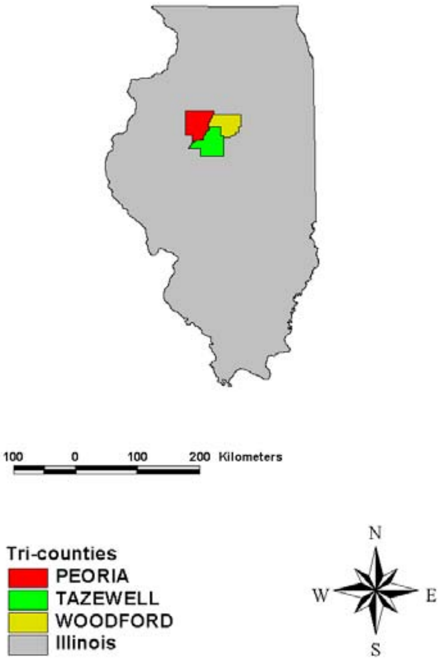

Figure 2 Study area

Computing Development Scores

As mentioned earlier, there are three steps in computing a development score for a cell with respect to a particular attractor. The first step is to develop a map, called an attractor map, for a particular type of attractor; this is based on travel time to the nearest attractor cell. The second step is to compute the frequency of urban development that is found in cells that are at a given travel time away from an attractor. The third step is to estimate development scores with regard to a given attractor map.

Attractor maps

The first step of this study involves computing the proximity of each cell to the nearest cell containing an attractor, and storing this information in an attractor map. This 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 in Arc® cover form were obtained from Illinois Department of Natural Resources, in which roads are classified into toll (class code 1), interstate highway (2), ramp (3), US route (4), state route (5), road (6), street (7), trail (8) and weigh station or rest area (9). Class code values 8 and 9 were considered unimportant and removed. To represent the lack of development immediately adjacent to limited access interstate highways, 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.

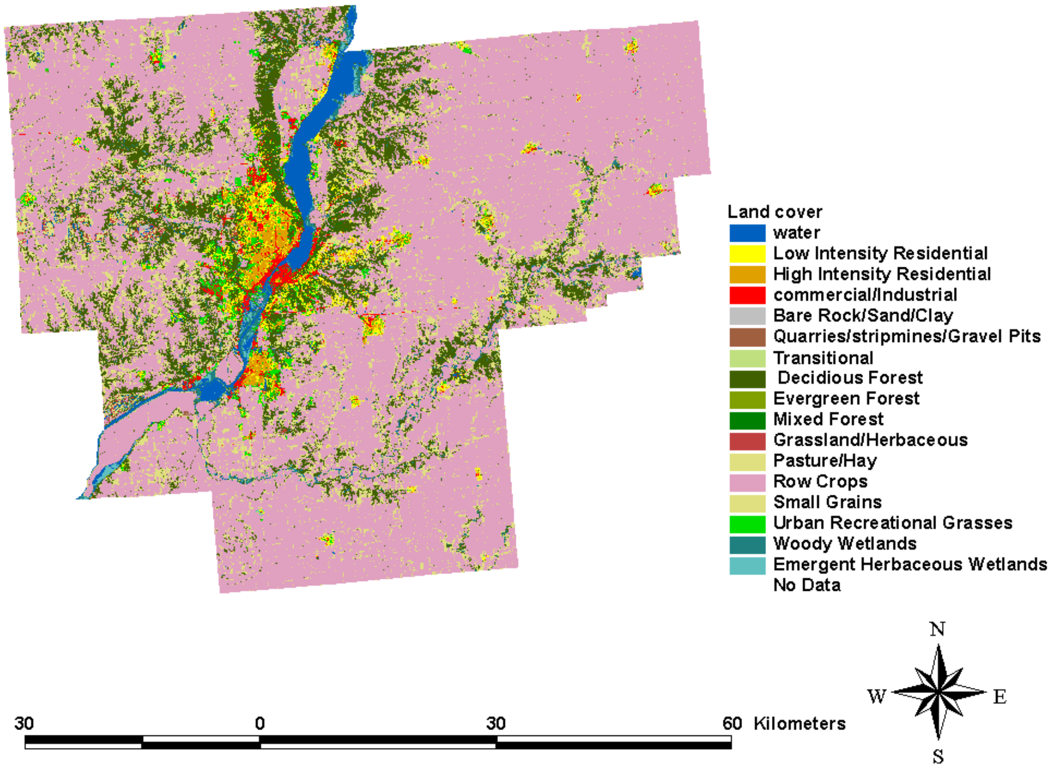

Figure 3 NLCD of the study area (from the U.S. Geological Survey)

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) shown in figure 3; these data represent land cover in the early 1990s. The combined grid was then transformed into a travel friction grid, where travel friction is represented by the speed, in miles per hour, with which a cell can be traversed. This speed is assumed as standard for different land-uses as shown in table 1 and figure 4. For example, cells 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 knowledge (e.g. 75 mph on interstate highways) while others were determined in a more arbitrary manner (e.g. non-road land cover). While generating the travel friction grid, care was taken so that interstate highways are not blocked by buffers created around ramps.

Table 1 Travel speeds on different road and land cover types

Road category or land cover	Speed limit (mph)
Interstate highway	75
US route	60
State route	45
Ramp	40
Other road	25
Non-road land cover	0.5
Interstate 70m buffer	0.001
Open water and wetland	0.001

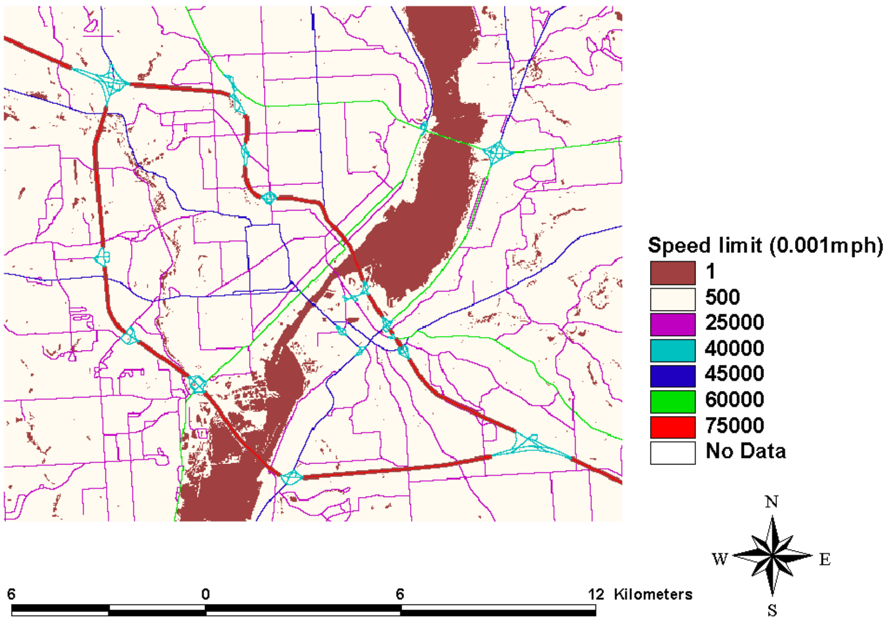

Figure 4 Travel friction map (zoomed in around the city of Peoria)

The travel friction 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, $1/(26.8224 \times 60)$ min/m = 1min/mile. Taking the multiplication of 1000 into account, the values for the travel-time grid were computed as follows:

$$\mathbf{TRAVELTIME} = 1000 / (26.8224 \times \mathbf{TRAVELSPEED})$$

Equation 1 Travel time

In equation 1, TRAVELTIME denotes the values in the travel time grid, and TRAVELSPEED the values in the travel speed grid (figure 4). 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 5 and 6). 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. The yellow cells in the figures are those with zero travel times, which means they are the attractor cells themselves or cells immediately adjacent.

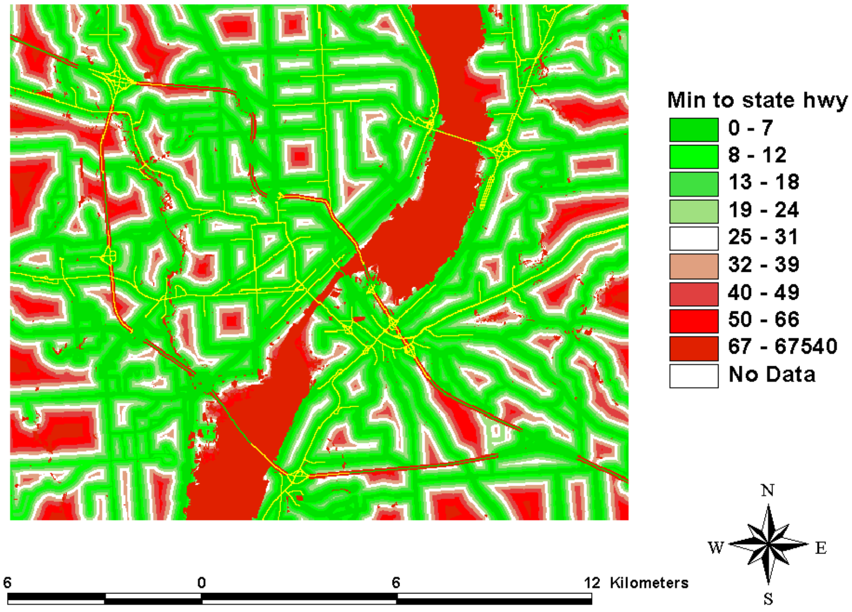

Figure 5 State highway attractor map (zoomed in around the city of Peoria). Yellow cells denote zero values.

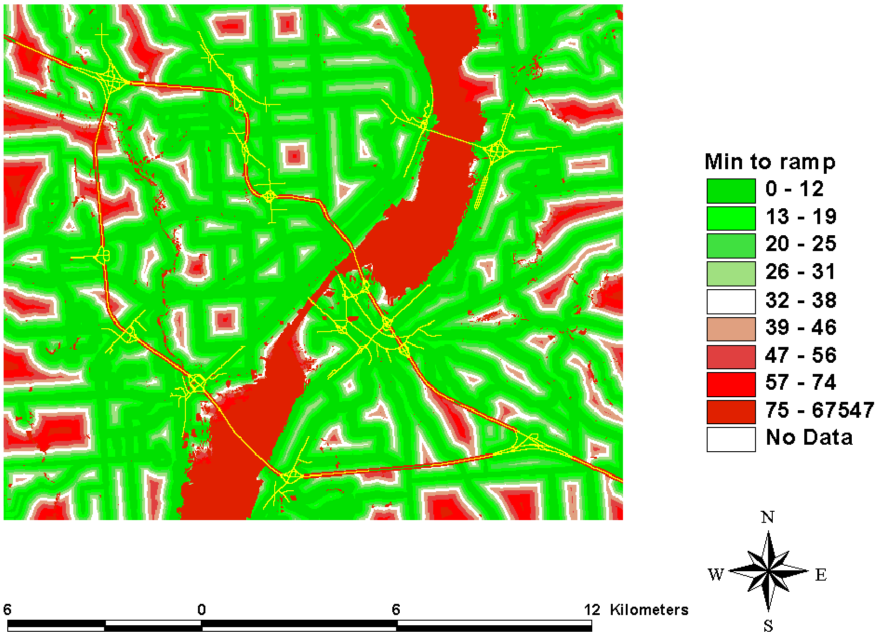

Figure 6 Ramp attractor map (zoomed in around the city of Peoria). Yellow cells denote zero values.

Spatial frequency analysis

After the attractor maps were generated, I 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 indicating three types of urban development: existing residential and commercial development, and new residential building permits (figure 7). The first two represent existing development because they were captured early 1990s, and the third represents new development. 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 house building permit grid was generated from a shapefile obtained from the Tri-County Regional Planning Commission, and shows building permits between 1994 and 2001.

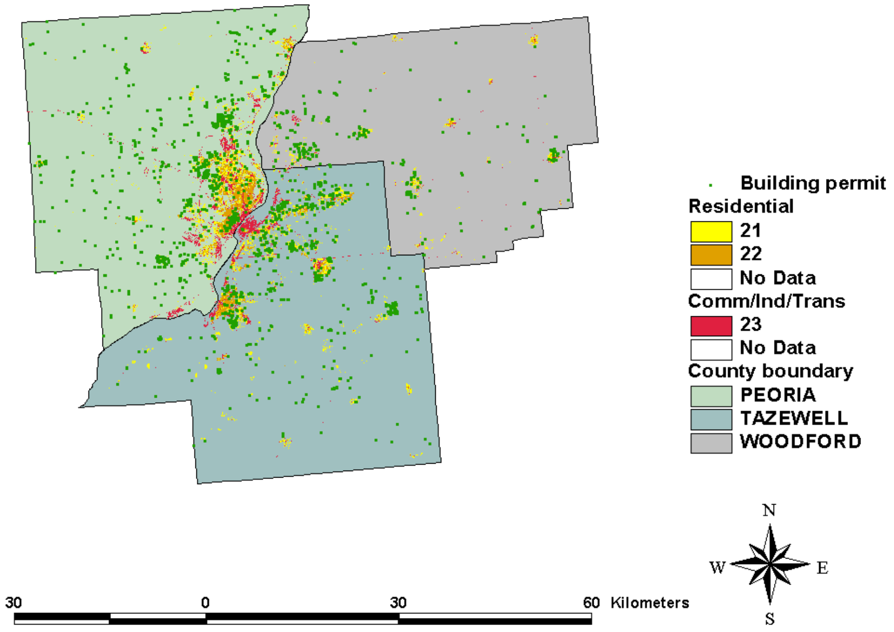

Figure 7 Existing and new developments

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® 3.2. The tables of the resulting grids were saved in a spreadsheet. Spatial frequencies for travel time larger than 30 were aggregated into one category because the effects of attractors on the cells in that category are assumed negligible. Therefore, the frequency was calculated for travel time from 0 through 30 minutes (with increments by one), and over 30. The number of cells with travel minute values larger than 30 is about the half of the total number of cells.

Development scores

Finally, the frequency for each development type was converted to development scores between 0 and 1. To allow comparisons between urban development at different distances from attractors, the development score has to be an index. To arrive at such an index, I first divide 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, I divide each ratio by the highest value computed. This produces a normalized score between 0 and 1. These scores are computed in this manner for residential and commercial development and for new housing permits separately. The results of these computations are shown in figures 8 and 9.

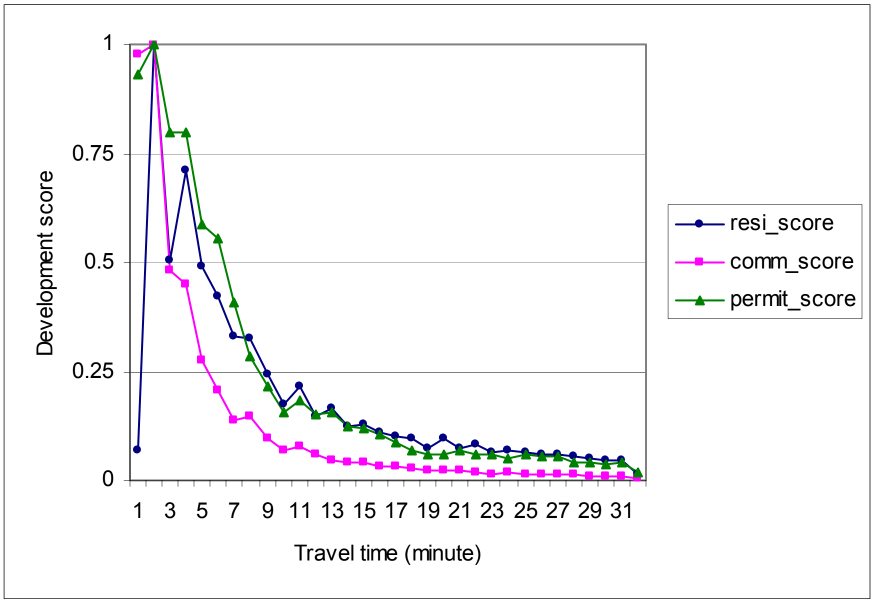

Figure 8 Development score with state highway attractor

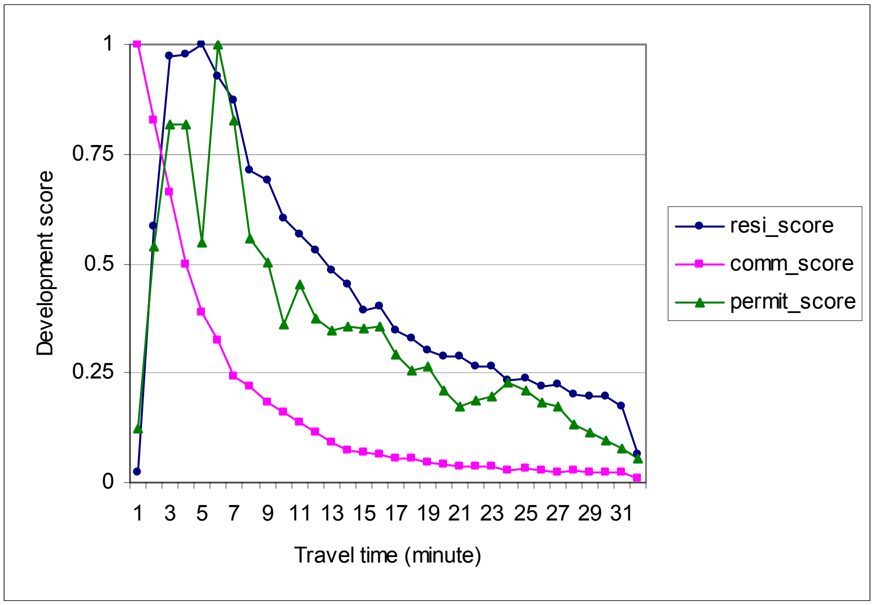

Figure 9 Development score with interstate ramp attractor

Results and Conclusions

The development scores generated by our approach in Peoria for state highways and interstate ramps, displayed in Figures 8 and 9, demonstrate that these scores are intuitive and meaningful. First, residential and commercial development appear to display very different trends as travel time to the attractor 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 8). This trend holds with respect to interstate ramps as well but is further exaggerated (Figure 9); commercial land-use appears more attracted to interstate ramps, while residential land-use is less attracted initially and 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. Second, the development scores for new residential permits appear to track very closely the trend for existing residential development. That a distinct dataset produced very similar trends suggests that I can infer a degree of reliability in our results.

I can also make some more detailed inferences from these results. For instance, with state highways, the most attractive location does not appear to be immediately adjacent (travel time value 0). This is probably because commercial development is concentrated in some areas while the state highways are evenly dispersed across the region (see Figure 10). Commercial cells in urban areas may be off the state highways (but with easy access to them) while a majority of land uses right next to state highways are rural land uses.

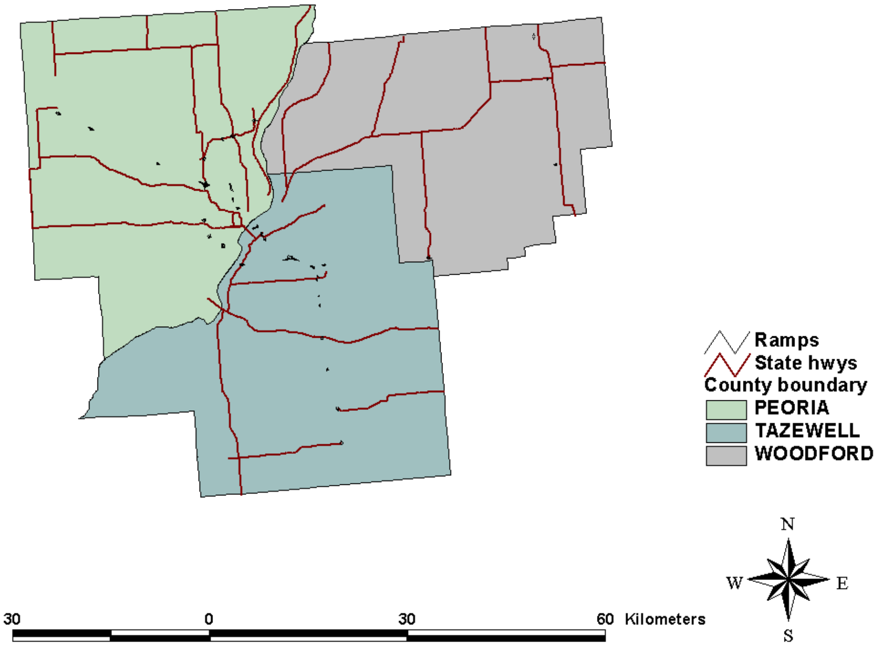

Figure 10 Location of state highways and ramps

The approach described in this paper reveals how existing and new 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 spontaneous developments in the study area, and the assessment of its effect is ongoing.

There are at least four ways in which this approach could improve. First, a more generic road classification would make this approach more portable. The road data used in this study was obtained from a local agency with its own unique classification system. Fortunately, the classification was appropriate for this study. It may not be so in another area with the road data from a different source. A better approach would probably involve consistent road data as is found in TIGER (Topologically Integrated Geographic Encoding and Referencing system) data from the Census Bureau. With its consistent CFCC (Census Feature Class Code) classification, it is possible to produce a generic travel speed map. CFCC distinguishes limited-access highways (not only interstate highways but other highways) from unlimited-access highways. Second, I 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. Third, the travel friction for non-road cells could be more sophisticated. Currently, it is too simplistic. Residential and commercial cells may have lower travel friction than agricultural or forest cells. Fourth, the total number of cells for each travel minute value has a wide range (from 12,658 to more than 100,000). They tend to increase with increasing travel time and become roughly flat after a threshold value. I must investigate how this might change if I aggregate travel time values so that each category has similar number of cells in it.

Acknowledgements

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