URBAN LAND DEVELOPMENT AND ROAD DEVELOPMENT IN HALIFAX-DARTMOUTH: A SPATIAL ANALYSIS USING PARCEL LEVEL DATA

By

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ABSTRACT

This dissertation examines transportation-land use interactions in the Halifax-Dartmouth region. First, it investigates the changing urban form of the region. Then, it examines both directions of the transportation-land use relationship by quantifying the impact of residential land development on road development and the impact of road development on residential land development.

The dissertation begins by computing kernel estimates to investigate the decentralization and deconcentration of residential and commercial land parcels, and to examine the segregation of land uses. The results suggest that changes in urban form were a combined result of infill, contiguous, and leapfrog development. Next, univariate and bivariate K functions are estimated to measure spatial dependence within and between the classes of residential and commercial land parcels. The results suggest that residential land parcels cluster together, commercial land parcels cluster together, and over time residential and commercial land parcels have become more clustered.

With a better understanding of the changes in urban form, the dissertation then examines both directions of the transportation-land use relationship. An ordered probit model is specified where residential land development is a function of either the change in accessibility or the distance to a high-speed road and other explanatory variables. A spatial lag model is estimated where the change in accessibility is a function of residential land development and other explanatory variables. The results of the first model suggest that road development does have an impact on land development. However, the results

of the second model indicate that land development does not drive road development. Collectively, the results of both models provide important insight into the transportation-land use relationship. Understanding the direction and strength of this relationship is imperative for making informed policy decisions.

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PREFACE

This dissertation is a compilation of four research papers that have either been submitted or will be submitted for publication. The four substantive chapters in the dissertation, Chapters 2–5, correspond to these research papers. Chapter 1, the introduction, sets the context for the dissertation research and discusses the overall objectives of the research. The research papers are as follows:

Chapter 2:

Cuthbert, A.L. and W.P. Anderson (2001). An Examination of Urban Form in Halifax-Dartmouth: Alternative Approaches in Data. Accepted to *Canadian Journal of Urban Research*.

Chapter 3:

Cuthbert, A.L. and W.P. Anderson (2001). Using Spatial Statistics to Examine the Spatial Pattern of Urban Land Development in Halifax-Dartmouth. Submitted to *The Professional Geographer*.

Chapter 4:

Cuthbert, A.L., W.P. Anderson, and F.L. Hall (2001). An Empirical Analysis of the Impact of Road Development on Residential Land Development in Halifax-Dartmouth. For submission to *Environment and Planning A*.

Chapter 5:

Cuthbert, A.L., W.P. Anderson, and F.L. Hall (2001). An Empirical Analysis of the Impact of Residential Land Development on Road Development in Halifax-Dartmouth. For submission to *Environment and Planning A*.

Each of these papers is written in a different format in order to satisfy the stylistic requirements of each journal. Because each substantive chapter is an individual research paper, some repetition of content is inherent.

While the papers are co-authored with either Dr. Bill Anderson (dissertation supervisor) or Dr. Bill Anderson and Dr. Fred Hall (member of dissertation supervisory committee), the majority of the research (data gathering, compilation, processing, and analysis) and the writing were completed by the candidate. Dr. Anderson and Dr. Hall's contributions to the papers were in the form of guidance on research methods and in editorial reviews.

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CHAPTER 1: Introduction

1.1 Introduction

This dissertation examines the spatial pattern of land development and road development, and the relationship between them, in the Halifax-Dartmouth region of Nova Scotia over the period 1970 to 1996. The impetus for this research stems from both a need for alternative methodologies to examine the changing form of urban areas and a gap in the empirical literature pertaining to the relationship between transportation and land use. Urban areas are currently facing many challenging issues such as urban sprawl, traffic congestion, and pollutant emissions. An understanding of the transportation-land use relationship is imperative in effectively addressing these issues.

First, the dissertation examines the changing urban form of Halifax-Dartmouth using spatial data analysis methods. Using an historical database of residential and commercial land parcel development, the dissertation computes kernel estimates and K function estimates to study the pattern of urban land development and the subsequent changes in urban form. Second, it examines both directions of the transportation-land use relationship. The impact of transportation on land use is examined by specifying an ordered probit model that quantifies the impact of changes in the transportation network on the pattern of residential land development. To examine the impact of land use on transportation, a spatial lag model is specified to quantify the impact of residential land parcel development on improvements to the transportation network.

Before proceeding with the empirical analyses, it is necessary to provide the context in which the dissertation is set. First, the concept of urban form is defined and several models of urban form are described. Next, the theory underlying the transportation-land use relationship is discussed. Then, an overview of the empirical literature pertaining to the relationship is provided. The chapter concludes by outlining the research objectives, discussing the importance of spatial data analysis methods to the research, and providing an overview of the organization of the dissertation.

1.2 Models of Urban Form

Urban form is described as the physical structure and organization of fixed elements within an urban area. This includes the spatial pattern of land uses and their densities as well as the spatial pattern of the transportation infrastructure (Anderson *et al.,* 1995). Urban spatial structure is a more comprehensive concept that encompasses urban form. According to Bourne (1982), urban spatial structure consists of three basic components:

i) urban form-the physical arrangement of activities, households, and institutions in urban space;

ii) interaction-linkages and flows of goods, people and information within and between the varied elements of urban form;

iii) a matrix of coefficients of change for both form and interaction variables.

Over the last several decades, the form of urban areas has changed considerably. Anderson *et al.* (1995) suggest that the fundamental transformation of urban form is characterized by three contributing trends: the outward expansion of the urban boundary (decentralization); the general decline in intensity of all forms of land use (deconcentration); and the segregation of residential land use from other land uses.

The classic models of land use were the first attempts to describe the process of urban change by means of a formal spatial structure. While the processes differ, the models suggest that urban form is a result of changes in the distribution of population and employment. The concentric zone model formulated by Burgess (1925) and others at the Chicago school of urban sociology attempts to explain residential differentiation and neighbourhood change. In the model, the city is composed of a series of concentric rings that house various social groups. As households move up the social ladder, they decentralize, moving to more outer rings. The goal of many households is to have a home in the outer ring, the commuter zone. In this model, the movement of households leads the growth and changing composition of the city.

Hoyt (1939) offered a model that evolved from a study of rental values in 142 U.S. cities between 1878 and 1928 (Knox, 1994). The study reveals that rent varies within cities by radial wedges. The highest rents are located within a single sector that extends continuously from the city centre. Intermediate rents are located in sectors adjacent to the high rent sector while low rents are located on the opposite side of the city from the high rent sector. In this model, the high rent sector drives the growth of the city. This sector grows outward along major transportation routes allowing households to combine accessibility with the amenities of suburban living. A filtering process occurs as wealthier households move further out in the periphery, allowing households in lower rent areas to move to areas that are more amenable.

As new urban forms began to emerge, Harris and Ullman (1945) proposed a new model of urban land use. The multiple nuclei model is a schematic representation of the relative locations of land uses. The model is based on the growth of the commercial and industrial nodes, which are located beyond the urban core. The decentralization of commercial and industrial activities to the suburbs results in the decentralization of households. The model postulates that office and retail centres attract middle class residential development while industrial centres attract working class residential development. Hence, the motor of urban growth is the decentralization of employment followed by the decentralization of residences.

In a well-known book titled "Edge City: Life on the New Frontier", Joel Garreau (1991) asserts that edge cities are the new form of cities. The processes preceding the development of edge cities are suburbanization and the development of regional malls. Unlike the multiple nuclei model, Garreau suggests that the decentralization of population initiates the process as people move to the suburbs. Next, retail establishments follow the population by locating in large regional malls. Finally, edge cities form with the decentralization of employment. The jobs move to where the people live and shop. Garreau suggests that edge cities contain all the functions of a city but in a spread out form; a form that is unrecognizable by many. Garreau contends that edge cities are at the early stage of development and as a result may not yet be recognized as cities. In the edge city model, population drives urban growth and the change in urban form.

Until recently, much of the work on urban form has been theoretical rather than empirical. Empirical studies commonly describe urban form by the geographical distribution of population and/or employment. The most widely used method in describing these distributions is to estimate the negative exponential density function. The function provides insight into the relationship between population and/or employment and distance to the city centre. The density gradient represents the percentage rate of change of density per unit of distance to the city centre (Jordan *et al.*, 1998).

The empirical literature suggests that many urban areas are experiencing a decentralization, deconcentration, and dispersion of population and/or employment (For examples see Jordon *et al.,* 1998; Barkley *et al.,* 1996; Mieszkowski and Smith, 1991; Bourne, 1989; Edmonston *et al.,* 1985). In some cases, urban areas have transformed from a monocentric urban form characterized by a single centre of commercial and economic activity to a polycentric urban form with several centres of commercial and economic activity. The result is an expanded urban area with low density and peripheral development.

The problem with much of the empirical literature on urban form is the widespread use of the traditional negative exponential density function. Many empirical studies employ aggregate zonal data such as census data for population and employment in the estimation of the function. While such data are readily available, there are associated problems such as the modifiable areal unit problem (Fotheringham and Wong, 1991;

Openshaw, 1984). Moreover, the processes that underlie changes in urban form are probably too complex and varied to by captured by a single density gradient parameter.

1.3 The Transportation-Land Use Relationship

The transportation–land use relationship is critical for understanding the nature and evolution of urban form. While many theories examine transportation-land use interactions, the most important is classical location theory. In general, the theory suggests that the location of activities is the result of a market mechanism that involves land, transport, and composite goods. Households and firms decide where to locate by considering different combinations of land, transport, and composite goods that allow for the maximization of utility and profits, respectively. The competition for land between all users results in an equilibrium pattern of land rents and land prices and an optimal allocation of land.

Evolving from the work of Ricardo, von Thünen (1842) was the first to explain the effect of transport costs on the location of activities. von Thünen studied the spatial distribution of crops around a central town and suggested that land uses are arranged concentrically around the town with land rents and land use intensity declining with distance from the town. The price of land at each location is based on savings in transportation that each location affords compared to a more distant site. This concentric pattern of land use is the outcome of competitive bidding between land users for use of the land, where the land is awarded to the highest bidder.

Alonso (1964) contributed to location theory by extending earlier work on urban land use. Alonso reconciled the concentric model of land rent with both the utility maximizing behaviour of households and the profit maximizing behaviour of firms. Alonso extended the concept of competitive bidding by adding the composite good to the budget constraint. Alonso also introduced the bid rent function, which is a set of land rents a household or firm is willing to pay at various distances from the centre in order to maintain a constant level of utility or profit, respectively.

Muth (1969) concentrated on residential land values by examining the influence of accessibility to the centre on the location of households and the intensity of residential land use by producers of housing. Muth also considered the effects of the age of neighbourhoods and preference factors associated with incomes of households on the production and consumption of housing services. Muth developed a model that maximized a utility function consisting of housing and all other goods and services. The utility function is also subject to a budget constraint where expenditure on composite goods, housing, and transport should not exceed total income. Muth described the relationship between composite goods, housing, and transport with two equilibrium conditions. First, the marginal utilities per unit of expenditure on housing and composite goods must be equal. Second, the marginal change in housing expenditure with a change in location must be equal to the marginal change in transport costs. In other words, if transport costs are positive, equilibrium requires that housing prices decrease with distance and that housing consumption increase with distance from the centre.

In general, the evolution of urban form may be explained by the role of transportation in shaping the locational decisions of households and firms. The basic concept underlying locational decisions is accessibility. Because the location of transportation infrastructure affects the accessibility of places, land values and land use reflect the locational advantages of transportation infrastructure. Location theory predicts that any transportation infrastructure development that improves accessibility will be capitalized in land values and reflected in land use changes responding to the shift in land values (Giuliano, 1995). As accessibility improves, there is a shift to higher value land uses such as the change from agricultural to residential land use. Improvements to the transportation network such as new roads can elicit this shift.

The challenge in examining the transportation-land use relationship is the issue of directionality. The transportation-land use relationship may be generalized as follows. Changes to the transportation network such as the construction of new roads or capacity expansions will affect accessibility. The distribution of accessibility influences locational decisions thereby resulting in changes to the land use system. Because land use is the spatial distribution of activities, land use can influence the pattern, scale, and mode of trips that use the transportation network. The distribution of activities requires spatial interaction in the transport system to overcome the distance between the locations of activities. If the capacity of the transportation network is reached because of this spatial interaction, the network may be expanded thereby changing accessibility. Congestion problems often bring pressure on governments to invest in new transportation infrastructure. This description portrays a bi-directional relationship between transportation and land use. Empirical analyses are required that isolate each direction of this relationship.

Four decades of empirical research have examined the impact of transportation on land use. The most common type of study is to investigate the impact of transportation infrastructure development on land values and economic growth. While earlier studies consistently show significant positive land value impacts of new highways, the results of more recent studies are mixed. (For examples see Adkins, 1959; Czamanski, 1966; Baird and Lipsman, 1990; Forkenbrock and Foster, 1990; Rietveld, 1994; Harmatuck, 1996). Some descriptive and historical studies have shown land development impacts along highways, including the tendency for clustering around major interchanges and for linear development along freeway frontages (Giuliano, 1989; Transportation Research Board, 1995). However, there is no firm quantitative evidence that transportation infrastructure affects land use. This lack of evidence stems from the paucity of empirical work that isolates and quantifies the impact of transportation on land use. No prior study has investigated the impact of transportation on land use by examining the spatial pattern of development at the regional scale.

Many studies have investigated the impact of land use on transportation by examining the impact of urban form on travel patterns (For a comprehensive review of such studies see Badoe and Miller, 2000). Many studies represent urban form with variables such as land use composition, land use mixing, density, or neighbourhood design; and travel patterns with variables such as trip rates, mode choice, trip distance, or vehicle ownership (For examples see Kockelman, 1997; Cervero and Kockelman, 1997;

McNally and Kilkarni, 1997; Cervero, 1996; Frank and Pivo, 1994). The results of these studies are also mixed. While some studies report that land use variables do have an impact on travel patterns, albeit a weak impact, other studies report no impacts. No prior study has investigated the impact of land use on transportation by examining the spatial pattern of development.

1.4 Research Objectives

The primary objective of the dissertation is to examine the relationship between transportation infrastructure development and urban land development. Specifically, the research attempts to draw an empirical link between road development and land development by examining the spatial pattern of development. The motivation of this research stems from this gap in the literature and from the growing concern about the impacts of development on urban sprawl, traffic congestion, and pollutant emissions.

To address this objective, the research required land use and transportation infrastructure data. Parcel level data were obtained from a Property Records Database maintained by Service Nova Scotia and Municipal Relations. The parcel level data indicate precisely where land is being developed and for what purpose (ie. residential or commercial). One variable that would be useful is the size or land area of each parcel. The lack of area data is unfortunate because the size of establishment is unknown. Data regarding the evolution of the arterial and collector road network were collected from provincial transportation reports and regional planning documents. Information on new road construction and capacity expansions were pieced together to provide a historical record of changes in the transportation network. The dissertation focuses on the time period 1970 to 1996.

In approaching the primary objective, the dissertation must address several research questions. Initially, the dissertation focuses on land development by investigating the changing urban form of the Halifax-Dartmouth region. By examining the spatial pattern of residential and commercial land development, the dissertation addresses the following research questions:

- What is the spatial pattern of land development?
- How do infill, contiguous, and leapfrog development contribute to the spatial pattern of development?
- Is there evidence of decentralization, deconcentration, and segregation of land uses?

With a better understanding of the spatial pattern of land development, the dissertation then examines the process that leads to changes in urban form. The dissertation employs a method to explicitly test for spatial dependence or clustering between the location of new residential and commercial land parcels. Evidence of clustering at different scales provides additional insight into the changing urban form of the region. To this end, the following research questions are addressed:

- Are new residential land parcels clustered over the entire time period?
- Are new commercial land parcels clustered over the entire time period?
- At what spatial scales are residential and commercial parcels clustered?
- Is the pattern of residential land development related to the pattern of commercial land development?

With insight into the spatial pattern of land development, the dissertation then examines the relationship between road development and residential land development. The objective is to quantify the strength of both directions of the transportation-land use relationship. To this end, Chapter 4 explores one direction of the transportation-land use relationship; that is, the impact of road development on residential land development. Chapter 5 examines the other direction of the transportation-land use relationship; that is, the impact of residential land development on road development. Collectively, the results from Chapter 4 and Chapter 5 address the following research question:

- Does road development drive residential land development or does residential land development stimulate road development, or both?

1.5 The Importance of Data and Spatial Analysis

The ability to examine the changing form of urban areas and to examine the transportation-land use relationship has improved in recent years due to advances in both data availability and quality, and in spatial data analysis methods. The availability of high quality, disaggregate data allow for a more effective analysis of changes in urban form. Such data allow for the quantitative measurement of urban form, which can yield important insight into the form and functioning of urban areas. Spatial data analysis allows for degrees of quantification and inference that are much more rigorous than traditional statistical methods. Improved data and statistical methods combined, extends the range and depth of urban analyses that are possible. Longley and Mesev (2000) assert that the innovation of geographical information systems (GIS), allied to the proliferation of new, detailed, and disaggregate data sources, is ushering in a new era of data-led generalizations about the empirical characteristics of urban systems at a variety of scales.

Spatial data analysis involves the accurate description of data relating to a process operating in space, the exploration of patterns and relationships in such data, and the search for explanations of such patterns and relationships (Bailey and Gatrell, 1995, 21). Spatial data analysis provides methods for the visualization, exploration, and modeling of spatial data. Visualization, the first step in examining spatial data, may identify patterns in the data and provide insight that may be used in the generation of hypotheses. Exploratory methods further the development of hypotheses by summarizing and investigating patterns and relationships in the data. Models allow for formal testing of hypotheses or estimations of the extent and form of possible relationships in the data.

Spatial data analysis methods have the ability to explicitly consider spatial effects inherent in the data. In particular, spatial data analysis provides methods for visualizing, exploring, and modeling both first order effects and second order effects. Bailey and Gatrell (1995) define first order effects as global or large scale effects that relate to variation in the mean value of a process in space; and second order effects as local or small-scale effects that result from the spatial correlation structure or spatial dependence in the process.

Geographical information systems play a vital role in the dissertation by facilitating the management, retrieval, visualization, analysis, and modeling of the spatial data. To examine the transportation-land use relationship, various types of spatial data are employed. Land development is represented as points, road development as lines, and socio-economic variables are measured over areas. These different types of data present a major methodological issue. To reconcile this, a grid cell approach is adopted where the grid cell represents the spatial unit of analysis. Representing point, line, and area data in terms of grid cells is a major undertaking, made only possible by the use of geographical information systems.

In outlining the organization of the dissertation, the next section explains how each chapter takes advantage of the disaggregate parcel level data and how spatial data analysis methods and geographical information systems are employed in addressing the research questions.

1.6 Organization of the Dissertation

The remainder of the dissertation is organized as follows. Chapter 2 provides the first substantive paper of the dissertation. The paper investigates the changing urban form of Halifax-Dartmouth by examining the spatial pattern of land development. The availability of disaggregate, parcel level data and the use of spatial data analysis methods make it possible to examine changes in urban form without reverting to traditional methods such as the negative exponential density function. The kernel estimate is a spatial data analysis technique that measures first order effects. The kernel estimate is a visualization approach rather than an inferential or parametric statistics approach. In the dissertation, the kernel estimate measures the intensity of land parcel development. By mapping the kernel estimates, temporal and spatial variations in the intensity of land development may be evaluated. The results of the kernel estimates suggest that changes in the urban form of Halifax-Dartmouth were a combined result of infill, contiguous, and leapfrog development. However, it is apparent that residential and commercial land parcels exhibit different spatial patterns of development.

Chapter 3 provides the second substantive paper, which examines the locational patterns of population and employment and the resultant changes in urban form. The paper employs univariate and bivariate K functions to measure spatial dependence within, and between the classes of residential and commercial land parcels. Specifically, the K function examines the relationship between the development of residential land parcels and commercial land parcels, and the effect that this relationship has on the changing urban form of the Halifax-Dartmouth region. The univariate K function tests explicitly for spatial dependence or clustering among parcels. The bivariate K function examines the relationship between two spatial processes under the assumption of independence. More specifically, the bivariate K function determines if the pattern of occurrences of residential land parcels is related to the pattern of occurrences of commercial land parcels. The results of the K function estimates suggest that residential land parcels cluster together, commercial land parcels cluster together, and over time residential and commercial land parcels have become more clustered. Evidence of clustering provides insight into the changing urban form of the region.

Chapter 4 presents the third substantive paper of the dissertation. This paper examines the transportation-land use relationship by quantifying the impact of road development on land development. The paper specifies an ordered probit model where residential land parcel development is a function of either the change in accessibility or the distance to a high-speed road. The results indicate that road development does have an impact on residential land development. Moreover, the models are able to capture this impact at both a local and a regional scale, and for different intensities of land development.

Chapter 5 provides the final substantive paper, which examines the impact of land development on road development. Time series data on road development are used to calculate changes in accessibility while land development is measured in terms of residential land parcel development. The paper specifies a spatial lag model where the change in accessibility is a function of residential land parcel development and other explanatory variables. The results do not support the proposition that land parcel development drives road development.

Chapter 6 provides summary remarks regarding the results, implications, and importance of the dissertation research. The findings of the research are summarized and the importance of the findings is discussed. The contribution of this research to the larger body of knowledge is also assessed. Given the findings of this dissertation, directions for future research are outlined.

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CHAPTER 2: An Examination of Urban Form in Halifax-Dartmouth: Alternative Approaches in Data

2.1 Introduction

According to Bourne (1987), urban form is the physical arrangement of activities, households, and institutions in urban space. Over the past several decades, there have been tremendous changes in the form of urban areas. Most notably, many urban areas have transformed from a monocentric to a polycentric urban form. The fundamental transformation of urban form is characterized by three contributing trends: the outward expansion of the urban boundary (decentralization); the general decline in intensity of all forms of land use (deconcentration); and the segregation of residential land use from other land uses (Anderson *et al.,* 1995).

Many empirical studies commonly describe urban form by the geographical distribution of population and/or employment (For examples see Mieszkowski and Smith, 1991; Bourne, 1989; Edmonston *et al.,* 1985). The results of these studies suggest that population and employment are decentralizing away from the urban core; that is, activity sites are re-locating from the urban core to the periphery. The result is an expanded urban area with low density and peripheral development. The most widely used method in describing these distributions is to employ zonal data in the estimation of the negative exponential density function. Despite the widespread use, zonal data and the density function provide only a limited picture of changes in urban form.

Parcel level data offer a valuable opportunity to explore the changing form of urban areas. Using point data rather than zonal data provides a better basis for examining the physical arrangement of activities, households, and institutions. In particular, the development of new residential land parcels explicitly shows where households are locating. Similarly, the development of new commercial land parcels shows where employment sites are locating. By examining the change in these household and employment locations over time, changes in urban form are apparent. Recent studies of urban structure suggest that urban form evolves through land conversion and land development processes (Wu and Gar-On Yeh, 1997). Thus, the analysis of land parcel development is a viable alternative to study changes in urban form.

This paper employs parcel level data in the computation of kernel estimates. The kernel estimate shows variations in the intensity of land parcel development over space. The kernel estimate reveals a general pattern of land development by smoothing the data and removing extraneous detail. The kernel estimate is a visualization approach rather than an inferential or parametric statistics approach. The mapped results of the kernel estimate provide a visual indication of the most intense land development. A comparison of kernel maps for different time periods and for different land uses indicates changes in urban form. This makes it possible to observe the three contributing trends that lead to the transformation of urban form: decentralization, deconcentration, and the segregation of land uses. The kernel estimate is a valuable tool in that it employs detailed, disaggregate data. Moreover, it is a relatively simple technique that may be easily applied to other urban areas for which point data are available.

The objective of this paper is to investigate the changing urban form of the Halifax-Dartmouth region by examining the spatial pattern of residential and commercial land development. To accomplish this, disaggregate parcel level data are employed instead of zonal densities. The paper also provides an alternative approach to the traditional exponential density function to explore transformations in urban form. The kernel estimate provides a visual, two-dimensional exploration of the spatial pattern of land development.

Using the parcel level data and the results of the kernel estimates, this paper addresses the following research questions. First, what is the spatial pattern of land development and how do infill, contiguous, and leapfrog development contribute to the spatial pattern of development? Second, is there evidence of decentralization; that is, are new parcels locating outside the urban core? Third, is there evidence of deconcentration; that is, has the intensity of land development declined? Finally, is there evidence of segregation of residential land parcels from commercial land parcels?

We organize the remainder of the paper as follows. First, we explain the traditional negative exponential density function and then review several empirical studies that employ the function. Next, we describe the study area. Using census data for the study area, we estimate the negative exponential density function for several census years. We then describe the parcel level data and the kernel estimate. Finally, we compute the kernel estimates and use the results to address the research questions.

2.2 Literature Review

Numerous studies document the changing form of urban areas. While the study areas may vary, the most commonly used method is to estimate the negative exponential density function. The negative exponential density function provides insight into the relationship between population and/or employment density and distance to the centre of the city. The population and/or employment densities are calculated for a sufficiently large number of urban zones over a period of time. The results show how the locational patterns of population and employment change over time. Essentially, the density function attempts to summarize a complex pattern with a single parameter, the density gradient.

Clark (1951) first modeled the density-distance relationship using the following mathematical form:

$$D_x = D_0 e^{-bx} \qquad (1)$$

where D is population or employment density, x is distance from city centre, D_0 is density at city centre, e is the natural logarithmic base, and b is the slope or density gradient. The density gradient serves as a summary statistic of decentralization. The more uniform density is, as a function of distance from the city centre, the smaller the value of b. Comparing values of b over time provides insight into the decentralization of population and employment. Decreases in b over time indicate increases in the decentralization of urban areas. Clark estimated the model for several cities and concluded that the negative exponential density function is the norm for urban population density patterns.

Since Clark's formulation, the negative exponential density function has been the basis of many empirical analyses that investigate the changing form of urban areas. Edmonston *et al.* (1985) examine differences in urban form through a comparative investigation of density gradients of residential populations for metropolitan centres in the United States and Canada. The results suggest that urban areas in both countries experienced similar decentralizing trends with central densities on average decreasing by half between 1951 and 1976 (Edmonston *et al.,* 1985). However, despite rapid decentralization, central densities in Canadian urban centres are twice as high as their U.S. counterparts. In Canada, *b* decreased from 0.93 in 1951 to 0.42 in 1976, while in the U.S., *b* decreased from 0.76 to 0.45 over the same time period. Based on these results, Edmonston *et al.* suggest that Canadian cities exhibit a more densely settled urban area and a more compact urban form.

In a comparative study of the 27 largest urban areas in Canada, Bourne (1989) examines population and employment data to reveal several trends in urban growth and urban form. Population density gradients indicate that average residential densities have declined and the slopes of the gradients have become much flatter and more convoluted; that is, less smooth because of more variability (Bourne, 1989). Bourne examines the decentralization of employment using journey-to-work distances and the location of work-trip destinations. The analysis suggests that average commuting distances have decreased for suburban residents and suburban employment locations, but have increased for inner city residents and central employment locations. Bourne concludes that population and employment have decentralized in Canadian urban areas.

Bourne also calculates a measure of the relative degree of population redistribution to determine how rapidly Canadian urban areas are decentralizing through a combination of suburbanization and inner city decline. Results of a linear regression model in which the rate of population change by census tract is regressed against distances to the central core suggest that all 27 urban areas experienced inner area population decline and overall spatial deconcentration (Bourne, 1989). Because of regional variability in the results, Bourne concludes that the emergence of a new and massively dispersed urban form has not occurred in Canadian urban areas.

Mieszkowski and Smith (1991) examine the pattern of population and employment decentralization in Houston. First, the study estimates the negative exponential density function using census tract data. The results reveal that decentralization in Houston involves both the absolute decline in inner city population and the infill of existing suburban areas. Next, the study estimates a population density function that employs actual land utilized for residential activity by census tract rather than total land area. The results suggest that much of the decline in density with respect to distance from the centre is attributable to declining rates of land utilization. Declines in aggregate density over time are explained by leapfrog development over large tracts of vacant land rather than by an increase in the amount of land per occupied housing unit (Mieszkowski and Smith, 1991).

Barkley *et al.* (1996) examine patterns of spatial structural change for functional economic areas in North Carolina, South Carolina, and Georgia by estimating population density functions using census tract data. Comparison of population density functions for

1980 and 1990 suggests that population decentralization accompanied metropolitan growth. The results indicate that residential densities declined near the metropolitan core and increased in the suburbs, in edge cities, and in rural areas proximate to the metropolitan fringe (Barkley *et al.,* 1996).

Jordon *et al.* (1998) estimate population density functions to analyze differences in rates of suburbanization in U.S. metropolitan areas between 1970 and 1990. The results indicate that while the average rate of suburbanization (the average rate of change in the density gradient) did not change significantly over the time period, all metropolitan areas experienced continuing decentralization. The results also show that smaller metropolitan areas have higher values of b and experience greater absolute changes in b than do larger metropolitan areas.

Despite the widespread use of the negative exponential density function, the growth and resultant urban form of contemporary urban areas brings into question the functions' applicability. Several studies suggest that the negative exponential density function is not appropriate for the non-monocentric nature of contemporary cities (Anderson, 1985; Crampton, 1991; Mieszkowski and Mills, 1993). Mieszkowski and Mills (1993) assert that while the exponential density function has been valuable in understanding past trends in decentralization, the emergence of new urban forms (polycentric) makes the function increasingly irrelevant.

In addition to the problems associated with negative exponential density function, there are several problems in using aggregate zonal data when estimating the function. Because zones are defined for a variety of purposes, actual values for any given variable will vary with the level of aggregation and with the configuration of the zoning system. The zones may not accurately represent the underlying geographical distribution of any particular variable. For example, census tracts are designed primarily for ease of enumeration rather than to represent the underlying geographical distribution of population or employment. This sensitivity of analytical results to the definition of zones for which data are collected is known as the "modifiable areal unit problem" (Fotheringham and Wong, 1991; Openshaw, 1984).

Census data may also be problematic when estimating densities because extensive unpopulated areas such as open water, industry, or agriculture are included in the land area measurements of the zone. In particular, peripheral zones are problematic, as they tend to be so spatially extensive that the population physically occupies a small proportion of the land area. Finally, census data are sensitive to demographic trends. For example, declining population densities in older neighbourhoods may be a function of decreasing household size and cannot be interpreted as a change in urban form. Thus, the density gradient will change because of demographic trends, even though urban form does not change.

Several important points emerge from the empirical literature regarding urban form. First, the form of urban areas is changing as a result of the continued decentralization of population and employment. The empirical results indicate that population and employment exhibit different decentralized patterns; that is, population tends to be more decentralized than employment. Moreover, the decentralized pattern may result from different processes such as the redistribution of growth from the core to the periphery or new growth in the periphery relative to the core.

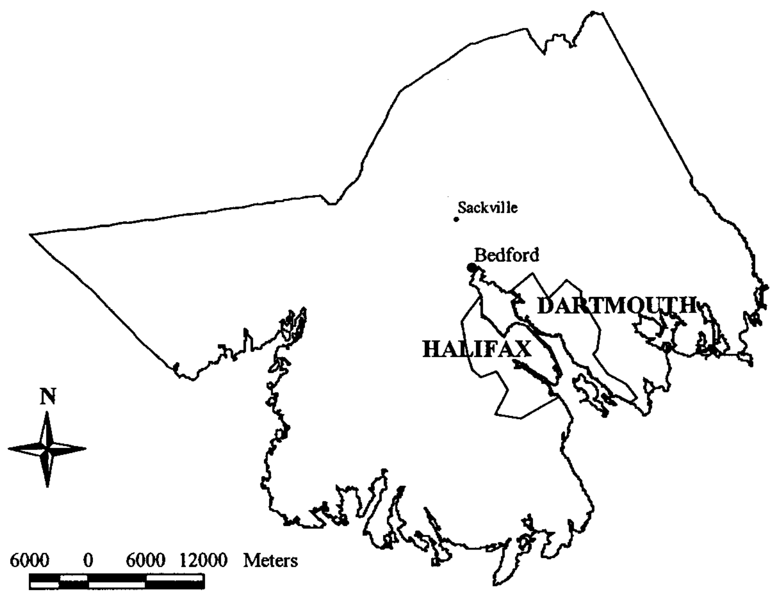
Second, many of the empirical studies employ the negative exponential density function in examining changes in urban form. However, there are several problems related to the density function in terms of the functional form and the use of census data. More importantly, the processes that underlie changes in urban form are probably too complex and varied to be captured by a single density gradient parameter. Thus, it is clear that an alternative method that employs less problematic data and takes a more explicit spatial approach would be valuable in examining the changing form of urban areas.

2.3 The Study Area

The Halifax Regional Municipality covers an area of 6200 square kilometres along the southern shore of Nova Scotia. The municipality consists of the cities of Halifax and Dartmouth, the town of Bedford, and the remaining rural periphery. Because urban land development is of interest, we define a functional urban area within the administrative region. While the eastern half of the region is primarily sparse rural development, the western half holds the majority of the land parcels and corresponds roughly to the Halifax Census Metropolitan Area (CMA). For the purposes of this paper, we only employ parcel level data for the western half of the Halifax Regional Municipality to examine the spatial pattern of land development. We refer to this sub-region as the Halifax-

Dartmouth region. Figure 2-1 provides a map of the study area with various points of interest that we highlight later in the discussion.

Figure 2-1: The Halifax-Dartmouth region



2.4 Estimation of the Negative Exponential Density Function for Halifax-Dartmouth

To effectively evaluate the viability of an alternative method and type of data to investigate urban form, it is necessary to provide results from the traditional method. We estimated the negative exponential density function using census tract data for the Halifax-Dartmouth region for the years 1971, 1976, 1981, 1986, 1991, and 1996. We defined the centre (D_0) as the Halifax census tract that contains the central business district. Table 2-1 provides the results.

Table 2-1: Density gradients for the Halifax-Dartmouth region 1971-1996

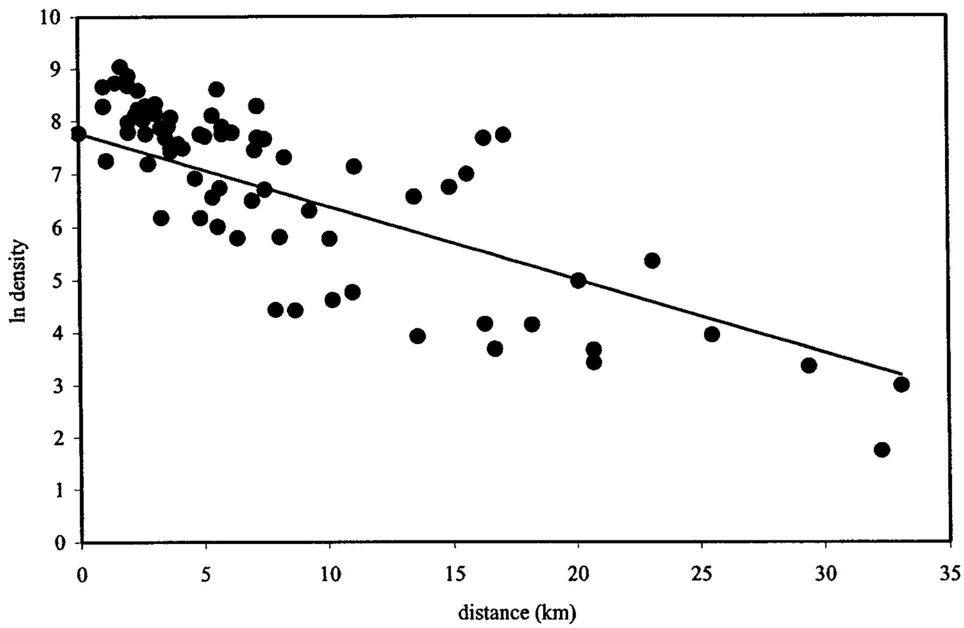
	N	D_0	b	R-square
1971	46	3164	-0.190	0.49
1976	55	1997	-0.168	0.69
1981	61	2200	-0.163	0.69
1986	73	2086	-0.151	0.62
1991	73	2695	-0.159	0.64
1996	73	2377	-0.147	0.62

Over the time period, the density gradient became slightly flatter. Compared to the density declines documented in the literature (particularly Edmonston *et al.,* 1985), these results suggest that the urban form of the Halifax-Dartmouth region did not experience significant change. Despite the lack of change, a scatterplot of population density and distance from the centre in Figure 2-2 reveals significant variability around the spatial trend. It is evident that there is much more going on than the density gradients indicate. The central densities fluctuate over the time period but indicate a decentralizing trend. The disaggregate parcel level data and the kernel estimates will provide additional insight into the changing urban form of the Halifax-Dartmouth region.

2.5 The Data Set

Parcel level data offer an excellent opportunity to examine the pattern of urban land development at a detailed spatial and temporal scale. For each year, the parcel level data indicate precisely where land is being developed. Through time, it is the development of individual land parcels that lead to the pattern of urban growth and the subsequent urban

Figure 2-2: Scatterplot of population density versus distance from centre, 1996



form. Wu and Gar-On Yeh (1997) assert that the change in the location of land development can reflect more readily the transformation of the urban spatial structure whereas the redistribution of population and changing land prices are results of land development. Thus, analysing the development of land parcels provides the opportunity to begin to understand the process that creates urban form.

Parcel level data are available from Service Nova Scotia and Municipal Relations (SNSMR) [1]. SNSMR maintains a Property Records Database that includes a Property Information Report for every land parcel in the province. For each land parcel, the Property Information Report provides the geographic coordinates, the year of parcel

[1]Service Nova Scotia and Municipal Relations was formerly the Nova Scotia Department of Housing and Municipal Affairs.

creation, and the land use type (i.e. residential or commercial[2]). In 1996, the Halifax-Dartmouth region contained approximately 90 000 developed land parcels. Of those 90 000 parcels, 54 773 parcels were developed between 1970 and 1996. One variable that would be useful is the size or land area of each parcel. The lack of area data is unfortunate because the size of establishment is unknown. Thus, a given commercial land parcel could be the site of a large factory or a convenience store while a given residential land parcel could be a single family home or an apartment building.

In order to examine changes in urban form, particularly decentralization, an urban core must be defined. The urban core, as defined by the 1971 Census of Canada[3] for the Halifax Census Metropolitan area, is used as the urban core for this paper. The urban core includes the cities of Halifax and Dartmouth. The remaining part of the region is considered the periphery. Figure 2-1 shows the extent of the urban core and the periphery in the Halifax-Dartmouth region.

Table 2-2 summarizes the number of commercial and residential land parcels created in the urban core and the periphery in each time period[4]. The aggregate data clearly shows that the majority of the residential land parcels are located in the periphery. Alternatively, the majority of the commercial land parcels are located in the urban core. Between 1970 and 1978, 80 per cent of all residential land parcels were developed in the

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[2] Commercial parcels include all secondary, tertiary, quaternary, and quinary activities.
[3] The urban core is a large urban area around which a CMA (census metropolitan area) is delineated. The urban core must have a population of at least 100 000.
[4] The choice of these time periods corresponds to the incremental time periods used later in the kernel analysis. The incremental time periods 1970-1978, 1979-1987, 1988-1996 divides the entire time period into an approximately equal number of years. Several other variations of time periods were tested and the results were robust.

periphery. This proportion decreased slightly between 1979 and 1987 when 71 per cent of the residential land parcels were developed in the periphery. The periphery increased its share of parcels between 1988 and 1996 with the development of 76 per cent of the residential land parcels.

Table 2-2: Number of residential and commercial land parcels developed in the Halifax-Dartmouth region 1970-1996

	1970-1978		1979-1987		1988-1996	
	Core	Periphery	Core	Periphery	Core	Periphery
Residential	3236	12712	5058	12356	3909	12469
	(20%)	(80%)	(29%)	(71%)	(24%)	(76%)
Commercial	375	309	475	333	546	345
	(55%)	(45%)	(59%)	(41%)	(61%)	(39%)

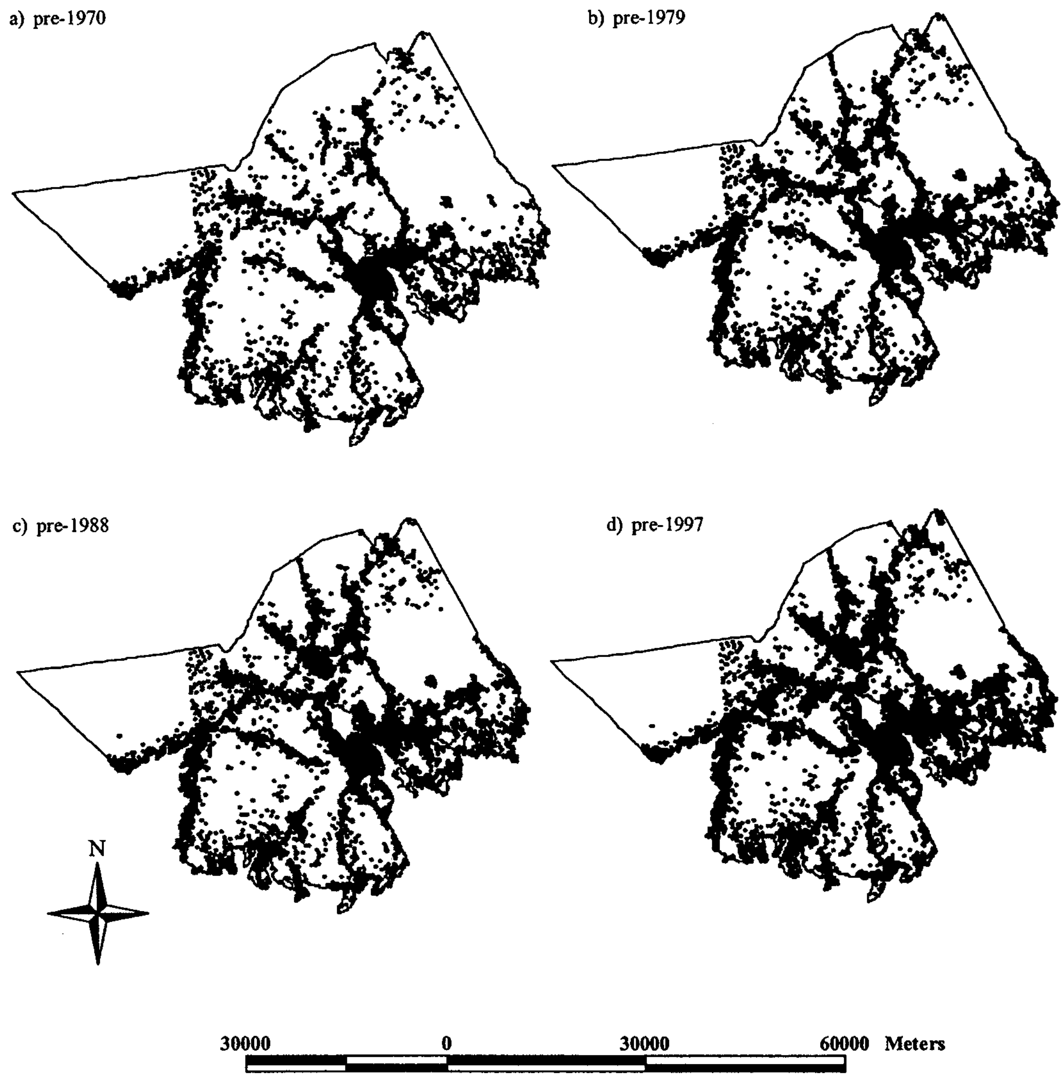
Commercial land parcels exhibit a much different spatial pattern of development. Between 1970 and 1978, the development of commercial land parcels was almost evenly split between the urban core (55 per cent) and periphery (45 per cent). Over the period 1979 to 1987, the urban core's share of new commercial land parcel development increased slightly to 59 per cent. Finally, between 1988 and 1996, the core captured 61 per cent of all new commercial land parcel development. Rather than decentralizing, these data suggest that commercial land parcel development has become more centralized. It should be noted however, that given the lack of area data, parcels developed in the periphery may be larger than those developed closer to the core.

To begin to visualize the spatial pattern of development, we plot the land parcels using ArcView geographical information software. The land parcel data are divided into 4 cumulative time periods: those land parcels created prior to 1970, those created prior to 1979, those created prior to 1988, and those created prior to 1997. Each period represents a snapshot of the physical arrangement of residential and commercial land parcels that existed at that time.

The dot maps in Figures 2-3a-d illustrate the location of new land parcels during the four time periods. By comparing the dot maps, particularly Figure 2-3a and 2-3d, it is evident that the Halifax urban edge expanded slightly outward over the time period, while the Dartmouth urban edge expanded more significantly. Several finger-like axes of development along important regional roads formed early in the time period and continued to expand. Significant development also occurred in the periphery.

While the dot maps provide some insight into the pattern of urban growth, the precise spatial pattern of land development is complicated and difficult to interpret. When dealing with approximately 90 000 land parcels, it is not surprising that interpretation is difficult. What is required is a way to simplify the development pattern. To accomplish this, kernel estimates are computed. The resultant kernel maps reveal a more general structure in the spatial pattern of development.

Figures 2-3: Land parcel development in the Halifax-Dartmouth region



2.6 Kernel Estimates

The kernel estimate is a spatial data analysis method that measures the variation in the mean value or intensity of a process in space. Essentially, the kernel estimate is a measure of the number of observed events per unit area. In this paper, we use the kernel estimate to measure the intensity of land parcel development. By mapping the kernel estimates, we can evaluate variations in the intensity of land development both spatially and temporally. For a complete derivation of the kernel estimate, refer to Appendix A.

The shading (gray scale) of the kernel maps corresponds to the intensity of land development where black is the highest intensity and white is the lowest. Because the kernel estimate smoothes the data, white does not necessarily imply that no development exists. The intensity of development, i.e. number of parcels, may just be so low relative to other areas that the value of intensity does not fall in the range of the gray scale. Because the level of commercial development is so small compared to residential development, the gray scales have different maximum values. Given this, we cannot directly compare the actual value of intensity represented by the shade of gray in the commercial and residential kernel maps. However, we can compare the spatial pattern of development and the location of the most intense areas of development.

We computed separate kernel estimates for both residential and commercial land parcels. As with the dot maps, we estimated cumulative time periods for land parcels created prior to 1970, parcels created prior to 1979, parcels created prior to 1988, and parcels created prior to 1997. The cumulative kernel maps illustrate the existing urban form in each time period, in terms of the physical arrangement or location of developed residential and commercial land parcels. We also computed kernel estimates for incremental time periods, 1970-1978, 1979-1987, and 1988-1996, to illustrate the areas of new residential and commercial land development.

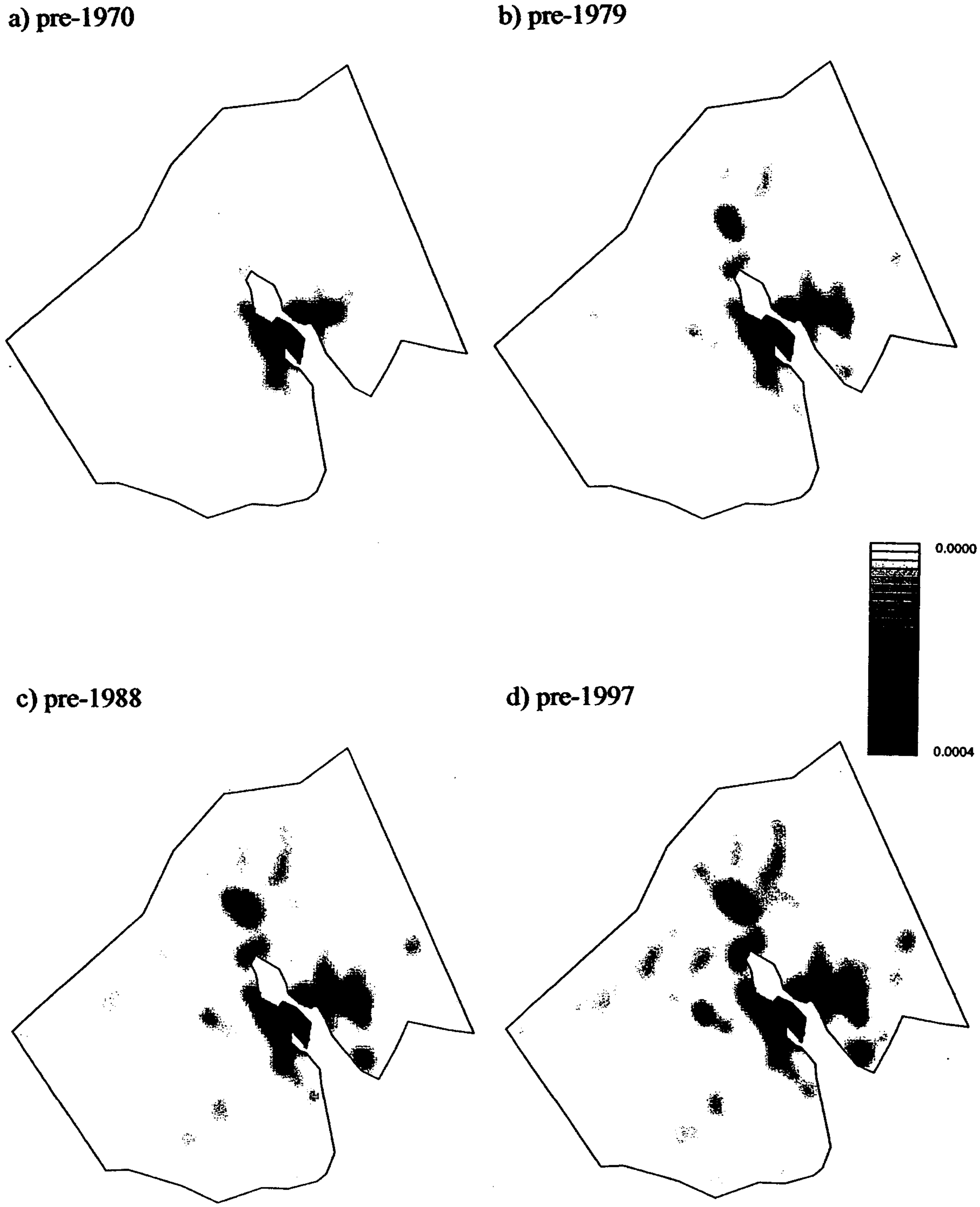
2.7 Addressing the Research Questions

Based on the results of the kernel estimates[5], we address the following research questions. First, 'what is the spatial pattern of land development and how do infill, contiguous, and leapfrog development contribute to the spatial pattern of development?'. An examination of the cumulative kernel maps, Figures 2-4a-d and 2-5a-d, suggest that growth in the Halifax-Dartmouth region was a combined result of infill, contiguous, and leapfrog development. We characterize infill development as the creation of new parcels within areas of existing development. Contiguous development is development that occurs adjacent to existing development. Leapfrog development is development that ignores vacant land closer to the urban core while land at further distances is developed instead.

Comparing the four time periods in Figures 2-4a-d and 2-5a-d, the spatial pattern of land development is apparent. Initially, the urban core was the most intensely developed with a combination of infill and contiguous development. The urban core promoted the form and pattern of growth by establishing a pattern from which subsequent growth foll-

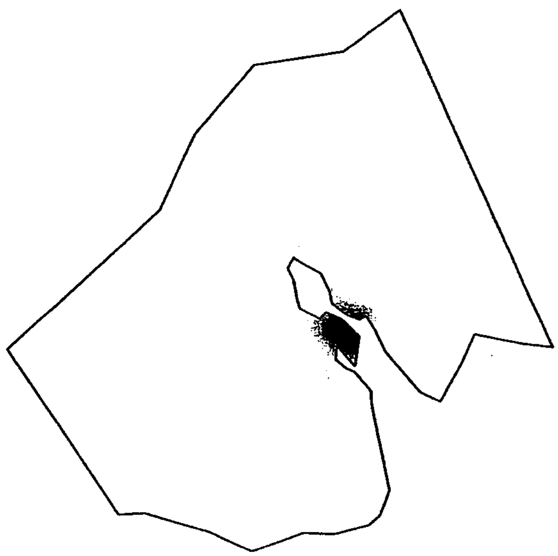
[5] Full scale kernel maps are provided in Appendix B.

Figures 2-4: Kernel maps of cumulative residential land parcel development

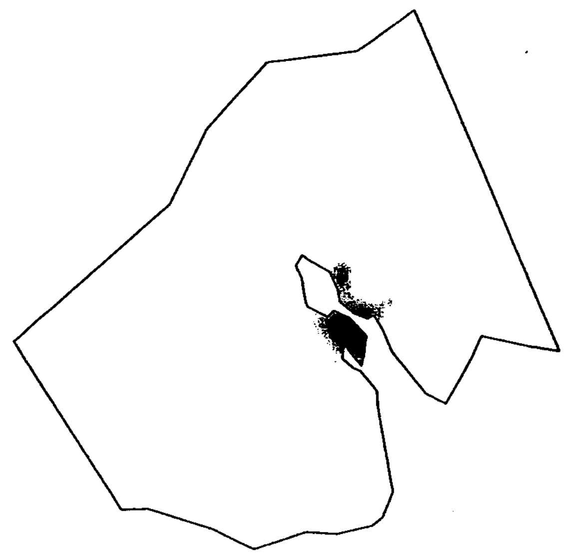


Figures 2-5: Kernel maps of cumulative commercial land parcel development

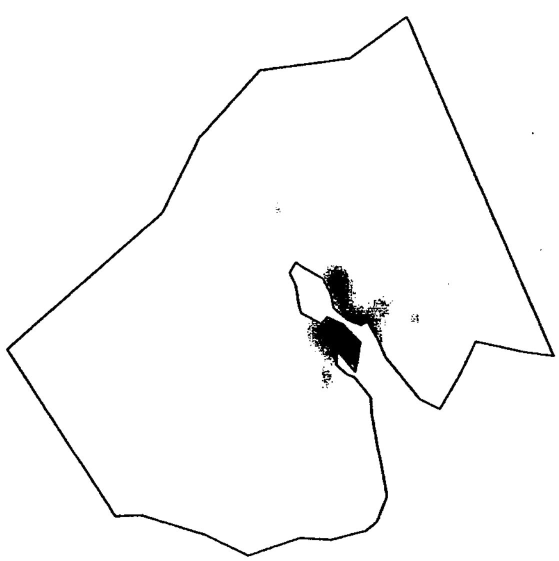
a) pre-1970



b) pre-1979



c) pre-1988



d) pre-1997

owed. As development consumed land within the core, clusters of development evolved outside the core. Subsequently, infill and contiguous development of these clusters occurred.

The development of finger-like axes along regional roads is also a common pattern of development. The initial finger-like pattern expanded with a combination of infill and contiguous development along these axes. Scattered development is also apparent in the peripheral areas. Such scattered development was isolated initially, but in some instances eventually developed into a larger cluster when subsequent contiguous development occurred. The result is an intensely developed urban core with several smaller clusters of development in the periphery.

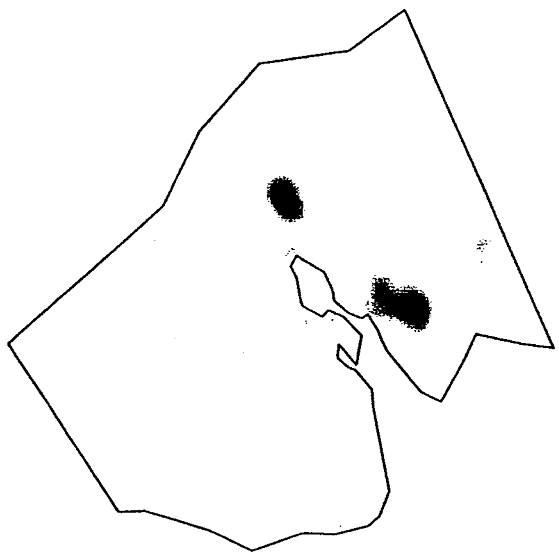
Results from the incremental kernel estimates address the research question 'is there evidence of decentralization?'. Decentralization results from the creation of new parcels outside the urban core. Leapfrog development clearly contributes to decentralization. Development that is contiguous to the urban core may also result in decentralization, as the urban core itself may become decentralized. However, leapfrog development and contiguous development have different scales of influence on decentralization. Leapfrog development, at a considerable distance from the urban core, may result in rapid decentralization, while development that is contiguous to the urban core may result in gradual decentralization. The result is land development that has decentralized from the original urban core.

The incremental kernel maps, Figures 2-6a-c and 2-7a-c, illustrate the location of new land development. By comparing the maps from the three time periods, it can be determined if the areas of new land development are in peripheral locations. Continual development in the periphery suggests that development is decentralizing over time. Figures 2-6a-c indicate that the majority of residential development occurred in periphery, particularly in the areas east of Dartmouth and in Sackville. Commercial land parcel development, as illustrated in Figures 2-7a-c, is highly centralized. The urban core experienced most of the commercial development in terms of the number of developed land parcels, but some smaller clusters of commercial development did appear in peripheral areas. During the period 1988-1996, commercial development contiguous to these peripheral clusters resulted in the coalescing of commercial development.

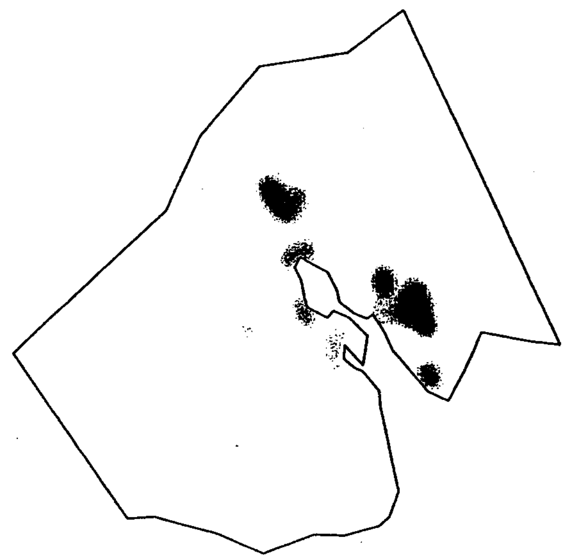
We examine deconcentration-the decline in intensity of land use-by examining the variation of the intensity of land parcel development over the study area. In particular, 'does the intensity of land development decline with distance from the urban core?'. Because the kernel estimate is essentially the number of parcels per unit area, declining intensity suggests fewer parcels per unit of land –deconcentration. Referring to Figures 2-6a-c, it is apparent that residential development is most intense in the core and diminishes with distance from the core. Intense development in the core is represented by the darkest colour of the gray scale, which becomes increasingly lighter with distance from the core. Between 1970 and 1996, there is substantial residential development in the periphery with several intense clusters of development. While these clusters intensify over time, the overall intensity of residential development continues to diminish with distance from the urban core. Peripheral residential development is less intense than res-

Figures 2-6: Kernel maps of incremental residential land parcel development

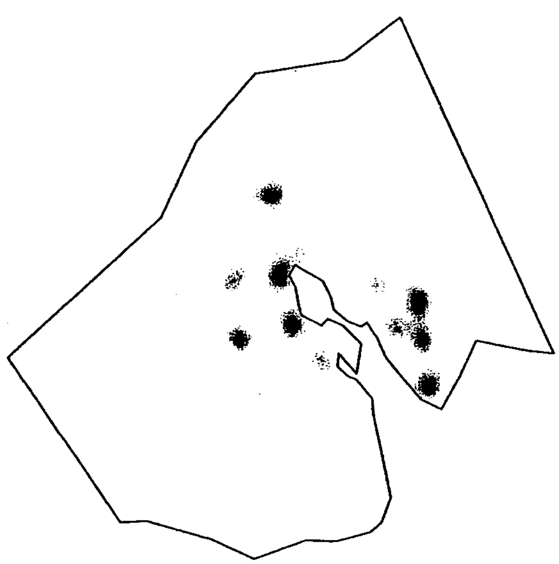
a) 1970-1978



b) 1979-1987

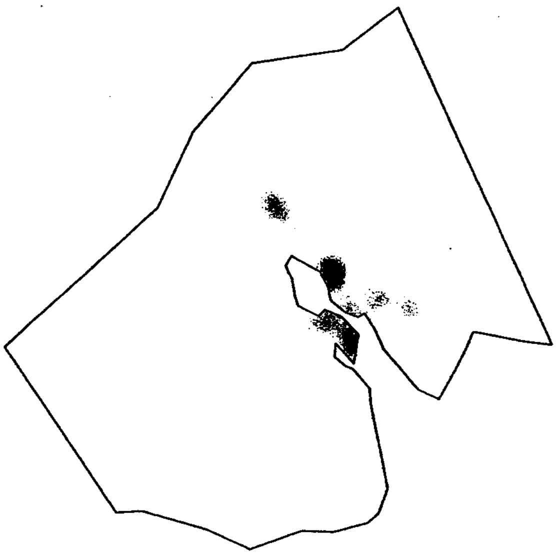


c) 1988-1996

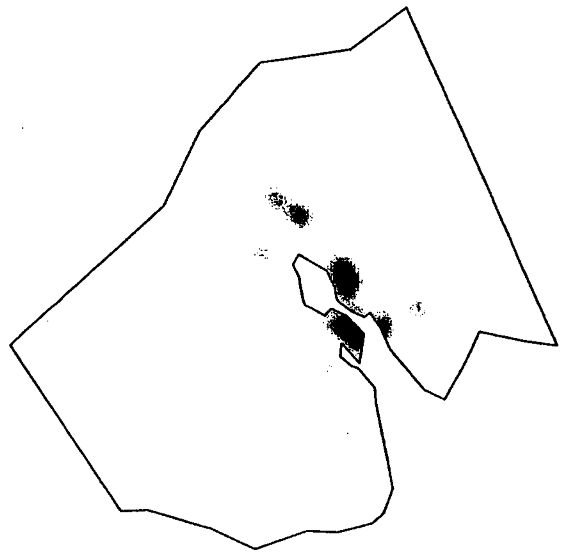


Figures 2-7: Kernel maps of incremental commercial land parcel development

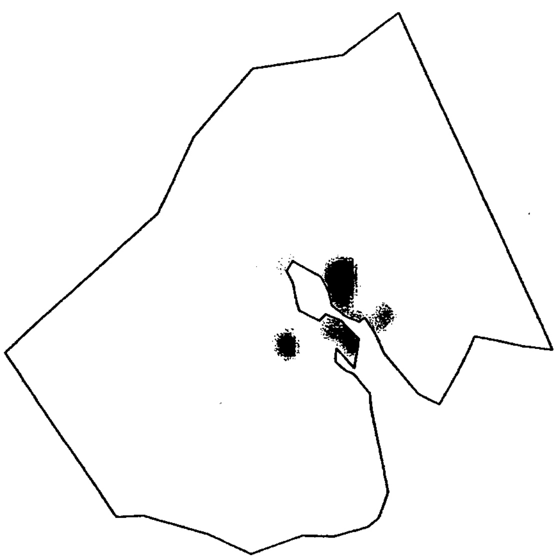
a) 1970-1978

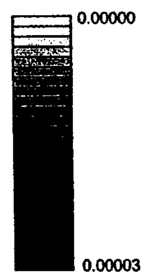


b) 1979-1987



c) 1988-1996





idential development in the urban core. Figures 2-7a-c indicate that commercial development is also the most intense in the urban core and the intensity decreases with distance. This pattern is consistent over time as there is little change in the intensity of commercial land development over the entire time period.

The final research question asks 'is there evidence of segregation of residential land parcels from commercial land parcels?'. From the cumulative kernel maps in Figures 2-4a-d and Figures 2-5a-d, it is evident that commercial land development is more centralized than residential land development in terms of intensity of land parcels. Residential land development exhibits a very different pattern of growth. Specifically, Halifax experienced contiguous growth resulting in a slightly expanded urban edge whereas in Dartmouth, extensive residential land development pushed the urban edge further and further into the rural periphery. Even more significant is the residential development in the Sackville area. From the initial development of a few clusters, intense contiguous and infill development caused the clusters to coalesce into a continuous mass of residential development.

While the traditional negative exponential density function suggests that the Halifax-Dartmouth region experienced little change in urban form, the kernel estimates provide more detailed insight. The results of the kernel estimates suggest that the urban form of the Halifax-Dartmouth region is a combined result of decentralization, deconcentration, and land use segregation. However, there are differences in terms of residential and commercial land development. Residential land parcels exhibited decentralization and deconcentration. Commercial land parcels remained centralized within the urban core but the intensity of development did decrease with distance from the core. It is apparent that residential and commercial land parcels exhibit different spatial patterns of development.

2.8 Discussion

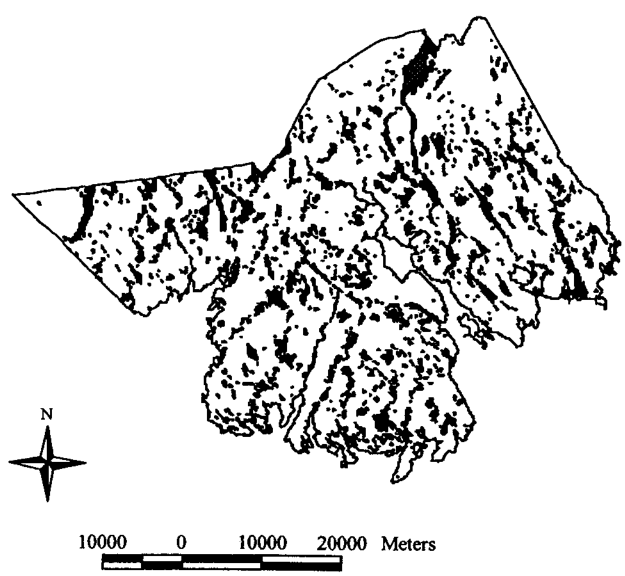
Numerous empirical studies have been conducted for a variety of urban centres to examine changes in urban form. The common result of these studies is that population and employment are decentralizing. The results of this study for the Halifax-Dartmouth region concur that population is decentralizing in the fact that residential land parcels are decentralizing. However, commercial land parcels have not decentralized to the same extent. Several factors may help to explain these spatial patterns of land development in the Halifax-Dartmouth region. These factors also provide insight into the process of land development.

The spatial pattern of land development is partly explained by the heterogeneity of the land. Land development in the Halifax-Dartmouth region is constrained by several factors including government ownership of land and the presence of numerous lakes. Figures 2-8a-b illustrate these constraints. Federal government land holdings, located mainly in the Halifax-Dartmouth core, consist of Department of National Defence lands. The larger tracts of land in the periphery correspond to provincially owned crown land and parkland. The smaller tracts of land within the urban core are mostly municipal land holdings corresponding to local parks. The Halifax-Dartmouth region is also scattered with numerous lakes, which constrain land development. In terms of the pattern of land development, such constraints may have contributed to the leapfrog development and subsequent infill and contiguous development in the region.

Figures 2-8: Constraints to land development in the Halifax-Dartmouth region

a) Government land holdings

b) Lakes



The role of planning in the Halifax-Dartmouth region also helps to explain the development patterns. The Halifax-Dartmouth Regional Development Plan was introduced in 1975 with the objective of directing growth to the Bedford-Sackville area, yet retaining a strong, viable core. The regional plan defined an urban development boundary and it established a framework for municipal planning. The results of the kernel estimates suggest that the regional plan was successful in directing growth to Bedford and Sackville. Despite this apparent success, interviews with Halifax Regional Municipality planners suggest that planning controls in the region have been permissive. Thus, a lack of planning control in other areas of the region may have contributed to the leapfrog development and subsequent contiguous and infill development.

The Regional Development Plan may have also succeeded in maintaining a strong, viable urban core. In terms of the number of land parcels, the data suggest that commercial land development has actually become more centralized over time. For waterfront cities like Halifax-Dartmouth such a trend is unusual. According to Bourne (1987), waterfront cities tend to have higher land and congestion costs and as a result, the degree of employment and population decentralization is more pronounced. This decentralization reflects the reduced centrality of the waterfront downtown core. Despite the peninsula topography of Halifax-Dartmouth, the urban core maintains a strong presence in the region.

The Halifax-Dartmouth region may have retained a strong urban core for other reasons as well. The twin city configuration of Halifax-Dartmouth contributes to the strength of the urban core. The cities have also invested in revitalizing the urban core. A revitalized waterfront and historic district, particularly in Halifax, helps to counterbalance the trend to decentralization and deconcentration. The fact that Halifax serves as a provincial and regional capital, and a regional service centre also contributes to the strength of the urban core. The Halifax central business district is the largest single employment centre in Atlantic Canada (Millward and Bunting, 1999). Located within the urban core are a Naval Dockyard, two large medical centres, and two academic institutions. Thus, the urban core holds agglomerative power, which has led to greater centrality.

Transportation infrastructure development has also played a vital role in maintaining the centrality of the urban core. The construction of two bridges that connect Halifax and Dartmouth have improved the accessibility of the urban core. High accessibility at the intersections of important regional roads has encouraged the development of several industrial parks in the region. Many of the peripheral clusters of commercial development evident in the kernel maps correspond to industrial parks at these highly accessible locations.

Several important factors have played a role in the pattern of land development in the Halifax-Dartmouth region. Heterogeneity of the land influences the pattern of development in terms of limiting what land can and cannot be developed. The presence of lakes also influences the spatial pattern of land development. Planning controls have influenced the pattern of growth by directing development to certain areas. Finally, transportation infrastructure development has improved the accessibility of certain locations thereby increasing the attractiveness of these locations for development.

2.9 Summary

Empirical studies suggest that many urban centres are experiencing a decentralization of both employment and population. Many studies, including those reviewed in this paper, evaluate these trends using aggregate measures of employment and population, specifically the negative exponential density function. Using parcel level data, this paper employs the kernel estimate to examine the spatial pattern of land development. The resultant kernel maps allow for an explicit examination of the land development process, which leads to the pattern of urban growth and the subsequent urban form. Because the kernel estimate is a visualization approach rather than a parametric approach, the maps reveal both quantitative and qualitative changes in urban form that cannot be inferred from changes in the gradient of the negative exponential density function. Additionally, the kernel estimate is simple to compute and may easily be applied to any urban area for which point data are available.

Changes in urban form are characterized by three contributing trends: decentralization, deconcentration, and the segregation of land uses. We used the results of the kernel estimates to determine if these trends are occurring in the Halifax-Dartmouth region. The kernel maps indicate significant residential land parcel development in the peripheral areas of the region. However, a corresponding pattern of commercial land parcel development is not evident. The kernel maps suggest that residential land parcel development experienced decentralization and deconcentration while commercial development did not. While the results of the kernel maps are robust, land area data for the parcels would provide additional insight into the decentralization/centralization of population and employment.

Using parcel level data, this paper explores the changing urban form of Halifax-Dartmouth by examining the spatial pattern of residential and commercial land parcel development. Although changes in urban form are apparent in the kernel maps, there are a number of factors that influence the specific spatial pattern of land development that must be considered more explicitly. Such factors include the availability of developable land, planning controls, and the development and location of transportation infrastructure. Of course, numerous other factors also influence development. To further our understanding of the process that leads to changes in urban form, additional analyses that explore the causal mechanism underlying urban growth and land development are required.

2.10 Appendices

Appendix A: Derivation of the Kernel Estimate

At a general location in the study area, *s*, the intensity of developed land parcels (events) is calculated. Following the notation of Bailey and Gatrell (1995), the intensity, $\lambda(s)$, at *s* is estimated by:

$$\hat{\lambda}_\tau(s) = \frac{1}{\delta_\tau(s)} \sum_{i=1}^{n} \frac{1}{\tau^2} k\left(\frac{(s - s_i)}{\tau}\right) \qquad (1)$$

where $k(\,)$ is a bivariate probability density function or the kernel

s_i is the location of observed event i

τ is the bandwidth

$\delta_\tau(s)$ is an edge correction

Bailey and Gatrell (1995) describe the bandwidth, τ, as the radius of a disc centred on s within which points s_i will contribute significantly to the intensity at s. The value of τ is determined through experimentation. The effect of increasing τ is to increase the radius around s within which the observed events influence the intensity estimate at s. A large value of τ will cause the kernel map to appear smooth and local details will be lost, while a small value of τ will result in a kernel map with a collection of spikes centred on s_i.

In conducting the kernel analysis, several values of τ were tested. Using intervals of 500 metres, values of τ ranging from 500 metres to 5 000 metres were tested. Because τ determines the amount of smoothing, the kernel estimates that employed higher values of τ ($2\,000 \leq \tau \leq 5\,000$) were too smooth and obscured the local detail. Alternatively, lower values of τ produced kernel maps that were too spikey to reveal general patterns. The most appropriate value of τ was 1500 metres, which allowed for the visualization of development in both the urban core and the periphery.

The most common choice of functional form for the kernel, *k( )*, and the one employed in this paper is the quartic kernel of the form:

$$k(\mathbf{u}) = \begin{cases} \dfrac{3}{\pi}(1-\mathbf{u}^{\mathrm{T}}\mathbf{u})^2 & \text{for } \mathbf{u}^{\mathrm{T}}\mathbf{u} \leq 1 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

According to Bailey and Gatrell (1995), the quartic kernel is a radially symmetric probability density function, which is centred on the location s and scaled up by a factor of τ to provide a weighting applied to observed events around s. At location s (distance of zero), the weight is $3/\pi\tau^2$ and it drops smoothly to a value of zero at distance τ (Bailey and Gatrell, 1995). Using the quartic kernel, the equation for intensity, $\lambda\,(s)$, at s then becomes:

$$\hat{\lambda}_\tau(s) = \frac{1}{\delta_\tau(s)} \sum_{h_i \le \tau} \frac{3}{\pi\tau^2}\left(1 - \frac{h_i^2}{\tau^2}\right)^2 \tag{3}$$

where h_i is the distance between the point s and the observed event location s_i

It is important to note that the summation is only over values of h_i that do not exceed τ, thus an event outside the region of influence is not considered (Bailey and Gatrell, 1995).

We computed the kernel estimates using the SPLANCS software package operating in the S-Plus programming environment. SPLANCS interfaces with S-Plus to display and analyze spatial point pattern data. SPLANCS employs a formulation for the kernel estimate that was proposed by Diggle (1985) and Berman and Diggle (1989).

Appendix B: Kernel Maps

Figure 2-4a: Cumulative residential land parcel development pre-1970

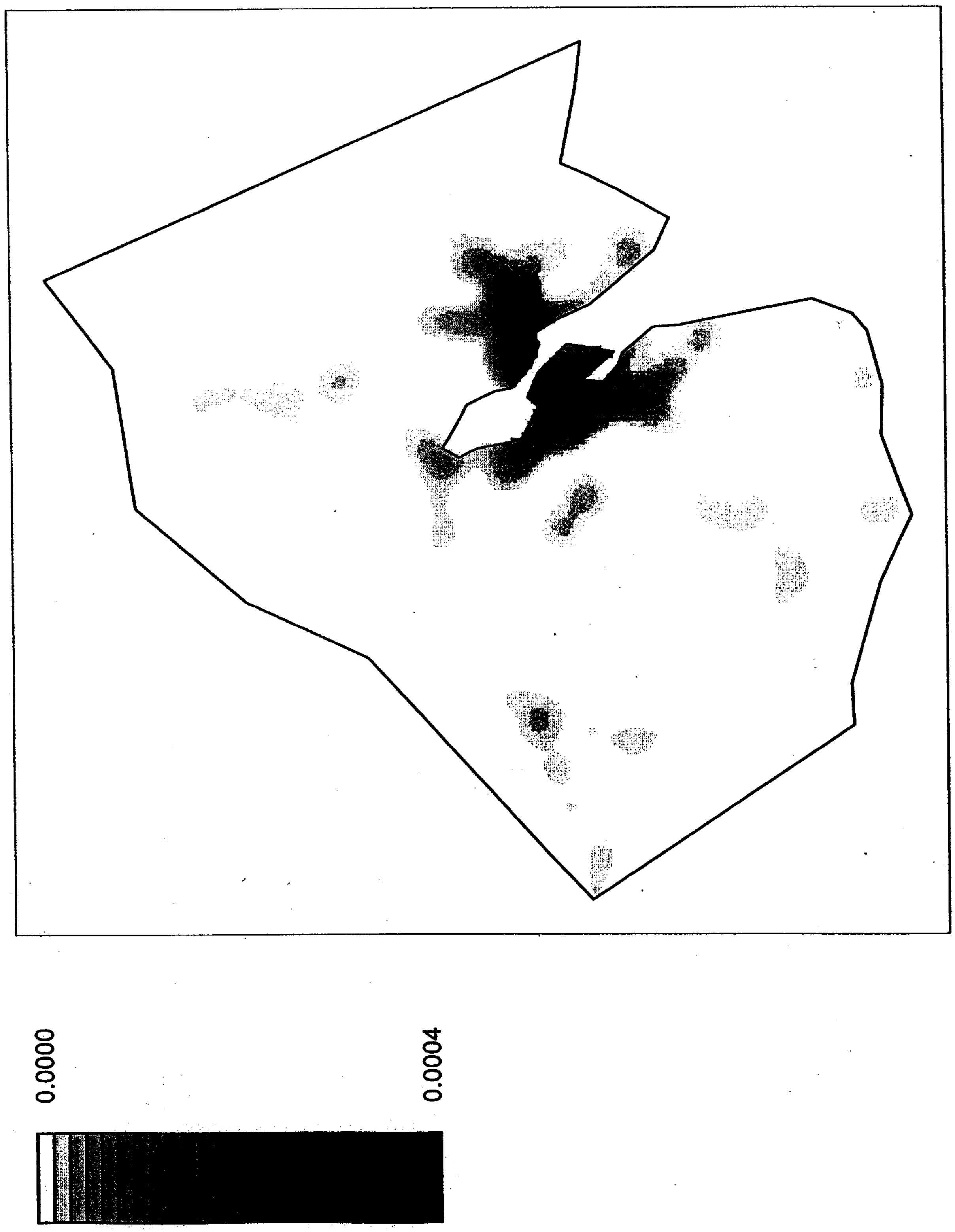


Figure 2-4b: Cumulative residential land parcel development pre-1979

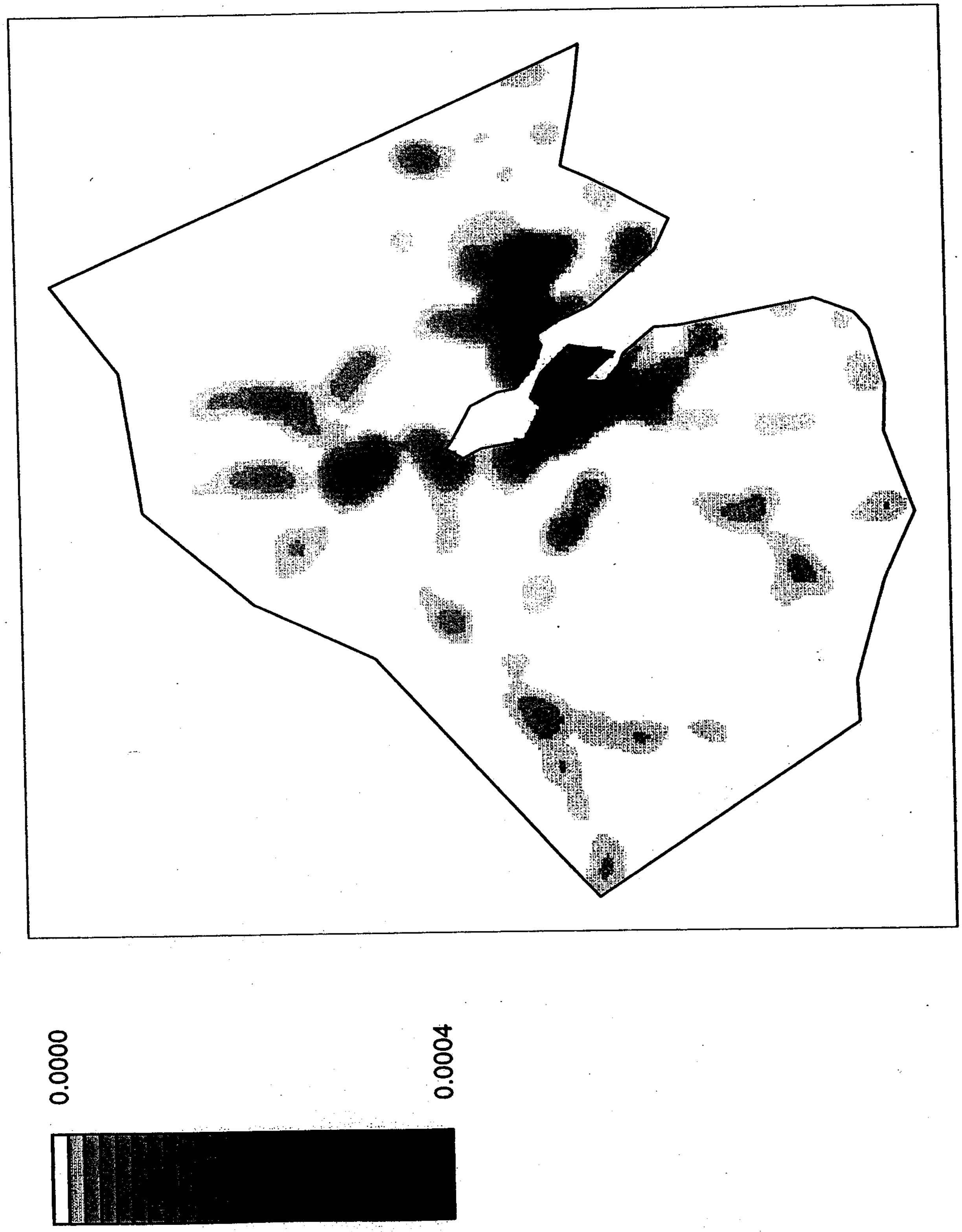


Figure 2-4c: Cumulative residential land parcel development pre-1988

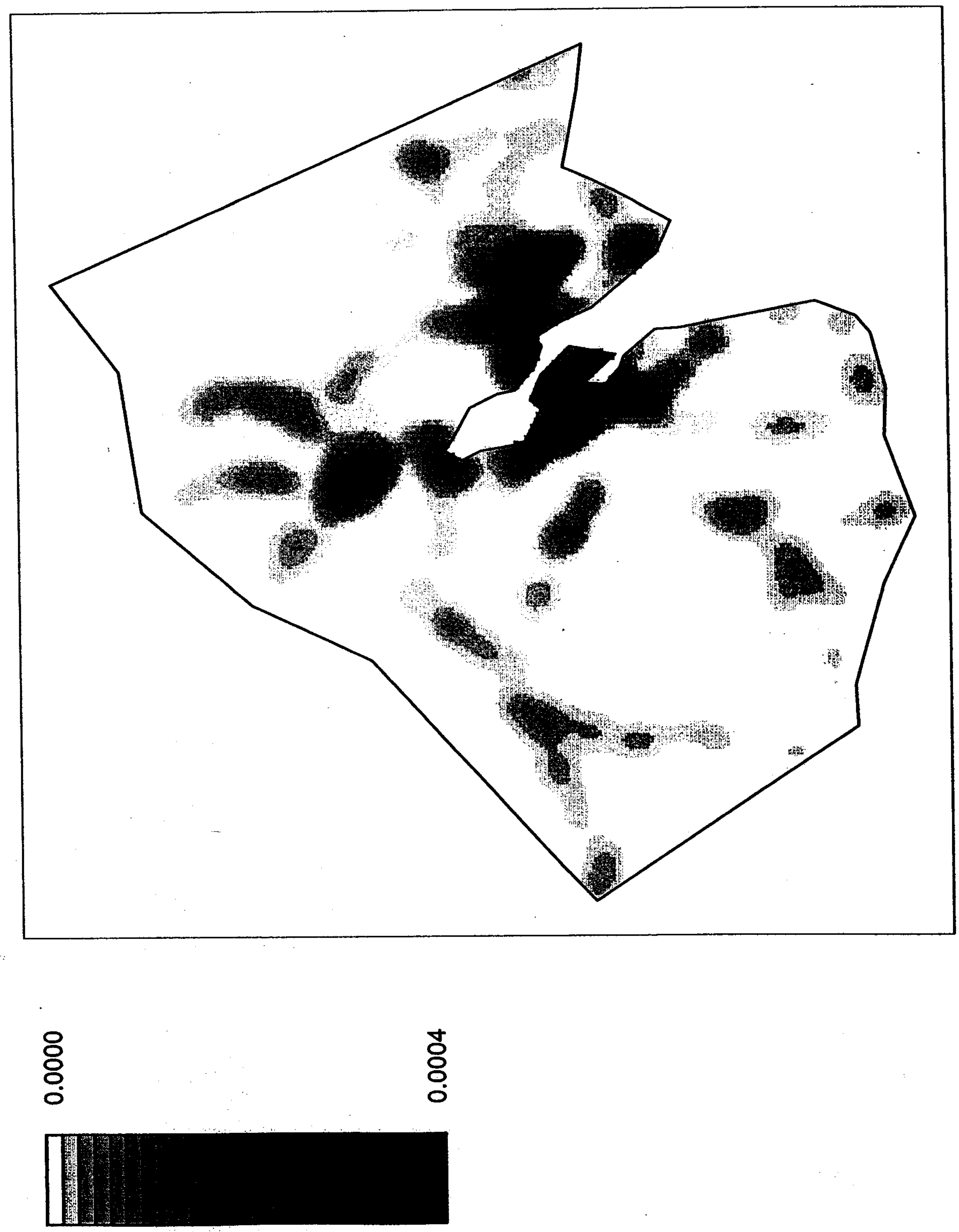


Figure 2-4d: Cumulative residential land parcel development pre-1997

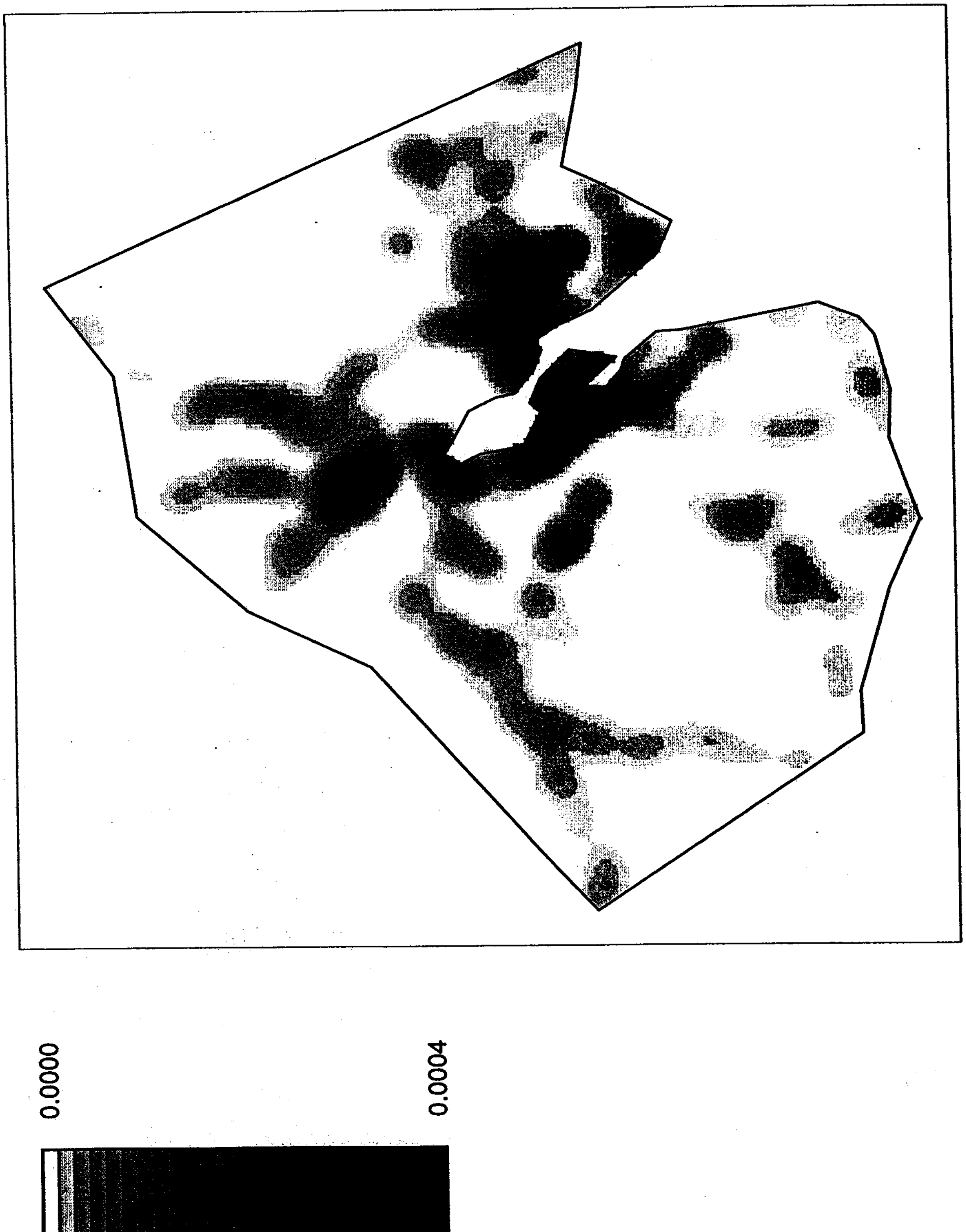
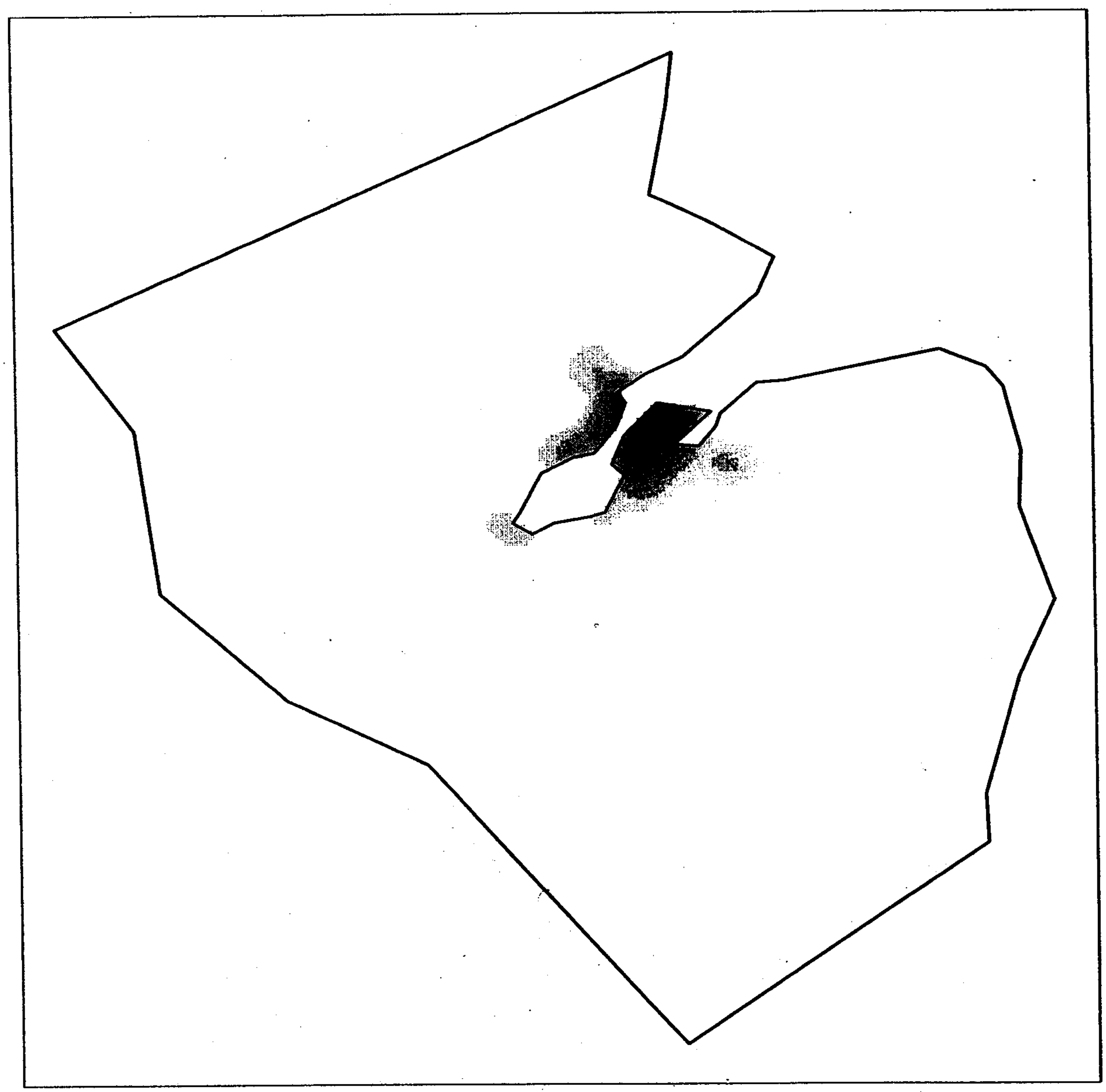


Figure 2-5a: Cumulative commercial land parcel development pre-1970



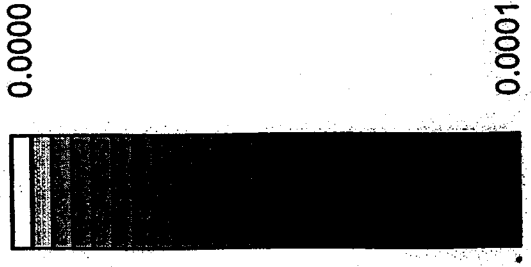


Figure 2-5b: Cumulative commercial land parcel development pre-1979

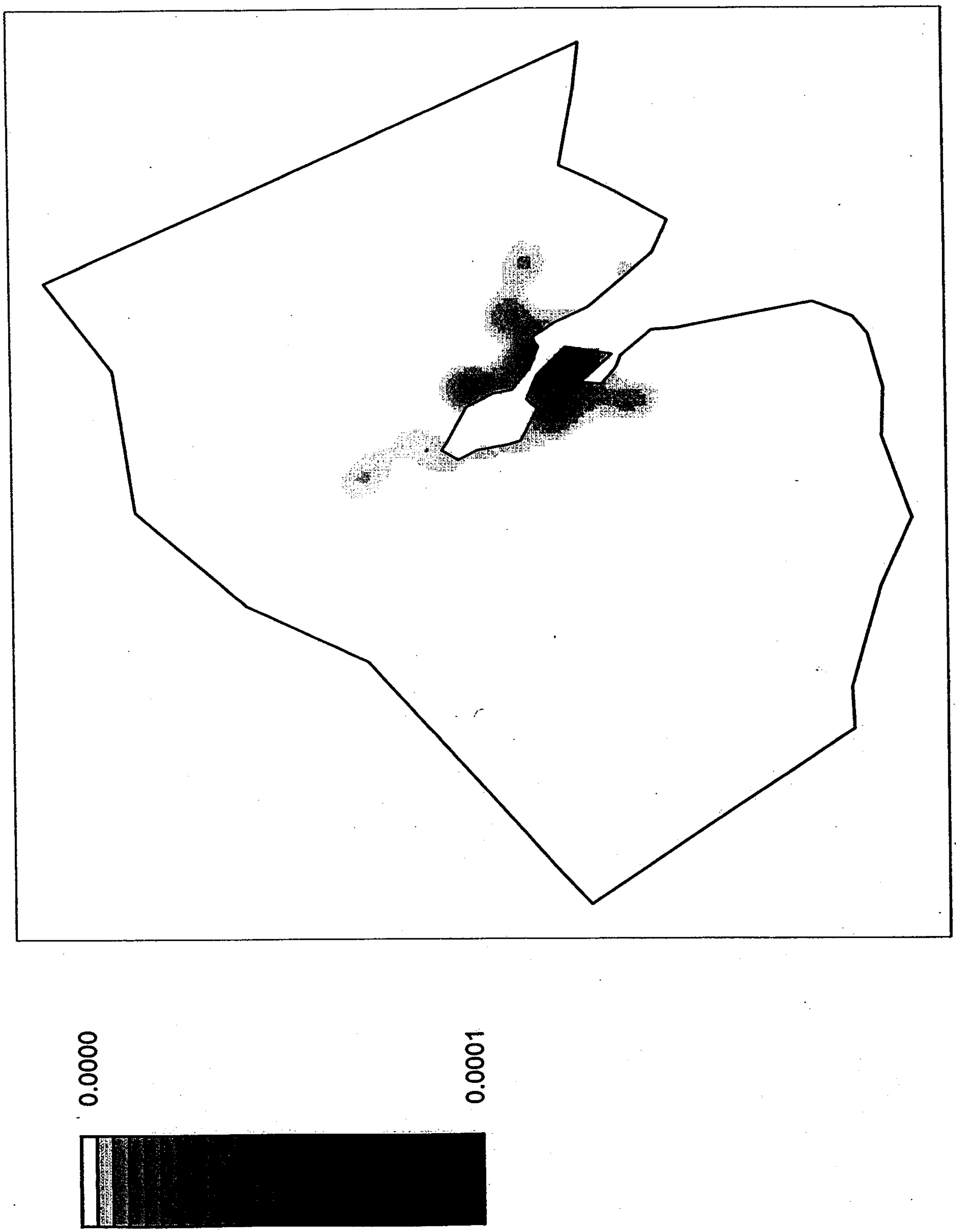


Figure 2-5c: Cumulative commercial land parcel development pre-1988

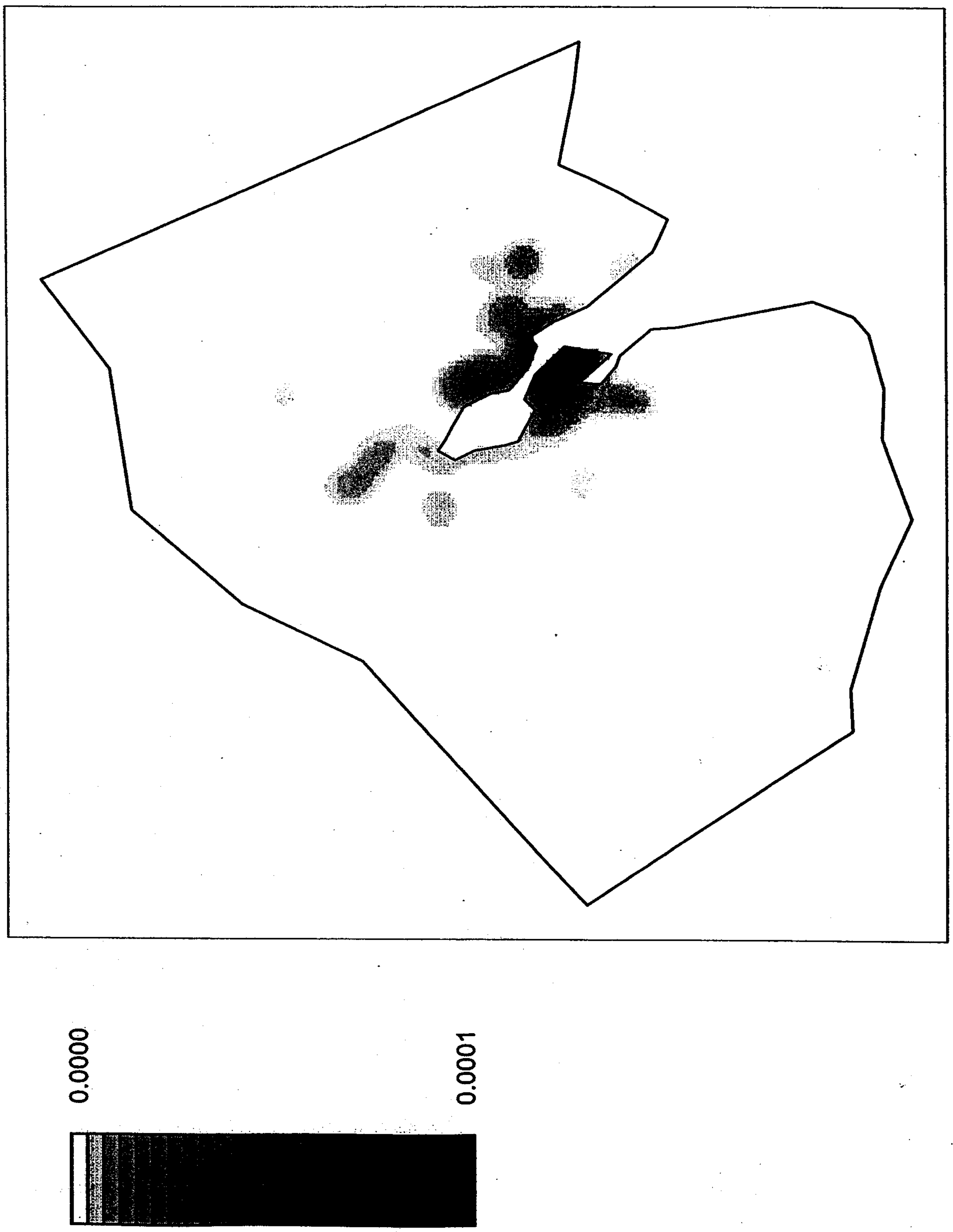


Figure 2-5d: Cumulative commercial land parcel development pre-1997

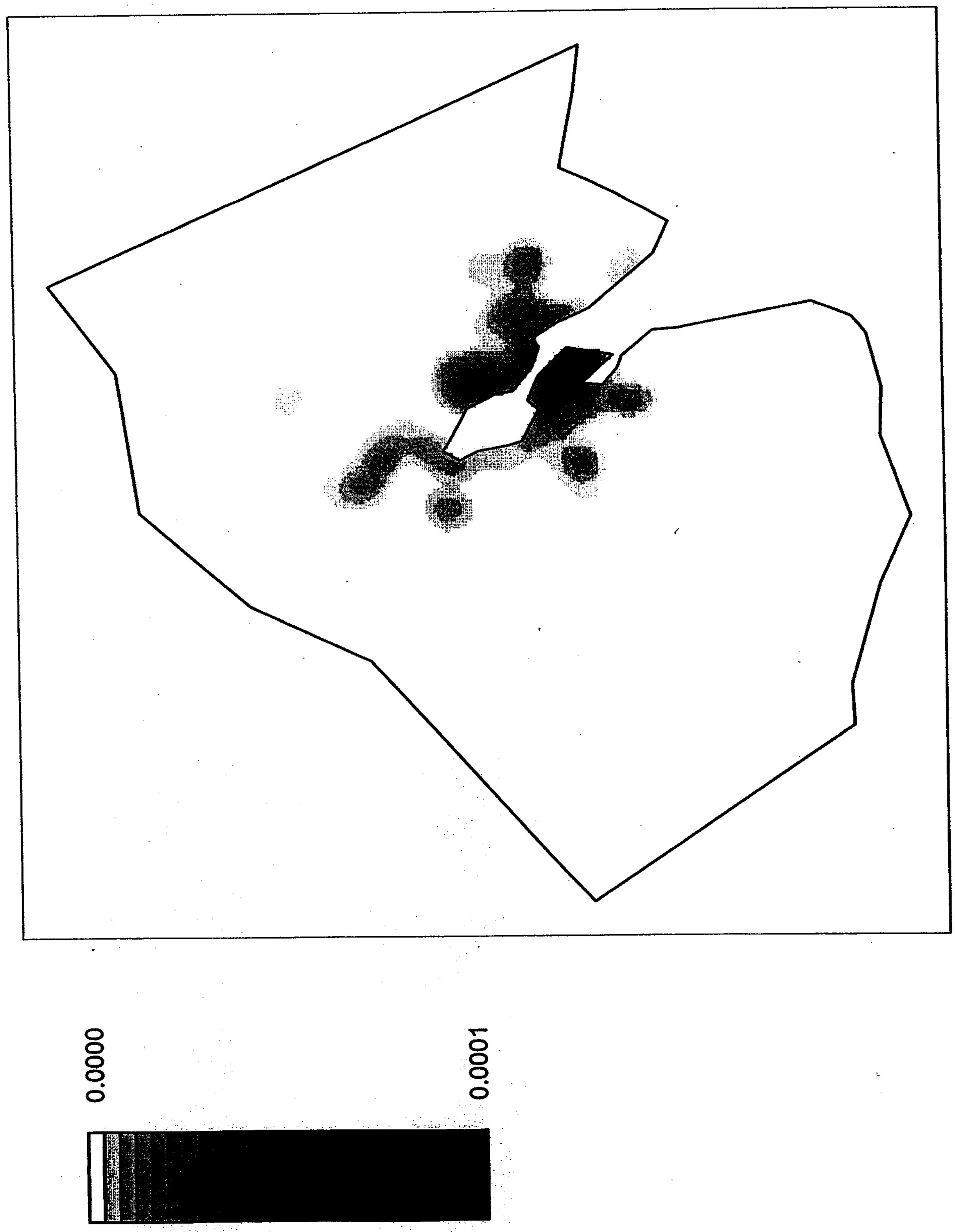


Figure 2-6a: Incremental residential land parcel development 1970-1978

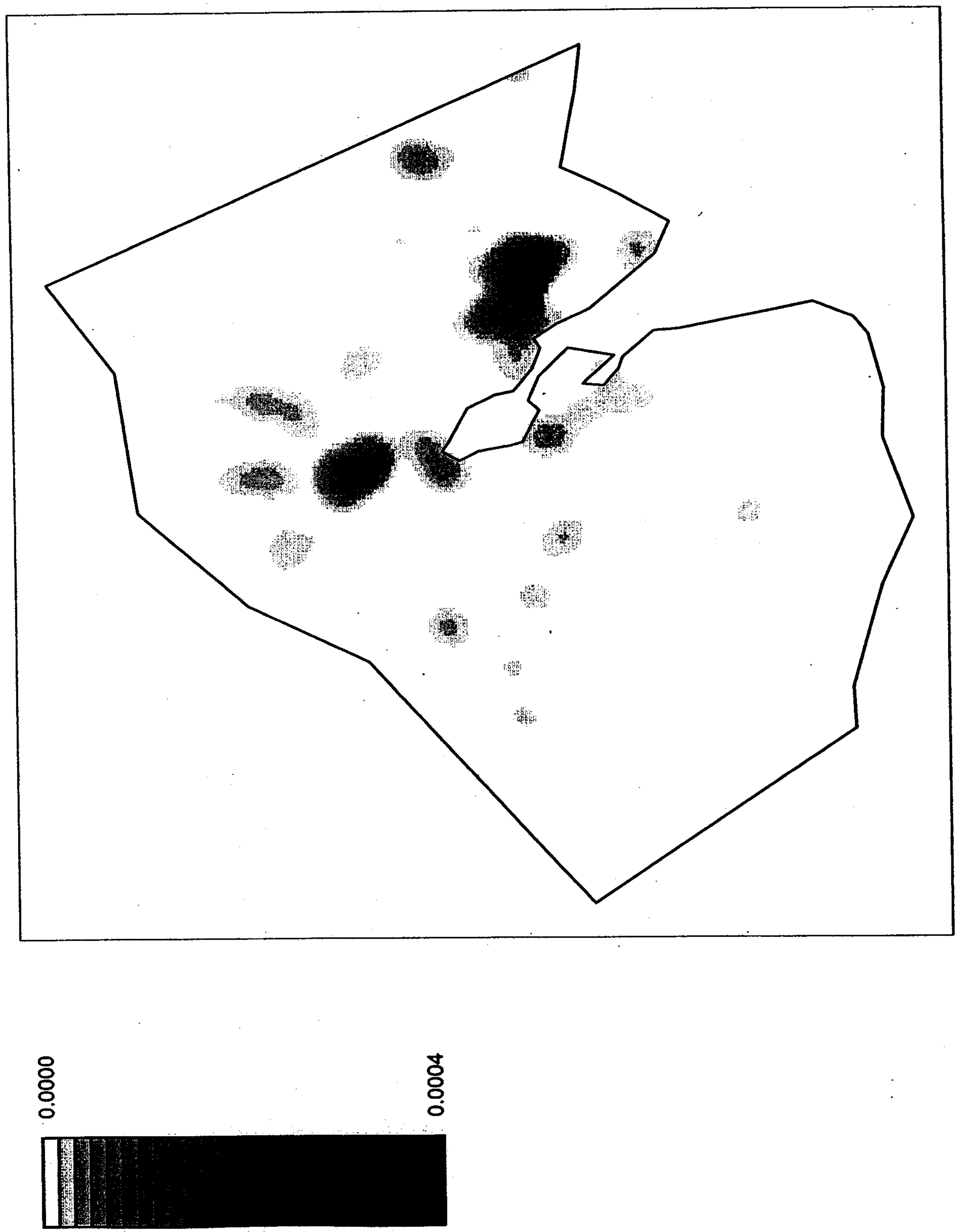


Figure 2-6b: Incremental residential land parcel development 1979-1987

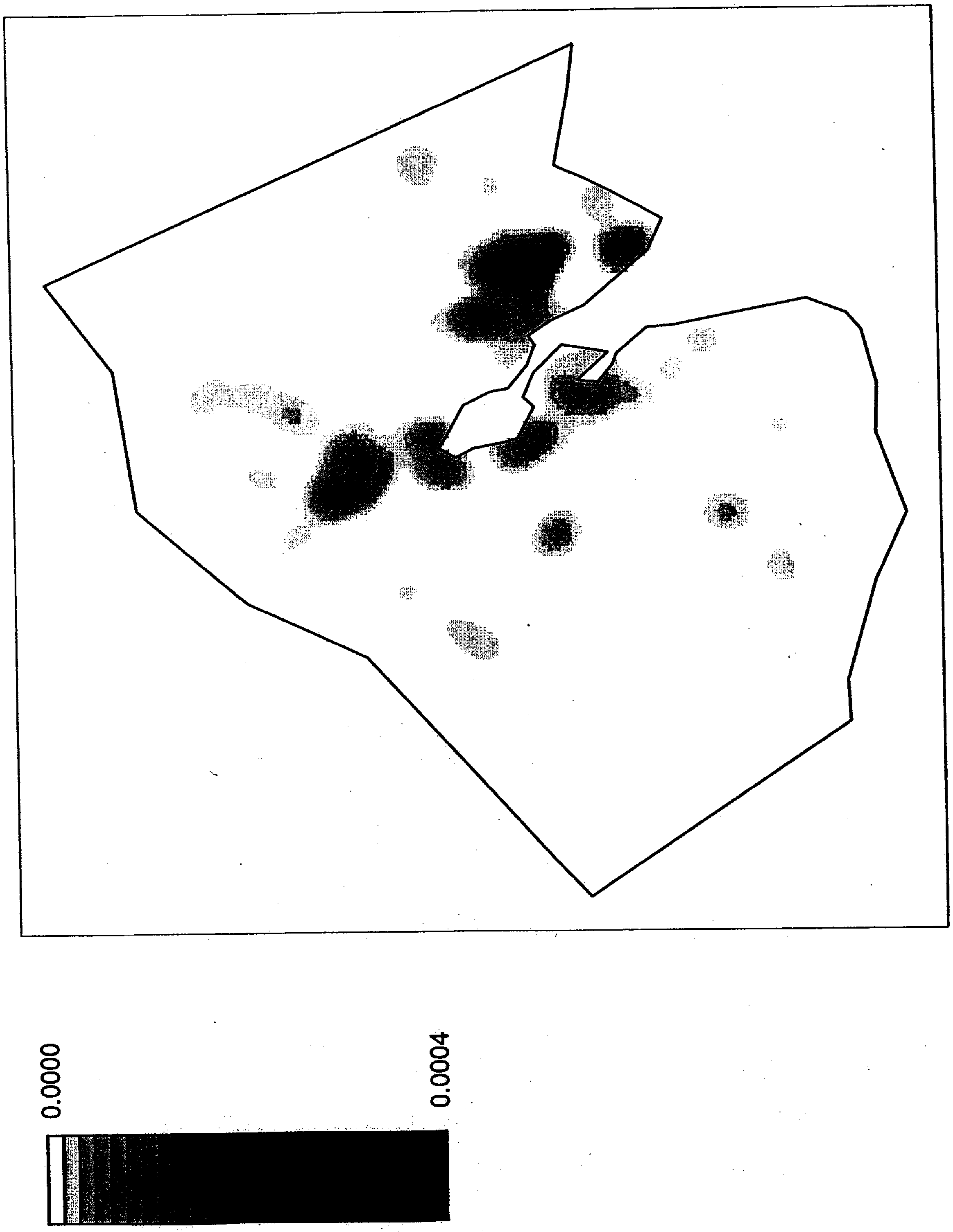


Figure 2-6c: Incremental residential land parcel development 1988-1996

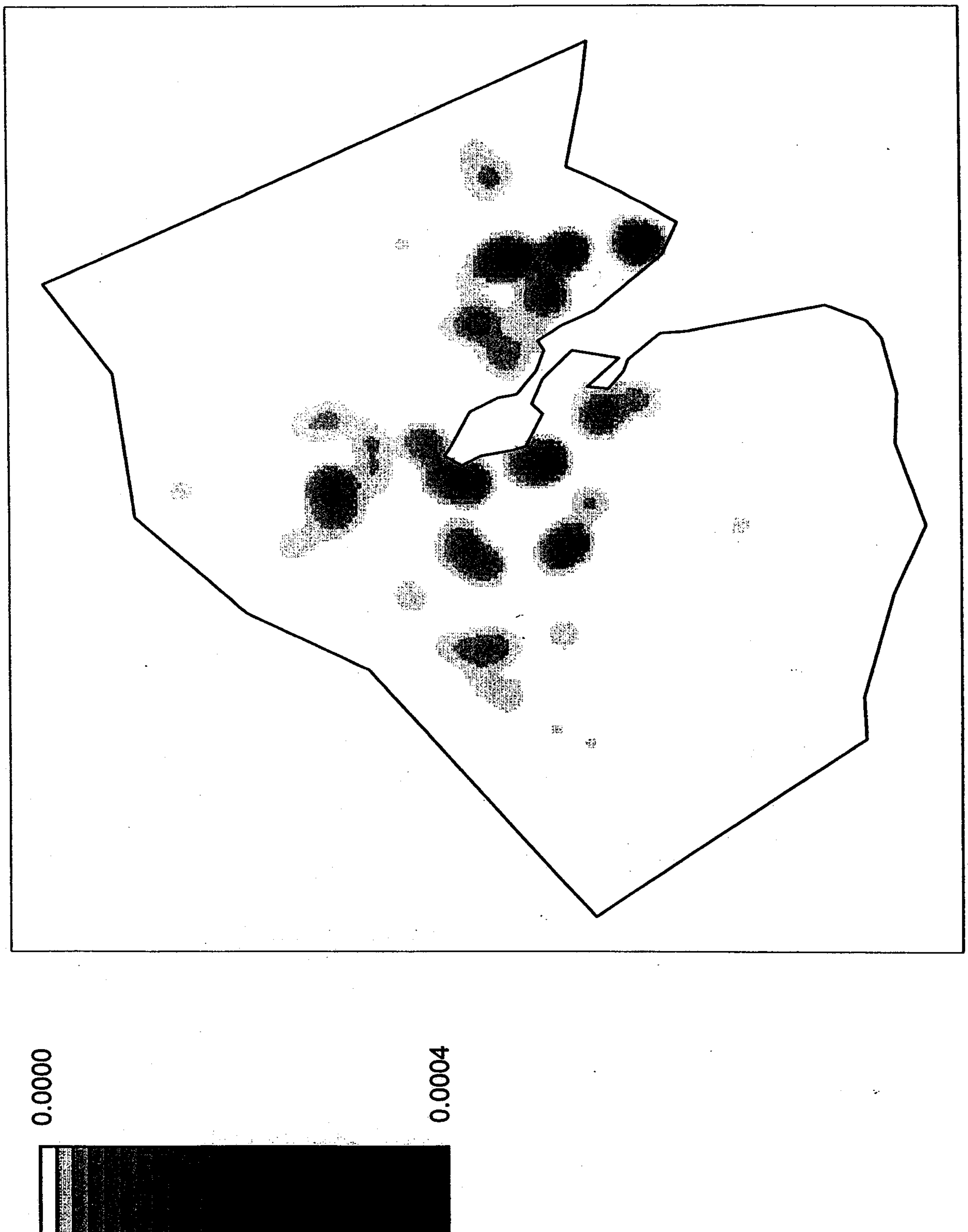


Figure 2-7a: Incremental commercial land parcel development 1970-1978

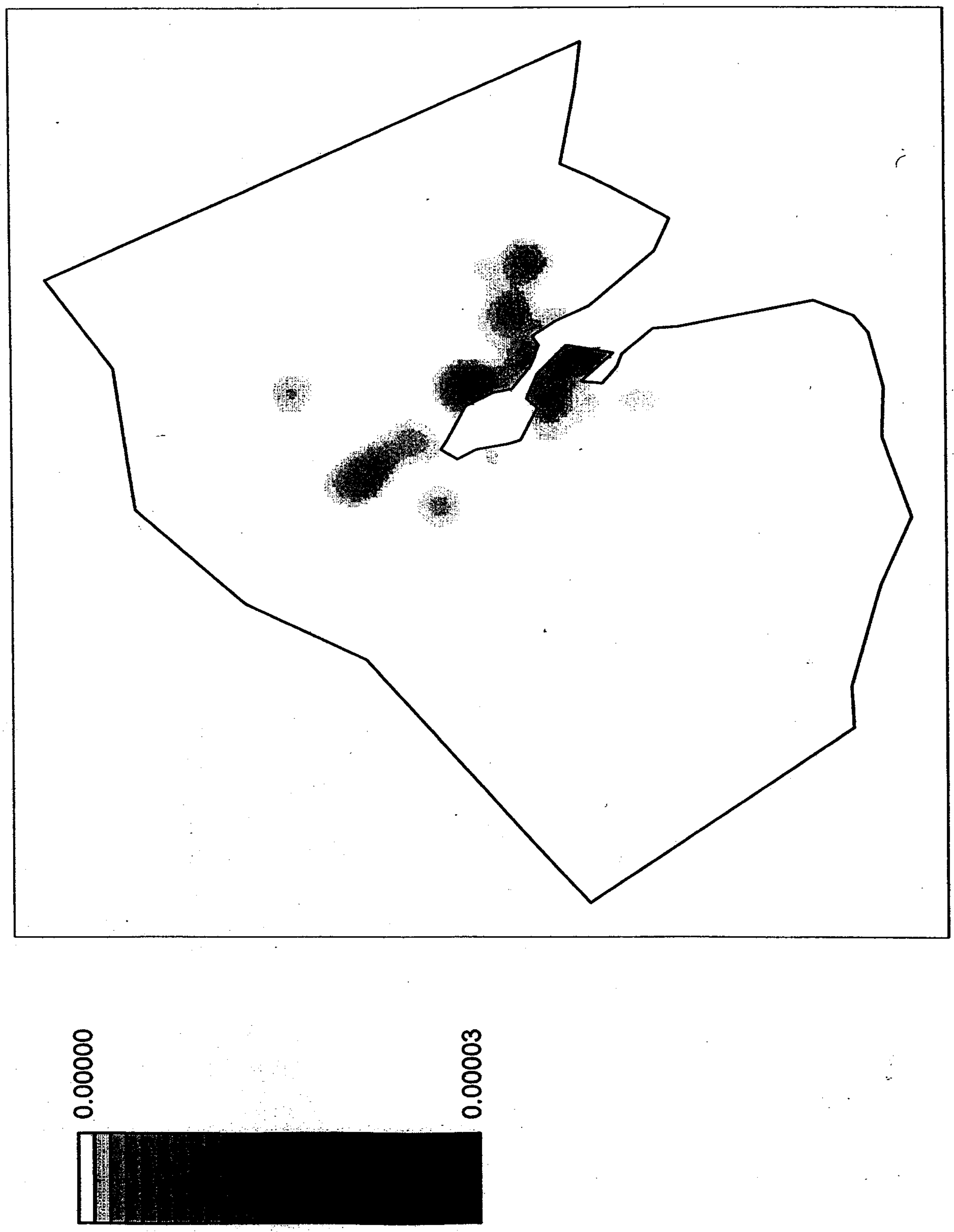


Figure 2-7b: Incremental commercial land parcel development 1979-1987

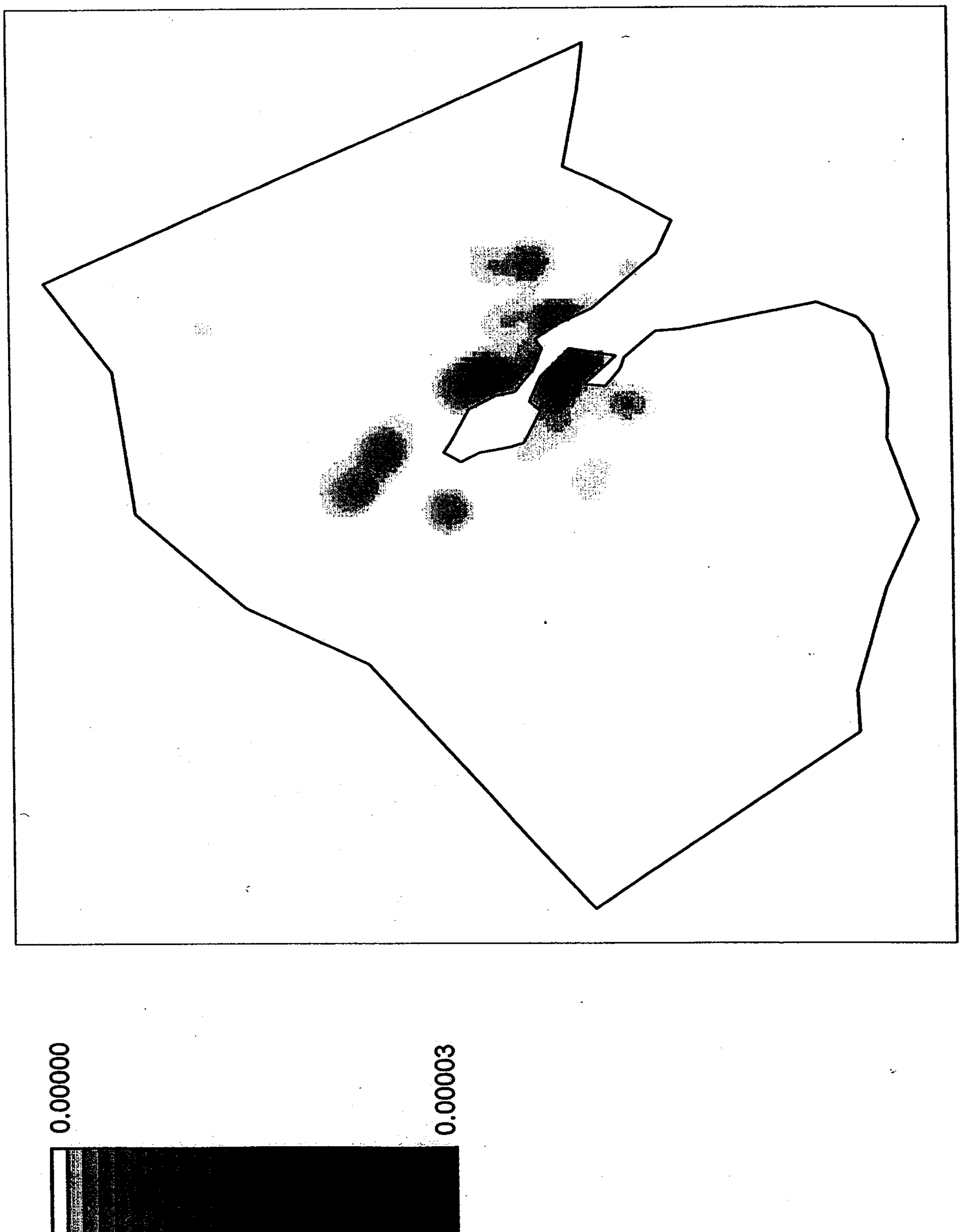


Figure 2-7c: Incremental commercial land parcel development 1988-1996

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CHAPTER 3: Using Spatial Statistics to Examine the Spatial Pattern of Urban Land Development in Halifax-Dartmouth

3.1 Introduction

For nearly 30 years, the monocentric models of Alonso (1964), Mills (1967), and Muth (1969) dominated urban land use theory. The monocentric model is characterized by a single centre of commercial and economic activity where employment and population densities are highest and decline exponentially outwards. More recently, some argue that suburbanization, decentralization, and dispersion have eroded the monocentric urban form (Berry and Kim, 1993). The result is a multinucleated (polycentric) urban form where employment and population are distributed in a pattern that has several foci.

Empirical research has been conducted to examine the change in urban form from monocentric to polycentric. Many studies document the changing pattern of population and/or employment locations that results from decentralization (Jordon *et al.,* 1998; Barkley *et al.*, 1996; Mieszkowski and Smith, 1991; Bourne, 1989; Gordon *et al.*, 1986; Edmonston *et al.*, 1985). The literature suggests that urban areas are experiencing a decentralization of population and/or employment. The outcome of this decentralization may range from dispersion and urban sprawl to multinucleation. Empirical results indicate that population and employment exhibit different decentralizing patterns; that is, population tends to be more decentralized than employment. Some studies suggest that this difference is a result of a lag between the decentralization of population and the decentralization of employment (Chinitz, 1991; Bourne, 1989). The implication for urban form is that in some urban areas, employment must continue to decentralize in a concentrated manner if a multinucleated urban form is to emerge.

The problem with much of the literature on urban form is the widespread use of the traditional negative exponential density function and reliance on aggregate zonal data. Despite the documented change in urban form from monocentric to multinucleated, many studies continue to employ the traditional negative exponential density function. Because the function measures the change in density with distance from a single city centre, it is not able to represent the non-monocentric nature of cities. Several studies have found that the negative exponential density function is inappropriate for contemporary cities because it attempts to summarize a complex pattern with a single parameter (Mieszkowski and Mills, 1993; Crampton, 1991; Anderson, 1985). The processes that underlie changes in urban form are probably too complex and varied to be captured by a single density gradient parameter.

Many empirical studies employ aggregate zonal data to estimate the density function. While such data are readily available, there are associated problems such as the "modifiable areal unit problem" (Fotheringham and Wong, 1991; Openshaw, 1984). Because zones are defined for a variety of purposes, actual values for any given variable will vary with the level of aggregation and with the configuration of the zoning system. Zonal data are also problematic when estimating densities because extensive unpopulated areas are included in the land area measurements of the zone. Peripheral zones in particular, are problematic, as they tend to be so spatially extensive that the population physically occupies a very small proportion of the land area. Despite their widespread use, the traditional exponential density function and aggregate zonal data provide a very limited picture of changes in urban form. This paper contributes to the literature by addressing these problems.

The objective of this paper is to provide an alternative method that employs point data to examine the locational patterns of population and employment and the resultant changes in urban form. Disaggregate parcel level point data are utilized to examine the spatial pattern of residential and commercial land development in Halifax-Dartmouth between 1970 and 1996. The locations of new residential and commercial land parcels explicitly identify where households and employment sites are locating. We employ these data in the estimation of the univariate and bivariate K functions. We use the univariate K function to test for spatial dependence or clustering among residential land parcels and for clustering among commercial land parcels. The bivariate K function provides a method to explicitly test for spatial dependence between the locations of new residential and commercial land parcels. The results will indicate whether clustering between residential and commercial land parcels is evident over the time period. Moreover, the univariate and bivariate K functions allow clustering to be analyzed over a wide range of spatial scales. As scale changes, different spatial patterns may emerge. Evidence of clustering at different scales will provide insight into the changing urban form of the region. Clustering of land parcels at large scales suggests metropolitan-wide clustering and perhaps even multinucleation. By comparing the scale of clustering over different time periods, the changing urban form of the Halifax-Dartmouth region may be examined.

To this end, we address the following research questions. Are new residential land parcels clustered over the entire time period? At what spatial scale are they clustered? We ask the same questions about commercial land parcels. Is the pattern of residential land development related to the pattern of commercial land development; that is, are new residential land parcels and new commercial land parcels clustered together? Finally, are residential and commercial land parcels decentralizing?

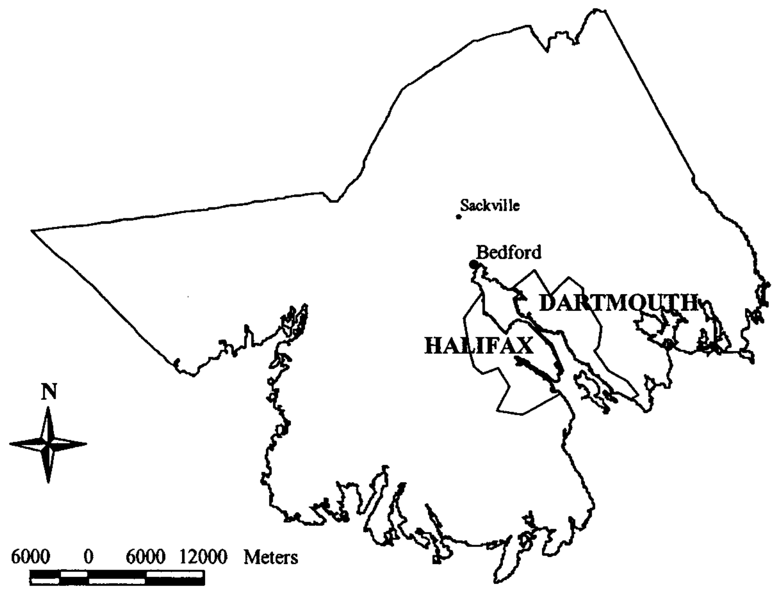
We organize the remainder of the paper as follows. First, we describe the study area and the data set. Next, we explain the univariate and bivariate K functions. Then, we examine the results of the K function estimates for evidence of spatial clustering between and among residential and commercial parcels at various scales. Finally, using the results of the K function estimates, we address the research questions.

3.2 The Study Area and Data Set

The Halifax-Dartmouth region is located along the southern shore of Nova Scotia. The region consists of the cities of Halifax and Dartmouth, the town of Bedford, and the remaining rural periphery. Because Halifax serves as the provincial capital and regional service centre, the regions' unemployment rate is low at 8.6% compared to the provincial rate of 13.3%. The region experienced a 6.4% population growth rate (annual average) over the period 1971 to 1996. The region had a population of approximately 356 000 in

2000. Figure 3-1 provides a map of the study area. The map also spatially defines the urban core, which we will refer to later in the paper.[1]

Figure 3-1: The study area



Parcel level point data are available for the study area for the period 1970-1996. In 1996, the region contained approximately 90 000 land parcels. Of those 90 000 parcels, 54 773 parcels were developed between 1970 and 1996. For each parcel, we have the following information: geographic coordinates, the year the parcel was created, and the land use type (i.e. residential or commercial). One variable that is missing is the size or

[1] The urban core is consistent with the 1971 census definition of the urban core for the Halifax Census Metropolitan Area consisting of the cities of Halifax and Dartmouth. An urban core is a large urban area around which a CMA (Census Metropolitan Area) is delineated. The urban core must have a population of at least 100 000.

area of each parcel, so unfortunately the size of residences or commercial establishments is unknown.

The availability of parcel level point data offers a valuable opportunity to examine the spatial pattern of population and employment locations. The development of residential and commercial land parcels is the underlying process that contributes to urban form. By simply examining the aggregate data provided in Table 3-1, it is evident that the majority of the residential land parcels are located in the periphery. Alternatively, the majority of the commercial land parcels are located in the core.

Table 3-1: Residential and commercial land parcel development in the Halifax-Dartmouth region

	1970-1978		1979-1987		1988-1996	
	Core	**Periphery**	**Core**	**Periphery**	**Core**	**Periphery**
Residential	3236 (20%)	12712 (80%)	5058 (29%)	12356 (71%)	3909 (24%)	12469 (76%)
Commercial	375 (55%)	309 (45%)	475 (59%)	333 (41%)	546 (61%)	345 (39%)

Over the entire time period, the periphery received the majority of residential land parcel development. Between 1970 and 1978, 80 per cent of all residential land parcels were developed in the periphery. This proportion decreased slightly between 1979 and 1987 when 71 per cent of the residential land parcels were developed in the periphery. The periphery increased its share of parcels between 1988 and 1996 with the development of 76 per cent of the residential land parcels.

Commercial land parcels exhibit a much different pattern of development. Between 1970 and 1978, the development of commercial land parcels was almost evenly split between the core (55 per cent) and periphery (45 per cent). Over the period 1979 to 1987, the core's share of new commercial land parcel development increased slightly to 59 per cent. Finally, between 1988 and 1996, the core captured 61 per cent of all new commercial land parcel development. Rather than decentralizing, these data suggest that commercial land parcel development became more centralized.

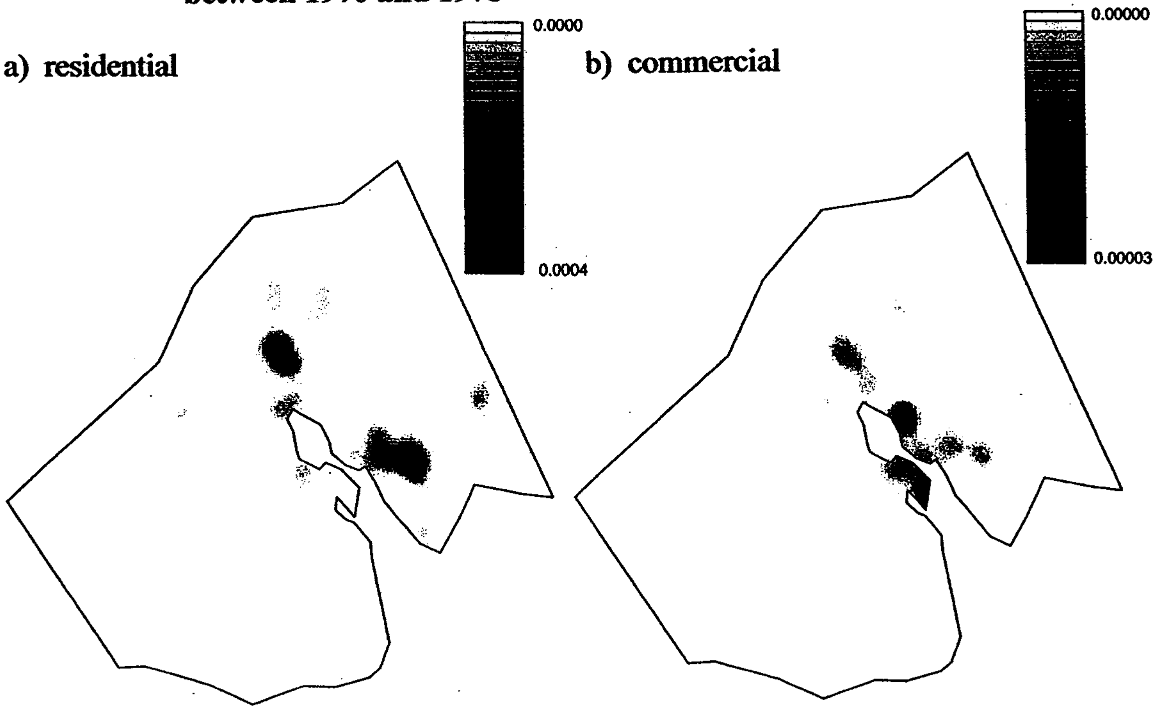
In previous research with this data set, we computed kernel estimates to measure the intensity of both residential and commercial land parcel development (Cuthbert and Anderson, 2001). The kernel estimate measures the variation in mean value or intensity of a process in space. In this case, we used the kernel estimate to measure the intensity of land parcel development. We mapped the results to provide a visual indication of the most intense areas of land development. This allowed us to evaluate variations in intensity both spatially and temporally.

The shading (gray scale) of the kernel maps in Figures 3-2a-b, 3-3a-b, and 3-4a-b corresponds to the intensity of land development where black is the highest intensity and white is the lowest. Because kernel estimation smoothes the data, white does not necessarily imply that no development exists. The intensity of development, i.e. number of parcels, may just be so low relative to other areas that the value of intensity does not fall in the range of the gray scale. Because the level of commercial development is so small compared to residential development, the gray scales have different maximum values. Thus, the actual value of intensity represented by the shade of gray cannot be directly compared between the commercial and residential kernel maps. However, the spatial pattern of development and the location of the most intense areas of development can still be compared.

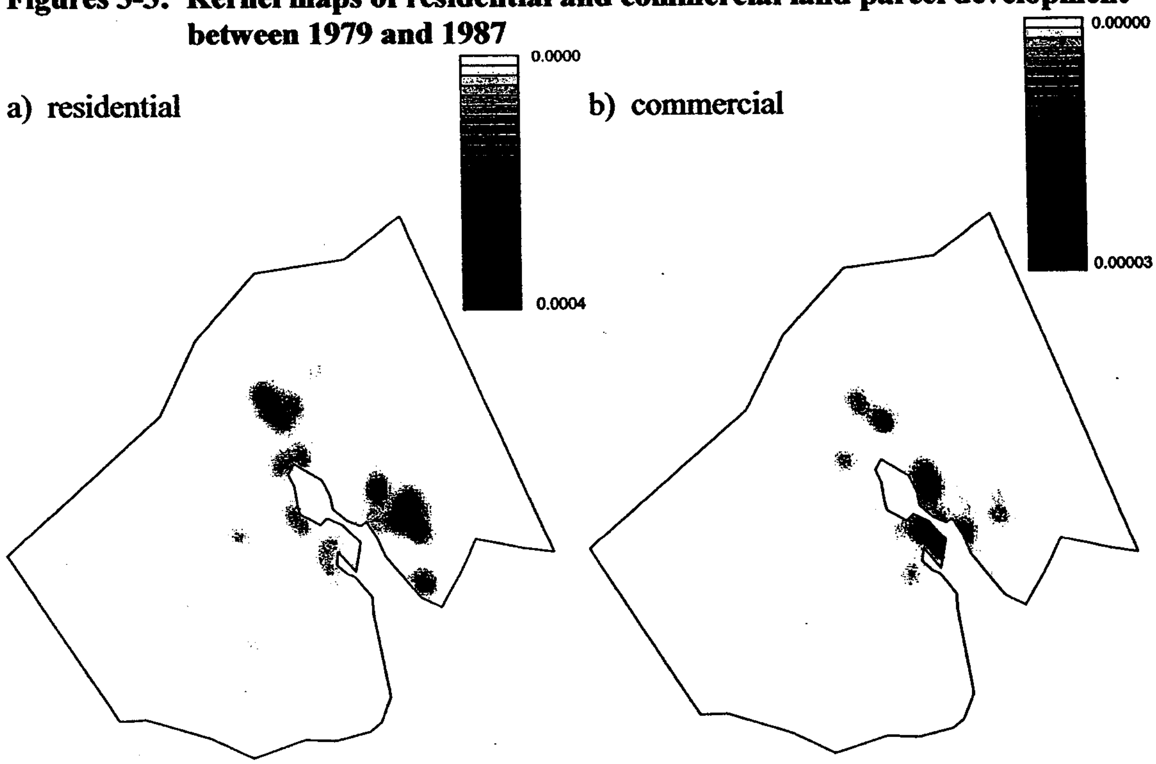
The resultant kernel maps in Figures 3-2a-b, 3-3a-b, and 3-4a-b indicate that residential development is much more decentralized than commercial development. The most intense residential development occurred outside the core, particularly in small peripheral communities. Commercial development, on the other hand, was concentrated in the core. However, some commercial development was also evident in smaller communities located in the periphery.

While the results of the kernel estimates suggest that the spatial pattern of new residential land parcels is more decentralized than commercial land parcels, the analysis provides no insight into the relationship between the locational patterns of residential and commercial land parcels. To examine this relationship, we require an explicit test for clustering between residential and commercial land parcels.

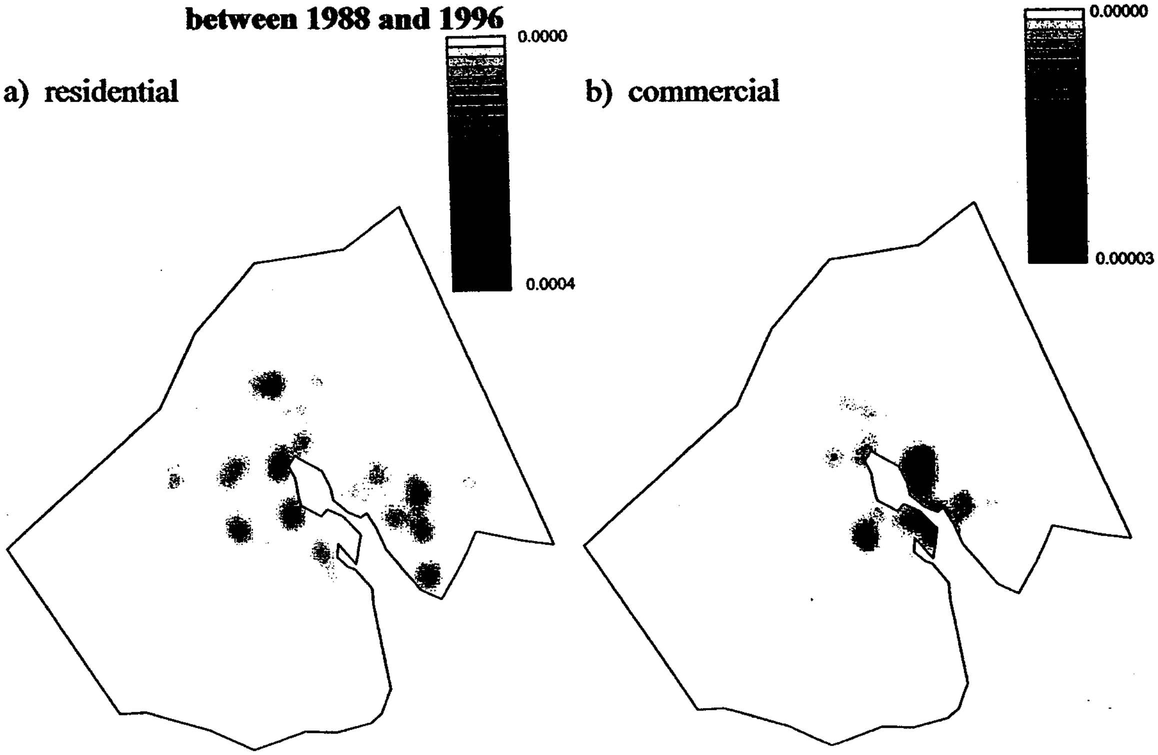
Figures 3-2: Kernel maps of residential and commercial land parcel development between 1970 and 1978



Figures 3-3: Kernel maps of residential and commercial land parcel development between 1979 and 1987



Figures 3-4: Kernel maps of residential and commercial land parcel development between 1988 and 1996



3.3 Univariate K Function

Given the problems associated with the traditional negative exponential density function and the aggregate zonal data used to estimate it, this paper provides an alternative methodology to examine urban form. Using parcel level point data, we investigate the urban form of the Halifax-Dartmouth region in an explicitly spatial manner using the univariate and bivariate K functions. While the kernel estimate provides a visual indication about the intensity of land parcel development, it provides no measure regarding spatial dependence or clustering of land parcel development. Getis (1983) employs a similar method in examining the residential population distribution of Chicago. However, the study employs aggregate zonal data to represent population. The results indicate a dispersion effect at distances up to 1 mile and then clustering at all spatial scales up to a distance of 15 miles (Getis, 1983). For other applications of the K function see Jones *et al* (1996), Barff and Hewitt (1989), and Barff (1987).

The univariate K function is an explicit test for spatial dependence or clustering among parcels. The univariate K function is defined as the expected number of parcels within distance h of a randomly selected parcel, divided by the overall intensity of parcels (Rowlingson and Diggle, 1993). To compute the K function, each parcel in the data set, in turn, is labelled i while all others are labelled j. A search radius h is established around parcel i. Within this radius, other j parcels are sought. The Euclidean distance between i and the next parcel j is represented by d_{ij}.[2] If a parcel is located within the circle around parcel i defined by h, it is recorded by an indicator function and the value of the estimator is incremented. This process is completed for every parcel in the study area.

Following the notation of Bailey and Gatrell (1995), the univariate K function is derived as follows. The intensity or mean number of parcels, λ, in region **R** is determined by:

$$\lambda = n / R \qquad (1)$$

where n is the number of parcels and R is the area of region **R.** For each of the n parcels, the expected number of parcels within distance h is given by the following:

$$\lambda K(h) = \text{E(\# parcels within distance } h \text{ of a randomly selected parcel)} \qquad (2)$$

[2] Given the peninsular topography of the Halifax-Dartmouth region, the use of Euclidean distance may be problematic. Because there are only two bridges that cross the peninsula, real world distances between some parcels will be longer than the Euclidean distance. This under-estimation may result in over-estimation of the intensity of clustering. Network distances had not been calculated when this paper was written.

where E( ) is the normal expectation operator. If the number of parcels in the region is determined by:

$$n=\lambda R \tag{3}$$

and the expected number of events within distance *h* of a specified parcel is given by:

$$\lambda K(h) \tag{4}$$

then the expected number of ordered pairs of parcels within distance *h* is given by:

$$(\lambda R)(\lambda K(h)) = \lambda^2 RK(h) \tag{5}$$

If d_{ij} is the distance between the *i*-th and *j*-th observed parcel in **R** and $I_h(d_{ij})$ is an indicator function which is 1 if $d_{ij} \leq h$ and 0 otherwise, then the observed number of such ordered pairs is:

$$\sum_{i=1}^{n}\sum_{j=1}^{n} I_h(d_{ij}) \tag{6}$$

Combining equations 5 and 6 and rearranging, an estimate of *K(h)* is as follows:

$$\lambda^2 R \hat{K}(h) = \sum_{i=1}^{n}\sum_{j=1}^{n} I_h(d_{ij}) \tag{7}$$

$$\hat{K}(h) = \frac{1}{\lambda^2 R}\sum_{i=1}^{n}\sum_{j=1}^{n} I_h(d_{ij}) \tag{8}$$

$$\hat{K}(h) = \frac{R}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n} I_h(d_{ij}) \tag{9}$$

One problem remains with the estimate of *K(h)* in equation 9, that being edge effects. Equation 9 excludes pairs of parcels for which the second parcel (parcel *j*) is located outside of region **R**. The equation must be edge corrected.

Consider a circle, centred on parcel i and passing through parcel j. Let w_{ij} represent the proportion of the circumference of the circle, which lies within **R.** This w_{ij} is the conditional probability that a parcel is observed in **R**, given that it is a distance d_{ij} from the i-th parcel. The edge-corrected estimate becomes:

$$\hat{K}(h) = \frac{R}{n^2} \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{I_h(d_{ij})}{w_{ij}} \tag{10}$$

We estimated the univariate K function using the SPLANCS software package running in the S-Plus programming environment. SPLANCS yields a plot with the estimated univariate K function at distance intervals up to distance h. According to Rowlingson and Diggle (1993), the general rule of thumb is to estimate the K function over a distance that is up to one-third the linear extent of the study area. At larger distances, the estimate becomes inefficient. In this case, the K function is estimated over distances up to 20 000 metres, which is one-third of the maximum extent of the study area. To test for significance, SPLANCS computes upper and lower simulation envelopes of the K function under complete spatial randomness. The confidence intervals provide a means to assess departures of the estimate of $K(h)$ from its theoretical value (Bailey and Gatrell, 1995). In this case, we use 100 simulations to estimate the confidence intervals. If the estimated univariate K function line is above the upper confidence interval, spatial dependence or clustering is present. If it is below the lower confidence interval, the parcels are dispersed. Values between the two limits indicate a random pattern.

The ability to test for clustering at different spatial scales (different values of h) is crucial, given the research objectives of this paper. Clustering of residential or commercial land parcels at small scales is to be expected, given the tendency of developers to co-produce units in residential subdivisions, industrial parks, and shopping plazas. Local clustering around highway intersections or along sewer and water lines is also to be expected. Clustering observed at much larger values of h, however, reveals a metropolitan-wide spatial structure and is therefore indicative of the formation of a few larger residential or commercial centres.

We estimated the univariate K function for residential land parcels that are developed during each of the three time periods: 1970-1978, 1979-1987, and 1988-1996. The results of the univariate K function for residential parcels indicate clustering at all spatial scales for each time period as the estimated K function line is above the upper confidence interval. We also estimated the univariate K function for commercial land parcels. Similarly, for each time period there is clustering of commercial land parcels at all spatial scales. Figure 3-5 provides an example of a univariate K function plot.[3]

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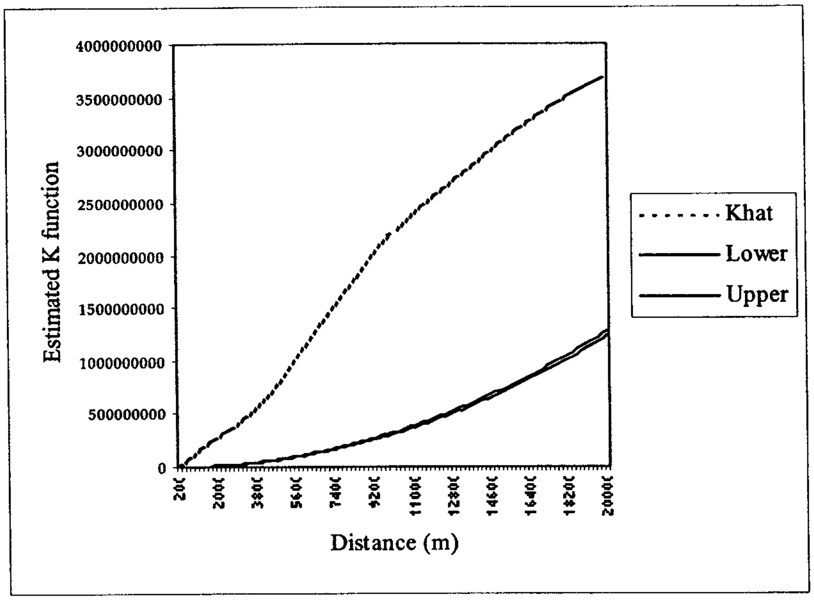
[3] Because the plots are virtually identical and to conserve space, only an example plot is provided.

Figures 3-5: Example of the univariate K function plot



3.4 Bivariate K Function

The bivariate K function is used to investigate the relationship between two spatial processes under the assumption of independence. The bivariate K function is defined as the expected number of points of pattern 1 within a specified distance *h* of an arbitrary point of pattern 2, divided by the overall density of the points in pattern 1 (Rowlingson and Diggle, 1993). We use the bivariate K function to determine if the pattern of occurrences of residential land parcels is related to the pattern of occurrences commercial land parcels.

Following the same notation as the univariate K function, the edge corrected $K_{ij}(h)$ is defined as:

$$\tilde{K}_{12}(h) = \frac{R}{n_1 n_2} \sum_{i=1}^{n_1} \sum_{j=1}^{n_2} \frac{I_h(d_{ij})}{w_{ij}} \tag{11}$$

where R is the area of the region **R**, n is the number of parcels, d_{ij} the distance between the i-th type 1 parcel and the j-th type 2 parcel, the indicator function $I_h(d_{ij})$ is 1 if $d_{ij} \leq h$ and 0 otherwise, and w_{ij} is proportional to the circumference of a circle (that is centred on the i-th type 1 parcel, passing through the j-th type 2 parcel) which lies within **R**.

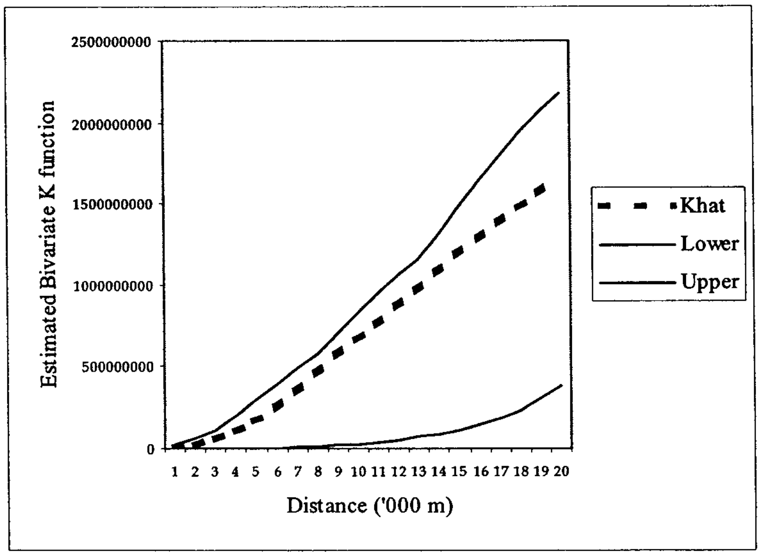
We estimated the bivariate K function using SPLANCS, which again yields a plot with the estimated bivariate K function at distances up to h. Additionally, SPLANCS computes upper and lower confidence intervals from a random toroidal shift of one point pattern relative to the other. If the estimated bivariate K function line is above the upper confidence interval, spatial dependence or clustering is present.

The bivariate K function is estimated for residential and commercial land parcels for each of the three time periods. Figure 3-6a plots the estimates of the bivariate K function for 1970-1978. Because the line of the estimate falls between the upper and lower confidence intervals, there is no clustering between residential and commercial land parcels. Figure 3-6b plots the results of the bivariate K function for 1979-1987. Some clustering between residential and commercial parcels is evident at 1 km as the broken line is above the upper confidence interval, but no clustering is apparent at other spatial scales. Figure 3-6c plots the estimates of the bivariate K function for 1988-1996.

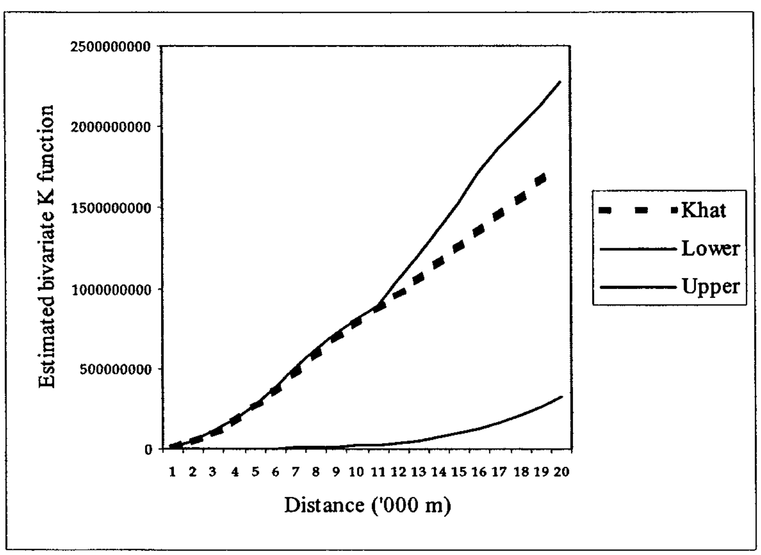
Residential-commercial clustering is evident at several distances: 0-2 km, 9-10 km, and at 13 km[4]. At the remaining spatial scales, no clustering is apparent.

Figures 3-6: Bivariate K function results

a) 1970-1978

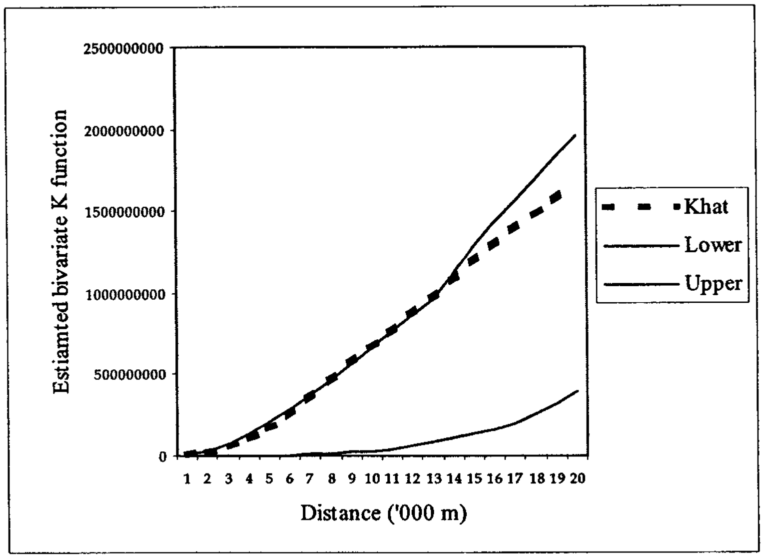


b) 1979-1987



[4] Visual closeness between the estimate and the confidence intervals led to inspection of the actual numbers.

c) 1988-1996



3.5 Discussion

The results of the univariate K function for residential land parcels indicate that the parcels are clustering together at all spatial scales. These results are also consistent over the three time periods. The clustering of residential parcels is not surprising given the nature of residential development. While some infill development is apparent from the previous kernel analysis, the majority of the residential development is contiguous to existing development. Because residential land parcel clustering is evident at all spatial scales, it cannot be attributed solely to subdivisions. Subdivision development would be indicative of highly localized clustering. However, clustering at large scales suggest the presence of larger sub-centres of residential development.

The univariate K function for commercial land parcels also reveals clustering at all spatial scales and over the entire time period. Again, such clustering, particularly clustering at large scales, is not surprising given the nature of commercial land development. Throughout the entire time period, some infill commercial development is evident in the Halifax-Dartmouth core. However, the majority of the commercial development is located in a few major industrial parks located on the outskirts of Halifax, Dartmouth, and Bedford.

The bivariate K function examines the extent and scale of mutual clustering between residential and commercial land parcels. During the first time period 1970-1978, there is no evidence of clustering between the two types of parcels. The results suggest that independent processes drive the locational patterns of new residential and commercial land parcels. These results are reflected not only in the aggregate data presented in Table 3-1 where 80 per cent of new residential land parcels and 45 per cent of new commercial land parcels were located in the periphery, but also in the kernel maps presented in Figures 3-2a-b. The kernel maps indicate that the most intense commercial land parcel development is located in the core while the most intense residential land parcel development is located in the periphery.

The results of the bivariate K function for the period 1979-1987 indicate clustering between residential and commercial parcels at a distance of 1 km. This spatial scale of clustering suggests that commercial and residential land parcels are being developed in close proximity to each other. However, such highly localized clustering suggests that this pattern of development is not evenly distributed throughout the region. From the kernel maps in Figures 3-3a-b, it is apparent that the development of proximate commercial and residential land parcels between 1979 and 1987 is concentrated in the cities of Halifax and Dartmouth, and the communities of Bedford and Sackville.

For the period 1988-1996, the results of the bivariate K function suggest clustering between commercial and residential land parcels at a much wider spatial scale. Clustering is evident at distances between 0 km and 2 km and at 9 km, 10 km, and 13 km. While there is localized clustering at distances less than 2 km, clustering is evident over a larger portion of the region. The kernel maps in Figures 3-4a-b indicate that the most intense residential development is located in several clusters in the periphery of Halifax-Dartmouth. The most intense commercial development is located on the outskirts of Halifax-Dartmouth. By interpreting the results of both the bivariate K function and the kernel estimates, the commercial land parcel development in the outskirts is significant enough to exhibit clustering with residential land parcels at several spatial scales.

In general, the results suggest that residential land parcels cluster together and commercial land parcels cluster together. Additionally, it is apparent through time that residential and commercial land parcels have become more clustered with each other. While the results of the kernel estimates suggest that the location of new residential land parcels is decentralizing to a greater extent than commercial land parcels, the results of the bivariate K function provide additional insight. The fact that residential-commercial land parcel clustering is increasing through time indicates that the location of new commercial land parcels may be decentralizing to a greater extent than is revealed in the kernel estimates. Moreover, the trend over time to clustering at large scales suggests the emergence of sub-centres in the Halifax-Dartmouth region.

Determining what the results suggest about the changing urban form of the Halifax-Dartmouth region remains a difficult proposition. Whether Halifax is a multinucleated region is difficult to say. If the trend continues and commercial land parcels continue to become more clustered with residential land parcels at large scales, a multinucleated urban form may appear in the future. As suggested by Bourne (1989) and Chinitz (1991), employment must decentralize in a concentrated manner if a multinucleated urban form is to emerge. The results of the bivariate K function suggest that this may be occurring in the Halifax-Dartmouth region.

When considering the other conclusions drawn by Bourne (1989) and Chinitz (1991), the results of the bivariate K function are even more interesting. Both Bourne and Chinitz suggest that a lag exists between the decentralization of population and the decentralization of employment. The results of the bivariate K function indicate that residential and commercial parcels are becoming more clustered through time. From these findings, two questions arise. First, is this increased clustering over time a result of a time lag between commercial and residential land parcel development? Second, if there is no lag, are there two different processes operating in the earlier time periods, one influencing the location of population and the other the location of employment? As time progressed, have these processes become more dependent?

We estimated bivariate K functions with time lags up to 5 years to explore the possibility of a lag between residential land parcel development and commercial land parcel development. The results were inconclusive in that there was no more clear evidence of clustering than in the contemporaneous results. An examination of the development and planning environment in the Halifax-Dartmouth region may provide additional insight.

Several important factors have played a role in the pattern of land development in the Halifax-Dartmouth region. Heterogeneity of the land influences the pattern of development in terms of limiting what land can and cannot be developed. The presence of lakes also influences the spatial pattern of land development. Finally, transportation infrastructure development has improved the accessibility of certain locations thereby increasing the attractiveness of these locations for development. Considering these factors, planning controls may have also influenced the pattern of growth by directing development to certain areas.

Understanding the role and effect of planning in the region is a difficult proposition. Before 1996, there were four separate planning agencies within the region corresponding to four distinct municipalities: the cities of Halifax and Dartmouth, the town of Bedford, and Halifax County[5]. Each agency had its own municipal plan, which was often incongruent with the other agencies in the region. The result was a power struggle between municipalities. Competition among the municipalities to attract development led to the annexation of land, often at the expense of Halifax County.

In 1969, the province introduced a Planning Act, which gave primacy to regional planning over municipal planning. The Act encouraged the formation of the Metropolitan Area Planning Commission (MAPC). By 1975, MAPC had developed the Halifax-Dartmouth Regional Development Plan. The plan established an Urban Development Boundary (UDB) beyond which sewer and water services would not be extended. The boundary served as a measure to control urban sprawl and to encourage

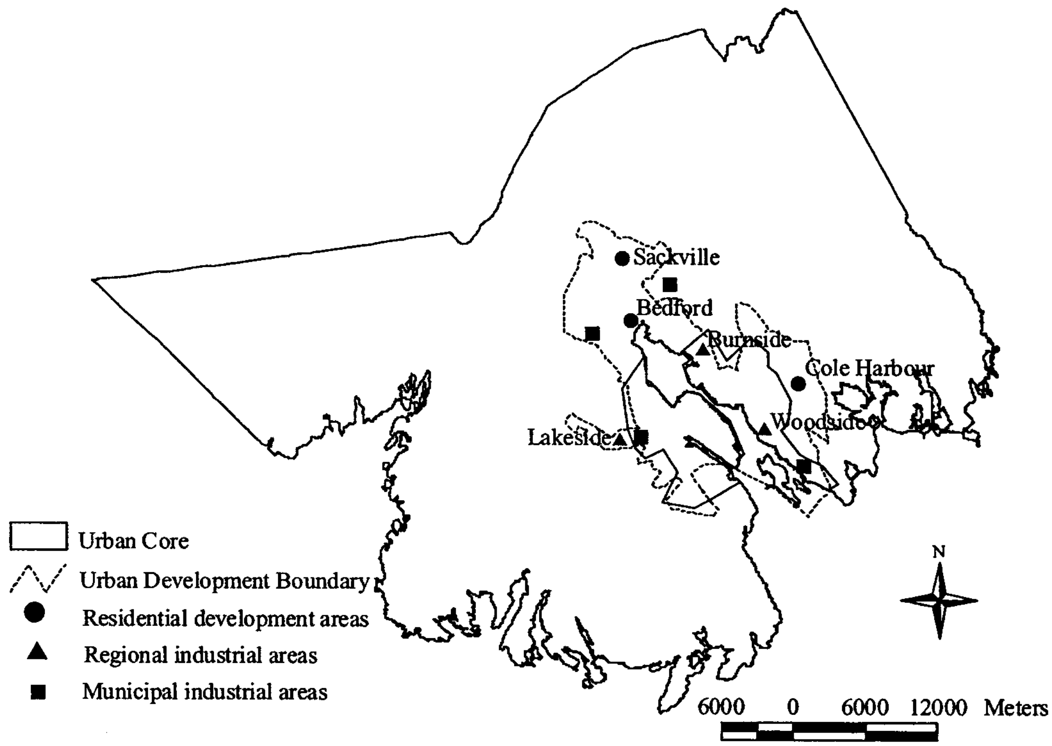
[5] The four municipalities were amalgamated in April 1996 to form the Halifax Regional Municipality.

development in areas that were already serviced. The plan also made recommendations in terms of directing new development. Most new residential development was directed to Bedford, Sackville, and Cole Harbour where sewer and water service was being under-utilized. Industrial development was directed to three locations: Burnside, Woodside, and Lakeside. Figure 3-7 delineates the UDB and highlights these residential and industrial locations. The regional plan was also to be used as a framework for municipal planning.

Despite the primacy given to regional planning, the Halifax-Dartmouth Regional Development Plan had limited success. Interviews with planners at the Halifax Regional Municipality suggest that planning controls were permissive during this time period as the municipalities were able to maintain autonomy over planning and development. MAPC was essentially redundant as all municipalities had their own plans. The municipalities continued to compete for development, particularly industrial development, by developing their own industrial parks. Figure 3-7 also shows the locations of municipal industrial areas. A new Planning Act was introduced in 1983, which gave primacy to municipal planning.

Although the regional plan seemed to have little success, some influence is apparent in the pattern of residential and commercial growth. The univariate K function for residential land parcels indicates clustering at all spatial scales. The Urban Development Boundary was successful in keeping most residential development contiguous to existing development. However, the large scale clustering suggests sub-centres of residential development. The regional plan may also have been successful in directing residential growth to Bedford, Sackville, and Cole Harbour. The univariate K function for commercial land parcels also indicates clustering at all spatial scales. The clustering at large scales may be a result of the development of the industrial parks recommended by the regional plan. The kernel maps also show evidence of this residential and commercial clustering.

Figure 3-7: Residential and industrial development areas



The results of the bivariate K function indicate that residential and commercial land parcels have become more clustered with each other through time. Again, the regional plan may have influenced development and the mutual clustering of residential and commercial parcels. Before the regional plan, the majority of residential development was located in the periphery while the majority of commercial development was located in the core. The bivariate K function results show no evidence of clustering over the first time period. Some mutual clustering was apparent in the bivariate K function results over the time period 1979-1987. This clustering may have been due to the regional plan directing industrial development to areas at the edge of the urban core. The effect is that in localized areas, the commercial land parcels became closer to the residential parcels in the periphery. The clustering between residential and commercial land parcels at much wider spatial scale over the final time period may have resulted from the development of the municipal industrial parks. The peripheral locations of the industrial parks combined with the decentralization of residential land parcels may have contributed to the mutual clustering.

From a methodological viewpoint, the combined use of the kernel estimate and K function is an alternative way to investigate the changing locational patterns of population and employment, and the resultant change in urban form. While the kernel estimate visually indicates the areas of most intense development, it does not provide any insight into spatial dependence between residential and commercial land parcels. The K function provides a statistical measure of the scale and significance of clustering to augment the visual representation of where new residential and commercial land parcels are being developed. This combined method is also advantageous over the traditional negative exponential density gradient because it is applicable for the non-monocentric nature of contemporary urban areas. Additionally, this method employs parcel level point data thereby offering a valuable opportunity to explore locational patterns and urban form at a very detailed spatial scale.

3.6 Summary

Using disaggregate parcel level point data, this paper explores the location, pattern, and timing of new residential and commercial land parcels in the Halifax-Dartmouth region between 1970 and 1996. By estimating univariate and bivariate K functions, the paper examines the scale and significance of clustering among residential land parcels, among commercial land parcels, and of clustering between residential and commercial land parcels. The results of the analyses provide insight into the spatial processes underlying the changing urban form of the Halifax-Dartmouth region.

This paper contributes to the literature on urban form by employing a method that takes advantage of disaggregate data. The K function employs parcel level point data as opposed to aggregate zonal data, which are commonly used in the calculation of population and employment density functions. The results of the univariate K function were not surprising; residential land parcels are clustered and commercial land parcels are clustered. The results of the bivariate K function are more interesting as they provide insight into the changing urban form of the region. The results of the bivariate K function suggest that residential and commercial land parcels are becoming more clustered through time. If such a trend continues, a multinucleated urban form may appear in the future.

The findings of this research present some interesting questions for future work. Primarily, is there a lag between the decentralization of population and the decentralization of employment? Alternatively, are there two separate processes that contribute independently to the decentralization of population and to the decentralization of employment? Spatial statistics such as the K-function can provide valuable insight by measuring spatial co-variation. To address these questions however, further analysis into the causal mechanism that underlies urban growth and development is required.

3.7 References

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CHAPTER 4: An Empirical Analysis of the Impact of Road Development on Residential Land Development in Halifax-Dartmouth

4.1 Introduction

There has been much debate regarding the nature of the relationship between transportation and land use. Numerous studies have examined the impact of transportation on land use by studying the economic impacts of transportation investments (For examples see Harmatuck, 1996; Rietveld, 1994; Baird and Lipsman, 1990; Forkenbrock and Foster, 1990). Many others have examined the impact of land use on transportation by studying the impact of urban form on travel patterns (For examples see Kockelman, 1997; McNally and Kulkarni, 1997; Handy, 1993). The results of such studies have raised questions regarding the direction and strength of the transportation-land use relationship. This paper and a companion paper (Cuthbert *et al.*, 2001) attempt to address such questions by drawing an empirical link between transportation and land use.

The objective of the research is to quantify the strength of both directions of the transportation-land use relationship to determine if the relationship is uni-directional or bi-directional. The companion paper explores the impact of residential land development on road development. The objective of the present paper is to examine the other direction of the transportation-land use relationship; that is, the impact of road development on residential land development. Specifically, this paper addresses the research question "does road development influence residential land development"?

While there is much debate concerning the relationship between road development and land development, the conceptual underpinnings of this paper are based on the hypothesis that road development influences land development by changing the spatial pattern of accessibility. The nature of the road network determines the accessibility of a given location. When improvements to the road network occur, accessibility will increase in some places. This paper tests two hypotheses regarding the relationship between road development and land development. The first hypothesis tests the impact of road development on land development at a regional scale while the second hypothesis tests the impact at a local scale. The first hypothesis is that the probability that a given location will be developed is greater if the accessibility of that location increases. A measure is devised to capture the effect that road development has on accessibility at all points throughout the region. The second hypothesis is that the probability that a given location will be developed is greater if it is close to a high-speed road. We use distance to a high-speed road to measure local impacts of road development.

Using data from the Halifax-Dartmouth region, we estimate an ordered probit model to examine the impact of road development on land development. We represent road development by the change in accessibility and distance to a high-speed road and land development by residential land parcel development. In general terms, the model estimates the probability that a given number of land parcels are developed as a function of accessibility or distance to a high-speed road, and several other explanatory variables.

The results of this research have important policy implications. Given the numerous environmental impacts of both road and land development, there is an increased urgency for policy makers to make informed decisions. With a better understanding of the relationship between road development and land development, the impacts of such development may be addressed.

We organize the remainder of the paper as follows. First, we provide an overview of the literature pertaining to the relationship between transportation and land use. Next, we explain the conceptual underpinnings of the research. Then, we describe the data set, the modeling approach, and the empirical model. Finally, we examine the model results and discuss the implications of the findings.

4.2 Literature Review

Over the past forty years, many studies have examined the relationship between transportation and land use. Many studies have explored this relationship by examining the economic growth effects of transportation investments. However, very few studies have explored transportation-land use interactions by explicitly examining the spatial relationship between transportation development and land development.

Historically, the literature suggests that a strong relationship exists between transportation and land use. Adams (1970) associates urban growth patterns with technological advancements in transportation. When walking and horsecar were the main modes of transportation, urban centres had strong urban cores and high population densities. With the introduction of electric streetcars, residential development moved from the urban core to the periphery. Later, the advent of the automobile had an unprecedented effect on urban centres. The result was deconcentration, low-density development, and a further expansion of the urban boundary.

The evolution of urban form is based on the role of transportation in shaping the locational decisions of developers. The basic concept underlying locational decisions is accessibility. In the 19th century, von Thünen (1842) recognized that the value of agricultural land depends on accessibility. Land that is closer to markets or is linked by superior road access is more valuable. In the 20th century, Alonso (1964) extended the ideas of von Thünen to residential land values. Because the location of transportation infrastructure determines the accessibility of places, land values and land use reflect the locational advantages of transportation infrastructure. Location theory predicts any transportation infrastructure development that improves accessibility will be capitalized in land values and reflected in land use changes (Giuliano, 1995).

Many early transportation studies were based on location theory and examined the impact of transportation investments on land values. Results reveal that the value of land adjacent to highways is significantly higher (Transportation Research Board, 1995; Czamanski, 1966; Adkins, 1959). More recent studies have examined land use along highways. While these studies are purely descriptive, they do note the tendency for clustering around major interchanges and for linear development along highway frontages (Transportation Research Board, 1995; Giuliano, 1989).

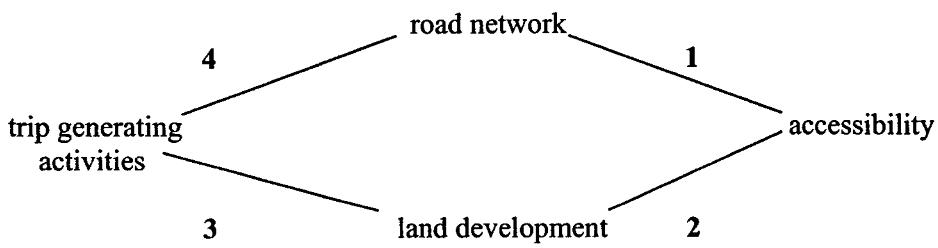
The majority of more recent studies examine the transportation-land use relationship by studying the economic growth effects of highway investments (For examples see Harmatuck, 1996; Rietveld, 1994; Baird and Lipsman, 1990; Forkenbrock and Foster, 1990). Such studies focus on the impact of transportation infrastructure expenditures or the economic activity resulting from expenditures.

Four decades of research have examined the impact of transportation infrastructure development on land values and economic growth. While earlier studies consistently indicate positive land value impacts, the results of more recent studies are mixed. However, no prior study has attempted to examine the transportation-land use relationship empirically by examining the spatial pattern of development. Unlike past research, this paper examines the spatial pattern of development resulting from transportation infrastructure development rather than just land values or aggregate economic growth. This paper examines land development, as opposed to economic development, and road development, as opposed to infrastructure expenditures.

4.3 Conceptual Framework

We base the research questions addressed in this paper and the companion paper on the conceptual framework outlined in Figure 4-1. The figure illustrates the two possible directions of the transportation-land use relationship. Steps 1 and 2 reflect the impact of road development on land development that results from changes in accessibility. Steps 3 and 4 show the impact of land development on road development that results from trip generating activities. The objective of this paper is to examine the impact of road development on land development.

Figure 4-1: The transportation-land use relationship



Source: Adapted from Giuliano (1995)

In Step 1, changes to the road network lead to changes in accessibility. In simple terms, accessibility is the potential for interaction. Most measures define accessibility as a function of a measure of attractiveness and the transportation system. The measure of attractiveness reflects the spatial distribution of activities. The transportation system reflects the ease of travel between different locations. This ease of travel is typically measured by travel distance, time, or cost. Both the structure and capacity of the road network influence the accessibility of different locations. Thus, the construction of a new road or the widening of an existing road will increase accessibility because of the resultant changes in travel distances, times, or costs.

Increases in accessibility may influence land development as reflected in Step 2. Given the transportation and attractiveness elements of the accessibility measure, locations with high accessibility are easier to get to and more attractive as destinations relative to other locations. Theory suggests that as the ease of travel between different locations increases, the propensity for interaction increases. Because of the increased propensity for interaction, locations with higher accessibility are more attractive to land developers. Thus, changes in accessibility may affect land development.

Land development in turn, affects travel patterns. As Step 3 illustrates, land development results in the establishment of trip generating activities. When land is undeveloped, it does not generate traffic. However, when land is developed, it then has an associated land use such as residential, commercial, or industry. These land uses do generate traffic.

Step 4 illustrates the impact of trip generating activities on the road network. Trip generating activities lead to increased traffic on the road network. In response to this traffic, the network may be expanded. New roads will be built or existing roads will be expanded to accommodate the increased traffic. If land development occurs in the absence of road development, there may be political pressure to build more roads. However, if the network is not expanded and the increased traffic is greater than the capacity of the network, the result is a deterioration of travel conditions due to traffic congestion.

The conceptual framework illustrates the two possible directions of the transportation-land use relationship. However, the framework gives no indication of the strength of the relationship. Does the road network have a stronger impact on land development, or does land development have a stronger impact on the road network? The models offered in this paper and the companion paper address these questions.

4.4 The Study Area

The Halifax Regional Municipality covers a 6200 square kilometre area along the southern shore of the Province of Nova Scotia. Located within the municipality are the cities of Halifax and Dartmouth, and the town of Bedford. Over the study period 1971 to 1996, the majority of both land development and road development occurred in the western half of the municipality, particularly in the vicinity of Halifax, Dartmouth, and Bedford. The eastern portion of the municipality is primarily sparse rural development. For the purposes of this research, the analysis focuses on the western half of the municipality. We refer to this area as the Halifax-Dartmouth region. Figure 4-2 provides a map of the study area showing the locations of Halifax, Dartmouth, and Bedford. The map also spatially defines an urban core and an urban development boundary (UDB), both of which we discuss later in the paper[1].

4.5 The Data Set

4.5.1 Land Development

We employ time series data on residential land parcel development in the region between 1971 and 1996 to represent land development. Each individual land parcel is defined by geographic coordinates. For each year, the data precisely indicate where land is being developed. Unfortunately, the size of each parcel is not known. Using the land parcel data, we derive the dependent variable and several explanatory variables.

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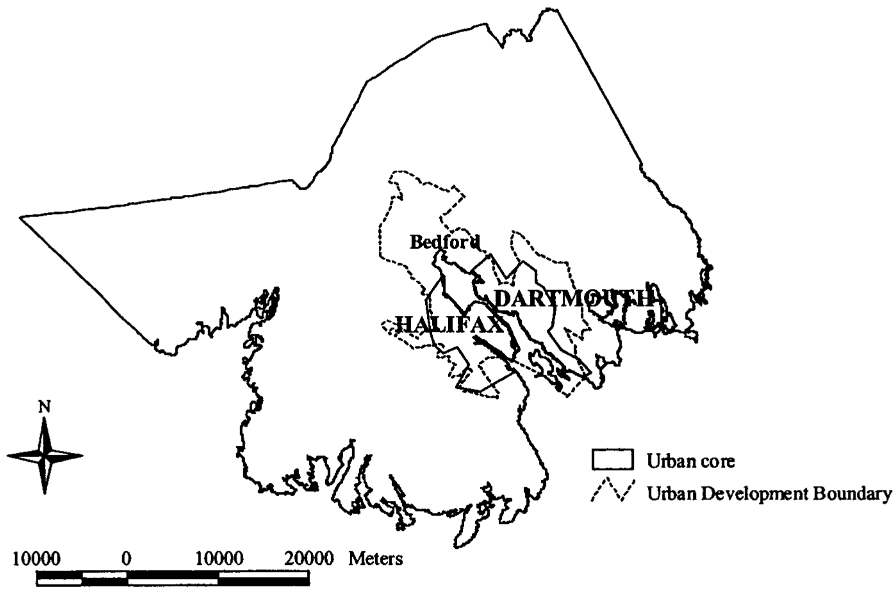
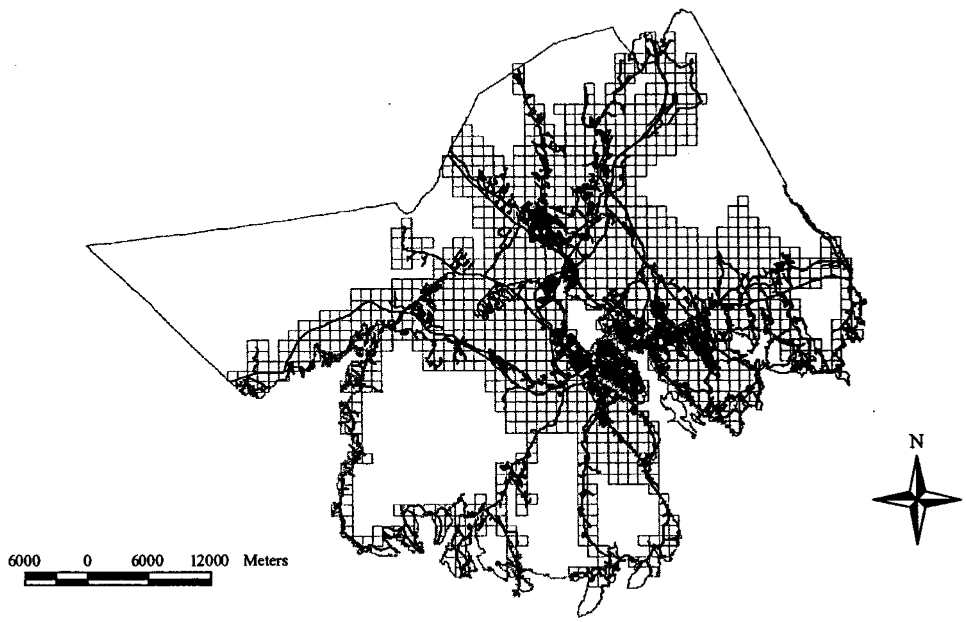
[1] The urban core shown in the map corresponds to the urban core defined by the 1971 Census of Canada. An urban core is a large urban area around which a CMA (Census Metropolitan Area) is delineated. The urban core must have a population of at least 100 000.

Figure 4-2: The study area



A methodological issue in examining the relationship between road development and land development is the fact that we are dealing with both line and point features. To reconcile this, we adopted a grid cell approach. Using ArcView GIS, we overlaid a lattice of 1 km by 1 km grid cells on a map of the road network. Grid cells of this size are small enough that each cell captures the homogeneity of the underlying transportation, land use, and population characteristics. To ease the computational requirements, we removed grid cells that were further than 1 km from a road and/or did not experience land parcel development over the time period 1971 to 1996. The total number of remaining grid cells was 1144. We used the grid cell as the spatial unit of analysis. Figure 4-3 illustrates this grid cell approach.

Figure 4-3: The grid cell approach



Using a simple ArcView script, we computed a count of the number of parcels that were developed in each grid cell during 5 time periods (1971-1976, 1976-1981, 1981-1986, 1986-1991 and 1991-1996). These land parcel counts represent the dependent variable.

We also used the residential land parcel data in the derivation of explanatory variables. We measure the total amount of development as the aggregate number of developed parcels in the grid cell. We expect an inverted U-shaped effect where initially there is a positive relationship between the aggregate number of parcels and the number of parcels developed in the current time period. Grid cells that are already developed are likely to experience more development. There is a contagious effect. However, there may be a point when a grid cell cannot sustain any more development because all available land has been consumed. To capture the fact that the total amount of development could have a negative effect on current development, we include the aggregate number of parcels squared as an explanatory variable. The two aggregate parcel variables represent a quadratic function; that is, the inverted U-shaped effect.

We measure previous land development by the number of parcels developed in a grid cell during the previous time period. Again, we hypothesize a positive relationship due to a contagious effect. Grid cells that experience land development in the previous time period are more likely to experience land development in the current time period.

4.5.2 Transportation

We collected data regarding the evolution of the arterial and collector road network from provincial transportation reports and regional planning documents. Between 1971 and 1996, 43 transportation projects were completed in the region. These projects included the construction of new roads and capacity expansions (road widening). For each of the projects, the year of completion is known.

Over the time period, the nature and scale of the transportation projects changed. In the 1970s, the majority of the projects involved new road construction, particularly the construction of regional expressways and highways in the periphery. In the 1980s and 1990s, new road construction was much more limited and smaller in scale. The majority of the construction projects involved the widening of existing roads.

Although information pertaining to the evolution of the road network was available in hardcopy for all years between 1971 and 1996, only the 1996 network was available in a digital format. The digital network file contains attribute information for every link in the network including the link type (for example: drive, court, street, road, highway), link name, link location, and link length. Information pertaining to speed limits or travel times were not available. Using a regional road map, we used the following classification system to assign speed limits to every link in the network.

Table 4-1: Link classification

Link Type	Speed Limit (km/hr)
Expressway	100
Highway	80
Regional Road	60
Other	50

Based on speed limit information collected during a "ground truthing" exercise, we adjusted the speed limit of links that were improved between 1971 and 1996. We used speed limit data and length of link data to calculate travel times for each link in the 1996 road network.

Using the digital 1996 network and the road construction data obtained from the transportation reports, a digital copy of the road network was created for each year over the time period. Starting with the 1996 network, we altered the network for each year. For example, if a new road was built in 1995, the 1995 and 1996 networks would include the new road but the road was deleted from the 1994 network.

Because the digital network file contained no information regarding link capacity, we adjusted speed limits to capture the effect of road widening. For example, if a highway was expanded from 2 lanes to 4 lanes in 1995, the links would be assigned 80 km in 1995 and 1996, and only 60 km in all years prior to the expansion. It is plausible that travel speeds on links are less than the posted speed limit because of congestion. Once the link is widened, travel speeds would increase. While this method of capturing the effect of road widening may not be optimal, it was the most consistent method given the available data.

For each year, every alteration (deletion of new roads and road widening) that we made to the network was carried back to the previous years. The result is that the 1971 road network has none of the 43 improvements, while the 1996 network has all of the improvements.

Given the evolution of the road network, we required a way to measure the impact of the road improvements. To accomplish this, we calculated two different measures. First, we calculated an accessibility measure to capture the regional impact of road improvements. Second, we used the distance from given locations to a high-speed road ($\geq$80 km/hr) to capture the local impact of road improvements.

Accessibility is a function of the extent of the road network and a measure of attractiveness. We calculate a gravity-type accessibility measure as follows (Hansen, 1959):

$$A_i = \sum_j \frac{w_j}{d_{ij}}$$

(1)

where A_i is the accessibility of location i

w_j is a measure of attractiveness

d_{ij} is the distance or travel time between location i and j

A large value of accessibility represents a more accessible location.

Using the grid cell approach, we calculated the accessibility of each grid cell. First, we overlaid the lattice of 1 km by 1 km grid cells on the road network maps for each year. Next, we connected the centroids of each grid cell to the network at slow travel speeds (40 km/hr). We calculated the shortest path distances and travel times between each centroid and every other centroid. The result was a series of matrices of shortest path distances and shortest path travel times for each year. We employed these matrices, which contain over 1.3 million entries, in the calculation of accessibility.

We used employment and population data to calculate two different measures of attractiveness. Because accessibility is spatially defined in terms of grid cells, we must also define the employment and population data in terms of grid cells. We obtained place-of-work data by traffic zone from the Halifax Regional Municipality for the census years between 1981 and 1996. To convert the employment data from traffic zones to grid cells, we employed the following method.

Using ArcView and a digital boundary file of the traffic zones, we calculated the spatial area of each traffic zone. Using the area of the traffic zone and the employment in the traffic zone, we computed the employment density of the traffic zone. Next, we overlaid the lattice of grid cells on the traffic zone map. The majority of the grid cells fell entirely in one traffic zone and were assigned the employment density of that traffic zone. For grid cells that fell along the boundary of more than one traffic zone (more than one traffic zone lies within the grid cell), we calculated a weighted average as follows. First, we calculated the proportion of each traffic zone in the grid cell. Then, we multiplied the proportion of the traffic zone by the employment density of the traffic zone. Finally, we summed the products of the proportion-density calculation for each traffic zone for each grid cell. Because the grid cells are 1 km by 1 km and the employment data are in terms of density, the employment value for each grid cell represents a measure of the number of employees per grid cell.

We gathered population data by census tract from the Census of Canada for the census years between 1971 and 1996. We used a similar method to calculate a weighted average to convert the population data from census tract to grid cell. We adjusted the calculation of land area for peripheral census tracts. Peripheral census tracts tend to be so spatially extensive that the population physically occupies a very small proportion of the land area. To account for this, we did not use the total area of the census tract in the calculation of population density for the large, peripheral census tracts. To determine where the population was located within the large, peripheral tracts, we overlaid the residential land parcel data on the census tract map. We subtracted areas of the census tract that did not have residential development from the area of the census tract. With these areas removed, we calculated the area of the census tract.

For each grid cell, we used the employment density and population density as the measures of attractiveness in the calculation of accessibility. We calculated four variations of accessibility where:

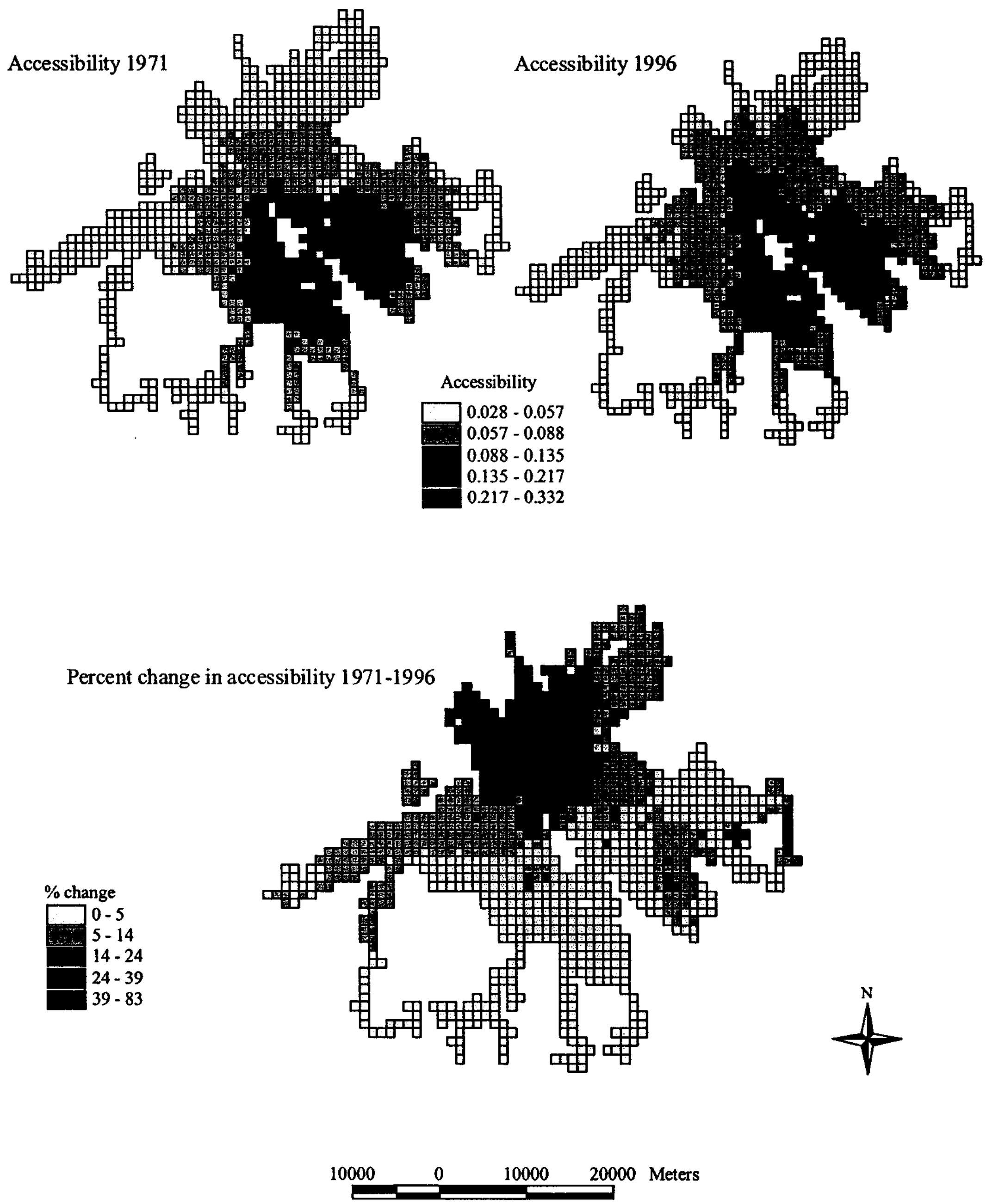
1. w_j is population and d_{ij} is distance
2. w_j is population and d_{ij} is time
3. w_j is employment and d_{ij} is distance
4. w_j is employment and d_{ij} is time

Because the impact of road improvements is of interest, it is the change in accessibility over a time period that is required rather than the absolute value of accessibility. In order to capture only changes in the road network rather than changes in population or employment, we held the measure of attractiveness constant when calculating the change in accessibility. For example, we computed the change in accessibility between 1991 and 1996 as follows:

$$\Delta A_{1991-1996} = \sum_j \frac{w_{j1991}}{d_{ij1996}} - \sum_j \frac{w_{j1991}}{d_{ij1991}} \tag{2}$$

We calculated the change in accessibility over each of the 5 time periods. Figures 4-4a-b show the spatial pattern of accessibility in 1971 and 1996, respectively. Figure 4-4c shows the percent change in accessibility over the time period 1971-1996. The accessibility measure does not have an intuitive unit of measurement; it is the relative values of accessibility that are of interest. The 1971 and 1996 maps clearly illustrate that the area with the highest level of accessibility is the urban core. However, the area that experienced the greatest change in accessibility is the periphery.

Figure 4-4: The spatial pattern of accessibility 1971 and 1996



We hypothesize a positive relationship between the number of parcels developed in the grid cell and the change in accessibility. We expect grid cells that have greater changes in accessibility to be more desirable for land development.

The second transportation measure is the distance to a high-speed road. We define high-speed roads as roads with speeds greater than or equal to 80 km/hr. In ArcView, we overlaid the centroids of each grid cell on the digital road network maps for the years 1971, 1976, 1981, 1986, 1991, and 1996. Using an ArcView script, we calculated the distance from each centroid to the closest high-speed road for each year. Through time, these distances reflect improvements to the road network such as the construction of new expressways and highways, and the widening of existing highways (Recall that the effect of widening was captured by changing the speed limit of links). We hypothesize a negative relationship between the distance to a high-speed road and land parcel development. We expect grid cells that are closer to a high-speed road to be more desirable for development as they provide better access in terms of shorter travel times to other locations.

We use both the accessibility measures and the distance to a high-speed road measure to capture the impact of road improvements on land development at different spatial scales. The accessibility measures capture the impact of road development on land development at a regional scale while the distance to a high-speed road captures the local impact of road improvements. The inclusion of these two types of measures will provide more detailed insight into the relationship between road development and land development. We will be able to determine if the proximity to a high-speed road is more important in deciding where to develop land than the overall accessibility of different locations.

4.5.3 Other Explanatory Variables

We also define a number of other explanatory variables for each grid cell. We represent the amount of developable land in a grid cell as the proportion of the grid cell that is considered developable. To do this, we overlaid the lattice of grid cells on a map of undevelopable areas. Such areas include water bodies, parks, industrial parks, airports, and government lands. All grid cells were initially assigned a value of 1. If a grid cell did not contain any undevelopable areas, it retained the value of 1. For the remaining grid cells, the proportion of the undevelopable areas within the grid cell were calculated and then subtracted from 1. The result is a measure of the amount of developable land in a grid cell. We hypothesize a positive relationship between the number of parcels developed and the amount of developable land. The availability of developable land is a prerequisite for development. Grid cells that have more available land to develop are more desirable and will likely experience more land development.

The availability of sewer and water service is an important consideration for land development. We represent data pertaining to sewer and water service by a dummy variable. The Metropolitan Area Planning Commission established an urban development boundary (UDB) in 1976 (refer to Figure 4-2). All land contained within the boundary has access to both sewer and water service. While the UDB has expanded since 1976, time series data pertaining to boundary expansions are not available. Thus, the 1976 urban development boundary is used for all time periods. Grid cells are assigned a 1 if they are within the urban development boundary and 0 otherwise. We hypothesize a positive relationship between the sewer/water dummy variable and land parcel development. We expect grid cells that have sewer and water service to experience more land development than grid cells that are not serviced.

We employ several socio-economic variables to account for demographic variations that may influence land development and reflect where developers will develop. All of the data are from the Census of Canada. Data such as average family income, average household income, median family income, median household income, average monthly housing payment, and average household size were defined by grid cell in a similar manner to the population and employment data used in the calculation of the accessibility measures.

We hypothesize a positive relationship between all of the census variables and land parcel development. We expect that areas with high income are more desirable to developers and as a result, are more likely to be developed. Such variables reflect housing values, and all things being equal, developers would prefer to build higher value homes. In addition, developers may anticipate higher prices adjacent to existing high-income areas. Higher average household size may translate into larger homes and higher housing payments, which may reflect higher household income.

4.6 The Model

We developed a base model to represent the impact of road development on land development. From this base model, we derived several variations. This base model is described as:

$$\Delta P_{it} = f(T_i, X_i) \quad (3)$$

where ΔP_{it} is the number of new parcels developed in grid cell i during time period t

T_i a measure of transportation development in grid cell i (accessibility or distance)

X_i is a vector of other explanatory variables

Because the dependent variable, the number of residential land parcels developed in a grid cell, is not a continuous variable, standard regression analysis could not be used to estimate the model. Poisson regression is commonly used for count data, but the nature of the parcel data violates the assumptions of the model. The Poisson distribution is based on the probability of an event occurring rarely, if at all. Land parcel development is not a rare event in the Halifax-Dartmouth region. While there are grid cells that do not experience land parcel development, other grid cells may have hundreds of land parcels developed in a given time period. Poisson regression is also not appropriate when the occurrence of one event increases the probability of others, which is the case with the land parcel data. A more appropriate approach is to estimate a discrete choice model.

Discrete choice models calculate the probability that a decision-maker will choose a particular alternative from a set of alternatives. In this paper, we consider the decision-maker the land developers, while the set of alternatives is the number of land parcels to develop. The land developers, modeled as a group with a common utility function, select the alternative with the highest utility. Utility is defined as follows:

$$U_n = V_n + \varepsilon_n \tag{4}$$

where U_n is total utility that decision-maker n (land developers) derives

V_n is the systematic or observed utility

ε_n is a random component

The observed utility, V_n is defined as a linear function of attributes that influence the choice decision:

$$V_n = \beta X_n \tag{5}$$

where β is a vector of parameters associated with the explanatory variables

X_n is a vector of explanatory variables

In terms of examining the impact of road development on land development, we used an ordered response model. In general terms, the ordered response model estimates the probability that a given number of land parcels, j, are developed in a grid cell. The utility of choosing a certain number of parcels is assumed to be a linear function of the explanatory variables that are related to each grid cell.

The ordered response model is used when the dependent variable is ordinal in nature and when there are 3 or more alternative choices. To transform the land parcel data into an ordinal variable, we classified each grid cell depending on the number of parcels that were developed in the grid cell during the time period. The initial classification, Code 1, was established by creating histograms of the land parcel counts by grid cell for each time period. The frequency distributions of the number of parcels per grid cell were very similar for each time period. Given this similarity, we decided to use the results for the 1991-1996 time period. We used the natural breaks apparent in the 1991-1996 histogram to create ranges for the classification categories. From the initial classification scheme of Code 1, we created and tested several other classification schemes. Table 4-2 provides the classification schemes that we used in the final models.

Table 4-2: Classification schemes for land parcel counts

Category	Number of parcels developed in time period Code 1	Code 2	Code 3
0	0	0	0
1	1-50	1-19	1-4
2	51-100	20-99	5-10
3	101-300	100-300	11-50
4	-	-	51-300

The ordered response model assumes local utility maximization as opposed to global utility maximization. Global utility maximization occurs when all alternatives in the choice set are considered simultaneously. Local utility maximization reflects a choice situation where each binary decision consists of whether to accept the current value or "take one more" (Ben Akiva and Lerman, 1985). For example, the land developers must decide whether to develop zero parcels or to develop the number of parcels in the next range. The decision to "take one more" is based on the definition of several "cut points" that represent each of the possible outcomes, 0,1,2,3...*j*. These cut points, λ, are defined such that no parcels will be developed in a given grid cell if $U<\lambda_1$, or:

$$P_{n0}=Pr\ (\beta X_n + \varepsilon_n \leq \lambda_1) \qquad (6)$$

where P_{n0} is the probability of zero parcels being developed

The probability of one or more parcels being developed in a grid cell is defined as the probability that $U_n>\lambda_1$ but less than a second cut point λ_2, or:

$$P_{n1}=Pr\ (\lambda_1 < \beta X_n + \varepsilon_n \leq \lambda_2) \qquad (7)$$

In general,

$$P_{nj}=Pr\ (\lambda_j < \beta X_n + \varepsilon_n \leq \lambda_{j+1}) \qquad \text{for } j=1,\ldots,j-1 \qquad (8)$$

and

$$P_{nJ}= 1- Pr\ (\beta X_n + \varepsilon_n \leq \lambda_J) \qquad (9)$$

For an ordered probit model, the assumption is that the random components are normally distributed. The functional form of the distribution is as follows:

$$P_{nj} = \int_{\infty}^{Z} \frac{1}{\sqrt{2\pi}} \exp\left(\frac{u^2}{2}\right) du \equiv \Phi(Z) \qquad (10)$$

where $Z = \Sigma\beta X_n$ and Φ denotes the standardized cumulative normal distribution (Aldrich and Nelson, 1984).

Given these assumptions, the choice probabilities are as follows:

$$P_{n0} = \Phi(\beta X_n - \lambda_1) \qquad (11)$$

$$P_{n1} = \Phi(\beta X_n - \lambda_2) - \Phi(\beta X_n - \lambda_1) \qquad (12)$$

$$P_{nj} = \Phi(\beta X_n - \lambda_{j+1}) - \Phi(\beta X_n - \lambda_j) \qquad \text{for all } j = 0, 1, \ldots, J-1 \tag{13}$$

$$P_{nj} = 1 - \Phi(\beta X_n - \lambda_J) \tag{14}$$

Estimates of β and $\lambda_1, \ldots, \lambda_j$ were obtained using Maximum Likelihood Estimation in an econometrics software package called LIMDEP. Unlike the multinomial probit, the ordered probit model does not require alternate specific parameters for each possible outcome. Because each outcome is essentially the same (i.e. number of land parcels to develop) but of a different magnitude (i.e. develop 0 parcels, 1-50 parcels etc.), only common parameters plus cut points are estimated.

4.7 Results

The objective of this paper is to address the research question 'does road development influence land development?' by quantifying the impact of road development on residential land parcel development. To this end, we estimated numerous model specifications to examine the impact of road development at both the regional scale and the local scale on residential land parcel development. Initially, we estimated models with each of the coding schemes as the dependent variable and with variables from the different groupings of explanatory variables (land development, transportation, demographic). We also tested specifications using values for the explanatory variables at the beginning of the time period, the end of the time period, and the change over the time period. We then combined the most significant explanatory variables from each grouping and re-estimated the models.

The following tables provide the results for each time period. These results are the best model specifications in terms of model fit and significance of the explanatory variables. Each table provides the estimated parameter, standard error, t-ratio, and P value for each of the explanatory variables. For each model, a chi-square value, degrees of freedom, and P value are provided to measure model fit. To compare the goodness of fit between models of the same time period and using the same dependent variable, a pseudo R^2 is calculated as follows:

$$pseudo \quad R^2 = 1 - \frac{L(\beta)}{L(c)} \tag{15}$$

where $L(\beta)$ is the log likelihood value of a model specified with all parameters

$L(c)$ is the log likelihood value of a model specified with only the constant

We also use the pseudo R^2 to compare the fit of the models that use the change in accessibility versus the distance to a high-speed road. The tables also indicate the coding scheme employed as the dependent variable (refer to Table 4-2 for the ranges of each scheme). Numerous coding schemes were tested for each time period. While the results were robust across the different schemes, the following results are the best in terms of significance of the explanatory variables.

The two transportation measures, change in accessibility and distance to a high-speed road, were also tested simultaneously in the models. In all cases, only one of the measures is significant indicating collinearity. We tested time lags with the two transportation measures (i.e. land parcel development in current time period as a function of the change in accessibility over the previous time period) but the results in terms of the significance of the lagged transportation variable are very poor. We also tested the residuals of each model for spatial autocorrelation. The results of the Moran's *I* indicate positive spatial autocorrelation. However, there is no simple method to account for the spatial autocorrelation in an ordered probit model.

Tables 4-3 to 4-7 provide the results for the models that include the change in accessibility as the transportation measure. As the tables indicate, there is consistency over time in the nature of the relationships between the dependent variable and many of the explanatory variables. The most inconsistent variable in terms of the direction of the relationship with the dependent variable is the change in accessibility measure.

For the time periods 1971-1976, 1976-1981, and 1986-1991, the results indicate a negative relationship between the change in accessibility and land parcel development. The results suggest that grid cells that experience smaller changes in accessibility experience more land parcel development. However, the change in accessibility coefficients are not significant for the two more recent time periods. The remaining two time periods, 1981-1986 and 1991-1996, show a positive and significant relationship between the change in accessibility and land parcel development. Grid cells with a larger change in accessibility experience more land parcel development.

For all time periods except the first, for which the number of parcels developed in the previous time period is unknown, there is a positive relationship between the number of parcels developed in the previous time period and land parcel development in the current time period. These results are intuitive given the nature of land development process. Residential land development usually occurs in phases. Once development is initiated in an area, further development is likely, given the availability of developable land. Grid cells with a higher number of parcels developed in the previous time period are more attractive for future development.

A negative relationship between the amount of developable land and land parcel development is apparent for all time periods. The results suggest that grid cells with less developable land experience more land development. These results are counterintuitive, as the hypothesis was that grid cells with more developable land would experience more land parcel development. The availability of developable land is a prerequisite for land development. This counterintuitive result may be due to the nature of the amount of developable land variable. We calculated the variable by removing areas from the grid cells that were considered undevelopable. Such areas included water bodies and parks, both of which could be considered amenities. Grid cells that have less developable land may have more water bodies and parks. Such grid cells would be desirable in terms of residential land development.

For all time periods, there is a positive relationship between the aggregate number of parcels developed in the grid cell and land parcel development in the current time period. Alternatively, there is a negative relationship between the aggregate number of parcels squared and the dependent variable. These two variables confirm the hypothesis of an inverted U-shaped effect. Initially the aggregate number of parcels in a grid cell has a positive effect on current land development while there is available land to develop.

At some point, the aggregate number of parcels has a negative effect on current land development as the available land in the grid cell decreases.

With the exception of the period 1991-1996, there is a positive relationship between the sewer/water dummy variable and land parcel development. Grid cells with sewer and water service experience more land parcel development, after controlling for other factors. The values of the sewer/water interaction terms suggests that the effect of the aggregate number of land parcels on new land parcel development is stronger outside the UDB than inside the UDB.

Other explanatory variables have significant impacts on land parcel development in the various time periods. For the period 1971-1976, a positive relationship between both the change in average household income and the change in average household size over the period, and land parcel development is apparent. Grid cells that experience a greater increase in average household income and size experience more land parcel development.

For the period 1981-1986, the change in average major monthly housing payment is positively related to land parcel development. Grid cells that experience a greater increase in payment also experience more land development. Areas of higher housing values are more attractive to developers. Finally, the results for the period 1986-1991 indicate a positive relationship between average household size and land parcel development. Average household size may be associated with larger homes. In turn, larger homes are associated with higher housing payments, which require higher household incomes. Thus, there is a positive relationship between land parcel development and average household size.

Table 4-3: Results of ordered probit model 1971-1976 (accessibility measure)

Variable	Coefficient	Standard error	t-ratio	P-value
constant	-1.37105	0.21581	-6.35312	0.00000
Change in accessibility 1971-1976 (population and time)	-54.0454	24.14620	-2.23825	0.02520
Amount of developable land	-0.58359	0.15857	-3.68029	0.00023
Aggregate number of parcels in cell	0.10371	0.00528	19.64910	0.00000
Aggregate number of parcels in cell squared	-0.00069	0.00005	-15.18430	0.00000
Sewer/water service in cell (dummy)	1.20581	0.11831	10.19220	0.00000
Sewer/water interaction term on aggregate # parcels	-0.09303	0.00522	-17.80460	0.00000
Sewer/water interaction term on aggregate # parcels squared	0.00068	0.00005	14.99950	0.00000
Change in average household income 1971-1976	0.00007	0.00002	2.69684	0.00700
Change in average household size 1971-1976	0.32789	0.10835	3.02622	0.00248
Cut points				
λ_1	2.20654	0.10489	21.03650	0.00000
λ_2	3.67837	0.17443	21.08740	0.00000
CODE 2				
Number of observations	1144			
Chi-square	806.96			
Degree of freedom	9			
Prob > chi-square	0.00000			
Log likelihood (constant)	-1099.06			
Log likelihood (beta)	-695.58			
Pseudo R^2	0.37			

Table 4-4: Results of ordered probit model 1976-1981 (accessibility measure)

Variable	Coefficient	Standard error	t-ratio	P-value
constant	-1.06212	0.09772	-10.86920	0.00000
Change in accessibility 1976-1981 (population and time)	-39.74440	24.42270	-1.62735	0.10366
Number of parcels developed 1971-1976	0.00528	0.00103	5.14484	0.00000
Amount of developable land	-0.55584	0.16915	-3.28614	0.00102
Aggregate number of parcels in cell	0.07502	0.00447	16.78470	0.00000
Aggregate number of parcels in cell squared	-0.00043	0.00003	-14.80670	0.00000
Sewer/water service in cell (dummy)	1.02936	0.12694	8.10933	0.00000
Sewer/water interaction term on aggregate # parcels	-0.06594	0.00443	-14.88730	0.00000
Sewer/water interaction term on aggregate # parcels squared	0.00042	0.00003	14.56150	0.00000
Cut point specific to				
λ_1	1.24516	0.07308	17.03940	0.00000
λ_2	1.87751	0.08615	21.79390	0.00000
λ_2	3.21802	0.13436	23.95090	0.00000
CODE 3				
Number of observations	1144			
Chi-square	741.55			
Degree of freedom	8			
Prob > chi-square	0.00000			
Log likelihood (constant)	-1003.744			
Log likelihood (beta)	-632.9694			
Pseudo R^2	0.37			

Table 4-5: Results of ordered probit model 1981-1986 (accessibility measure)

Variable	Coefficient	Standard error	t-ratio	P-value
Constant	-1.23221	0.12788	-9.63568	0.00000
Change in accessibility 1981-1986 (population and time)	71.2606	23.65000	3.01313	0.00259
Number of parcels developed 1976-1981	0.01768	0.00275	6.42880	0.00000
Amount of developable land	-0.65009	0.16381	-3.96857	0.00007
Aggregate number of parcels in cell	0.07877	0.00485	16.22970	0.00000
Aggregate number of parcels in cell squared	-0.00043	0.00003	-12.60420	0.00000
Sewer/water service in cell (dummy)	0.79480	0.13004	6.11198	0.00000
Sewer/water interaction term on aggregate # parcels	-0.06594	0.00474	-13.89710	0.00000
Sewer/water interaction term on aggregate # parcels squared	0.00042	0.00003	12.32520	0.00000
Change in average major monthly housing payment 1981-1986	0.00220	0.00063	3.46210	0.00054
Cut points				
λ_1	3.59072	0.17840	20.12710	0.00000
λ_2	4.38381	0.21063	20.81330	0.00000
CODE 1				
Number of observations	1144			
Chi-square	881.49			
Degree of freedom	9			
Prob > chi-square	0.00000			
Log likelihood (constant)	-1012.01			
Log likelihood (beta)	-571.269			
Pseudo R^2	0.44			

Table 4-6: Results of ordered probit model 1986-1991 (accessibility measure)

Variable	Coefficient	Standard error	t-ratio	P-value
constant	-1.80089	0.33286	-5.41033	0.00000
Change in accessibility 1986-1991 (population and time)	-142.762	94.11260	-1.51692	0.12929
Number of parcels developed 1981-1986	0.00385	0.00068	5.67234	0.00000
Amount of developable land	-0.73150	0.14104	-5.18662	0.00000
Aggregate number of parcels in cell	0.05137	0.00365	14.08150	0.00000
Aggregate number of parcels in cell squared	-0.00023	0.00002	-10.36870	0.00000
Sewer/water service in cell (dummy)	1.22497	0.10756	11.38870	0.00000
Sewer/water interaction term on aggregate # parcels	-0.04997	0.00364	-13.74140	0.00000
Sewer/water interaction term on aggregate # parcels squared	0.00025	0.00002	11.23750	0.00000
Average household size 1986	0.41005	0.10522	3.89702	0.00010
Cut points				
λ_1	2.02516	0.08914	22.71830	0.00000
λ_2	3.33663	0.12649	26.37840	0.00000
CODE 2				
Number of observations	1144			
Chi-square	740.32			
Degree of freedom	9			
Prob > chi-square	0.00000			
Log likelihood (constant)	-1199.02			
Log likelihood (beta)	-828.857			
Pseudo R^2	0.31			

Table 4-7: Results of ordered probit model 1991-1996 (accessibility measure)

Variable	Coefficient	Standard error	t-ratio	P-value
constant	-0.53070	0.08588	-6.17930	0.00000
Change in accessibility 1991-1996 (population and distance)	15.6146	2.65927	5.87179	0.00000
Number of parcels developed 1986-1991	0.00937	0.00115	8.14036	0.00000
Amount of developable land	-0.33058	0.13487	-2.45115	0.01424
Aggregate number of parcels in cell	0.03264	0.00227	14.40360	0.00000
Aggregate number of parcels in cell squared	-0.00011	0.00001	-12.35450	0.00000
Sewer/water service in cell (dummy)	0.87012	0.11285	7.71050	0.00000
Sewer/water interaction term on aggregate # parcels	-0.02841	0.00235	-12.06540	0.00000
Sewer/water interaction term on aggregate # parcels squared	0.00011	0.00001	11.85330	0.00000
Cut points				
λ_1	2.10953	0.08624	24.46020	0.00000
λ_2	3.12226	0.12736	24.51470	0.00000
CODE 2				
Number of observations	1144			
Chi-square	612.47			
Degree of freedom	8			
Prob > chi-square	0.00000			
Log likelihood (constant)	-1114.68			
Log likelihood (beta)	-808.44			
Pseudo R^2	0.27			

Tables 4-8 to 4-12 provide the results for models that include the distance to a high-speed road variable. A comparison of the pseudo R^2 indicates that for all time periods, the models with the change in accessibility variable are a better fit than the models with the distance to a high-speed road variable. Despite the poorer fit, the models do provide some interesting results.

For each time period, three different distance measures were tested:

1. distance based on the network at the beginning of the time period
2. distance based on the network at the end of the time period
3. change in distance over the time period

In all cases, the distance measure based on the network at the end of the time period results in the best model fit. As expected, the results indicate a negative relationship between the distance to a high-speed road and land parcel development. Grid cells that are closer to a high-speed road experience more land development. However, the distance coefficients are only significant for the time periods 1976-1981 and 1986-1991.

The behaviour of the other explanatory variables is, in most cases, consistent with the previous models and the interpretations remain the same. However, some of the explanatory variables did drop out of the models.

Table 4-8: Results of ordered probit model 1971-1976 (distance measure)

Variable	Coefficient	Standard error	t-ratio	P-value
Constant	-0.00244	0.07388	-0.03310	0.97360
Distance to a high-speed road	-0.00001	0.00001	-1.04490	0.29607
Amount of developable land	-0.97465	0.14703	-6.62890	0.00000
Aggregate number of parcels in cell	0.01239	0.00052	24.01860	0.00000
Aggregate number of parcels in cell squared	-0.00001	0.00000	-25.09370	0.00000
Change in average household size 1971-1976	0.32420	0.09202	3.52314	0.00043
Cut points				
λ_1	1.56740	0.07566	20.71550	0.00000
λ_2	2.99503	0.17564	17.05200	0.00000
CODE 2				
Number of observations	1144			
Chi-square	432.92			
Degree of freedom	5			
Prob > chi-square	0.00000			
Log likelihood (constant)	-1099.06			
Log likelihood (beta)	-882.06			
Pseudo R^2	0.20			

Table 4-9: Results of ordered probit model 1976-1981 (distance measure)

Variable	Coefficient	Standard error	t-ratio	P-value
Constant	-0.23240	0.07412	-3.13546	0.00172
Distance to a high-speed road	-0.00006	0.00003	-2.46093	0.01386
Number of parcels developed 1971-1976	0.00852	0.00078	10.99640	0.00000
Amount of developable land	-0.86745	0.15169	-5.71862	0.00000
Aggregate number of parcels in cell	0.01098	0.00060	18.31430	0.00000
Aggregate number of parcels in cell squared	-0.00001	0.00000	-19.45640	0.00000
Cut points				
λ_1	0.95256	0.05801	16.41980	0.00000
λ_2	1.49114	0.07275	20.49780	0.00000
λ_3	2.86013	0.12074	23.68870	0.00000
CODE 3				
Number of observations	1144			
Chi-square	560.35			
Degree of freedom	5			
Prob > chi-square	0.00000			
Log likelihood (constant)	-1281.59			
Log likelihood (beta)	-1001.42			
Pseudo R^2	0.22			

Table 4-10: Results of ordered probit model 1981-1986 (distance measure)

Variable	Coefficient	Standard error	t-ratio	P-value
constant	-0.41518	0.11624	-3.57180	0.00035
Distance to a high-speed road	-0.00005	0.00003	-1.73869	0.08209
Number of parcels developed 1976-1981	0.01819	0.00254	7.17267	0.00000
Amount of developable land	-0.88395	0.15509	-5.69946	0.00000
Aggregate number of parcels in cell	0.01337	0.00077	17.40790	0.00000
Aggregate number of parcels in cell squared	-0.00001	0.00000	-18.53240	0.00000
Change in average major monthly housing payment 1981-1986	0.00188	0.00060	3.12963	0.00175
Cut points				
λ_1	3.02832	0.15956	18.97980	0.00000
λ_2	3.97990	0.19822	20.07800	0.00000
CODE 1				
Number of observations	1144			
Chi-square	654.94			
Degree of freedom	6			
Prob > chi-square	0.00000			
Log likelihood (constant)	-1012.01			
Log likelihood (beta)	-684.54			
Pseudo R^2	0.32			

Table 4-11: Results of ordered probit model 1986-1991 (distance measure)

Variable	Coefficient	Standard error	t-ratio	P-value
constant	-0.81055	0.34534	-2.34707	0.01892
Distance to a high-speed road	-0.00007	0.00002	-3.01596	0.00256
Number of parcels developed 1981-1986	0.00388	0.00059	6.55591	0.00000
Amount of developable land	-0.98348	0.13063	-7.52875	0.00000
Aggregate number of parcels in cell	0.00162	0.00026	6.29503	0.00000
Aggregate number of parcels in cell squared	0.00003	0.00000	7.47653	0.00000
Average household size 1986	0.37002	0.11280	3.28018	0.00104
Cut points				
λ_1	1.59497	0.06711	23.76530	0.00000
λ_2	2.91346	0.11844	24.59800	0.00000
CODE 2				
Number of observations	1144			
Chi-square	437.63			
Degree of freedom	6			
Prob > chi-square	0.00000			
Log likelihood (constant)	-1199.02			
Log likelihood (beta)	-980.20			
Pseudo R^2	0.18			

Table 4-12: Results of ordered probit model 1991-1996 (distance measure)

Variable	Coefficient	Standard error	t-ratio	P-value
constant	-0.02500	0.07288	-0.34310	0.73152
Distance to a high-speed road	-0.00003	0.00002	-1.24978	0.21138
Number of parcels developed 1986-1991	0.00702	0.00111	6.29523	0.00000
Amount of developable land	-0.65614	0.13033	-5.03439	0.00000
Aggregate number of parcels in cell	0.00766	0.00056	13.66180	0.00000
Aggregate number of parcels in cell squared	-0.00001	0.00000	-14.39270	0.00000
Cut points				
λ_1	1.86464	0.07495	24.87940	0.00000
λ_2	2.90498	0.11737	24.74980	0.00000
CODE 2				
Number of observations	1144			
Chi-square	419.41			
Degree of freedom	5			
Prob > chi-square	0.00000			
Log likelihood (constant)	-1114.68			
Log likelihood (beta)	-904.98			
Pseudo R^2	0.19			

4.8 Discussion

A comparison of the two sets of model results indicates inconsistencies in the behaviour of the two transportation measures. While the signs of the change in accessibility coefficient vary between time periods, the signs for the coefficients on the distance measure are consistently negative. However, the significance of the coefficients for both measures is not consistent for all time periods. Despite these inconsistencies, an interesting pattern does emerge from the results.

With the exception of 1971-1976, for time periods when the coefficients of the change in accessibility are positive and significant, the coefficients of the distance measure are not significant. Alternatively, when the coefficients of the distance measure are significant, the coefficients of the change in accessibility variable are negative and not significant. Given the nature of the transportation variables in terms of spatial scale, these results suggest that through time, the scale of the impact of road development on residential land parcel development may vary.

For the time periods 1981-1986 and 1991-1996, the results indicate a significant and positive relationship between the change in accessibility[2] and residential land parcel development. These results suggest that the impact of road development on residential land development is at a regional scale. The coefficients of the change in accessibility are positive and significant and the distance coefficients are not significant. For the time periods 1976-1981 and 1986-1991, the results suggest that the impact of road development on land development is at a local scale. The coefficients for the distance to

[2] Accessibility measure calculated with time for 1981-1986 and with distance for 1991-1996.

a high-speed road variable are significant while the coefficients for the change in accessibility are not significant.

The results for the time period 1971-1976 indicate a negative and significant relationship between the change in accessibility and land parcel development. This suggests that grid cells with a smaller change in accessibility experience more land development. There is also a negative relationship between the distance to a high-speed road and land development but the relationship is not significant.

The results of the four most recent time periods show that road development has a significant impact on land development. However, the scale of the impact varies from time period to time period. A possible explanation of this variation is related to the intensity of land parcel development. Table 4-13 shows the average, over five years, of the annual percent change in the number of residential land parcels. The annual number of residential land parcels developed over those time periods is significantly higher when the change in accessibility coefficient is positive. Over the period 1981-1986, the annual number of residential land parcels developed increased by 118 percent while over the period 1991-1996, the annual number increased by 28.4 percent. Alternatively, the annual number of residential land parcels developed increased only marginally between 1976-1981 and decreased between 1986-1991 when the distance to a high-speed road coefficients are significant.

Table 4-13: Average, over 5 years, of the annual percent change in number of residential land parcels

Time period	Percent change
1971-1976	1.6
1976-1981	1.3
1981-1986	*118.0*
1986-1991	-46.0
1991-1996	*28.4*

This potential relationship between the type of transportation measure and intensity of annual residential land parcel development suggests that road development has a local impact on land parcel development when land development is was as intense. Alternatively, road development has a regional impact on land development when land parcel development was more intense. A possible explanation of these relationships is related to the spatial pattern of land parcel development.

When land parcel development is intense, the development is more spatially extensive; that is, there are more grid cells throughout the region with a higher number of parcels being developed. Because of this spatial pattern, the change in the accessibility measure, which is regional in nature, is more effective in capturing the impact of road development on land development. However, when land parcel development is less intense, the development is less spatially extensive and much more localized. Thus, for time periods of less intense land development, the local transportation variable –the distance to a high-speed road– is more effective in capturing the impact of road development on land development.

The effectiveness of the two transportation variables for different time periods may also be influenced by the nature of the road improvements completed in the associated time period. When the local transportation measure is effective in capturing the impact of road development on land development, the majority of the road improvements were located in the periphery. When the regional transportation measure is effective, the majority of the road improvements were located in the core or adjacent to the core. While this pattern may seem counterintuitive, an explanation of the relative impact of the road improvements will show otherwise.

An examination of Figure 4-3 clearly illustrates that the road network is much more dense and well developed in the core area. In terms of accessibility, the core has a much higher level of accessibility than the periphery. When roads are improved in the periphery, a greater relative impact will be felt in peripheral locations where accessibility is lower. Although the improvement will affect locations through out the region, the local impact will be much stronger. Because this impact is more localized, the local transportation measure is more effective in capturing the impact of road development on land development. Alternatively, when roads are improved in and around the core area, the impact will be felt on a regional scale. Because the road network is well developed in the core, the relative impact of an improvement will not be as strong. However, given the nature of the accessibility measure, a road improvement in the core will also have an impact in the periphery. This improvement will have a greater relative impact in the periphery because the accessibility is lower compared to the core. Thus, the regional transportation measure is more effective when the road improvements are in the core area.

Given all of these possible relationships (spatial scale of the transportation measure, intensity of land parcel development, location of road improvements), is there a direct relationship between road development and residential land parcel development? The data suggest that when road development is directed to the periphery, land parcel development is less intense. On the other hand, when road development is directed to the core, land parcel development is more intense. Table 4-14 shows the percent of residential parcels developed in the core and the periphery for each time period. While the majority of the parcels are developed in the periphery, in those time periods when road improvements were directed to the core, the percent of land parcels developed in the core did increase slightly.

Table 4-14: Percent of residential land parcels developed in core and periphery

Time period	Core	Periphery
1971-1976	24.5	75.5
1976-1981	25.3	74.7
1981-1986	*33.4*	*66.6*
1986-1991	27.5	72.5
1991-1996	*28.2*	*71.8*

More important however, is the effectiveness of the models in capturing the impact at both a local and a regional scale[3], for different locations of road development, and for different intensities of land development. When land development is intense and road development occurs in the core, the change in accessibility measure captures the impact of road development on land development. When land development is less intense and road development occurs in the periphery, the distance to a high-speed road variable is more effective. For every time period, with the exception of the earliest, the results indicate that road development does influence land development.

4.9 Implications

While the results of this paper quantify a link between transportation and land use, it does not confirm the direction of causality. A companion paper examines the other direction of the transportation-land use relationship; the impact of residential land development on road development. The paper estimates a model where the change in accessibility is a function of residential land parcel development. If residential land development does drive road development, the number of parcels developed in previous time periods should be a significant factor in explaining the change in accessibility. However, the results suggest that land development does not influence road development.

Collectively, the results of these two papers provide extremely important insight into the transportation-land use relationship. Numerous studies have examined this

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[3] The results of the models would be stronger if both the accessibility and distance measures were included. However, the variables could not be included simultaneously because of multicollinearity.

relationship but the results have been inconclusive. However, no prior study has examined the transportation-land use relationship by examining the spatial pattern of development as this one has. By quantifying both directions of the transportation-land use relationship, the results of this study fill an important gap in the literature. This research shows that, in the case of the Halifax-Dartmouth region, road development has an impact on residential land development, but residential land development does not have an impact of road development.

More important are the policy implications of the research. Many governments invest in transportation infrastructure to address a variety of concerns. Some governments use transportation investments as a method to stimulate economic activity, while others use investments to deal with traffic congestion problems. Such investments may have little success without fully understanding the relationship between transportation and land use.

The continued expansion of road networks has several ramifications. Wegener (1986) argues that the location and capacity of transportation infrastructure have very long-term implications with respect to urban form. The literature suggests that the expansion of transportation infrastructure contributes to the decentralization of urban areas (Muller, 1986; Adams, 1970). Decentralized development encourages travel by private automobile. Because of the increased dependency on automobiles, many urban areas are facing severe traffic congestion problems. A common response to these problems is new road construction or capacity expansions.

Environmental implications of automobile dependence and decentralization include increased energy consumption and air emissions. Miller and Ibrahim (1998) note that energy consumed by the transportation sector depends directly on the level and spatial distribution of activities within the urban area. Thus, understanding the relationship between transportation and land use is imperative. Because the spatial distribution of activities has become more dispersed, the total number of vehicle kilometres traveled is increasing (Miller and Ibrahim, 1998). Increased energy use and vehicle kilometres traveled translates into increased air emissions. Highway vehicles account for nearly three-quarters of total transportation energy use and are the largest source of transport related pollutants for nearly every type of pollutant (Transportation Research Board, 1995).

Understanding the transportation-land use relationship is essential for effective policy formulation. This research provides important insight by quantifying the strength of both directions of the relationship. The results suggest that impact of road development on residential land development is much stronger than the impact of residential land development on road development. Thus, policies related to the provision of transportation infrastructure may be more effective in dealing with several issues currently facing urban centres.

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CHAPTER 5: An Empirical Analysis of the Impact of Residential Land Development on Road Development in Halifax-Dartmouth

5.1 Introduction

Numerous studies have examined the relationship between transportation and land use. Many studies have studied the impact of land use on transportation by examining the influence of urban form on travel patterns (For examples see Kockelman, 1997; McNally and Kulkarni, 1997; Handy, 1993). Studies have investigated the other direction of the transportation-land use relationship by examining the impact of transportation investments on economic development (For examples see Harmatuck, 1996; Rietveld, 1994; Baird and Lipsman, 1990; Forkenbrock and Foster, 1990). Despite the plethora of research, no prior study has attempted to isolate and quantify the direction or strength of the transportation-land use relationship. Moreover, no prior study has examined the transportation-land use relationship by examining the spatial pattern of development.

The objective of this research is to investigate both directions of the transportation-land use relationship. In particular, this paper examines the impact of land development on road development while a companion paper studies the impact of road development on land development (Cuthbert *et al.*, 2001). The results of the companion paper indicate that road development does have an impact on land development. Given this result, questions remain regarding the strength and direction of causality of the transportation-land use relationship. The objective of this paper is to examine the other direction of the transportation-land use relationship. This paper addresses the question "does land development drive road development?"

We base the paper on the hypothesis that land development creates trip generating activities, which affect the expansion of the road network. To answer the research question, we formulate a base model that represents the relationship between land development and road development. We use road and land development data for the Halifax-Dartmouth region in the model. Specifically, we use data pertaining to the development of the road network in the calculation of an accessibility measure, while we measure land development in terms of residential land parcel development. We estimate variations of the base model for five time periods between 1971 and 1996.

We organize the remainder of the paper as follows. First, we summarize the conceptual framework that underpins the empirical analysis. Second, we review the study area and the data used in the model. Next, we outline the base model representing the impact of residential land development on road development and we explain the estimation methodology. Then, we discuss the results of the different model specifications. Finally, we discuss the policy implications of the analysis and offer some concluding remarks.

5.2 Conceptual Framework

We base the research question addressed in this paper on the conceptual framework outlined in the companion paper. To summarize, the framework illustrates the two possible directions of transportation-land use relationship: the impact of road development on land development that results from changes in accessibility and the impact of land development on road development that results from trip generating activities. The objective of this paper is to examine the latter impact; that is, the impact of residential land development on road development.

Land development affects road development through the creation of trip generating activities. When land is developed, it has an associated land use such as residential, commercial, or industry. These land use activities generate trips, which have an impact on the road network. In response to the increase in trips, the network may be expanded. New roads will be built or existing roads will be expanded to accommodate the increased traffic. However, if the network is not expanded and the increased traffic is greater than the capacity of the network, the result is a deterioration of travel conditions due to congestion.

5.3 The Study Area and Data Set

As with the companion paper, we employ data for the Halifax-Dartmouth region of Nova Scotia. Figure 5-1 provides a map of the study area, which spatially defines an urban core and an urban development boundary (UDB), both of which we discuss later in the paper[1].

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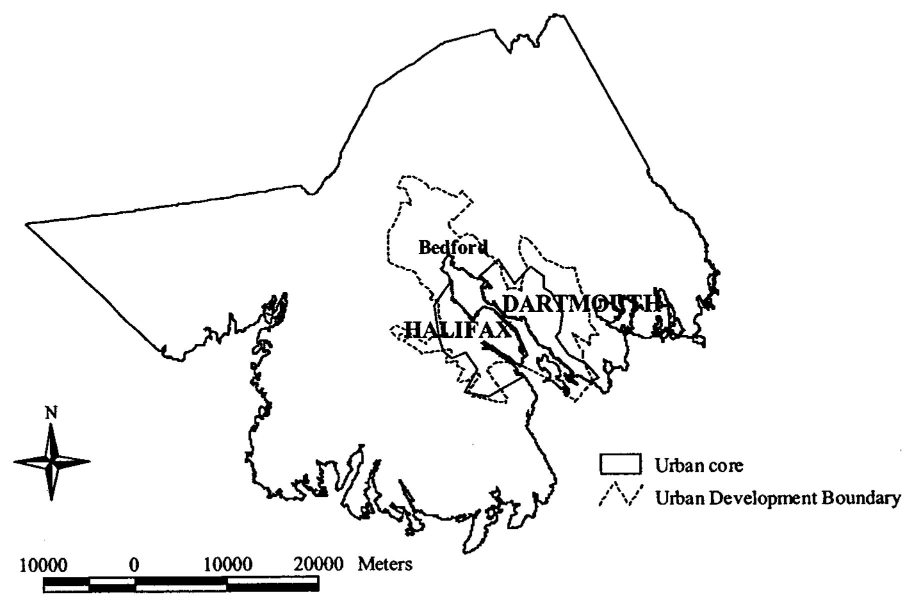
[1] The urban core shown in the map corresponds to the urban core defined by the 1971 Census of Canada. An urban core is a large urban area around which a CMA (Census Metropolitan Area) is delineated. The urban core must have a population of at least 100 000.

Figure 5-1: The study area



The transportation, land parcel, and socio-economic data are the same as described in the companion paper. Again, the spatial unit of analysis is the 1 km by 1 km grid cell. In this paper, the change in accessibility over time period t is employed as the dependent variable[2]. We calculated a gravity-type accessibility measure as follows (Hansen, 1959):

$$A_i = \sum_j \frac{w_j}{d_{ij}} \tag{1}$$

where A_i is the accessibility of grid cell i

w_j is a measure of attractiveness (population or employment density) of grid cell j

[2] The change in accessibility was used as the dependent variable as no data were available with regards to trip generation.

d_{ij} is the distance or travel time between grid cell i and j

In order to capture only changes in the road network rather than changes in population or employment density, we held the measure of attractiveness constant when calculating the change in accessibility. For example, we calculated the change in accessibility for the time period 1991-1996 as follows:

$$\Delta A_{i1991-1996} = \sum_j \frac{w_{j1991}}{d_{ij1996}} - \sum_j \frac{w_{j1991}}{d_{ij1991}} \tag{2}$$

where ΔA_i is the change in accessibility of location i

w_j is a measure of attractiveness

d_{ij} is the distance or travel time between location i and j

We capture road development indirectly by using the change in accessibility. Because we hold the measure of attractiveness constant, any changes in accessibility are a result of expansions to the road network.

We calculated four different accessibility measures where:

1. w_j is population and d_{ij} is distance
2. w_j is population and d_{ij} is time
3. w_j is employment and d_{ij} is distance
4. w_j is employment and d_{ij} is time

Corresponding to inter-censal time periods, we examined five time periods: 1971-1976, 1976-1981, 1981-1986, 1986-1991 and 1991-1996.

We use the land parcel data and census data to derive the same explanatory variables as discussed in the companion paper. Table 5-1 lists these explanatory variables. We describe the hypothesized relationships between the change in accessibility and the explanatory variables below.

Table 5-1: Explanatory variables employed in the models

Number of parcels developed in previous time period
Number of parcels developed in current time period
Aggregate number of parcels in cell
Amount of developable land
Sewer/water service in cell (dummy variable)
Average family income
Average household income
Median family income
Average major monthly housing payment

We hypothesize that land parcels developed in the previous time period will have a positive impact on the change in accessibility. We expect grid cells that experience land parcel development in the previous time period to experience an increase in accessibility in the subsequent time period resulting from the changes to the road network. Similarly, we hypothesize that current land development will have a positive impact on the change in accessibility. In this way, grid cells that gain a large number of land parcels will experience a greater increase in accessibility. As described in the conceptual framework, land development affects road development through the creation of trip generating activities. These activities determine the scale and pattern of trips that use the road network. In response to the increased number of trips, transportation decision makers may elect to expand the road network. Because accessibility is a function of the structure of the road network, expansion of the network will lead to an increase in accessibility. The previous development variable, in particular, is extremely important in quantifying the strength of the impact of land development on road development. If land development does influence road development, the number of parcels developed in the previous time period should be a significant predictor of the change in accessibility.

We hypothesize a negative relationship between the aggregate number of parcels and the change in accessibility. Grid cells with a higher aggregate number of land parcels are most likely to be located in the core area. However, we expect that grid cells located in the periphery will experience greater relative changes in accessibility. The core area has a well-developed road network and as a result, it has a high level of accessibility. The road network in peripheral areas is not as well developed and as a result, these areas have a lower level of accessibility. Given these existing levels of accessibility, any road improvement will have a greater relative impact on the dependent variable, which in turn will be associated with areas that have a lower number of parcels.

We hypothesize positive relationships between the change in accessibility and both the amount of developable land and the sewer/water dummy variable. Road improvements may occur in anticipation of land development. Grid cells with the greatest potential for development would have developable land and sewer/water service. Such grid cells may also experience the greatest change in accessibility.

We employ several socio-economic variables to account for demographic variations that may influence the likelihood of improvements to the road network. We hypothesize a positive relationship between the income variables and the change in accessibility.

Higher income households tend to have a greater demand for transportation as they make more trips than low income households (Hanson and Schwab, 1995). Because of this greater demand, higher income areas tend to receive more investments than low income areas (Hodge, 1995). In addition, higher income areas tend to exert more influence on road improvements. Thus, high-income areas can be expected to experience more road improvements and in turn, greater changes in accessibility.

5.4 The Model

We formulated a base model representing the impact of land development on road development. From this base model, we derived several variations. The base model is described as:

$$\Delta A_{it} = f(P_i, X_i) \qquad (3)$$

where ΔA_{it} is the change in accessibility in grid cell i over time period t

P_i is a vector of land parcel development variables in grid cell i (aggregate, current, previous)

X_i is a vector of other explanatory variables

We estimated numerous variations of the base model for the 5 time periods between 1971 and 1996. First, we used stepwise regression to determine which explanatory variables had the greatest impact on the change in accessibility. Then, given the results of the stepwise regression, we re-estimated the models by ordinary least squares (OLS) to test various combinations of the explanatory variables and the four accessibility measures. Finally, we tested for spatial autocorrelation and estimated a spatial lag model for each time period. Table 5-2 provides a summary of the model specifications while

Tables 5-3 to 5-6 provide the OLS results for each time period. These models represent the best specifications in terms of model fit and significance of the explanatory variables.

As Tables 5-3 to 5-6 indicate, model fit for all time periods is very poor. The R^2 ranges from 0.048 to 0.088. The signs of the coefficients are not always as expected and there are inconsistencies in the signs between time periods. Because the impact of land development on the change in accessibility is of interest, the land parcel variables (aggregate, previous and current) were forced into the models for all time periods. In many cases, these variables were not significant.

Because the data are geographical in nature, it is necessary to test for spatial autocorrelation. To do this, we re-estimated the final models using a software package called SpaceStat. SpaceStat tests for two types of spatial autocorrelation: substantive and nuisance. Substantive spatial autocorrelation pertains to the dependent variable and nuisance pertains to the error term. In all of the models, diagnostics indicated the presence of substantive spatial autocorrelation. To deal with the spatial autocorrelation, we estimated a spatial lag model for each time period.

The spatial lag model, also referred to as a mixed regressive spatial autoregressive model, includes a spatially lagged dependent variable, Wy, as one of the explanatory variables. W is a spatial weights matrix based on either a rook (common boundaries) or queen (common boundaries and common corners) contiguity structure. Following the notation of Anselin (1992), the form of the spatial lag model is as follows:

Table 5-2: Summary of OLS model specifications

	Change in Accessibility				
	1971-1976a	1976-1981a	1981-1986a	1986-1991b	1991-1996b
Amount of developable land	x				x
Number of parcels developed in previous time period			x		x
Aggregate number of parcels	x	x		x	x
Sewer/water service in cell (dummy variable)	x	x	x	x	
Median family income (beginning of time period)			x		
Median household income (beginning of time period)					x
Change in median household income				x	
Change in average family income	x				
Change in average household income		x			
Average major monthly housing payment (beginning of time period)			x		x
Change in average major monthly housing payment				x	
Sewer/water interaction term on average major monthly housing payment			x	x	

[a, b] accessibility calculated with time and distance respectively

Table 5-3: OLS results 1971-1976

Variable	Coefficient	t	Prob
Constant	0.002088	4.213	0.00000
Sewer/water service in cell (dummy variable)	0.001278	7.512	0.00000
Aggregate number of parcels in cell	-0.00000172	-2.872	0.00400
Amount of developable land	0.0008043	3.642	0.00000
Change in average family income 1971-1976	-0.000000203	-3.459	0.00100

Dependent variable: Change in accessibility 1971-1976 (population and time)
No. of Observations=1144
$R^2 = 0.070$

Table 5-4: OLS results 1976-1981

Variable	Coefficient	t	Prob
constant	0.002288	6.724	0.00000
Sewer/water service in cell (dummy variable)	0.000626	5.339	0.00000
Aggregate number of parcels in cell	-0.000001283	-3.267	0.00100
Change in average household income 1976-1981	-0.000000216	-5.167	0.00000

Dependent variable: Change in accessibility 1976-1981 (population and time)
No. of Observations=1144
$R^2 = 0.048$

Table 5-5: OLS results 1981-1986

Variable	Coefficient	t	Prob
constant	-0.001163	-2.839	0.00500
Sewer/water service in cell (dummy variable)	-0.001613	-2.694	0.00700
Number of parcels developed 1976-1981	-0.000004425	-2.441	0.01500
Median family income 1981	0.000000112	4.923	0.00000
Average major monthly housing payment 1981	-0.0000031	-3.128	0.00200
Sewer/water interaction term on average major monthly housing payment	0.000005641	3.984	0.00000

Dependent variable: Change in accessibility 1981-1986 (population and time)
No. of Observations=1144
$R^2 = 0.087$

Table 5-6: OLS results 1986-1991

Variable	Coefficient	t	Prob
constant	-0.00005619	-0.400	0.68900
Sewer/water service in cell (dummy variable)	0.0005378	3.579	0.00000
Aggregate number of parcels in cell	0.00000047	2.830	0.00500
Change in median household income 1986-1991	-0.000000027	-3.083	0.00200
Change in average major monthly housing payment 1986-1991	0.000003401	5.449	0.00000
Sewer/water interaction term on change in average major monthly housing payment	-0.000002671	-3.429	0.00100

Dependent variable: Change in accessibility 1986-1991 (population and distance)
No. of Observations=1144
$R^2 = 0.062$

Table 5-7: OLS results 1991-1996

Variable	Coefficient	t	Prob
constant	0.0002728	0.071	0.94300
Aggregate number of parcels in cell	0.00001642	4.700	0.00000
Amount of developable land	-0.009465	-6.497	0.00000
Median household income 1991	0.00000028	2.762	0.00600
Average major monthly housing payment 1991	-0.0000257	-4.730	0.00000
Number of parcels developed 1986-1991	0.00003902	2.067	0.03900

Dependent variable: Change in accessibility 1991-1996 (population and distance)
No. of Observations=1144
$R^2 = 0.088$

$$y = \rho Wy + X\beta + \varepsilon \qquad (4)$$

where: y is a N by 1 vector of observations on the dependent variable

Wy is a N by 1 vector of spatial lags for the dependent variable

ρ is the spatial autoregressive coefficient

X is a N by K matrix of observations on the explanatory variables

B is a K by 1 vector of regression coefficients

ε is a N by 1 vector of normally distributed random error terms

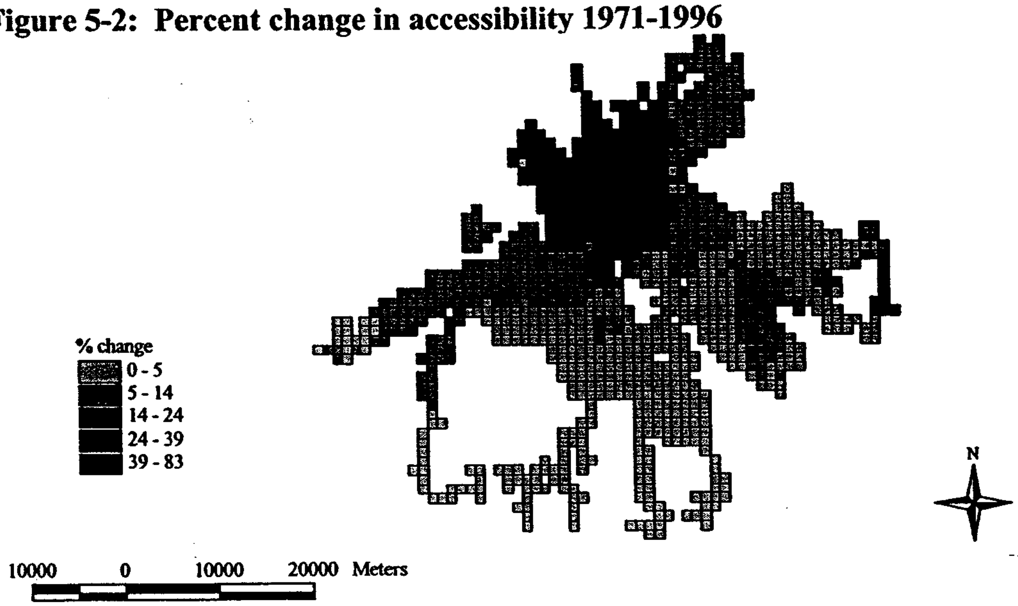
Anselin (1992) compares the presence of the spatial lag coefficient to the inclusion of endogenous variables on the right hand side in systems of simultaneous equations. The spatial lag model is estimated by maximum likelihood because the inclusion of the spatial lag causes OLS results to be inconsistent. Because the spatial autoregressive coefficient is unknown, it is estimated simultaneously with the regression coefficients. The inclusion of the spatially lagged dependent variable allows for the assessment of the significance of the other explanatory variables while controlling for spatial dependence.

The results of the re-estimations are poor in terms of the significance of the explanatory variables. For several of the time periods, many of the explanatory variables that are significant in the OLS results are no longer significant in the spatial lag results. In an attempt to improve the models, we replaced the insignificant variables with other similar variables and re-estimated the models. For example, if median household income was not significant, we replaced it with average household income or change in median household income and then re-estimated the model. We tested numerous combinations of explanatory variables, along with the two different contiguity structures of the weight matrices. In all cases, the queen convention provided the best results. However, the removal and replacement of explanatory variables did not improve the models in terms of significance of the explanatory variables. Anselin (1992) states that changes in the regression coefficients are expected whenever the spatial autoregressive coefficient is highly significant as the original OLS estimates are biased in the presence of spatial autocorrelation. Despite the lack of significance of several explanatory variables, the spatial lag model successfully controlled for spatial dependence. Diagnostics provided by SpaceStat indicate that spatial autocorrelation is eliminated.

The results presented in Tables 5-8 to 5-12 are the best spatial lag model specifications in terms of model fit and the explanatory variables that are significant. The most important result from the spatial lag models are the variables that are not significant. As in the OLS estimations, we forced the residential land parcel variables (aggregate, previous and current) into the spatial lag models. Again, the variables are not significant, the signs of the coefficients are not as expected, or the signs are inconsistent between time periods. Of particular interest, is the previous land development variable. If residential land development has an impact on the change in accessibility, land parcels developed in the previous time period should be a significant variable in the models. However, it is not significant in any time period.

In all models, the spatial autoregressive coefficient is highly significant, indicating spatial clustering of the accessibility variable. We expect such clustering given the nature of the accessibility variable. Accessibility is based on the extent of the road network (travel time or distance) and a measure of attractiveness (population or employment density), both of which are defined by grid cell. In general, grid cells located in close proximity to each other will have similar travel time/distance values and similar population/employment density values. It follows that such grid cells will also have similar levels of accessibility. Figure 5-2 clearly illustrates the spatial clustering of grid cells with similar changes in accessibility.

Figure 5-2: Percent change in accessibility 1971-1996



As Tables 5-8 to 5-12 indicate, the aggregate number of parcels variable is significant in three of the five time periods. However, the direction of the relationship is not consistent. For the two earliest time periods (Tables 5-8 and 5-9), a negative relationship between the aggregate number of parcels and the change in accessibility is apparent. In the final time period (Table 5-12), the results indicate a positive relationship.

The negative relationship between the change in accessibility and the aggregate number of parcels suggests that grid cells with fewer land parcels already developed experience greater changes in accessibility. It is intuitive that grid cells with a higher aggregate number of parcels are located in the urban core of Halifax and Dartmouth. Grid cells in the core are typically developed at higher densities than peripheral grid cells. Thus, grid cells experiencing the greatest change in accessibility are also located in the periphery. The majority of the road improvements during the 1971-1976 and 1976-1981 time periods were a result of new road construction in the periphery.

For the time period 1991-1996 (Table 5-12), the results indicate a positive relationship between the change in accessibility and the aggregate number of parcels. Grid cells that have a higher number of parcels already developed experience greater changes in accessibility. During this time period, the amount of developable land is also a significant variable in the model. A negative relationship is apparent between the change in accessibility and the amount of developable land. The significance and signs of both the aggregate number of parcels and the amount of developable land suggest that grid cells that are more developed experience more road development as reflected in greater changes in accessibility. All of the road improvements during this time period were located in either the core area of Halifax and Dartmouth or in areas just adjacent to the core.

Both the time period and the location of the road improvement influence the relative impact of the change in accessibility. Given the nature of the road improvements over time (new road construction vs. expansion), the relative impact over time is not consistent. With new road construction in the periphery in early time periods, the greatest relative change in accessibility is in peripheral grid cells where accessibility was initially low. Because grid cells with the highest aggregate number of parcels are located in the core, a negative relationship with the change in accessibility is apparent.

As accessibility increases over time due to subsequent road improvements, the relative difference between accessibility in the core and in the periphery decreases. In later time periods, road improvements consist mainly of capacity expansions to existing roads in both the core and areas directly adjacent to the core. Although accessibility is still the highest in the core, the relative difference between accessibility in the core and periphery has decreased. In the final time period, the greatest change in accessibility resulting from the capacity expansions to existing roads is to grid cells in the core and adjacent to the core. Because grid cells with the highest aggregate number of parcels are located in the core, a positive relationship is apparent.

For the first four time periods, there is a positive relationship between the sewer/water dummy variable and the change in accessibility (refer to Tables 5-8 to 5-11). Even with the changing scale and location of road improvements over the entire time period, the results indicate that grid cells with sewer/water service experience greater changes in accessibility. The 1991-1996 results are interesting in that the sewer/water dummy variable drops out of the model. Consider also that the aggregate number of parcels is once again significant but with a positive sign on the coefficient, and the amount of developable land enters the model with a negative sign on the coefficient. An examination of the sewer/water dummy variable and the location of road improvements that occurred during the time period help to explain this result.

The results for the earlier time periods suggest that grid cells located within the UDB experience the greatest change in accessibility. However as Figure 5-3 illustrates, these grid cells are not necessarily located in the urban core. The UDB actually extends beyond the urban core and into the periphery. There are grid cells with sewer/water service located in the periphery. However, grid cells with the highest aggregate number of parcels are located in the core. In the early time periods, most of the road improvements were located in peripheral areas, particularly the areas lying between the UDB and the urban core. Thus, a negative relationship between the change in accessibility and the aggregate number of parcels, and a positive relationship between the change in accessibility and the sewer/water dummy variable are explained for the two earliest time periods.

Figure 5-3: Grid cells located outside the urban core but within the UDB

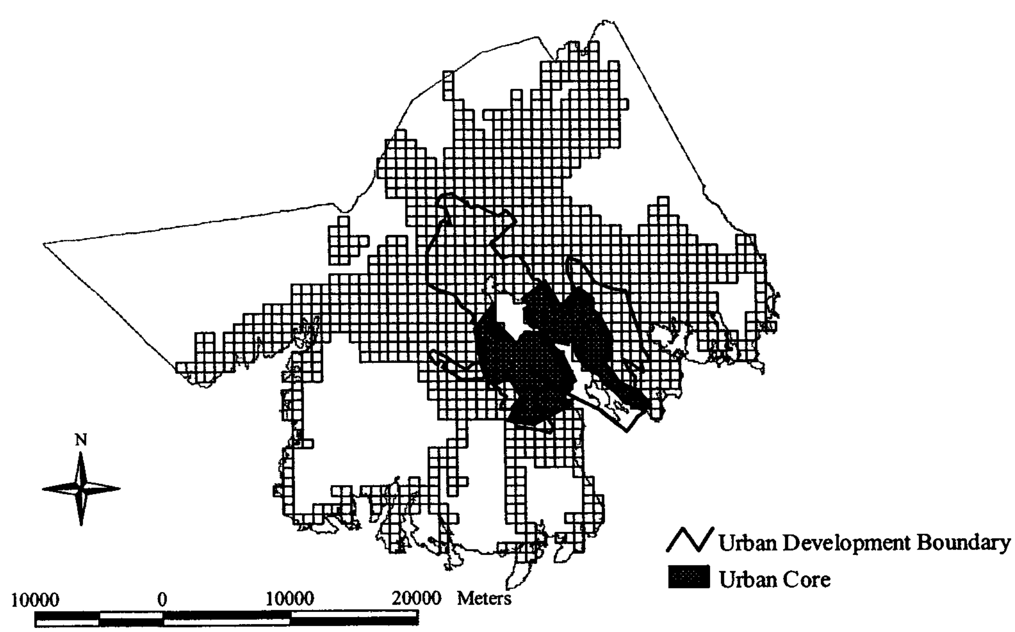


Table 5-8: Spatial lag model results 1971-1976

Variable	Coefficient	z-value	Prob
Constant	0.00028	3.75606	0.00017
Sewer/water service in cell (dummy)	0.00059	3.88633	0.00010
Aggregate number of parcels in cell	-0.0000013	-2.47802	0.01321
Spatial autoregressive coefficient	0.58886	18.63862	0.00000

Dependent variable: Change in accessibility 1971-1976 (population and time)
No. of Observations=1144
$R^2 = 0.16$

Table 5-9: Spatial lag model results 1976-1981

Variable	Coefficient	z-value	Prob
constant	0.00079	3.00379	0.00267
Sewer/water service in cell (dummy)	0.00028	2.78894	0.00529
Aggregate number of parcels in cell	-0.0000008	-2.41123	0.01590
Change in average household income 1981-1986	-0.00000007	-2.24535	0.02475
Spatial autoregressive coefficient	0.61162	20.38962	0.00000

Dependent variable: Change in accessibility 1986-1991 (population and time)
No. of Observations=1144
R = 0.18

Table 5-10: Spatial lag model results 1981-1986

Variable	Coefficient	z-value	Prob
constant	0.00005	1.48481	0.13759
Sewer/water service in cell (dummy)	0.00012	1.98116	0.04757
Spatial autoregressive coefficient	0.85572	54.43108	0.00000

Dependent variable: Change in accessibility 1981-1986 (population and distance)
No. of Observations=1144
$R^2 = 0.49$

Table 5-11: Spatial lag model results 1986-1991

Variable	Coefficient	z-value	Prob
constant	0.00005	2.21251	0.02693
Sewer/water service in cell (dummy)	0.00008	1.96888	0.04897
Spatial autoregressive coefficient	0.72385	29.5189	0.00000

Dependent variable: Change in accessibility 1986-1991 (population and distance)
No. of Observations=1144
$R^2 = 0.25$

Table 5-12: Spatial lag model results 1991-1996

Variable	Coefficient	z-value	Prob
constant	-0.00127	-2.18036	0.02923
Aggregate number of parcels in cell	0.0000071	3.05939	0.00222
Amount of developable land	-0.00426	-3.61019	0.00031
Spatial autoregressive coefficient	0.67201	24.77079	0.00000

Dependent variable: Change in accessibility 1991-1996 (population and distance)
No. of Observations=1144
R^2= 0.25

5.5 Discussion

The objective of this paper is to address the research question 'does land development drive road development?' by quantifying the impact of residential land development on road development. To this end, we tested numerous model specifications to examine the impact of residential land parcel development on changes in accessibility. Different land parcel variables such as the aggregate number of parcels, the number of parcels developed in the current time period, and the number of parcels developed in the previous time periods were forced into the models. If land development does drive road development, it follows that a significant relationship should exist between the change in accessibility and the land parcel variables, particularly the number of parcels developed in previous time periods. As the results indicate, this relationship is not apparent.

The change in accessibility does not appear to be a function of actual land development. There is no significant relationship in any time period between the change in accessibility and the number of residential land parcels developed in the previous time periods or current time period. Three of the time periods do have a significant land parcel variable in terms of the aggregate number of parcels but the direction of the relationship is not consistent.

Given the absence and inconsistency of the various land parcel variables in the models, the results do not support the hypothesis that residential land development drives road development. However, the inclusion and significance of the sewer/water dummy variable suggests that road development may lead residential land development. The availability of sewer and water service as captured by the dummy variable represents the potential or conditions for development. Grid cells that have sewer/water service are located within the UDB. Delineated by regional planners, the UDB represents an area in which development is permitted. Compared to land outside the UDB where permission to develop would have to be sought, the potential for development within the UDB is higher. Thus, grid cells within the UDB have a higher potential for development. From the perspective of developers, land that is already serviced and permitted for development would be more attractive than land that is not. Thus, grid cells within the UDB exhibit the right conditions for development. The results indicate a positive relationship between the change in accessibility and sewer/water service. Grid cells with the potential or conditions for land development experience the greatest change in accessibility. This suggests that road development leads land development as confirmed in the companion paper.

The significance of the sewer/water dummy variable provides insight into the infrastructure planning process of the region. While the objective of the UDB is to delineate an area beyond which sewer and water services will not be extended, the results suggest that the boundary may have influenced road development as well. It is possible that planning decisions concerning the provision of sewer/water services and transportation infrastructure are coordinated. The positive relationship between the change in accessibility and the sewer/water dummy variable indicates that most road development occurred within the UDB. Perhaps, the UDB has been successful at not only directing land development but road development as well.

A potential explanation of the absence and inconsistency of the various land parcel variables in the models is the possibility that roads improvements are occurring in anticipation of residential land development that is expected to occur in the future. Because the planning process can take time, there may be a lag between the date of planning approval and actual land development. However, it is important to note that approval does not necessarily imply development; projects may be approved but for whatever reason, development does not occur. The model in this paper tests the hypothesis that road development is influenced by contemporaneous or lagged residential land parcel development. Although we do not have data pertaining to dates of planning approvals, we believe that data on land parcels better represents land development given the fact that approval does not imply development.

5.6 Summary

Does land development drive road development? Using a base model to capture the impact of residential land development on road development, the paper addresses this question. The results of the model suggest that land development does not drive road development. Rather, road development may actually occur in advance of land development.

If land development does drive road development, the number of parcels developed in previous time periods should have been a significant variable in the model results. The only significant land parcel variable was the aggregate number of parcels. However, given the negative relationship between the aggregate number of parcels and the change in accessibility in the early time periods, road improvements were not occurring in areas of existing developed land. Given the nature of the planning process, the possibility exists that road development is occurring in anticipation of land development.

The inclusion of the sewer/water dummy variable in four of the five of the models indicates a positive relationship between the change in accessibility and the availability of sewer/water service. The sewer/water dummy variable may actually be capturing the potential or conditions for land development. Areas that have the appropriate conditions for land development (i.e. sewer/water service) experience the greatest change in accessibility. Thus, road development may actually influence land development. The results of the companion paper confirm this hypothesis.

The companion paper examines the impact of road development on residential land development by estimating an ordered probit model. In the model, the number of residential land parcels developed in a grid cell is a function of either the change in accessibility or the distance to a high-speed road. We use these two transportation measures to capture both the regional and local impact of road development on land development. The results indicate that road development does have an impact on residential land development.

Collectively, the results of both papers provide important insight into the transportation-land use relationship. The results suggest that, in the case of the Halifax-Dartmouth region, road development does have an impact on residential land development, but residential land development does not have an impact on road development. Understanding the direction and strength of the transportation-land use relationship is imperative for making informed policy decisions. Policy makers must understand the transportation-land use relationship in order to address such pressing problems as urban sprawl, traffic congestion, and pollutant emissions. Such problems are inherently rooted in the transportation-land use relationship. The results of this research indicate that road development has a much stronger impact on land development than land development has on road development. Given these results, land development policies designed to promote changes in travel behaviour and to reduce transportation requirements may have limited success. If road development drives land development, policies related to the provision of transportation infrastructure may have more of an impact on land development. These results suggest that policy makers should address the problems above with transportation policies, as land use policies may not be effective.

5.7 References

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CHAPTER 6: Conclusion

6.1 Summary of Results

The primary objective of this research is to examine the relationship between transportation infrastructure development and land development in the Halifax-Dartmouth region. To realize this objective, the research began by investigating the changing urban form of the region. Then, the research examined both directions of the transportation-land use relationship by quantifying the impact of residential land development on road development and the impact of road development on residential land development.

For decades, empirical studies that examine changes in urban form have relied on the negative exponential density function, despite the fact that many studies suggest that the function is not appropriate for the non-monocentric nature of contemporary urban areas. Given the changing form of urban areas, alternate methods are required. Using disaggregate parcel level data, the dissertation computed kernel estimates and K function estimates to explore the location, pattern, and timing of new residential and commercial land parcel development. Results of the kernel estimates suggest that over the period 1970 to 1996, residential land parcel development experienced decentralization and deconcentration to a greater extent than commercial land parcel development. Results of the K function estimates indicate that residential land parcels cluster together, commercial land parcels cluster together, and over time residential and commercial land parcels have become more clustered with each other. This increasing residential-commercial land parcel clustering through time indicates that the location of new commercial land parcels may be decentralizing to a greater extent than is revealed in the kernel estimates. Moreover, this clustering trend over time suggests the emergence of sub-centres in the Halifax-Dartmouth region. If such a trend continues, a multinucleated urban form may appear in the future. The results of these analyses provide insight into the spatial processes underlying the changing urban form of the Halifax-Dartmouth region. Moreover, the results support Garreau's (1991) edge city model of urban form where population drives urban growth and the change in urban form.

The dissertation draws an empirical link between transportation and land use by examining the spatial pattern of road development and residential land development. To quantify the impact of road development on residential land development, ordered probit models were specified where residential land parcel development was a function of either the change in accessibility or the distance to a high-speed road, and other explanatory variables. The change in accessibility variable represents a regional measure of the impact of road development while the distance variable represents a local measure. Models were estimated for five time periods between 1971 and 1996. The results of the four most recent time periods show that road development has a significant impact on residential land development. However, the spatial impact varies from time period to time period. A regional impact is evident for the time periods 1981-1986 and 1991-1996, as there is a positive relationship between the change in accessibility and residential land development. A local impact is evident for the time periods 1976-1981 and 1986-1991, as there is a negative relationship between the distance to a high-speed road and residential land development. Despite the inconsistencies, the results of the ordered probit models support the proposition that road development does drive residential land development.

To quantify the impact of residential land development on road development, spatial lag models were estimated where the change in accessibility was a function of residential land development and other explanatory variables. Models were estimated for the five time periods between 1971 and 1996. Based on the model results, the change in accessibility does not appear to be a function of residential land development. There was no significant relationship in any time period between the change in accessibility and the number of residential land parcels developed in the previous time periods or current time period. Three of the time periods did have a significant land parcel variable in terms of the aggregate number of parcels but the direction of the relationship was not consistent. The results of the spatial lag model do not support the proposition that residential land development drives road development.

6.2 Contributions of the Dissertation

6.2.1 Contribution to the Literature

The results of this dissertation contribute significantly to the literature on urban form and transportation-land use interactions. Moreover, the dissertation makes a methodological contribution in applying spatial data analysis methods to the examination of urban form. Using spatial data analysis methods, the dissertation utilized an alternative approach to examine the changing urban form of the Halifax-Dartmouth region. Such an approach may be easily applied to other urban areas for which point data are available, and it is more appropriate for the multinucleated form of contemporary urban areas. The dissertation contributes to the literature on transportation-land use interactions by quantifying the strength of both directions of the relationship. Many studies examine the impact of transportation on land use by studying the economic impacts of transportation investments. Other research examines the impact of land use on transportation by studying the impact of urban form on travel patterns. No prior study has examined the transportation-land use relationship empirically by examining the spatial pattern of development at the regional scale.

6.2.2 Implications for Planning and Policy

Urban areas are currently facing many challenging issues including urban sprawl, traffic congestion, and pollutant emissions. The causes of these issues are embedded in the transportation-land use relationship. Urban sprawl is characterized by an outward expansion of the urban boundary; a general decline in intensity of land use; a transportation network that provides high connectivity between points; and a segregation of residential land use from other land uses (Anderson *et al.,* 1995). Traffic congestion stems from the spatial clustering of destinations, automobile dependence, and induced demand. Increased pollutant emissions are directly related to increased motor vehicle use. Motor vehicles are the largest source of transportation related pollutants for nearly every type of pollutant (Transportation Research Board, 1995). Factors that affect motor vehicle emissions include travel demand, vehicle kilometres traveled (VKT), and traffic congestion, all of which are influenced by the spatial distribution of activities. Because all of these issues are rooted in the transportation-land use relationship, effective policy instruments to address them cannot be developed without fully understanding this relationship.

The results of this dissertation show that road development has a much stronger impact on residential land development than residential land development has on road development. Given these results, transportation planners must realize that their decisions have a significant impact on urban form. This realization is not new; other researchers have drawn a similar conclusion. Wegener (1986) asserts that decisions about the location and capacity of transportation infrastructure have very long term implications with respect to urban form. Watterson (1993) calls for long term transportation and land use strategies that will encourage change in the structure of urban areas to a less automobile dependent form. The difference between this dissertation and other studies is that the dissertation provides quantitative evidence to support the above suggestions. No prior study has quantified the relationship between transportation and land use as this one has.

In many urban areas, transport problems are addressed with transport policies and land use problems are addressed with land use policies. As a result, transportation planning and land use planning remain separate decision-making processes. This lack of coordination has resulted in limited success in addressing many policy issues. Policy-makers must utilize both the transport planning system and the land use planning system to direct new development. Transport planners must consider both land use plans and the land use impacts of their decisions. In the United States, the federal Intermodal Surface Transportation Efficiency Act (ISTEA) requires that transportation plans include the likely effect of transportation policy decisions on land use and development, and the consistency of transportation plans and programs with the provision of all applicable short- and long-term land use and development plans (Kelly, 1994). The results of this dissertation indicate that the coordination of land use and transportation policy decisions is necessary to effectively address the issues that currently challenge many urban areas.

6.3 Directions for Future Research

Given the existing dataset and the results of the dissertation, there are several avenues for future research. First, sensitivity analysis is required to examine the effect of grid cell size on the model results. In the dissertation, the spatial unit of analysis for all variables was the 1 km by 1 km grid cell. It would be useful to experiment with other grid cell sizes, both large and small, to determine if the transportation-land use relationship remains consistent. Second, it would be valuable to estimate the models using commercial land parcels rather than residential land parcels. The results of such analyses would indicate if the transportation-land use relationship is consistent across different types of development.

Third, a comparative study would be useful to ensure that the relationship between road development and land development is consistent in different contexts; that is, across urban areas. The models in the dissertation were calibrated using data for a slow-growing urban area. A comparative study would be useful to examine the relationship in a fast growing urban area. The city of Calgary would be ideal for comparison as the population and land area of the metropolitan area has increased substantially over the past two decades. The city also has an excellent land parcel database from which to develop the model. The database is extremely detailed in terms of information such as year of construction, current land use, frontage, and floor area. Data pertaining to the evolution of the transportation network is available in hard copy.

Finally, it would be useful to extend the models estimated in the dissertation for use as a forecasting tool. To start, the models must be validated as to their predictive accuracy. Model validation involves the comparison of the model results with observed data over an extended period of time. The validated models may then be used to forecast future development. Given the numerous environmental implications of road and land development, there is an increased urgency for policy-makers to make informed decisions. With the ability to predict such development, the models will serve as tools for the anticipation, management, and guidance of road and land development.

6.4 References

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