

## **Logistics Land Use and the City: A Spatial-Temporal Modeling Approach**

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### **ABSTRACT**

This paper presents a novel approach to examining the transportation / land use (TLU) relationship from a logistics land use perspective. The key question concerns quantifying the influence of transportation system performance on the pattern of logistics land use in a city. We focus on distribution, logistics and warehousing (DLW) land development and use a spatial-temporal approach, based on spatial-autoregressive modeling where the development of logistics related parcels over time is related to the influence of network accessibility elements (congested travel times), timing of services (sewer water), and available land in a given time frame. The paper focuses on the development and testing of the spatial autoregressive models, as well as the specification of the accessibility and parcel level variables. A critical assessment of the modeling approach is presented alongside preliminary findings.

## INTRODUCTION

A challenge for scholars and urban planners alike is to understand how urban structure develops and evolves. In fact, it has been suggested that “understanding cities and regions represents one of the major scientific challenges of our time” (Wilson, 2000, p 1). Transportation (T) and land use (LU) are elements of this problem; however, it is well recognized that much is yet unknown about the interrelationship between these two key elements of urban form.

A review of the literature reveals several methodological issues pertaining to the examination of the TLU relationship. First, given the overall complexity of city systems, attempts to understand these systems tend to be equally complex. For example, most integrated urban models tackle a multitude of variables, however, “it might be difficult to obtain new insights into [a] problem because of the difficulty of untangling the many complex cause-effect relationships” (de la Barra, 1989, p 13). Second, factors related to the variables that contribute to this complexity (spatial variability, spatial dependence, and temporal variability) have yet to be fully defined. For example, accessibility, which is highly spatial and uneven (e.g., Weber & Kwan, 2002), is commonly accepted as an important influence on location choice. However, the measurement of accessibility varies (Lomax et al., 1997) and there is no commonality in its expression (Handy & Niemeier, 1997). It is also generally understood that TLU variables operate on different time scales, but to date quantification of this timing is limited only to broad categories (e.g., Bourne, 1982; Wegner & Fürst, 1999). Furthermore, given the likelihood of clustering of various land use types (Shukla & Waddell, 1991), it is expected that spatial autocorrelation will be present in land use data. As such, most commonly used statistical methods (e.g., ordinary least squares regression) are inappropriate. Finally, these issues are

exacerbated by an inherent lack of comprehensive historical data with respect to urban systems. Consequently, there is not a common view on how to quantify and model the TLU relationship.

In response to these methodological issues, this paper presents a novel approach to examining the TLU relationship. Considering that most attempts to understand city systems are complex, the methodology presented here represents a simplified approach to an otherwise complex problem. The approach is simplified in the sense that the aim is to test a specific component of the TLU problem as opposed to tackling a multitude of variables. In this case, we examine the relationship of transportation system costs (a component of accessibility) to land use development. As an example, we focus on non-residential land use types associated with distribution, logistics and warehousing (DLW); however, the methodology is equally applicable to other use types. We use a spatial-temporal approach in order to take advantage of an extensive historical TLU database. The use of an extensive historical database affords a unique opportunity to test for temporal variability and response lags in the TLU relationship using actual TLU data, thereby achieving a potentially more realistic understanding than would be achieved using modelled data, the more common approach. A spatial or geographical approach is favoured since geographical approaches seem to be useful for addressing the broader interactions and flows within the spatial environment of a city system (Hesse and Rodrigue, 2004).

## **BACKGROUND**

### *Spatial variability (accessibility)*

It is widely accepted that accessibility influences urban land use. Although there is little agreement regarding what constitutes a good measure, it is basically understood that most accessibility-type measures consist of two elements: transportation and activity (Handy &

Niemeier, 1997). The transportation element represents transportation costs related to travel, while the activity element captures the attractiveness of a location as a trip destination. The focus in this paper is on the transportation element, specifically transportation costs including distance, time, access to roads and traffic congestion. Traffic congestion is defined here as travel time or delay in excess of that normally incurred under free-flow conditions (Lomax et al., 1997). In this case, we consider daily persistent congestion as opposed to non-recurrent congestion resulting from events such as traffic accidents and road construction.

In order to assess the impact of accessibility (transportation cost) on urban land use distribution, it is necessary to measure it. This is a difficult challenge because accessibility exhibits considerable spatial variability (Weber & Kwan, 2002). Costs related to intraurban transportation have typically been measured as travel distance or travel time, but a wide range of approaches at varying degrees of detail and complexity exist for determining these measures. Distance has generally been estimated as straight-line distance (Baxter & Lenzi G., 1975; Stanilov, 2003) or as linear distance through a network (Vickerman, 1974; Talen & Anselin, 1998), whereas time-based measures are more diverse. Common travel time measures include actual (Wickstrom, 1971) or perceived (Wachs & Kumangai, 1973) travel time as directly measured in field surveys, or distance-based travel times measured through a network. Time-based measures are a preferred means of assessing network impedance (Ortúzar & Willumsen, 1996; Lomax et al., 1997; Ryan, 1999; Larsen, 2001), but the challenge of determining time-based measures through a complex urban road network is considerable. Major issues to consider include resolution of the network, land use resolution, and the scale and timing of network flows.

There have been a variety of approaches to these issues. From the network perspective, even though a complex network is possible (e.g., hierarchy of streets, multiple lanes, speeds,

capacity, signalization and interchanges), a simplified urban road network is often invoked in the interest of expediency (Wang, 2000). Similar to the street network, land use is typically represented as an aggregation such as a census tract (Helling, 1998) or transportation zone (Wang, 2000); although, some have argued in favour of finer resolution (Miller et al., 2003). As for traffic flows, some have excluded them entirely. Muraco (1972) estimated travel time based on speed limits; Brandeau (1989) reviewed over fifty location models and found only one was volume dependent; and Handy (1993) used free flow conditions to measure travel time. On the other hand, many have included flows, either modelled (Weber & Kwan, 2002; Medda et al., 2003) or actual (Miller & Demetsky, 1998), in their estimation. If flows are included, consideration has also been given to whether uncongested (off peak) or congested (peak) times should be used (Handy & Niemeier, 1997). The preference has been to use congested times (Wachs & Kumangai, 1973; Lomax et al., 1997; Miller & Ibrahim, 1998; Martin & McGuckin, 1998), but other periods have been examined as well (Weber & Kwan, 2002). One effective output based on travel time is an accessibility surface. For example, MacKinnon and Lau (1973) developed an accessibility surface for Toronto based on simple travel time to strategic locations. More recently, Weber (2002) created a surface for the Portland area based on space-time measures.

### *Spatial dependence*

A variety of methods have been used to quantify the TLU relationship including, among others (see reviews by, Vessali, 1996; Badoe & Miller, 2000), ordinary regression (e.g., Sivitanidou, 1996; Boarnet, 1996; Miller & Ibrahim, 1998; Davis, 1999; Kawamura, 2001), hedonic models (e.g., Bowes, 2001) and four stage models (including gravity models) (e.g.,

Hirschman & Henderson, 1990; Miller & Demetsky, 1998). Where conventional statistical methods have been applied, there is an underlying assumption that the data is statistically independent and identically distributed (iid) (Anselin, 1995b: 266). However, given the likelihood of clustering of various land use types (Shukla & Waddell, 1991; Ellison & Glaeser, 1997), it should be expected that spatial autocorrelation is present in the land use data. The iid assumption does not hold in the presence of spatial autocorrelation.

For zone-based data, similar to the data structure used in this approach, spatial autocorrelation refers to a condition where the value of an attribute in one zone depends on the values of the attribute in neighbouring zones (Vasiliev, 1996; Fotheringham et al., 2000: 12). (Goodchild, 1986; Griffith, 1987; Odland, 1988) The consequence of spatial autocorrelation for standard regression is the presence of remaining spatial dependence in the residuals even after structural similarities of neighbouring zones have been controlled for (Anselin, 1988; Fotheringham et al., 2000: 166-171; Baller et al., 2001; Anselin, 2002). This is contrary to the assumption of independent error terms. Considering this condition, analytical methods selected for this research are influenced by the recent work of Haider and Miller (2000) and others (Anselin, 1988; Baller et al., 2001; Anselin, 2002) who advocate the use of spatially autoregressive models (SAR) as a preferred method in the presence of spatial autocorrelation.

Two different approaches to modelling spatial dependence in zone-based data apply here: i) the spatial lag model and ii) the spatial error or moving average model (for a thorough discussion, see Anselin, 1988; Fotheringham et al., 2000: 166-171; Baller et al., 2001; Anselin, 2002). The spatial lag model stipulates the effect of neighbouring zones through the inclusion of an extra explanatory variable in the standard regression model (e.g., mean of the dependent variable for adjacent zones) expressed as

$$y = X\beta + \rho W y + \varepsilon \quad \text{Equation 1}$$

where  $y$  is the dependent variable,  $W$  is an adjacency or spatial weights matrix for the zones, and  $\rho$  is a regression coefficient or spatial autoregressive parameter for the adjacency variable.

Equation 1 expressed in reduced form

$$y = (I - \rho W)^{-1} X\beta + (I - \rho W)^{-1} \varepsilon \quad \text{Equation 2}$$

demonstrates that this model captures the influence of unmeasured independent variables in the error term as well as the effect of neighbouring zones in the dependent variable. This type of model is appropriate under the assumption that activity in a zone will somewhat mimic that of its neighbouring zones (Fotheringham et al., 2000: 166-171), which is expected in this case.

Alternatively, the spatial error or moving average model focuses on the error term. In this case, the regression model is expressed as

$$y = X\beta + u \quad \text{Equation 3}$$

$$\text{where } u = \rho W u + \varepsilon.$$

Solving for  $u$  and substituting into the regression equation produces

$$y = X\beta + (I - \rho W)^{-1} \varepsilon. \quad \text{Equation 4}$$

revealing that although the spatial error model captures the influence of missing independent variables, it ignores any spatial dependence in the dependent variable. Although various methods have been developed to contrast these approaches (Anselin, 1988), it is often difficult to distinguish which approach best addresses the spatial dependence in question (Fotheringham et al., 2000: 170).

An additional challenge lies in the specification of the weights matrix ( $W$ ). Overall, specification of  $W$  is problematic in that “there is very little formal guidance in the choice of the correct spatial weights in any given application” (Anselin, 2002). This is an issue since

regression results are sensitive to the selection of  $W$ . Various approaches have been suggested for the selection of  $W$  (Haining, 1990: 341-344); however, in the absence of strong theoretical grounds for a choice, which is the case in this research, Haining (1990) and Anselin (2002) recommend fitting the regression model under several different forms of  $W$  and then gauging the sensitivity of regression results to the various forms of  $W$  revealed in the measures of fit.

### *Temporal variability (response lag)*

For our purposes, temporal variability refers to the timing of the feedback mechanisms in the TLU relationship. Typically, land use has been determined in response to current or recent transportation conditions as is the case for most geographic location type models (e.g., Von Thunen, 1826; Weber, 1929; Alonso, 1964; Mills, 1970; McCann, 1998) or spatial interaction type models (e.g., Stewart, 1942; Huff, 1964; Wilson, 1970). However, it may not be the case that current land use exists in response current or recent transportation conditions.

If we consider models that simulate the interaction between the transportation and land use systems (e.g., Lee, 1973; Wegener, 1994; Miller et al., 1999; Wegner & Fürst, 1999), we see that the TLU relationship is generally expressed as a feedback cycle of trips generated on a transportation network by a land use model versus accessibility provided to the land use model by the transportation network. Figure 1 illustrates this concept in its most basic sense. TLU cycle completion time is recognized as having an important bearing on the relationship, particularly with respect to the timing of the various components (Meyer & Miller, 2001:129).

Figure 1 The land use – transport feedback cycle (Source: adapted from (Wegner & Fürst, 1999)

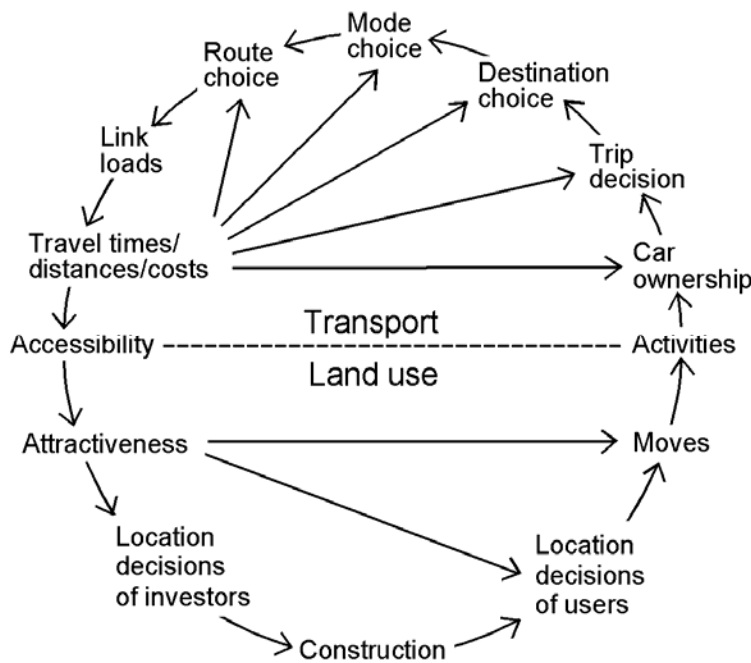


Table 1: Urban change processes:

Source: adapted from (Wegner & Fürst, 1999:43; Shaw & Xin, 2003)

Urban change process	Examples
Very slow change	<i>Networks</i> (e.g., transport networks): are the most permanent elements of cities
Slow change	<i>Land use</i> : distribution is often stable, changes are incremental <i>Workplaces</i> (e.g., warehouses, office buildings, shopping centers): exist much longer than the firms or institutions that occupy them
Fast change	<i>Housing</i> : exist longer than the households that live in it <i>Employment</i> : refers to firms that open, close, expand, or relocate <i>Population</i> : refers to households that form, grow, decline, dissolve, or relocate
Intermediate change	<i>Goods transport</i> : adjusts quickly to changes in demand <i>Travel</i> : adjusts quickly to changes in traffic conditions

As such, a lag is normally invoked between the transportation model and the land use model. This lag is typically applied through feedback of the transportation model output into the next period's land use model and visa versa (Abraham & Hunt, 1999).

However, there are limitations in our understanding of the magnitude of the lag. It is widely recognized that the various model components operate on different time scales, but to date quantification of this timing is limited to broad categories (e.g., Bourne, 1982; Wegner & Fürst, 1999), such as those illustrated in Table 1. This implies that, although a lag is typically incorporated into most integrated models, there is insufficient evidence to suggest an optimal lag period.

Furthermore, given that the relationship between transportation and land use is normally established using modeled data as opposed to actual data, it is questionable as to whether or not a lag can be accurately determined using these methods. This is particularly true given that the most widely used approach to modeling transportation flows has been, and continues to be, the urban transportation modelling system (UTMS) or four-stage modelling approach (e.g., see discussions by Moore & Thorsnes, 1994). Given the known limitations of this method, even a comprehensive (e.g., well-defined network) dynamic assignment model will likely produce flawed output leading to dubious predictions. To illustrate this point, we note, for example, the Committee for the Study of Impacts of Highway Capacity improvements on Air Quality and Energy Consumption (1995) found that “with few exceptions, regional travel demand models cannot adequately forecast truck travel or the likely effects of travel time reductions ... on carrier and shipper behaviour.”

## **METHODS**

### *Data and Procedures*

This work benefits from an extensive historical TLU dataset provided by The City of Calgary. Transportation data for Calgary includes average weekday traffic volumes (AWDT) on major roads for the years 1964 to 2000 in the form of paper flow maps. Data from the flow maps is manually incorporated into a GIS database and merged with an existing dual carriageway road network to produce a subset road network of only major roads with traffic volume attributes (see Figure 2) (Sheldrake, 2001; Staley, 2002). To facilitate temporal analysis, the subset network is also coded to reflect historical presence/absence of roads based on existing paper road maps for the City of Calgary (Figure 3). Thus, it is possible to represent both historical traffic volume and network structure.

Calgary land use data derives from several sources. First, a comprehensive registered land parcel rolling database (pardat) provides approximately 270,000 parcel records including attributes such as parcel address, geographic coordinates, zone (e.g. I-2 industrial), use type (e.g. multi bay warehouse) and year of construction (Table 2). Use type consists of approximately 415 separate codes to describe individual parcel land use. Year represents initial year of development and is documented from the year 1900 to present. The fact that this is a rolling database means that land use type and year only reflect the original date of development and any changes are lost. Therefore, transportation influence on land use is considered from the perspective of new growth as opposed to changes to existing land use. It is important to note, however, that the negative aspect of data loss due to the rolling nature of the database is somewhat offset by the fine detail offered by the micro scale (parcel level) of the database.

Figure 2: Base Road Network and Traffic Volume

This figure illustrates the transfer of bi-directional AWDT traffic volumes from paper flow maps into a GIS database. Part a) represents an existing GIS dual carriageway road network. Part b) represents a section of a paper flow map that matches the inset in part a. Part c) represents a section of existing GIS road network captured in the inset of part a. Part d) represents the corresponding attribute table for the road section of part c. AWDT volumes from the paper flow map (b) are attached to a corresponding GIS link (c) and registered as an attribute tagged with a section name (d). AWDT volume attributes were developed for the years 1964 to 2000.

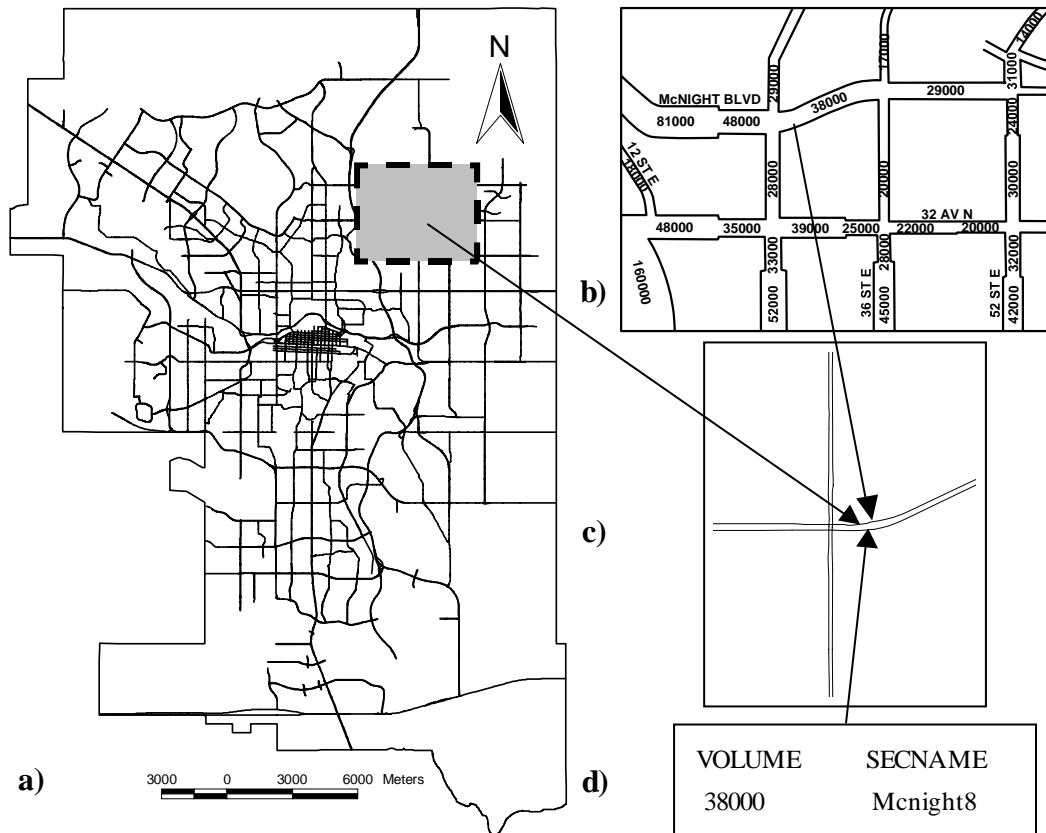


Figure 3: Historical road networks

Two historical road networks are compared here: 1975 and 1995. Note, for example, i) the substantial infrastructure development in the NW quadrant of the city and ii) the construction of a major north/south expressway on the east side of the city (shown in bold).

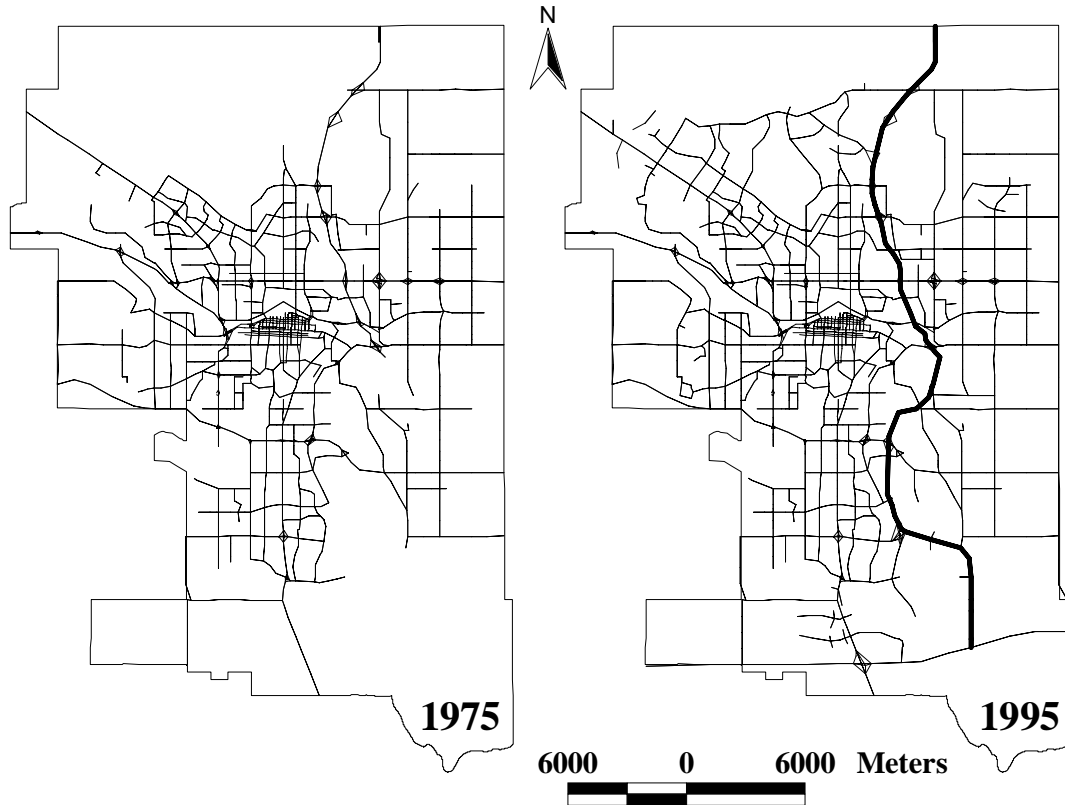


Table 2: Sample table from rolling land parcel database (pardat)

ID_PARC	ADDRESS	XCOORD	YCOORD	ZONE	TYPE	YEAR
40566	2323 24 AV NE	-425.821	5659766.797	I-2	Multi-Bay Warehouse	1989
41161	2612 24A ST SW	-8358.366	5654991.689	R-2	Res. Detached Dwelling - Single Unit	1989
45151	5799 3 ST SE	-4017.1	5651794.526	I-2	Warehouse - With Internal Office Space	1989
64381	2504 7 AV NE	-8.95	5658048.263	I-2	Retail Veh/Acc-Combo Gas/Kiosk/Serv Stn/Store/Carw	1989
62983	220 61 AV SW	-4860.224	5651282.75	I-2	Retail Store - Stand Alone	1989

Pardat is supplemented with parcel polygons, building footprints, a vector representation of water mains and a general land use classification. The parcel polygons represent all land parcels within the Calgary city limits and when joined with pardat provide area, use type and year of development attributes for all land parcels. The building footprints contribute a building polygon that can be joined with pardat and the parcel polygons to produce a comprehensive spatial representation of every land parcel in Calgary (Figure 4). Water mains provide a proxy for historical municipal services or serviced land in that they include a year of construction. The land use classification provides a more aggregate representation of Calgary land use.

The approach incorporates three main strategies: variable development, spatial analysis and temporal analysis (Figure 5). In order to establish an empirical link between transportation system costs and land use development, i) transportation variables are created from the existing data set to represent transportation costs (accessibility) and ii) land use variables are created to represent land development intensity and available land. Quantification of the link first involves the use of exploratory spatial data analysis (ESDA) (for a review, see Anselin, 1998) to test for spatial autocorrelation (e.g., Anselin, 1996) and heterogeneity or systematic patterns. Exploratory analysis leads to the use of modelling procedures designed to estimate the effects on land use development of independent variables (e.g., network performance, available land and serviced land) with adjustments for spatial dependence and heterogeneity. A model that best addresses the spatial dependence is selected to quantify the relationship. Finally, modelling efforts are expanded to include historical transportation system costs as a means to capture a specific temporal lag in the TLU relationship.

All variables are developed based on a regular sample grid. The most common method of aggregation is the census tract or transportation zone, however, there is no agreement in the

Figure 4: Parcel data detail: This figure illustrates the parcel data set. On the left is a graphic showing parcels (parcel polygon) with building footprints (footprint polygon) and a point representing pardat output (pardat point). The tables represent the attributes associated with the features of the parcel indicated with an arrow.

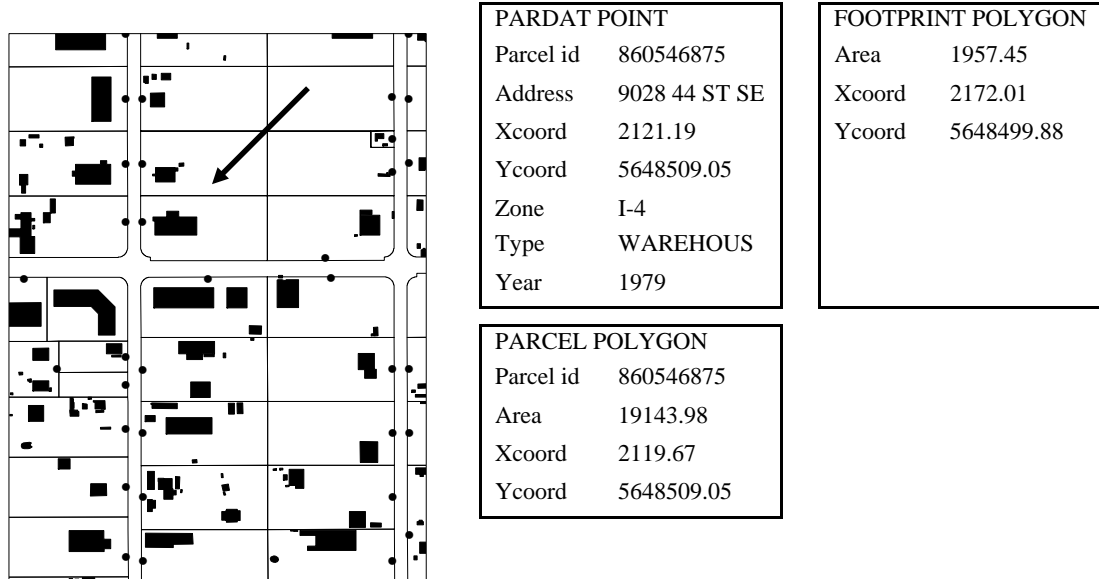
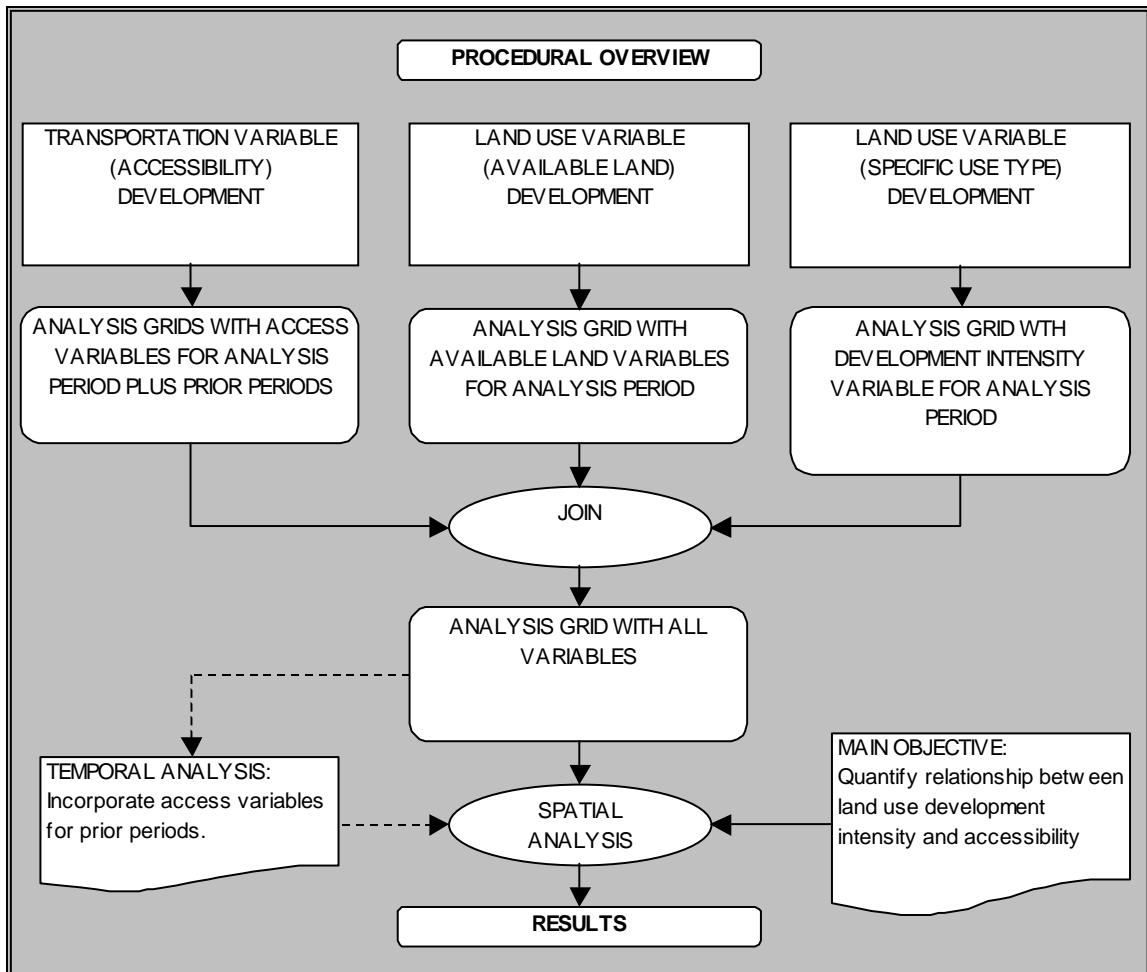


Figure 5: Procedural overview



literature with respect to spatial aggregation of urban data. Miller et al. (2003) suggest that grid cells may provide a better alternative. According to Miller et al., “grid cells provide a stable representation of space, are generally computationally more efficient to work with than zones, and, if determined on a sufficient scale, will largely avoid aggregation bias problems. On the other hand, they are a very artificial construct and their use can (perhaps) lead to an overly abstracted representation of space and spatial processes.” Considering this argument, grid cells form the base analysis unit. Scale is arbitrarily determined at a grid cell size of 855 m<sup>2</sup>, producing a total of 1,017 grid cells encompassing the entire Calgary city limit (Figure 6).

Geoprocessing is performed in a geographical information system (GIS) using Environmental Systems Research Institute (ESRI) ArcInfo, ArcGIS and ArcView. Spatial modelling is performed using SpaceStat (Anselin, 2001) and is primarily based on procedures prescribed by Anselin (1988; 1998).

### *Representing Accessibility*

Urban transportation cost (accessibility) is highly spatial and uneven (Weber & Kwan, 2002). Representing this variable in detail is often difficult given the complexity of urban transportation networks and limitations in data availability. For our purposes, accessibility (independent variable) is represented as a historical time-based measure from an origin to a destination through a network (Lomax et al., 1997; Larsen, 2001) using congested travel times to determine shortest paths (Martin & McGuckin, 1998). Development of such a time-based measure involves i) creation of a transportation network with base attributes suitable for

Figure 6: Sample grid with centroids (cell size 855 m<sup>2</sup>)

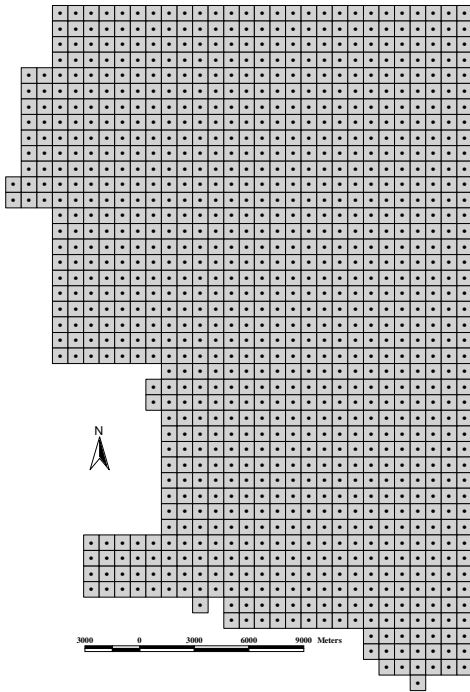
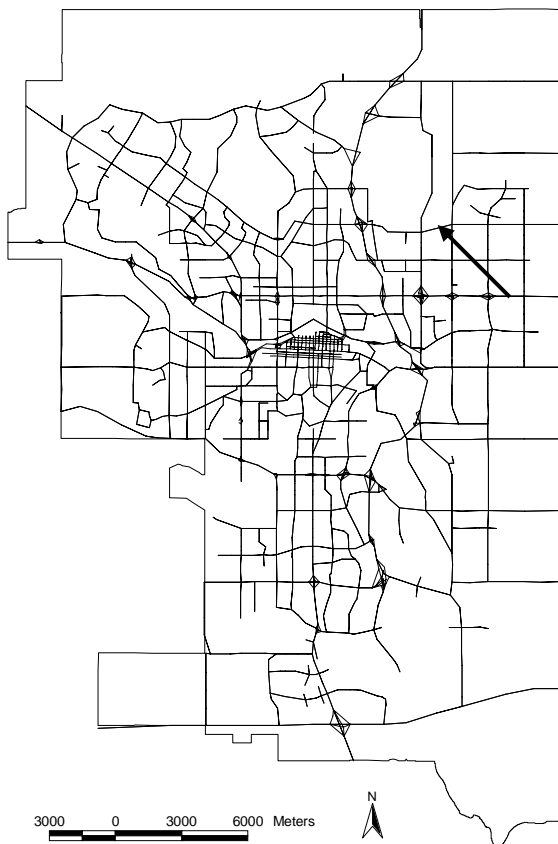


Figure 7: EMME/2 network with sample attribute table. Attributes displayed are associated with the EMME/2 link indicated by the arrow. Attributes include number of lanes (lanes), speed limit (speed), capacity per hour per lane (cap\_h\_lane), signalization (contr\_type), flow direction (flow\_dir), and historical AWDT from 1964 (AWDT64) to 2001 (AWDT01).



Length	115.280
Model01r	5397
Mode	Cbehstv
Link_type	5
Lanes	2
Vdf	24
Speed	80
From_x	2403.00
From_y	5662204.00
To_x	1287.72
To_y	5662204.00
Full_stree	MCKNIGHT BV NE
Secname	MCKNIGHT9
Cap_h_lane	800
Cap_h_tot	1600
Contr_type	Signal
Flow_dir	SW
AWDT64	1000
	↓
AWDT01	32834

historical network analysis, ii) disaggregation of historical AWDT volumes into analysis hour volumes, iii) calculation of a network impedance variable, and iv) network analysis.

A suitable network structure coupled with the appropriate attributes forms the foundation for network analysis. In this case, network analysis involves the use of shortest path analysis, which requires a single carriageway network. Shortest path procedures find a path with the minimum cumulative impedance, as defined by an impedance matrix, between nodes on a network (Miller & Shaw, 2001). Definition of the impedance matrix dictates the base attribute set required. Given that the historical time-based measure is developed using congested travel times, base attribute requirements include historical link presence/absence, speed limits, lanes, signalization, capacity and historical traffic volumes.

Creation of a transportation network with base attributes suitable for network analysis is accomplished by joining the existing transportation data set to an output from *The Calgary Transportation Model* (The City of Calgary, 1991). The existing data set incorporates historical AWDT volumes and historical link presence/absence codes. The transportation model is an a.m. peak hour model of the City of Calgary and surrounding region based on a single carriageway road network subset, and implemented using the EMME/2 system. Key model attributes include, number of lanes, capacity, posted speed limit, signalization and link length. The transportation model also provides traffic volumes, but these are modeled volumes as opposed to the actual volumes included in the existing transportation data set. The joining of data sets is accomplished by i) generation of an EMME/2 output, which is in text format, into an ArcInfo coverage and ii) joining the existing road network to the EMME/2 network such that AWDT volumes are added to the EMME/2 network. The result is a single carriageway network with attributes suitable for network analysis (Figure 7).

Traffic analyses typically focus on 15-minute or hourly flows and frequently on the peak hour of traffic for the peak direction because this represents the highest capacity requirements (Transportation Research Board, 2000). However, there are those that suggest other times of day should also be considered – particularly with respect to truck movements. According to Woudsma (2001), data indicate that peak truck travel occurs in the mid morning and mid afternoon between the am and pm peak hours suggesting that an analysis hour between the peak hours is appropriate. Given these arguments, AWDT volumes are disaggregated into a range of analysis hour volumes.

Analysis hour volumes are produced using conversion factors developed directly from City of Calgary year 2001 six hour 15-minute traffic counts collected for the am peak period (7 to 9 am), midday (11 am to 1 pm), and pm peak period (4 to 6 pm). Conversion factors for these periods are developed based on the data structure provided by the City of Calgary. The City of Calgary records directional flow in all four cardinal directions. This flow is then aggregated into two primary flow directions: north and east (N/E), and south and west (S/W). Accordingly, conversion factors are developed for each link by first calculating an analysis hour directional volume (N/E and S/W) from the highest four 15-minute counts for each period (am, midday and pm). Then, each analysis hour link volume is divided by the 24-hour total volume to generate a directional conversion factor.

Analysis hour volumes are extracted from AWDT volumes using the directional conversion factor applied to each respective link volume. The appropriate directional volume is calculated first by coding each link with its azimuth, then link AWDT volumes are multiplied by the appropriate directional factor (N/E or S/W) for each of the analysis hours according to the link azimuth: N/E azimuth range 0-145 and 315-360 degrees; S/W azimuth range 145-315

degrees. In this way, each link is associated with the appropriate directional analysis hour volumes.

These directional analysis hour volumes are then used as input to produce a time-based friction or impedance variable representing congested link travel time. A common means to calculate congested link travel time is found in a formulation developed by the U.S. Bureau of Public Roads (BPR) to estimate link travel times as a function of the volume/capacity ratio (Martin & McGuckin, 1998). In this formulation, impedance  $t_a(x_a)$  is a measure of the congested travel time on link  $a$  given the traffic volume  $x_a$  on that specific link. If  $x_a^0$  is the link design capacity of link  $a$ , and  $t_a^0$  is the free flow travel time that corresponds to link design capacity and  $x_a$  is the flow on link  $a$ , then the link performance function of link  $a$  is defined as

$$t_a(x_a) = t_a^0 \left[ 1 + \alpha \left( \frac{x_a}{x_a^0} \right)^\beta \right] \quad \text{Equation 5}$$

where typical values for  $\alpha$  and  $\beta$  are 0.15 and 4.0 respectively (Martin & McGuckin, 1998: 94). Volume ( $x_a$ ) is represented by the directional analysis hour volume. Capacity is extracted from the *EMME/2* model output and represents the City of Calgary's estimation of actual road capacity. Road capacity is calculated within the *EMME/2* model using automobile volume-delay functions designed by the City of Calgary specifically for each link type based on field data and link characteristics including signalization. In this way, an impedance variable is developed to represent the basic influence of increasing traffic volume without the complexity of estimating delays due to cuing of traffic.

The resulting friction or impedance variable provides a transportation cost for network analysis input – referred to interchangeably as congested travel time or accessibility. Given that all variables are developed based on a regular sample grid, network analysis is preceded by the

connection of all sample grid centroids to the nearest node on each individual historical *EMME/2* network for the years 1965, 1970, 1975, 1980, 1990, 1995, and 2000 (Figure 8). Then, shortest path procedures are implemented. Shortest path procedures follow an iterative process of finding the shortest distance from an origin node to a destination node and all intermediate nodes on the path (e.g., Heywood et al., 1998; Miller & Shaw, 2001; Chang, 2002). Inputs include i) the *EMME/2* network in 5-year increments with connected grid centroids representing origins and destinations, ii) congested link travel time representing impedance, and iii) free flow travel time representing impedance. Shortest paths are iteratively run from each grid centroid to every other grid centroid for each year first using free flow travel time and then congested travel time as the impedance value. The resulting cumulative shortest path values become attributes that represent the cost of travel from a grid centroid to any other grid centroid.

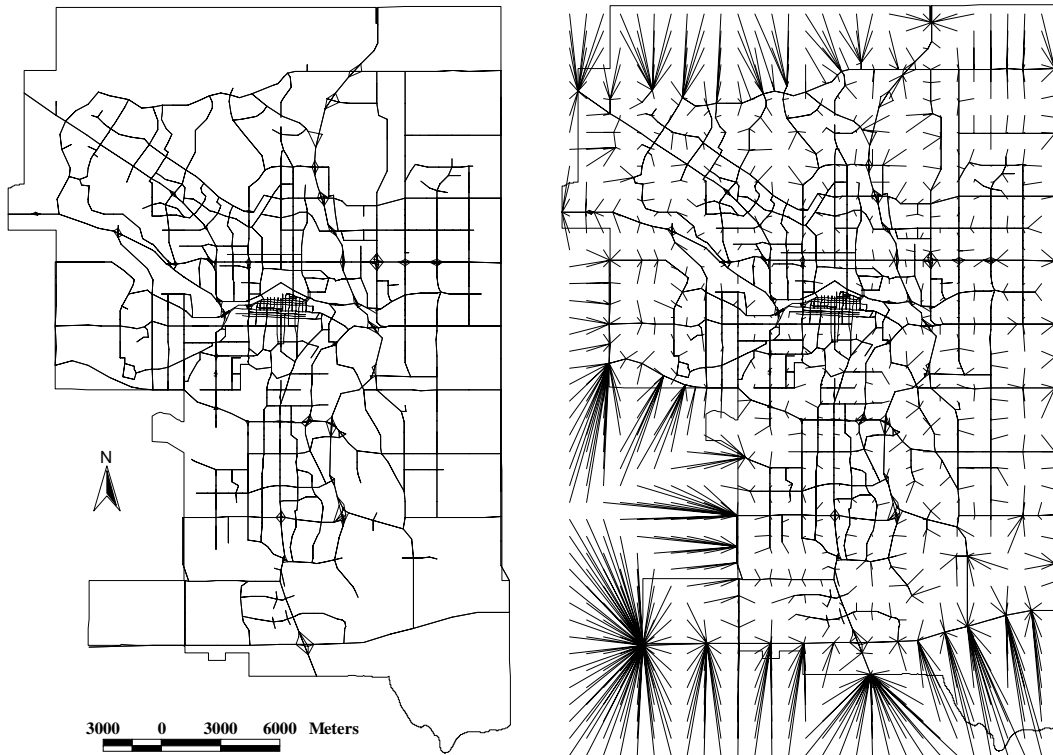
In order to relate land use development specifically to transportation system performance, the shortest path impedance values are further refined to focus on the influence of traffic congestion exclusive of distance. Shortest path analysis inherently generates a distance bias by virtue of the fact that distance is included in the calculation. This is evident in that near destinations normally generate a lower impedance cost than far destinations. In a effort to remove this distance bias, an additional transportation variable ( $C$ ) is developed based on the percent change between free flow and congested travel time (see Lomax et al., 1997 for a discussion about congestion measures), calculated as

$$C = \frac{tc_a - t_a}{t_a} \quad \text{Equation 6}$$

where  $t_a$  represents free flow travel time (cumulative shortest path) in grid cell  $a$  and  $tc_a$  represents congested travel time (cumulative shortest path) in grid cell  $a$ .

Figure 8: EMME/2 network with grid connectors

Comparison of *EMME/2* network with and without grid connectors added (year 1995).



This variable represents an attempt to capture the influence of traffic congestion exclusive of distance.

### *Representing Land use*

Some have suggested that transportation influence is minimal in the presence of other structural variables (e.g., Haider & Miller, 2000), thus this approach seeks to extract the transportation influence by including only two independent land use variables: available land and serviced land. Available land or land available for development for a specific use type in a target time period represents an important controlling structural variable arising out of an assumption that land cannot develop unless it is available for development. Therefore, in light of the available data set, land use is represented for each analysis period as i) available land, ii) serviced land and iii) land use development intensity (dependent variable).

Similar to urban transportation cost, urban land use is also highly spatial and uneven (Shukla & Waddell, 1991). Representing this variable in detail (spatially and temporally) is typically difficult partly due to an inherent lack of data access and availability. For our purposes, representation of available land is founded on an underlying assumption that all lands developed or designated for a target use type as of a base year 2001 could potentially have been developed for such use at any time in the past. Whereas, lands developed or designated for other purposes could not have been developed for the target use. In this case, target land use development classes are designated as non-residential (industrial, commercial and warehousing), residential, other (parks, churches, schools, etc.) and urban reserve (land available for development, but not yet designated to a type).

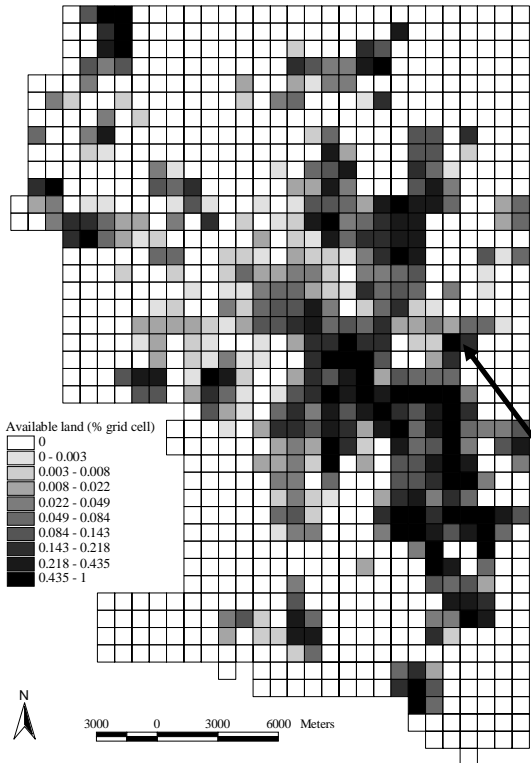
Available land is determined based on an intersection of i) the sample grid ii) the Calgary Land Classification (year 2001) and iii) the merged pardat/parcel polygon database. The result is a parcel polygon data set that includes sample grid id, major land use classes and pardat attributes (year of construction and use type). This intersection is summarized on sample grid cell id in order to produce areal amounts per grid cell representing available land in the form of total and proportional areas for a target time period. As an example, Figure 9 illustrates sample grid cells with land available for non-residential development in the 1996-2001 time period. Areal amounts are calculated to express land available as of the end of the year 1995. Thus, for each sample grid cell, it is possible to identify for each land use development class i) total area, ii) developed area, and iii) vacant area or available land.

The presence of watermains provides a proxy for serviced land (e.g., water, power, sewage). Serviced land is established based on an intersection of the Calgary watermain network and the sample grid. Sample grid cells are coded according to the presence or absence of water mains based on year of construction present in the watermain dataset. The result is a proxy representation of serviced land.

Land use development intensity is represented as  $m^2$  of development per sample grid cell per time period. The merged pardat/parcel polygon database is subset by a query designed to extract only a target use type(s) (e.g., warehouse) from the 415 actual use codes. This output is further subset by query to only include development for a specific time period. The resulting subset is intersected with the sample grid and summarized on grid cell id to add an areal development variable attribute. Figures 10 and 11 illustrate this procedure. Figure 10 represents DLW parcels developed in the period 1996-2000. Given the scarcity of DLW land use development in any given year, a five-year time block is arbitrarily selected to ensure that

Figure 9: Sample grid – available non-residential land (period 1996-2001)

An example attribute table for the grid cell indicated by the arrow is presented to the right of the sample grid. Note that 23% of the total grid cell is vacant or available for development (all use types) while only 7.68% (56,122 m<sup>2</sup>) of the grid cell is available for non-residential development.



Grid cell area	731025.0000
Total non-res	68765.6485
Total res	213995.8912
Total urban reserve	230641.5873
Total other	39209.5515
Total all types	552612.6785
Unavailable land	178412.3215
Proportion non-res	0.0941
Proportion res	0.2927
Proportion urban reserve	0.3155
Proportion other	0.0536
Proportion all types	0.7559
Proportion unavailable	0.2441
Developed non-res	12643.3303
Developed res	192968.6956
Developed urban reserve	178840.4220
Developed other	4.7912
Developed all types	384457.2391
Vacant non-res	56122.3182
Vacant res	21027.1956
Vacant urban reserve	51801.1653
Vacant other	39204.7603
Vacant all types	168155.4394
% Vacant non-res	7.68
% Vacant res	2.88
% Vacant urban reserve	7.09
% Vacant other	5.36
% Vacant all types	23.00

Figure 10: DLW parcels developed in the period 1996 - 2000

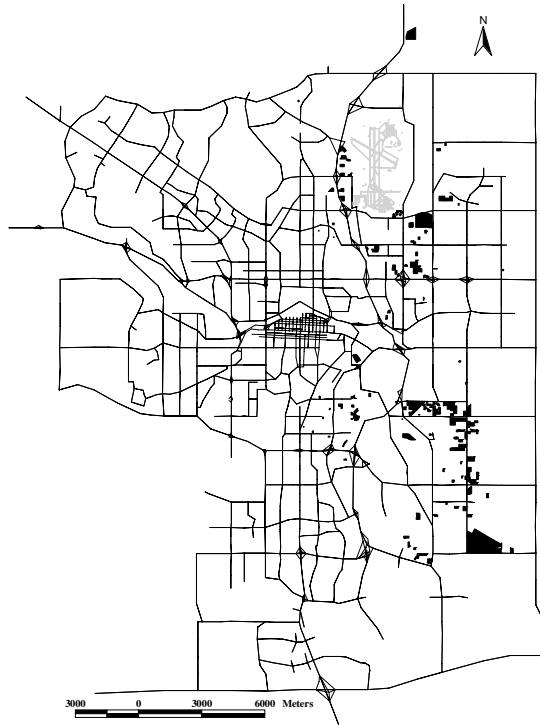
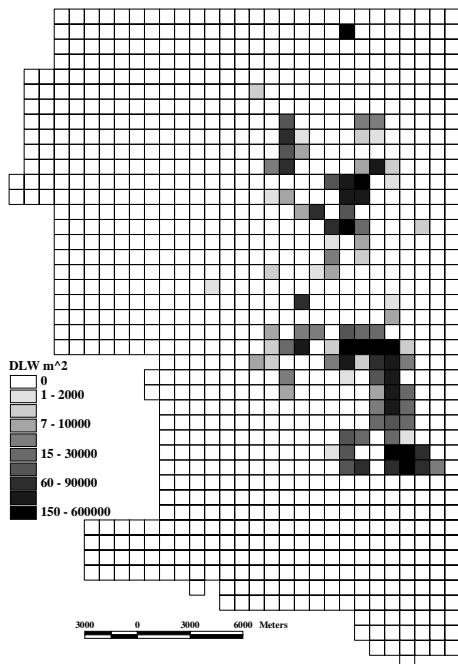


Figure 11: DLW development per grid cell (1996 – 2000)



sufficient development is captured to facilitate meaningful statistical analysis. These parcel polygon subsets are then intersected with the sample grid and summarized on total developed DLW parcel area per grid cell (m<sup>2</sup> per sample grid cell per time period). The resulting sample grid, which includes the attribute DLW development intensity, is represented in Figure 11.

### *Coping with Spatial Dependence*

Although this is not specifically a modelling exercise, the framework of the analytical methods is the specification of a SAR model(s) that will allow the quantification of the relationship in question. In this case, the dependent variable is land development m<sup>2</sup> per grid cell per time period. To test how accessibility (transportation cost) might influence land development, accessibility measures both including and excluding distance are entered into the model(s) while controlling for available and serviced land.

Given the expectation that spatial autocorrelation will be present in the dependent variable, exploratory spatial data analysis is used to test for structural invariance in the form of global and local patterns of spatial autocorrelation in land use development (Anselin, 1996; Anselin, 1998). Global autocorrelation is assessed using Moran's I statistic. Moran's I is expressed by the formula (Fotheringham et al., 2000: 202)

$$I = \left( \frac{n}{\sum_i \sum_j w_{ij}} \right) \left( \frac{\sum_i \sum_j w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_i (x_i - \bar{x})^2} \right) \quad \text{Equation 7}$$

where  $i$  and  $j$  index  $n$  spatial units,  $\bar{x}$  is the mean of  $x$  and  $w_{ij}$  is a weight between zones  $i$  and  $j$ .

A positive and significant Moran's I indicates clustering in space of land use development.

Local autocorrelation is assessed using Anselin's (1995a) local Moran statistic. Anselin's

(1995a) localized version of Moran's I (LISA) is expressed by (Fotheringham et al., 2000: 101-102)

$$I_i = \frac{(x_i - \bar{x}) \sum_j w_{ij} (x_j - \bar{x})}{\sum_i (x_i - \bar{x})^2 / n} \quad \text{Equation 8}$$

where  $x_i$  is the observed value of  $x$  at location  $i$ ,  $\bar{x}$  is the mean of  $x$ ,  $n$  is the number of observations and  $w_{ij}$  represents the strength of the linkage between  $i$  and  $j$ , usually measured by spatial proximity. Results are expressed in ArcView in the form of a Moran scatterplot map (Anselin, 1996).

Moran's I can be visualized by means of a Moran scatterplot (Anselin, 1996) which has standardized variates of Moran's I on the x-axis and a row-standardized spatial weights matrix based on average standardized variates of Moran's I on the y-axis. This allows for the categorization of the spatial association of a cell with its neighbours into four quadrants according to positive or negative spatial autocorrelation: i) positive spatial autocorrelation - high surrounded by high, low surrounded by low and ii) negative spatial autocorrelation - high surrounded by low, low surrounded by high. Local Moran's I can be visualized through categorization of the LISA statistic's significance: 1 =  $p < 0.05$ , 2 =  $p < 0.01$ , 3 =  $p < 0.001$ . Combined, this information comprises a Moran scatterplot map that shows locations with significant LISA along with colour coding according to Moran scatterplot quadrant. A Moran scatterplot map helps to visualize the location of significant clusters and also facilitates the identification of spatial regimes. Spatial regimes are subsets in the data which correspond to regions or spatial clusters that manifest different intercepts and/or slopes in the regression equation (Anselin, 1992: 235).

ESDA is followed by ordinary least squares (OLS) regression of land use development on the explanatory variables. Initially, a series of OLS regressions is run using the dependent variable and various combinations of the independent variables. The best fitting run is examined for compliance with OLS assumptions (normal, homoskedastic and uncorrelated error terms) using a battery of diagnostics provided by SpaceStat (Anselin, 1988; Anselin, 1992). Particular attention is given to whether the errors or variables in the model demonstrate spatial dependence.

OLS diagnostics included tests for multicollinearity, non-normal errors and heteroskedacity (for a detailed discussion, see Anselin, 1988; Anselin, 1992). SpaceStat provides a multicollinearity indicator in the form of a condition number. SpaceStat regression output also includes, among others, the results of the Jarque-Bera test for normality of errors. The Jarque-Bera test determines whether the sample skewness and kurtosis are unusually different than their expected values, as measured by a chi-square statistic.

It is also considered prudent to test and control for heteroskedasticity (Anselin, 1988). Heteroskedasticity, or error terms with non-constant variance, is an indication of potential model misspecification. Ignoring this issue has consequences for model estimates including biased coefficient estimates and overstated significance levels. This problem is frequently encountered when there are systematic regional differences in the relationships modelled, expressed as varying coefficients (e.g., spatial regimes). A variety of tests against heteroskedasticity are implemented in SpaceStat (Anselin, 1992), but a test developed by White (1980) was selected since there is little prior information about the form of the heteroskedasticity and this test has power against such a condition. This test was supported with a spatial regime regression (Anselin, 1992), which jointly estimates model coefficients and allows them to vary across more than one subset of the data (regimes). The spatial regimes were set as the east and west sides of

the city based on information acquired from a Moran scatterplot map. In SpaceStat, the spatial regime regression generates a spatial Chow test on the stability of switching coefficients across regimes. Rejection of the null hypothesis of joint equality of coefficients is an indication of regional instability.

Assuming that spatial dependence is still observed after controlling for spatial heterogeneity, investigations are initiated with respect to selection of a spatial lag or spatial error model. By default, SpaceStat provides diagnostics for contrasting these two model types in the form of several tests (for full discussion, see Anselin, 1988; Anselin, 1992; Anselin, 1995b): i) several Lagrange Multiplier (LM) tests, including two that are robust to the opposing form of dependence, ii) a robust test for a spatial error alternative developed by Kelejian and Robinson (1992) which, unlike the Lagrange Multiplier tests, does not require normality for error terms, and iii) a Lagrange Multiplier test for joint spatial lag and error.

In this case, a spatial lag model, estimated using a maximum likelihood approach, is selected based on results obtained from ESDA and the OLS diagnostics. Model inputs include land use development as the dependent variable along with accessibility (both including and excluding distance), available land and serviced land based on a sample grid representing the east region of the City of Calgary and including only those cells with development potential for the target year and land use type.

In addition, two weights matrices ( $W$ ) derived on i) distance and ii)  $k$  nearest neighbours are included as inputs for the SAR model. The selection of a suitable  $W$  from potential  $W$ 's was accomplished by fitting the regression model under several different forms of  $W$  and then gauging the sensitivity of regression results to the various forms of  $W$  revealed in the measures of fit and diagnostics for spatial dependence. SpaceStat diagnostics for spatial dependence in the

spatial lag and spatial error models include i) a Likelihood Ratio test on the spatial autoregressive coefficient and ii) a Lagrange Multiplier test for spatial autocorrelation in the opposite form of spatial dependence (e.g., test for spatial error autocorrelation in the spatial lag model) (Anselin, 1988). The null hypothesis for the Likelihood Ratio test is no difference between the SAR model and a standard regression model with the same set of explanatory variables. A significant result for the LM test indicates that not all spatial dependence has been eliminated, which casts doubt on the appropriateness of the spatial weights specification in the model.

Given these inputs, an exhaustive and systematic set of model runs is carried out considering all possible variable and weights matrix combinations. Specification of the matrix of explanatory variables is carried out under two overarching selection criteria (Griffith & Amrhein, 1997). First, inclusion of a variable in the final model(s) is contingent on a significant t-statistic (or z value) at the 10% significance level. Second, the final subset(s) of variables is selected from all possible sets of variables based on their predictive capabilities as indicated by the largest possible  $R^2$  adjusted (variance accounted for in Y by X) and the smallest possible mean square error (identified as SIG-SQ in the SpaceStat output). Note that the traditional  $R^2$  measure of fit is not appropriate for the spatial lag or the spatial error model (Anselin, 1988; Anselin, 1992). Instead, SpaceStat reports a pseudo  $R^2$  measure ( $R^2$ ), which is a ratio of the variance of the predicted values over the variance of the observed values for the dependent variable.

Neither the traditional nor the pseudo  $R^2$  measures are suitable for comparison of different model types. As such, Anselin (1988; 1992) recommends use of the Akaike Information Criterion (AIC) as the preferred means to distinguish between models. This

measure is comparable between the standard regression model and the spatial lag and spatial error models, while the  $R^2$  measures are not. The model with the lowest AIC is best.

### *Capturing the Temporal lag*

The availability of an extensive historical data set affords an excellent opportunity to test for a temporal lag in the TLU relationship. Assuming that such a lag exists and acknowledging that this lag has yet to be clearly quantified, the analysis is extended to include a temporal component. In order to identify a specific lag, the best model runs are re-run using the same dependent variable and identical combinations of accessibility variables, but for other time periods. Specifically, the dependent variable is held to the target time period while accessibility variables are entered for different time periods. The results of these temporal runs are examined in ascending order according to year in order to determine the historical point at which variables become significant.

## **RESULTS AND DISCUSSION**

The value of the approach presented here can be characterized by a brief discussion about selected results from a specific application of the methodology. The approach is applied to examine the relationship of transportation system costs (accessibility) to non-residential land use types associated with distribution, logistics and warehousing (DLW). Specifically, DLW development in the period 1996-2000 is examined with respect to am peak hour accessibility in 1995. In addition, temporal tests are conducted using accessibility for the periods 1980, 1985 and 1990. In this context, the discussion highlights three of the key methodological issues identified above: accessibility, spatial dependence and temporal lag.

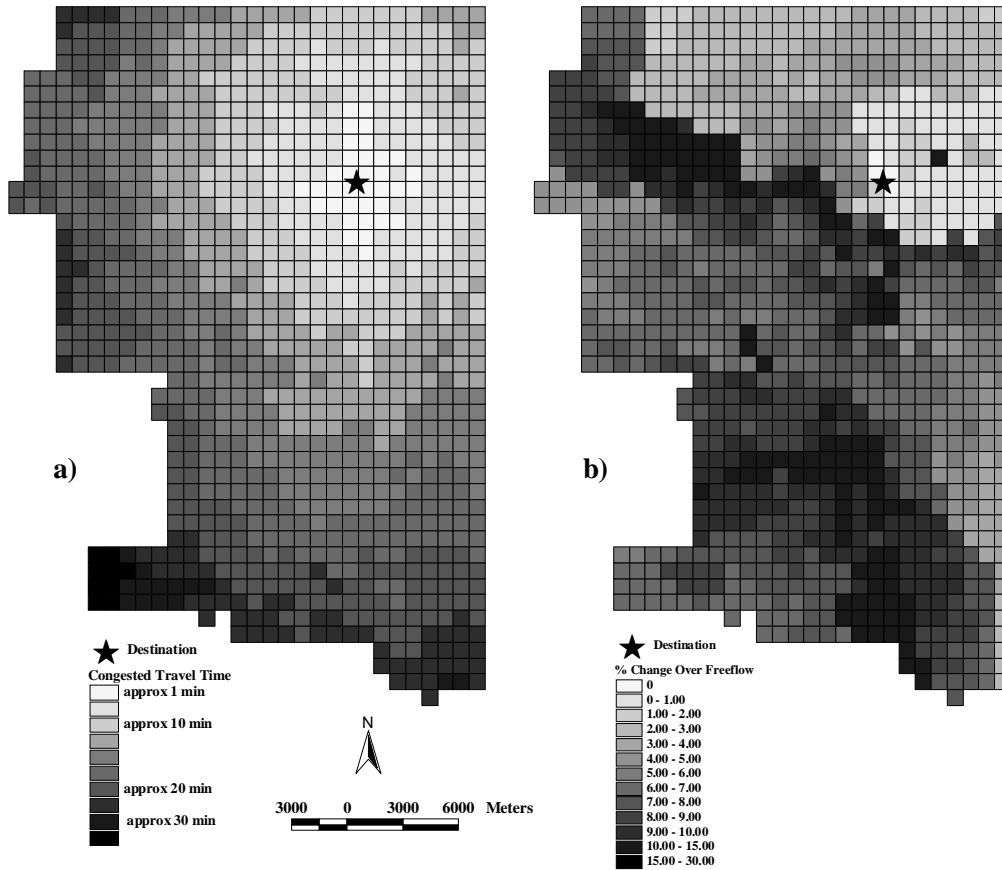
### *Accessibility*

Given that there is little agreement regarding what constitutes a good measure of accessibility, this approach produces two different accessibility measures suitable for the expression of urban transportation cost - a common measure and one less common measure. Figure 12a illustrates accessibility measured based on congested travel time. Lighter colours indicate areas with better accessibility relative to the airport. Examination of this figure reveals that accessibility based on congested travel time varies according to location in the city with respect to the destination. Note the influence of distance in that accessibility decreases in concentric rings away from the airport. Overall, Figure 12a suggests that proximity to a destination has overwhelming implications for accessibility regardless of traffic. This notion is widely held in the literature.

The notion of congestion influence exclusive of distance is not as well understood. However, it is recognized that traffic congestion is an important influence on site selection (Ogden, 1991; Rabianski et al., 2001; Cambridge Systematics Inc., 2002; Hickey, 2003). Figure 12b illustrates accessibility to the airport, but exclusive of distance (see Equation 6). This measure offers an interesting opportunity to examine the influence of congestion alone on land use development. Again, lighter colours indicate areas with better accessibility. Note that when distance is excluded the concentric rings disappear and accessibility becomes spatially uneven. In fact, while Figure 12a mirrors the classic monocentric model where accessibility decreases proportionally with increasing distance from a destination, Figure 12b appears to refute this notion.

Figure 12: Shortest path analysis – output examples

Part a represents congested link travel time (distance included) from each grid cell centroid to the grid cell containing the airport for the year 1995. Part b represents the influence of traffic congestion exclusive of distance (% change between free flow travel time and congested link travel time)



### *Spatial dependence*

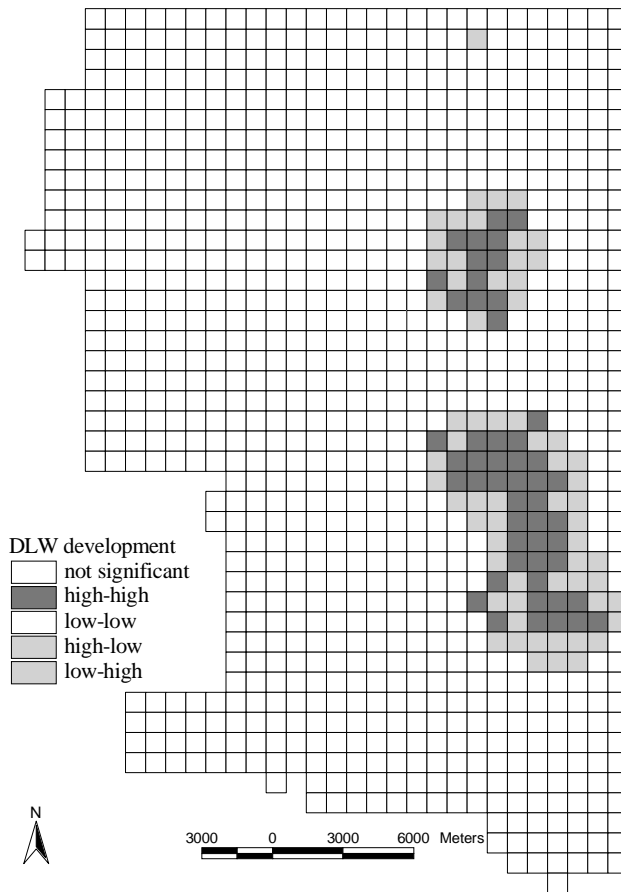
With a few exceptions (e.g., Haider & Miller, 2000), examinations of the TLU relationship do not typically account for spatial dependence. However, a Moran scatterplot map (Figure 13) reveals that DLW land use types are not evenly distributed in space. Note that DLW development in Calgary is clustered with a distinct concentration in the east half of the city. This indicates two forms of spatial dependence: spatial autocorrelation and spatial heterogeneity.

The presence of spatial autocorrelation and spatial heterogeneity is confirmed by both a significant Moran's I ( $I = 0.315, p < 0.01$ ) and SpaceStat OLS diagnostics. An OLS regression including i) a distance-based weights matrix, ii) DLW development as the dependent variable, iii) independent variables for accessibility (access to various locations within Calgary based on both congested travel and transport cost exclusive of distance) and iv) available land results in a significant White test (484.985,  $p < 0.01$  with 26 degrees of freedom) (White, 1980). The null hypothesis of homoskedasticity is rejected with a significant White statistic. Furthermore, an OLS spatial regime regression (Anselin, 1992) set for the east and west sides of the city produces a significant Chow statistic (18.526,  $p < 0.01$  with 1003 degrees of freedom). In SpaceStat, the spatial regime regression generates a spatial Chow test on the stability of switching coefficients across regimes. Rejection of the null hypothesis of joint equality of coefficients is an indication of regional instability.

These results lend credence to our use of i) TLU modeling based on regimes (e.g., test the east and west sides of Calgary separately) and ii) use of a spatial autoregressive technique. Preference for a spatial autoregressive technique is further supported by LM lag and LM error statistics. Comparison of test statistics in this specific case suggests a spatial lag model, given

Figure 13: Moran scatterplot map (DLW development for the period 1996-2000)

Map interpretation: high-high (high DLW development intensity adjacent to high DLW development intensity), low-low (low DLW development intensity adjacent to low DLW development intensity), high-low (high DLW development intensity adjacent to low DLW development intensity and low-high (low DLW development intensity adjacent to high DLW development intensity). All classes except for low-low indicate DLW development.



that the LM lag value is significant (5.304,  $p < 0.05$ ) and the LM error value is not (0.017, not significant) (Anselin, 1988; Anselin, 1992).

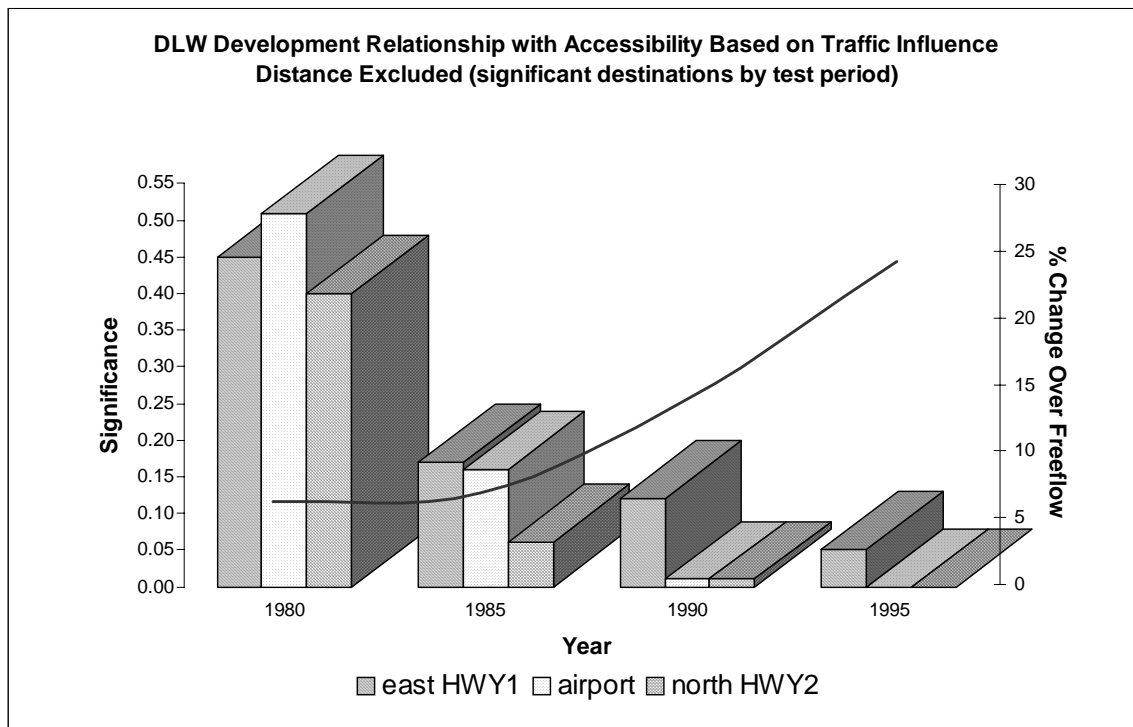
The consequences of ignoring spatial dependence are poorly specified coefficient estimates and overstated significance levels. This is evident in a comparison of OLS and SAR modeling results. Table 3 presents a comparison of results from identical OLS and SAR model runs for one key accessibility variable (access to the airport). Note that the OLS result is more significant than the SAR result.

### *Temporal lag*

As previously stated, it may not be the case that current land use exists in response current or recent transportation conditions. Furthermore, quantification of this lagged relationship is limited at best. Figure 14 reveals that this approach provides a means to address this deficiency. The graph represents the results ( $p$  values) of temporal analysis based on accessibility, exclusive of distance (percent change between free flow and congested travel time), using three important destinations: east Trans Canada Highway, the airport, and north Highway 2. In this example, 1996-2000 DLW development  $m^2$  per grid cell (dependent variable) is modelled using 1995, 1990, 1985 and 1980 accessibility. In other words, this graph represents the historical influence of traffic on DLW development patterns.

Note that differences arise over time. Examination of Figure 14 reveals that Hwy 2 and the airport drop out of significance at the ten year mark, while Hwy 1 drops out of significance at the five year mark. This historical significance drop-off suggests a 5–10 year DLW development response lag with respect to traffic congestion. Thus, accessibility in 1985 with respect to Hwy 2 north and the airport is not related to development patterns in 1996-2000, but 1995 accessibility

Figure 14: Temporal relationship between accessibility (exclusive of distance) and DLW development. Results are based on SAR models where DLW development is held at the period 1996-2000, while the accessibility variable is allowed to vary temporally. The bars represent the *p* value for accessibility variables that capture each of three destinations in Calgary: Trans Canada Highway 1 East, airport, and Highway 2 north (major provincial economic corridor). The curve represents global accessibility exclusive of distance (% change between congested and freeflow travel time).



is inversely related to development patterns in 1996-2000. Given that five year time increments were used in this example analysis, the relationship emerged sometime between 1985 and 1990 indicating a 5–10 year lag. This lagged relationship suggests that areas of the city that experience reduced access (am peak travel time increase due to congestion) in 1995 will likely have less DLW development in subsequent periods 5 – 10 years into the future than those areas that have better access (experience less congestion with respect to am peak travel times).

These results lend support for application of this approach as a means to quantify the temporal lag in the TLU relationship. Furthermore, results such as these have implications for integrated TLU modellers, urban planners and developers. For integrated modellers, the results suggest that TLU models should incorporate a more clearly defined lag with respect to DLW response to transportation system performance. For planners and developers, the results indicate that knowledge of a specific temporal lag may provide clues about future land use patterns based partly on current traffic conditions.

## **CONCLUSION**

This paper has presented an approach designed to address several methodological issues with respect to understanding the TLU relationship. The approach is based on the use of an extensive historical TLU database to develop detailed transportation and land use variables essential to the quantification of the TLU relationship. Furthermore, the approach is simplified in order to minimize the complexities often associated with attempts to identify nuances hidden within a multitude of variables - often, we cannot see the forest for the trees.

Selected results support the appropriateness of the overall approach and provide support for the value of the specific methodologies applied. Evidence supports the use of an accessibility

measure that excludes distance. Such a measure provides a means to extract the relationship between traffic congestion and land use development. Exploratory spatial data analysis and regression diagnostics indicate that spatial dependence is present in the data, which lends credence to the use of spatial autoregressive modelling techniques, rather than traditional statistical methods, to examine the TLU relationship. Finally, temporal tests validate the use of historical traffic volume data to identify the known, but not quantified, lag in the TLU relationship. Results indicate that it is possible to pinpoint a specific time where accessibility becomes a significant influence on land use development.

## Reference List

- ABRAHAM, J., & HUNT, J. (1999). Firm location in the MEPLAN Model of Sacramento. in *Proceedings of the 79th Annual Meeting of the Transportation Research Board* Washington, DC.
- ALONSO, W. (1964). *Location and land use*. Cambridge, M.A.: Harvard University Press.
- ANSELIN, L. (1988). *Spatial econometrics: Methods and models*. Dordrecht: Kluwer Academic Publishers.
- ANSELIN, L. (1992). *SpaceStat tutorial*. Regional Research Institute, West Virginia University, Morgantown, WV.
- ANSELIN, L. (1995a). Local indicators of spatial association - LISA. *Geographical Analysis*, 27, pp. 93-115.
- ANSELIN, L. (1995b). *SpaceStat version 1.80 user's guide*. Regional Research Institute, West Virginia University, Morgantown, WV.
- ANSELIN, L. (1996). The Moran scatterplot as an ESDA tool to assess local instability in spatial association. in M. Fischer, H. J. Scholten, & D. Unwin (editors), *Spatial analytical perspectives on GIS: GIS data IV* (pp. 111-125). London: Taylor & Francis.
- ANSELIN, L. (1998). Exploratory spatial data analysis in a geocomputational environment. In P. A. Longley, S. M. Brooks, R. McDonnell, & B. Macmillan (Editors), *Geocomputation: A Primer*. John Wiley & Sons Ltd.

ANSELIN, L. (2001). *SpaceStat, a software program for the analysis of spatial data, version 1.91*. Regional Research Institute, West Virginia University, Morgantown, WV.

ANSELIN, L. (2002). Under the hood: Issues in the specification and interpretation of spatial regression models. *Agricultural Economics*, 17(3), pp. 347-267.

BADDOE, D. A., & MILLER, E. J. (2000). Transportation-land-use interaction: Empirical findings in North America, and implications for modeling. *Transportation Research D*, 5 (4), pp. 235-263.

BALLER, R. D., ANSELIN, L., MESSNER, S. F., DEANE, G., & HAWDINS, D. F. (2001). Structural covariates of U.S. county homicide rates: Incorporating spatial effects. *Criminology*, 39(3), pp. 561-590.

BAXTER, R. S., & LENZI G. (1975). The measurement of relative accessibility. *Regional Studies*, 9, pp. 15-26.

BOARNET, M. G. (1996). The direct and indirect economic effects of transportation infrastructure. The University of California Transportation Center, University of California at Berkeley, *Working Paper UCTC* No. 340, pp. 1-26.

BOURNE, L. S. (1982). Urban spatial structure: An introductory essay on concepts and criteria. In L. S. Bourne (editor), *Internal Structure of the City: Readings on Urban Form, Growth, and Policy* (second ed., pp. 28-45). New York: Oxford University Press.

BOWES, D. R. (2001). Identifying the impacts of rail transit stations on residential property values. *Journal of Urban Economics*, 50, pp. 1-25.

BRANDEAU, M. L., & Chiu, S. S. (1989). An overview of representative problems in location research. *Management Science*, 35, pp. 645-674.

CAMBRIDGE SYSTEMATICS Inc. (2002). *Freight impacts on Ohio's roadway system*. Cambridge, Massachusetts: Cambridge Systematics Inc.

CHANG, K. (2002). *Introduction to geographic information systems*. Boston: McGraw Hill.

THE CITY OF CALGARY. (1991). *1991 Calgary regional transportation model primer*. , City of Calgary

COMMITTEE FOR STUDY OF IMPACTS OF HIGHWAY CAPACITY IMPROVEMENTS ON AIR QUALITY AND ENERGY CONSUMPTION. (1995). *Expanding metropolitan highways: Implications for air quality and energy use*. Transportation Research Board Special Report 245 . Washington D.C.: National Academy Press.

DAVIS, J. S. (1999). *Land use impacts of transportation: A guidebook*. NCHRP Report 423A . Washington D.C.: National Academy Press.

DE LA BARRA, T. (1989). *Integrated land use and transport modelling: Decision chains and hierarchies*. Cambridge, U.K.: Cambridge Urban and Architectural Series, no. 12. Cambridge University Press.

ELLISON, G., & GLAESER, E. L. (1997). Geographic concentration in U.S. manufacturing industries: A dartboard approach. *The Journal of Political Economy*, 105(5), pp. 889.

FOTHERINGHAM, A. S., BRUNSDON, C., & CHARLTON, M. (2000). *Quantitative geography: perspectives on spatial data analysis*. London: Sage Publications.

- GOODCHILD, M. F. (1986). *Spatial Autocorrelation: catmog 47*. (pp. 1-56). Norwich, England: Geo Books.
- GRIFFITH, D. A. (1987). *Spatial autocorrelation: a primer*. Washington: Association of American Geographers.
- GRIFFITH, D. A., & AMRHEIN, C. G. (1997). *Multivariate statistical analysis for geographers*. Upper Saddle River, N.J.: Prentice Hall.
- HAIDER, M., & MILLER, E. J. (2000). Effects of transportation infrastructure and location on residential land values: application of spatial-autoregressive techniques. *Transportation Research Record*, 1722, pp. 1-8.
- HAINING, R. P. (1990). *Spatial data analysis in the social and environmental sciences*. Cambridge, England: Cambridge University Press.
- HANDY, S. L., & NIEMEIER, D. A. (1997). Measuring accessibility: An exploration of issues and alternatives. *Environment and Planning A*, 29, pp. 1175-1194.
- HANDY, S. (1993). Regional versus local accessibility: Implications for nonwork travel. *Transportation Research Record*, 1400, pp. 58-66.
- HELLING, A. (1998). Changing intrametropolitan accessibility in the U.S.: Evidence from Atlanta. *Progress in Planning*, 49, pp. 55-108.
- HESSE, M., & RODRIQUE, J. (2004). The transport geography of logistics and freight distribution. *The Journal of Transport Geography*, Vol. 12, No. 3, pp. 171-184.

HEYWOOD, I., CORNELIUS, S., & CARVER, S. (1998). *An introduction to geographical information systems*. Upper Saddle River, New Jersey: Prentice Hall.

HICKEY, C. (2003). Location, location, location - Transportation looms large when choosing a warehouse or distribution site. *Traffic World*, 267(17), pp. 22.

HIRSCHMAN, I., & HENDERSON, M. (1990). Methodology for assessing local land use impacts of highways. *Transportation Research Record*, 1274.

HUFF, D. L. (1964). Defining and estimating a trading area. *Journal of Marketing*, 28, pp. 34-38.

KAWAMURA, K. (2001). Empirical examination of relationship between firm location and transport facilities. *Transportation Research Record*, 1747, pp. 97-103.

KELEJIAN, H., & ROBINSON, D. P. (1992). Spatial autocorrelation: A new computationally simple test with an application to per capita county policy expenditures. *Regional Science and Urban Economics*, 22, pp. 317-331.

LARSEN, M. (2001). Direction for freight performance measures. In *Performance Measure to Improve Transportation Systems and Agency Operations*, Transportation Research Board Conference Proceedings 26 (pp. pp 143-146). Washington, D.C.: National Academy Press.

LEE, D. A. (1973). Requiem for large-scale models. *Journal of the American Institute of Planners*, 39(3), pp. 163-178.

LOMAX, T., TURNER, S., SHUNK, G., LEVINSON, H. S., PRATT, R. H., BAY, P. N., &

DOUGLAS, G. B. (1997). *Quantifying congestion: Volume 1, final report*. National Cooperative Highway Research Program (NCHRP) Report 398 . Washington D.C.: National Academy Press.

MACKINNON, R. D., & LAU, R. (1973). Measuring accessibility change. In L. S. Bourne, & R. D. J. W. MacKinnon (editors), *The form of cities in central Canada : selected papers* (pp. 120-137). Toronto: University of Toronto Press.

MARTIN, W. A., & MCGUCKIN, N. A. (1998). *Travel estimation techniques for urban planning*. National Cooperative Highway Research Program (NCHRP) Report 365 . Washington D.C.: National Academy Press.

MCCANN, P. (1998). *The economics of location: A logistics-costs approach*. Heidelberg: Springer-Verlag.

MEDDA, F., NIJKAMP, P., & RIETVELD, P. (2003). Urban land use for transport systems and city shapes. *Geographical Analysis*, 35(1), pp. 46-57.

MEYER, M. D. , & MILLER, E. J. (2001). *Urban transportation planning: a decision-oriented approach*: Second edition. Boston : McGraw Hill.

MILLER, E. J., HUNT, J. D., ABRAHAM, J. E., & SALVINI, P. A. (2004). Microsimulating urban systems. *Environment and Urban Systems* 28:1 pp. 9-44.

MILLER, E. J., & IBRAHIM, A. (1998). Urban form and vehicular travel: some empirical findings. *Transportation Research Record*, 1617, pp. 18-27

MILLER, E. J., KRIGER, D. S., & HUNT, J. D. (1999). *Integrated urban models for simulation of transit and land-use policies: guidelines for implementation and use*. Transit Cooperative Research Program (TCRP) Report 48 . Washington D.C.: National Academy Press.

MILLER, H. J., & SHAW, S.-L. (2001). *Geographic information systems for transportation: Principles and applications* (spatial information systems). Oxford University Press.

MILLER, J. S., & DEMETSKY, M. J. (1998). *Using historical data to measure transportation infrastructure constraints on land use*. (Report No. FHWA/VTRC 98-R32). Charlottesville, VA: Virginia Transportation Research Council.

MILLS, E. S. (1970). *Urban economics*. Glenview, IL.: Scott, Foresman.

MOORE, T., & THORSNES, P. (1994). *The transportation/land use connection: a framework for practical policy*. American Planning Association Planning Advisory Service Report, 448/449.

MURACO, W. A. (1972). Intraurban accessibility. *Economic Geography*, 48, pp. 388-405.

ODLAND, J. (1988). *Spatial Autocorrelation*. Newbury Park: Sage publications.

OGDEN, K. W. (1991). Truck movement and access in urban areas. *Journal of Transportation Engineering*, 117(1), pp. 71-90.

ORTÚZAR, J. d. D., & WILLUMSEN, L. G. (1996). *Modelling transport*. Second ed., ). Chichester: John Wiley & Sons.

RABIANSKI, J. S., DELISLE, J. R., & CARN, N. G. (2001). Corporate real estate site selection: A community-specific information framework. *The Journal of Real Estate Research*, 22(1/2), pp. 165.

RYAN, S. (1999). Property values and transportation facilities: finding the transportation-land use connection. *Journal of Planning Literature*, 13(4), pp. 412-427.

SHAW, S. L., & XIN, X. (2003). Integrated land use and transportation interaction: A temporal GIS exploratory data analysis approach. *Journal of Transport Geography*, 11, pp. 103-115.

SHELDRAKE, M. (2001). *Migration of traffic volume flow map from CADD to GIS*. University of Calgary, Department of Geography (unpublished report).

SHUKLA, V., & WADDELL, P. (1991). Firm location and land use in discrete urban space. *Regional Science and Urban Economics*, 21, pp. 225-253.

SIVITANIDOU, R. (1996). Warehouse and distribution facilities and community attributes: An empirical study. *Environment and Planning A*, 28, pp. 1261-1278.

STALEY, R. (2002). *Traffic flow GIS database development*. University of Calgary (unpublished report), pp. 1-52.

STANILOV, K. (2003). Accessibility and land use: The case of suburban Seattle, 1960-1990. *Regional Studies*, 37(8), pp. 783-794.

STEWART, J. Q. (1942). A measure of the influence of population at distance. *Sociometry*, 5, pp. 63-71.

TALLEN, E., & ANSELIN, L. (1998). Assessing spatial equity: An evaluation of measures of accessibility to public playgrounds. *Environment and Planning A*, 30, pp. 595-613.

TRANSPORTATION RESEARCH BOARD. (2000). *Highway capacity manual - HCM 2000 (Metric Units)*. , Transportation Research Board, Washington D.C.

- VASILIEV, I. R. (1996). Visualization of spatial dependence: an elementary view of spatial autocorrelation. in S. L. Arlinghaus (editor), *Practical handbook of spatial statistics* (pp. 17-30). Boca Raton: CRC Press.
- VESSALI, K. V. (1996). Land use impacts of rapid transit: a review of the empirical literature. *Berkeley Planning Journal*, 11, pp. 71-105.
- VICKERMAN, R. W. (1974). Accessibility, attraction, and potential: A review of some concepts and their use in determining mobility. *Environment and Planning A*, 6, pp. 675-691.
- VON THUNEN, J. H. (1826). *Der Isolierte Staat in Beziehung auf Landschaft und Nationaloekonomie, Hamburg*. Translated by C. Wartenberg (1966) *Von Thunen's Isolated State*. Oxford: Pergamon Press.
- WACHS, M., & KUMANGAI, T. G. (1973). Physical accessibility as a social indicator. *Socio-Economic Planning Science*, 7, pp. 437-456.
- WANG, F. (2000). Modeling commuting patterns in Chicago in a GIS environment: A job accessibility perspective. *Professional Geographer*, 52(1), pp. 120-133.
- WEBER, A. (1929). *Theory of the location of industries*. Chicago: University of Chicago Press.
- WEBER, J., & KWAN, M.-P. (2002). Bringing time back in: A study on the influence of travel time variations and facility opening hours on individual accessibility. *The Professional Geographer*, 54(2), pp. 226-240.

WEGENER, M. (1994). Operational urban models: State of the art. *Journal of the American Planning Association*, 60, pp. 17-29.

WEGNER, M., & FÜRST, F. (1999). *Land use transport interaction: State of the art*. Deliverable 2a of the project TRANSLAND of the 4th RTD Framework Programme of the European Commission. Institut für Raumplanung, University Dortmund.

WHITE, H. (1980). A heteroskedastic-consistent covariance matrix estimator and a direct test for heteroskedasticity. *Econometrica*, 48, pp. 817-838.

WICKSTROM, G. B. (1971). Defining balanced transportation: A question of opportunity. *Traffic Quarterly*, 25, pp. 337-350.

WILSON, A. G. (1970). *Entropy in urban and regional modelling*. London: Pion.

WILSON, A. G. (2000). *Complex spatial systems : the modelling foundations of urban and regional analysis*. New York: Pearson Education.

WOUDSMA, C. (2001). Understanding the movement of goods, not people: Issues, evidence and potential. *Urban Studies*, 38(13), pp. 2439-2455.