PERGAMON

Journal of Transport Geography 11 (2003) 103–115

JOURNAL OF TRANSPORT GEOGRAPHY

www.elsevier.com/locate/jtrangeo

Integrated land use and transportation interaction: a temporal GIS exploratory data analysis approach

Shih-Lung Shaw *, Xiaohong Xin

Department of Geography, The University of Tennessee, Knoxville, TN 37996-0925, USA

Abstract

Land use and transportation interaction is a complex, dynamic process. Many models have been used to study this interaction process during the past several decades. Empirical studies suggest that land use and transportation interaction patterns can be highly variable between geographic areas and at different spatial and temporal scales. This paper presents a temporal geographic information systems (GIS) design that offers exploratory data analysis capabilities to interactively examine land use and transportation interaction at user-specified spatial and temporal scales. A spatiotemporal interaction framework, implemented with temporal GIS databases, provides a foundation for the development of spatiotemporal analysis functions to systematically explore land use and transportation interaction.

Keywords: Land use; Transportation; Spatiotemporal; Exploratory data analysis; Geographic information system

1. Introduction

Land use and transportation interaction is a dynamic process that involves changes over spatial and temporal dimensions between the two systems. Changes in land use systems can modify the travel demand patterns and induce changes in transportation systems. Transportation system evolution, on the other hand, creates new accessibility levels that encourage changes in land use patterns. Since the 1960s, many theories and models have been used to study land use and transportation interaction (e.g., Alonso, 1964; Anas, 1982; Anas and Duann, 1986; Boyce, 1980, 1990; Hansen, 1959; Kim, 1983; Prastacos, 1986; Kim et al., 1989; Hirschman and Henderson, 1990). Giuliano (1995, p. 3) argues that most models "are generally static, partial equilibrium models" even though they employ iterative methods and equilibrium concepts. Without incorporating time explicitly in a model, iterative methods only provide an equilibrium solution for a given point in time. Also, holding some variables fixed (e.g., treating land use activities as exogenously given variables in a travel demand model) such models are, at best, partial equilibrium approaches.

Effects of transportation system changes on land use, and vice versa, occur at varying spatial and temporal scales. For example, the construction of a new rail transit line tends to have larger effects on land use changes along the transit line corridor and around the rail stations than on the urban area as a whole. A highway construction project may introduce a traffic increase shortly after its completion and lead to some land use changes in its immediate vicinity. However, its impacts on land use patterns at the regional scale may be insignificant in both short and long-terms due to the relatively small changes to the accessibility levels on other parts of the metropolitan area. Wegner and Fürst (1999) classify eight types of major urban subsystems into those that experience very slow changes, slow changes, fast changes, and immediate changes (Table 1). Physical infrastructure such as transportation networks and land use patterns based on existing buildings take longer time to exhibit significant changes. People and firms, on the other hand, show faster adjustments to changes in traffic conditions and fluctuations in demand with respect to their location choices and travel choices. Identifying these complex changes at varying spatial and temporal scales presents a major challenge. When we recognize that long-term changes could be affected by other factors such as population growth, economic development, and policy decisions, the challenge becomes even more overwhelming. Most existing land use and

* Corresponding author.
E-mail address: sshaw@utk.edu (S.-L. Shaw).

0966-6923/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0966-6923(02)00070-4

Table 1
Urban change processes (source: Wegner and Fürst, 1999, p. 43)

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

transportation interaction models are based on some prior theories and use mathematical or simulation approaches to study the problem. However, the literature also suggests that little consensus regarding the conclusions can be drawn from empirical studies that apply these models (Giuliano, 1995). There is a clear research need to develop alternative methods that will allow us to examine the land use and transportation interaction patterns in more flexible ways and to help us identify potential improvements to the existing models.

This paper presents a temporal geographic information systems (GIS) design that offers exploratory data analysis (EDA) capabilities to interactively examine the land use and transportation interaction at user-specified spatial and temporal scales. The spatiotemporal patterns and the summary statistics derived from this interactive exploratory analysis process can be used to help us evaluate the hypotheses and modify the structures used in the existing models. The results also can suggest additional analyses for a better understanding of land use and transportation interaction. The remaining sections of this paper are organized as follows. First, we provide a brief review of integrated land use and transportation models in terms of their different approaches. Next, we present the relevance of EDA and temporal GIS to this study. It is followed by discussions of the design and implementation of a temporal GIS-based system that allows analysts to interactively explore and visualize land use and transportation interaction at varying spatial and temporal scales. Finally, we offer our concluding remarks and future research needs.

2. Integrated land use and transportation modeling

Land use and transportation interaction has been a research subject for several decades. Research efforts have been based on early approaches such as urban forms (Hoyt, 1939; Harris and Ullman, 1945), bid rent curve (Alonso, 1964), spatial interaction models (Lowry, 1964; Wilson, 1970), and time geography (Hägerstrand, 1970), to more recent approaches like microsimulation models (e.g., Landis and Zhang, 1998a,b). In recent years there has been a renewed interest in the development of integrated land use and transportation models on both sides of the Atlantic Ocean. On the United States side, the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 required that "transportation plans must take into account the likely effect of transportation policy decisions on land use and development and the consistency of transportation plans and programs with land use and development plans" (quoted in Miller et al., 1999, p. 3) The Transportation Equity Act for the 21st Century (TEA-21) of 1998, which succeeds the ISTEA Act, also recognizes the land use and transportation relationship within a broader context of economic development and environmental issues. In addition, both ISTEA and TEA-21 require transportation plans to conform with the requirements of the Clean Air Act Amendments (CAAA) of 1990. Recognizing the inadequacy of existing models to address the legislative requirements, the US Department of Transportation and the US Environmental Protection Agency jointly established a Travel Model Improvement Program (TMIP) in 1993. The TMIP includes six tracks. One of the tracks focuses on improving modeling capabilities and data for integrated analysis of land use and transportation interaction, while the other tracks investigate the relationships between transportation and air quality (Miller et al., 1999).

In Europe, a number of research projects under the European Union's Fourth Programme Framework are related to land use and transportation interaction. Among them, the TRANSLAND research project focuses on innovative policies and future research needs in the field of integrated urban transport and land use planning. In a TRANSLAND project report, Wegner and Fürst (1999) provide a comprehensive review of seventeen integrated land use and transportation models (Table 2). Six of the seventeen models (i.e., BOYCE, KIM, METROSIM, MUUSA, RURBAN, and STASA) are classified as *unified* models that have a tightly inte-

Table 2
The seventeen integrated land use and transportation models reviewed by the TRANSLAND project of the European Union's 4th Programme Framework

Model	Description
BOYCE	Combined models of location and travel choice developed by D.E. Boyce
CUFM	California urban futures model developed at the University of California at Berkeley
DELTA/START	Land use modeling package of DELTA developed by David Simmonds Consultancy, Cambridge, UK linked with the transport model of START developed by MVA Consultants and the Institute of Transport Studies at the University of Leeds
HUDS	Harvard urban development simulation developed by J.F. Kain and W.C. Apgar Jr.
IMREL	Integrated model of residential and employment location developed by C. Anderstig and L.G. Mattsson
IRPUD	Model of the Dortmund region developed by M. Wegner
ITLUP	Integrated transportation and land use package (often referred to as DRAM/EMPAL) developed by S.H. Putman
KIM	Non-linear version of the urban equilibrium model developed by T.J. Kim
LILT	Leeds integrated land use/transport model developed by R.L. Mackett
MEPLAN	Integrated modeling package developed by Marcial Echenique and Partners
METROSIM	Microeconometric land use and transport model developed by A. Anas
MUSSA	Five-stage land use and transport model developed by F.J. Martinez for Santiago de Chile
POLIS	Projective optimization land use information system developed by P. Prastacos for the Association of Bay Area Governments, California, USA
RURBAN	Random-utility URBAN model developed by K. Miyamoto
STASA	Master equation based integrated transport and urban/regional model developed by G. Hagg
TRANUS	Transport and land use model developed by T. de la Barra
URBANSIM	Microeconomic model of location choice of households and firms developed by P. Waddell

Source: Wegner and Fürst (1999, p. 44).

grated model structure. The other eleven models are *composite* models, which consist of a set of loosely coupled submodels with their own independent internal structures. Regarding their theoretical approaches, all models are based on random utility or discrete choice theory, except for the CUFM that generates population growth based on regression equations, allocates population growth among developable land units (DLUs) stored in a GIS database, and annexes DLUs to adjacent cities or to create new municipalities. For modeling techniques, CUFM and HUDS apply microsimulation techniques at the disaggregate level, the rest are all aggregate models. Furthermore, all seventeen models subdivide time into discrete periods. Southworth (1995), on the other hand, classifies land use and transportation models into five general types: Lowry and related models, mathematical programming, multisector models, urban economic models, and microsimulation models.

With the rapid advancement and adoption of information and communications technologies (ICTs), the transportation research community also actively looks into the effects of ICTs (e.g., teleworking, teleshopping, and logistic supply chains) on land use and transportation systems. Research networks on this topic are currently sponsored by the European Commission's Fifth Framework Programme with projects such as the Sustainable Transport in Europe and Links and Liaisons with America (STELLA) (www.stellaproject.org) and by the US National Science Foundation on the Sustainable Transportation Analysis and Research (STAR) project (www.ncgia.ucsb.edu/stella).

3. Exploratory data analysis and temporal GIS

Most land use and transportation interaction studies take a *confirmatory* analysis approach that is based on some of the prior theories or models discussed above. These studies certainly have helped us establish theoretical bases and solution methods in our attempts to gain a better understanding of land use and transportation interaction. Nevertheless, the inconsistent findings from empirical studies also suggest the existence of significant spatial and temporal variations between different geographic areas. For example, Giuliano (1995) reviewed several empirical studies and reported that rail transit systems had no systematic influence on urban structures between different cities in the United States and Canada. Even in the same city, land development occurred near some rail stations but not around other stations. In addition, she referenced a beltway study of 54 US cities (27 with beltways) and pointed out that, while portions of a beltway in each metropolitan area experienced significant development, other portions underwent insignificant or no changes (Payne-Maxie Consultants, 1980).

Land use and transportation system changes take place in a highly dynamic system that involves many forces such as economic development, population growth, and policy decisions. Models built on a confirmatory analysis approach are often based on a prespecified spatial and temporal scale; therefore, they are less flexible of examining the dynamic nature of various forces acting at different spatial and temporal scales on land use and transportation interaction. EDA, on the other hand, takes a speculative and systematic approach to assist us in searching for patterns and processes hidden in the data sets (Openshaw, 1994; Goodchild, 2000). EDA emerged in the 1970s as methods of revealing what would otherwise go unnoticed with the use of standard statistical analysis (Tukey, 1977). The GIS research community began to develop methods for exploratory spatial data analysis in the 1980s. The main challenges of integrating EDA with GIS are to develop methods of sifting through large spatial data sets and to design visualization tools of presenting the patterns and relationships hidden in the large data volume. Visual data analysis of examining maps to search for hidden patterns and relationships is a useful form of spatial analysis (Goodchild, 2000). EDA does not impose scale-specific assumptions on the analysis procedure; therefore, the patterns and relationships could emerge from the analysis rather than be imposed under a confirmatory data analysis approach. In recent years, use of EDA with GIS has been actively pursued in spatial data mining and spatial knowledge discovery (e.g., Miller and Han, 2001).

GIS by design are rich in spatial analysis and visualization functions. Various analysis and modeling procedures have been applied to GIS for transportation (GIS-T) (Miller and Shaw, 2001). These GIS-T applications range from travel demand analysis (e.g., Anderson and Souleyrette, 1996; Ding, 1998; Miller and Storm, 1996), corridor planning and route selection (e.g., Hartgen and Li, 1994; Jankowski and Richard, 1994; Jha and Schonfeld, 2000), highway safety (e.g., Kim and Levine, 1996), pavement management (e.g., Sarasua and Jia, 1995), intelligent transportation systems (e.g., Dailey et al., 1999; Peng and Huang, 2000), emergency evacuation (e.g., Cova and Church, 1997), to logistics (e.g., Ralston, 2001). Many of these GIS-T applications are good candidates for EDA within a GIS environment. For example, we could explore spatio-temporal traffic accident patterns using traffic accident data (e.g., accident type, vehicle type, driver characteristics, time in a day) with GIS layers of highway characteristics (e.g., speed limit, pavement condition, curvature, lighting) and environmental data (e.g., weather, terrain). For studies of land use and transportation interaction, spatial analysis and visualization functions in a GIS coupled with an EDA approach will allow us to examine the different patterns caused by various forces related to land use and transportation changes between urban areas as well as their effects at different spatial and temporal scales within a specific urban area. Specifically, a GIS-based exploratory spatial analysis system for land use and transportation interaction should meet the following objectives:

1. The system must include temporal GIS databases that allow investigations of land use and transportation interaction at different temporal scales (i.e., short-term and long-term effects of land use and transportation interaction).
2. The system must permit analysts to investigate relationships among all GIS map layers that represent the various forces (e.g., population growth, economic development, transportation investments) underlying the process of land use and transportation interaction at different spatial scales for various time periods.
3. The system must provide methods for a systematic exploration of relevant data sets and offer visualization tools and basic summary statistics to show the land use and transportation interaction patterns.

Such a GIS-based exploratory analysis system does not replace the existing confirmatory modeling approaches. Instead, it serves as a complement to the confirmatory analysis approach. Findings from the GIS-based exploratory analysis system can be used to revisit the existing model structures or to validate the model parameters for a particular study area. They also may suggest new hypotheses for researchers to examine hidden spatiotemporal patterns of land use and transportation interaction.

4. Design of a temporal GIS-based exploratory analysis system

Like many other spatial processes, land use and transportation interaction involves the time element (when), the location element (where), and the attribute element (what) that are interrelated with each other. Sinton (1978) proposes a measurement framework to treat location, time, and attribute as "fixed", "controlled", and "measured" components when performing measurements of a single phenomenon (Table 3). Conventional GIS with a snapshot approach, which represents data for each GIS layer at a given point in time, correspond to a subset of Sinton's measurement framework. A raster GIS implementation of the snapshot approach is equivalent to the scenario 3 in Sinton's framework that fixes time and controls locations (i.e., pre-determined cell size) to measure attributes (e.g., land use types). A vector snapshot GIS implementation, on

Table 3
Measurement framework proposed by Sinton (1978)

	Fixed component	Controlled component	Measured component
Scenario 1	Location	Time	Attribute
Scenario 2	Location	Attribute	Time
Scenario 3	Time	Location	Attribute
Scenario 4	Time	Attribute	Location
Scenario 5	Attribute	Location	Time
Scenario 6	Attribute	Time	Location

the other hand, fixes time and controls attributes (e.g., land use types) to measure their locations (i.e., boundaries of land use zones). This follows scenario 4 of Sinton's measurement framework. Under either implementation, transportation planners can answer questions such as "Where were residential or commercial land use zones in 2000?" using the query functions in a GIS.

The snapshot GIS approach, however, is ineffective in dealing with the other four scenarios in Sinton's measurement framework. For instance, scenario 1 measures attribute changes (e.g., land use changes) over a controlled time period (e.g., 1980 through 2000) at a fixed location. Since a snapshot GIS stores data at each given time point in a separate layer and does not explicitly handle the temporal relationships among the layers, we must perform overlay analyses of all GIS layers covering the specified time period repeatedly in order to find out, for example, the land use changes during the 1980–2000 period. To overcome this shortcoming, from the late 1980s active research efforts have been placed on the development of temporal GIS. Among them, the space–time composite data model combines the snapshots of a phenomenon (e.g., land use or highway system) at different time points into a single composite GIS layer (Langran and Chrisman, 1988; Langran, 1992). Each record in a space–time composite layer represents a spatial unit with its unique attribute changes over time. Peuquet (1994) proposes a TRIAD database framework to integrate time into GIS. One implementation of the TRIAD framework is an event-based spatiotemporal data model (ESTDM) using raster GIS (Peuquet and Duan, 1995). The ESTDM builds an event list with time-stamped entries that record the grid cells experiencing attribute changes from $t(i-1)$ to $t(i)$ and the locations of those grid cells. Although the event list approach is effective of tracking changes between raster GIS data layers, it does fit well with vector GIS data that do not share a fixed grid size among the snapshot layers.

Worboys (1992, 1994), on the other hand, suggests an object-oriented spatiotemporal data model that consists of multidimensional objects: two-dimensional spatial objects with a third dimension for the event time associated with each object. The basic element in the data model is a spatiotemporal atom (ST-atom) that has homogeneous properties in both space and time. ST-atoms are used to form spatiotemporal objects (ST-objects) that represent changes of real world entities. He later extends the approach to a spatio-bitemporal model that includes both event time and database time to record the existence of an object in the real world and in a database system, respectively (Worboys, 1998). One important contribution of Worboys' approach is to maintain the object identity through time. Yuan (1996, 1999) proposes a three-domain data model that consists of semantic domain, temporal domain, and spatial domain, along with domain links. The semantic domain defines real world entities with unique identifiers throughout the study duration. The temporal domain stores each time instance as a unique object, while the spatial domain is based on the space–time composite data model to derive a set of common spatial features with unique identifiers. Domain links are used to record the links among semantic, temporal, and spatial objects with their unique identifiers. These temporal GIS data models provide useful concepts to extend the static snapshot GIS approach. The temporal GIS database design in this study adapts the space–time composite concept and extends it to incorporate the semantic concept and the object identity concept with time-based object classes that track the change history of vector GIS data.

In addition to the design of temporal GIS databases, another main challenge is to design a systematic method for explorations of various data sets relevant to land use and transportation interaction. As mentioned earlier, Sinton's measurement framework focuses on the measurements of a single phenomenon. When we need to examine the interactions between two phenomena (i.e., land use system and transportation system), it is necessary to extend this framework. To explore the interactions between two systems, a generic question can be formulated as "What were the possible changes in one system related to the changes in another system over time?" The three key components included in this generic question are "changes in system A", "changes in system B", and "time". Each system here may include temporal GIS databases of multiple layers. For example, one system could be the land use system that consist of changes of land use types, census data, building permits data, and property tax data, while the other system could be the transportation system that covers the changes in transportation network layouts, traffic count data, and transportation improvement projects. By fixing one of the three components, controlling another component, and measuring the third component, it allows us to explore the effects of various forces interacting between the two systems over time. For example, transportation planners who examine land use and transportation interactions are likely to ask questions such as:

1. When did major land developments take place within a one-mile zone of a new rail transit line after its completion?
2. Where were the areas that experienced greater than 10% land value increases during one-year, three-year, and five-year periods after the completion of a new beltway?
3. Where were the vacant land parcels within a one-mile zone of ongoing transportation projects in 1996?

Table 4
Spatiotemporal interaction framework for exploratory analysis of land use and transportation interaction

	Fixed component	Controlled component	Measured component
Scenario 1	Transportation (space–attribute–time)	Land use (space–attribute–time)	Time
Scenario 2	Transportation (space–attribute–time)	Time	Land use (space–attribute–time)
Scenario 3	Time	Transportation (space–attribute–time)	Land use (space–attribute–time)
Scenario 4	Time	Land use (space–attribute–time)	Transportation (space–attribute–time)
Scenario 5	Land use (space–attribute–time)	Transportation (space–attribute–time)	Time
Scenario 6	Land use (space–attribute–time)	Time	Transportation (space–attribute–time)

4. Which street segments that are adjacent to commercial land use in the study area had a traffic volume/capacity ratio greater than 1 in 1998?
5. When did traffic volumes on major streets increase by more than 30% in those traffic analysis zones reaching an employment density of 10,000 per square mile?
6. What were the traffic volumes on major streets in each census tract with an annual population growth rate over 5% from 1990 to 2000?

It is obvious that data collected for each system have their own time, location, and attribute elements. Table 4 shows a proposed spatiotemporal interaction framework for exploring land use and transportation interaction. In this framework, all data related to the land use system and the transportation system are stored in temporal GIS databases with their respective spatial, attribute, and temporal elements. Since all spatial or attribute changes in either system and between the two systems take place over time, we therefore use time as the key component in this framework to facilitate spatiotemporal analysis of land use and transportation interaction. Therefore, the three elements (spatial, attribute, and time) can be accessed either separately or in combination via custom user interfaces presented in the implementation section below.

If our task is to find out "When did major land developments take place within a one-mile zone of a new rail transit line after its completion?" We can first use the temporal transit network GIS layer to retrieve the location of the specific rail transit line and its completion date (i.e., the fixed component). The temporal GIS databases of land development/building permits then are used to retrieve all major land developments that are located within the one-mile buffer zone and after the completion date (i.e., controlled component) of the specific rail transit line. A report of the times when the major land use developments took place and their relevant summary statistics (e.g., total acreages by year) can be presented as the measured component. This example corresponds to the scenario 1 in Table 4, which measures the time points/periods associated with the changes of land use component under some controlling factors with respect to the fixed transportation component.

For the sample question 2 listed above (corresponding to the scenario 2 in Table 4), we again first use temporal transportation database to fix the location and completion date of the specified beltway. One-year, three-year, and five-year time periods then serve as the control component to find the areas that experienced greater than 10% land value increases during each of the three time periods. Question 3 above (corresponding to the scenario 3 in Table 4), on the other hand, specifies a fixed time (i.e., 1996) and controls the transportation component (i.e., a one-mile zone of ongoing transportation projects) to measure the land use component (i.e., vacant land parcels). The other three sample questions are similar to the three sample questions discussed above, except that our interest now is to explore the effects of land use changes on the transportation system rather than the effects of transportation system changes on land use patterns.

The proposed spatiotemporal interaction framework provides a systematic and flexible design for transportation planners to explore land use and transportation interactions. By treating time as an integration component, it makes it possible to implement temporal relationships such as "before", "coincide", "overlap", and "after" between two different phenomena in order to explore their interactions of various temporal durations (e.g., short-term versus long-term). Combined with the creation of temporal GIS databases of both the land use and the transportation components (shown as consisting of spatial, attribute, and temporal data in Table 4), this framework is capable of exploring spatial and attribute changes between the land use and transportation components along the time dimension. It also is flexible enough to examine "when" the changes took place by fixing and controlling the spatial and attribute data of land use and transportation components, respectively.

Most GIS packages today already provide powerful functions of handling spatial and attribute data in an integrated environment. This study therefore takes an approach of extending an existing commercial GIS package to incorporate temporal data in the system design for exploratory analysis of land use and transportation interaction. Whenever the existing GIS capabilities can help accomplish specific tasks, they are used in the system design. Development of custom functions in this study focuses mainly on extending the snapshot GIS databases into temporal GIS databases, adding time-based analysis functions, and integrating temporal data with spatial and attribute data in order to support spatiotemporal exploration of land use and transportation interaction. The next section presents how these custom functions are developed and implemented.

5. A prototype implementation

A prototype system based on the system design discussed above is implemented with the geodatabase data model and ArcObjects of the ArcGIS software (Environmental Systems Research Institute, Redlands, CA). The geodatabase data model is an object-oriented data model that is implemented using object-relational database technology (Zeiler, 1999). Map features in a geodatabase are implemented as a set of relational tables. A geodatabase also can define relationship classes between features and objects (i.e., non-spatial data), bind the behavior of feature to the tables that store the features, and allow users to develop their own application data models (Zeiler, 1999). ArcObjects, which is built on the Microsoft Component Object Model (COM) technology, allows users to extend and to customize their GIS applications using any COM-compliant development languages such as Visual Basic and Visual C++ (Zeiler, 2001). Custom programs can be compiled into dynamic link libraries and added into the user interfaces of ArcGIS applications.

The data used in this study are for Dade County (Miami), Florida. These data sets include land use, building permits, property tax, census data, traffic counts, traffic analysis zones, street networks, level of service, and transportation improvement projects for multiple years. Some of the data sets (e.g., census data and property tax) are used to explore the effects of other demographic and socioeconomic factors on land use and transportation system changes. With these snapshot data sets at hand, the first step is to geocode and convert them into geodatabases. The snapshot geodatabases are then combined into temporal geodatabases such that exploratory analysis functions can be developed to implement the spatiotemporal interaction framework presented in Table 4. This task is accomplished with a set of custom programs that are integrated with ArcObjects to create space–time composite geodatabases, time objects, time2space objects, and semantic objects. The space–time composite geodatabases are based on the concept proposed by Langran (1992). One shortcoming of the space–time composite approach is that it requires queries on multiple attribute fields to identify the existence of features at multiple time points. This becomes inefficient when we deal with large temporal GIS databases. To overcome this shortcoming, time and time2space objects are created during the process of converting snapshot GIS layers into space–time composite geodatabases. Fig. 1 shows a unified modeling language

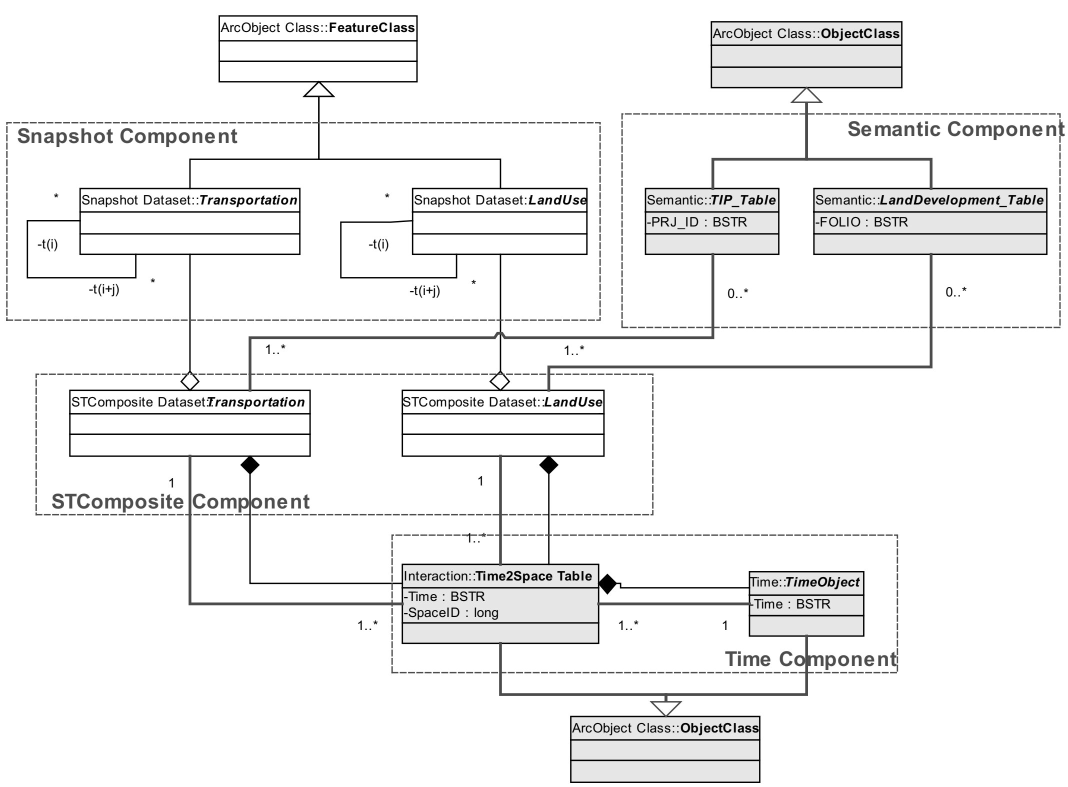


Fig. 1. UML diagram of the system design.

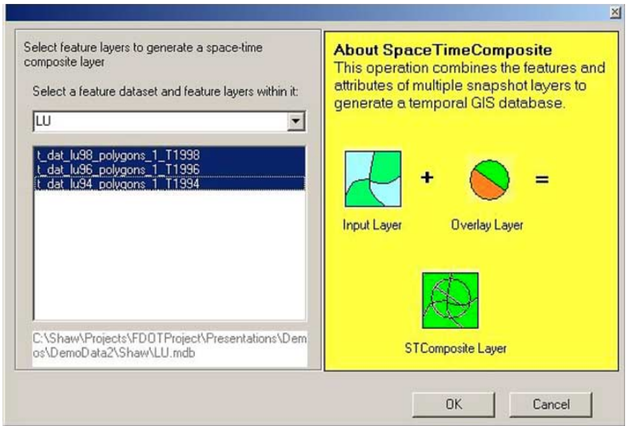


Fig. 2. Custom user interface of creating temporal GIS databases from snapshot GIS layers.

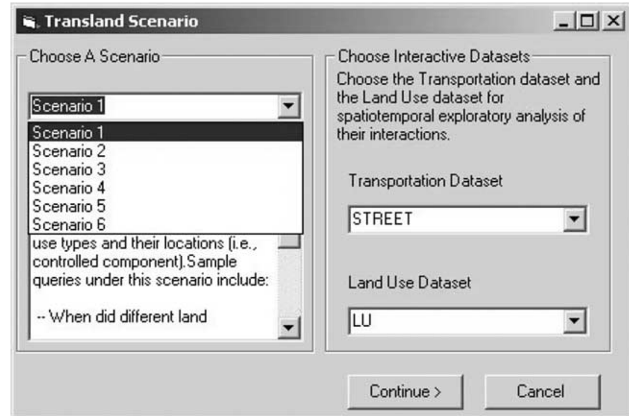


Fig. 3. Six scenarios for spatiotemporal exploration of land use and transportation interaction.

(UML) diagram of the system design. The time object class records all unique time instances associated with the snapshot GIS layers, while the time2space object class associates the unique identifier of each geographic unit in a space–time composite database with all time instances that existed in the individual snapshot layers over time. In other words, the time object class and the time2space object class together keep track of the change history of each feature in the space–time composite geodatabases. Fig. 2 shows the custom dialog window that assists analysts to build temporal GIS databases and space–time object tables from the snapshot geodatabases.

Semantic objects refer to the objects with a persistent identification (ID) that have different locations and attribute data values in different time periods. For example, a transportation improvement project often has several phases and each phase may be associated with different locations (e.g., road widening along different segments of a highway) and attributes (e.g., budget spent, percent of work completion). Many large residential and commercial land development projects also may consist of several phases that last for a few years. The impacts of these transportation improvement projects and land development projects over time therefore must be analyzed according to their different locations and characteristics in each phase. Semantic object tables are created for these transportation and land development projects so that transportation planners can simply refer to the unique project IDs to access all relevant data over time. Locations associated with a particular semantic object are normally referenced to an existing GIS geodatabase. For example, the different phases of a transportation improvement project can be referenced to different segments in a temporal highway GIS layer and the different phases of a land development project are linked to different polygons in a temporal land parcel GIS database. Implementation of these semantic objects follows the semantic domain concept suggested by Yuan (1996, 1999).

Once all snapshot data sets have been converted into temporal geodatabases in ArcGIS, we are ready to implement the spatiotemporal interaction framework as outlined in Table 4. EDA is not a blind search through the data sets. A key requirement here is to develop a systematic method so that the user interfaces help analysts to sift through various data sets and to explore the hidden patterns and relationships. This is accomplished by the design of a series of dialog windows that guide the analysts through their exploratory analysis processes. Fig. 3 shows the first dialog window that allows analysts to select among the six scenarios and choose the specific data sets related to the land use and the transportation components. The dialog window also provides a description of what each scenario does with examples, based on the particular scenario chosen from the drop down list. Depending on the chosen scenario, the system automatically brings up the next dialog window to guide the analyst. For example, the analyst would like to explore when land use changes took place in the study area after the completion of a transportation improvement project. The analyst chooses scenario 1 and the system displays another dialog window for the analyst to specify the transportation component (Fig. 4). Analysts could choose multiple transportation projects or features to be included in the analysis.

Analysts may want to control the spatial extent and the attribute values in search for the relationships between transportation and land use data sets. Another dialog window with tools to specify spatial constraints (i.e., interactively define the spatial search extent using different geometric shapes; select among spatial operators such as contain, overlap, intersect, cross, and touch) and/or define attribute queries is made available to the analyst (Fig. 5). If the analyst does not specify any spatial constraints, the system defaults the search to the

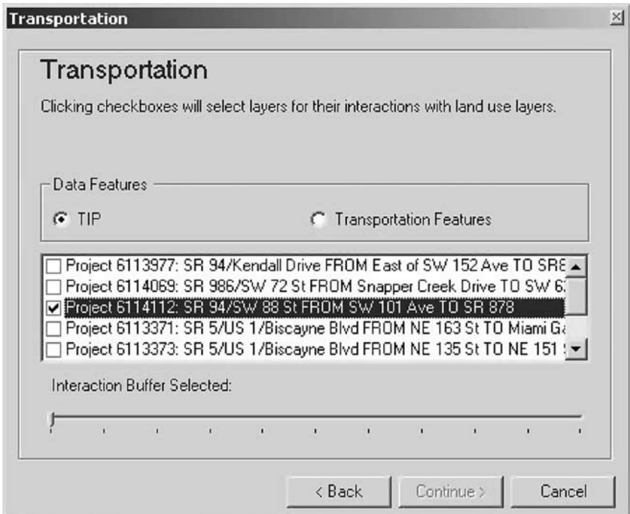


Fig. 4. Dialog window of choosing the transportation component.

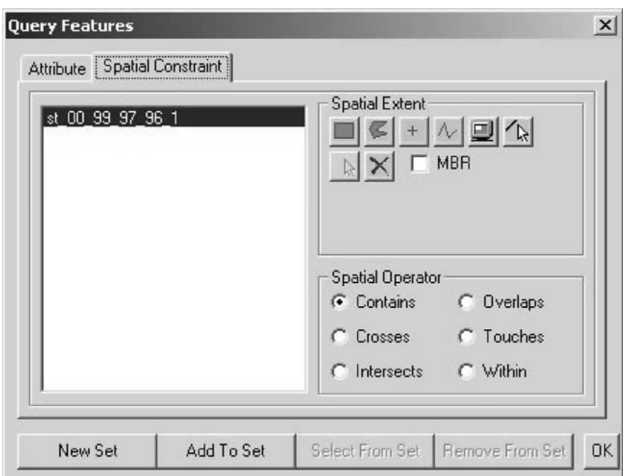


Fig. 5. Tools available to control spatial and attribute constraints for exploratory analysis.

entire study area. These tools allow analysts to explore land use and transportation interactions at varying spatial scales ranging from immediate vicinity, to traffic analysis zone, to metropolitan area, to a regional scale.

If time is used as the fixed component, analysts can specify the time periods for both land use and transportation components to perform a spatiotemporal analysis. Fig. 6 shows an example of the scenario 4 to explore the effects of land use changes of 1989–1990 on transportation systems during the period of 1991–1995. Again, analysts can specify different time periods to assess either short-term or long-term effects of one system on the other system. It should be noted that, with the extension of snapshot data sets into temporal GIS databases under the spatiotemporal interaction framework, the fixed, controlled, and measured components in this framework behave differently from the same

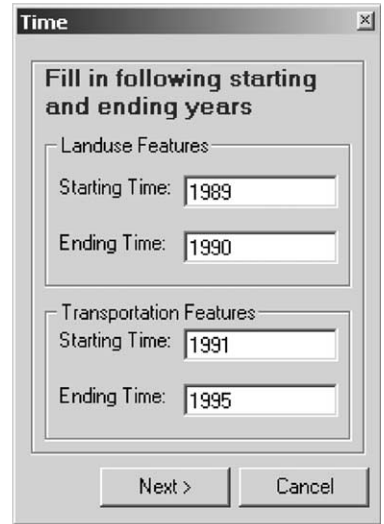


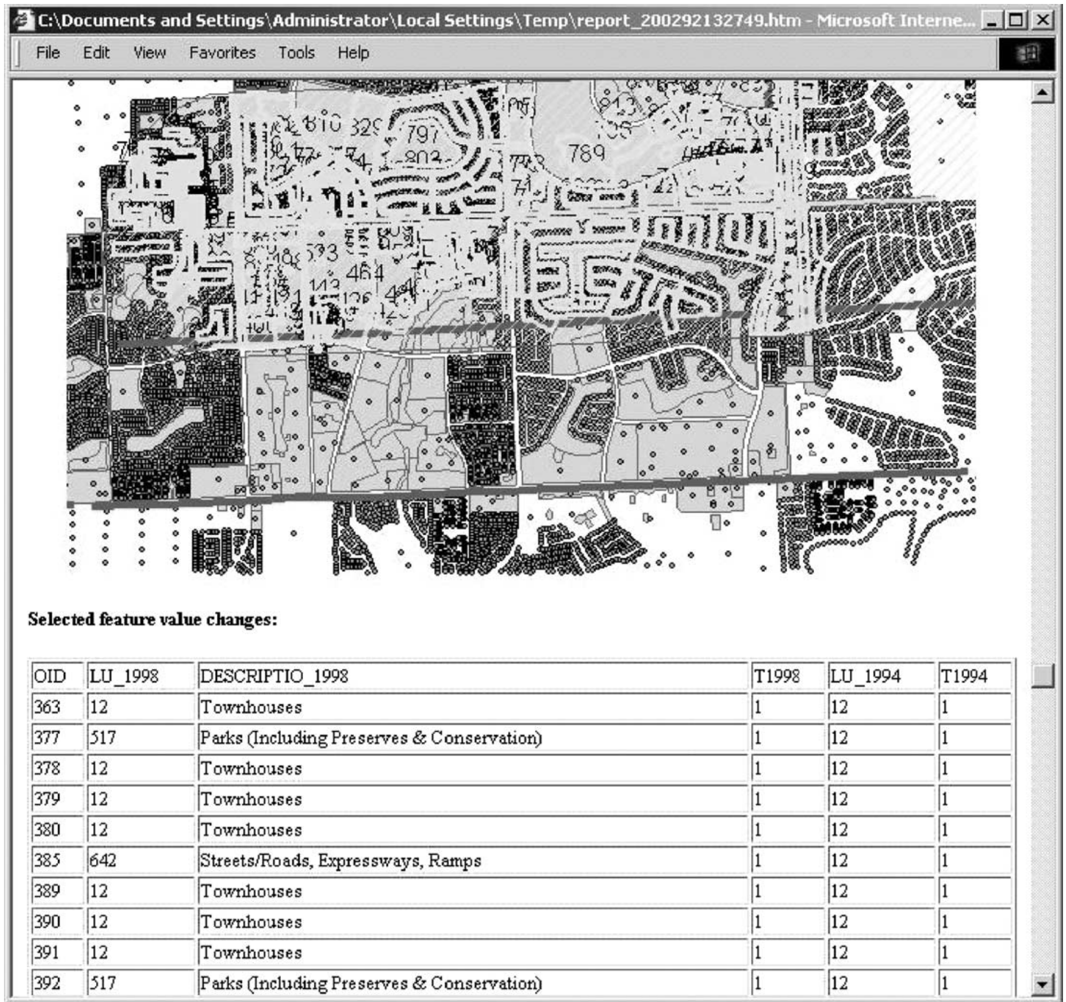
Fig. 6. Dialog window for specifying time periods in a spatiotemporal exploratory analysis.

terms used in the Sinton's framework. Temporal GIS databases integrate spatial, attribute, and temporal elements within a unified environment. As a consequence, we can use any, or a combination, of these three elements to fix/control the land use and transportation components. This makes it possible to perform spatiotemporal exploratory analysis of land use and transportation interaction.

For the final presentation of exploratory analysis results, analysts have options to choose the specific attribute data items to be included in the summary report. The system then generates a hypertext markup language (HTML) file that includes a series of maps showing the change patterns, a list of changes identified from the analysis, and summary statistics of the selected data items (Fig. 7). This HTML file is automatically displayed using a browser at the end of each analysis task. In addition, the system includes an animated visualization tool, written in Java script, to show the dynamic interaction patterns between land use and transportation over time (Fig. 8). Analysts can use this animated visualization tool to adjust the display speed, to pause the animation, and to replay the animated displays.

6. Conclusions

Land use and transportation interaction has been a major research topic for several decades. Many theories and models are suggested to study this well-known, yet extremely complex, process. Using a confirmatory analysis approach based on prior theories and models certainly has helped us gain some insights into this complex process of land use and transportation interaction. However, empirical studies suggest that land use



Selected feature value changes:

OID	LU_1998	DESCRIPTIO_1998	T1998	LU_1994	T1994
363	12	Townhouses	1	12	1
377	517	Parks (Including Preserves & Conservation)	1	12	1
378	12	Townhouses	1	12	1
379	12	Townhouses	1	12	1
380	12	Townhouses	1	12	1
385	642	Streets/Roads, Expressways, Ramps	1	12	1
389	12	Townhouses	1	12	1
390	12	Townhouses	1	12	1
391	12	Townhouses	1	12	1
392	517	Parks (Including Preserves & Conservation)	1	12	1

Fig. 7. A sample HTML output file of spatiotemporal exploratory analysis results.

and transportation interaction patterns can be highly variable between geographic areas. Each geographic area tends to have its own unique characteristics that could lead to a different patter of land use and transportation interaction. The interactions patterns also are likely to vary as we examine them at different spatial and temporal scales. As geographic processes often exhibit properties of both spatial dependency and spatial heterogeneity, our challenge is to identify the spatiotemporal patterns underlying these complex geographic variations.

With recent advancements of GIS technology and an ongoing research progress on temporal GIS, we are now equipped with better research tools to tackle complex geographic processes. This study proposes and implements a temporal GIS, coupled with an exploratory analysis approach, to allow a systematic and interactive way of analyzing land use and transportation interaction among various data sets and at user-selected spatial and temporal scales. Use of temporal GIS databases in this study makes it feasible to analyze spatiotemporal interaction patterns in a more efficient and effective way than the conventional snapshot GIS approach. Extending Sinton's measurement framework into a spatiotemporal interaction framework, on the other hand, provides a systematic means of exploring land use and transportation interaction. Preliminary experiments of data collected for Dade County (Miami), Florida suggest that the temporal GIS-based exploratory analysis system implemented in this study can help transportation planners identify and visualize interaction patterns of land use and transportation by controlling the spatial, attribute, and temporal elements. Although the identified interaction patterns do not necessarily lead to rules that can be applied to different geographic areas, they do provide useful information for transportation modelers to re-evaluate the current model structure and to validate the existing model parameters.

There are many possible areas for future improvements to this prototype implementation. The spatiotemporal interaction framework used in this study offers a general structure to lead analysts in a systematic

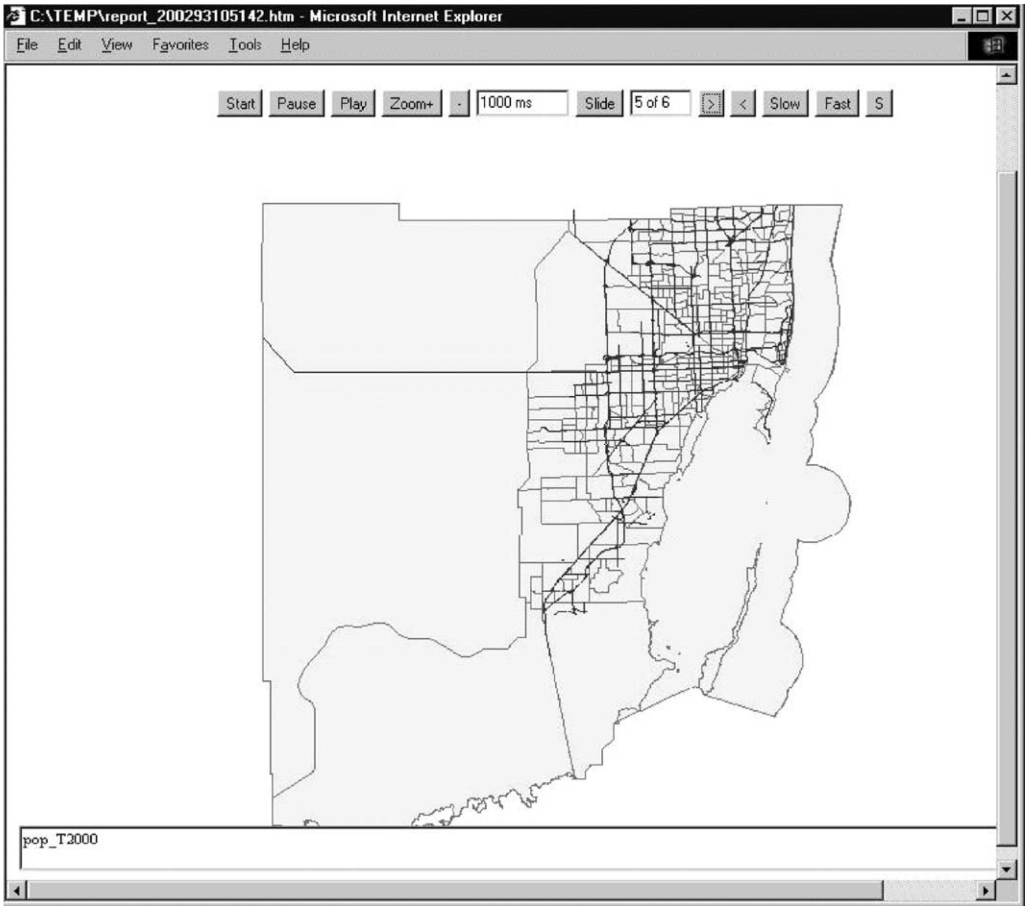


Fig. 8. Animated visualization tool to show the dynamic interaction patterns of land use and transportation over time.

manner of exploring land use and transportation interaction. This framework however may be too cumbersome for analysts with limited GIS background to follow. Additional custom application tools are needed to make it a more user-friendly system. Integration of existing land use and transportation models into the system will be another improvement. The rich set of temporal GIS databases can be used to generate input data for the existing land use and transportation models. Results from these models can be compared with the interaction patterns identified from spatiotemporal exploratory analyses to validate the models. The temporal GIS design in this system also has room for further improvements. For example, temporal GIS databases can quickly grow into very big files. This requires innovative approaches to database design and spatiotemporal analysis procedures to achieve a reasonable performance level. In addition, remote sensing data, especially with the availability of high-resolution images, could be very useful for analyzing land use and transportation interaction. However, incorporation of remote sensing data will require an extension of the temporal exploratory GIS design presented in this paper to facilitate the simultaneous analysis of both vector and raster GIS data. These improvements will help make spatiotemporal EDA a useful approach to studying land use and transportation interaction.

Acknowledgements

We are grateful for the funding provided by the Florida Department of Transportation's University Research Program to support this research project. We also would like to acknowledge the inputs from our research collaborators in the Department of Civil and Environmental Engineering at Florida International University and the constructive and helpful comments received from Dr. Bruce Ralston and two anonymous reviewers.

References

Alonso, W., 1964. Location and Land Use. Harvard University Press, Cambridge, MA.

Anas, A., 1982. Residential Location Models and Urban Transportation: Economic Theory, Econometrics, and Policy Analysis with Discrete Choice Models. Academic Press, New York.

Anas, A., Duann, L.S., 1986. Dynamic forecasting of travel demand, residence location, and land development: policy simulations with the Chicago area transportation/land use analysis system. In: Hutchinson, B.G., Batty, M. (Eds.), Advances in Urban Systems Modelling. North-Holland, Amsterdam, The Netherlands, pp. 299–322.

Anderson, M.D., Souleyrette, R.R., 1996. Geographic information system-based transportation forecast model for small urbanized areas. Transportation Research Record 1551, 95–104.

Boyce, D.E., 1980. A framework for constructing network equilibrium model of urban location. Transportation Science 14, 77–96.

Boyce, D.E., 1990. Network equilibrium models of urban location and travel choice: new research agenda. In: Chatterji, M., Kuene, R. (Eds.), New Frontiers in Regional Science, vol. 1. Macmillan Publishers Limited, London, UK, pp. 238–256.

Cova, T.J., Church, R.L., 1997. Modelling community evacuation vulnerability using GIS. International Journal of Geographical Information Systems 11, 763–784.

Dailey, D.J., Loseff, D., Meyers, D., 1999. Seattle smart traveler: dynamic ridematching on the world wide web. Transportation Research 7C, 17–32.

Ding, C., 1998. The GIS-based human-interactive TAZ design algorithm: Examining the impacts of data aggregation on transportation-planning analysis. Environment and Planning 25B, 601–616.

Goodchild, M.F., 2000. Spatial analysis: methods and problems in land use management. In: Hill, M.J., Aspinall, R.J. (Eds.), Spatial Information for Land Use Management. Gordon and Breach Science Publishers, Amsterdam, The Netherlands, pp. 39–51.

Giuliano, G., 1995. Land use impacts of transportation investments: highway and transit. In: Hansen, S. (Ed.), The Geography of Urban Transportation. Guilford Press, New York, pp. 305–341.

Hägerstrand, T., 1970. What about people in regional science? Papers of the Regional Science Association 24, pp. 7–21.

Hansen, W.G., 1959. How accessibility shapes land use. Journal of the American Institute of Planners 25, 73–76.

Harris, C.D., Ullman, E.L., 1945. The nature of cities. Annals of the American Academy of Political and Social Sciences 242, 7–17.

Hartgen, D.T., Li, Y., 1994. Geographic information systems applications to transportation corridor planning. Transportation Research Record 1429, 57–66.

Hirschman, I., Henderson, M., 1990. Methodology for assessing local land use impacts of highways. Transportation Research Record 1274, 35–40.

Hoyt, H., 1939. Structure and Growth of Residential Neighborhoods in American Cities. US Federal Housing Administration, Washington, DC.

Jankowski, P., Richard, L., 1994. Integration of GIS-based suitability analysis and multicriteria evaluation in a spatial decision support system for route selection. Environment and Planning 21B, 323–340.

Jha, M.K., Schonfeld, P., 2000. GIS-based analysis of right-of-way cost for highway optimization. Proceedings of the 79th Annual Meeting of the Transportation Research Board. Washington, DC, January 9–13, CD-ROM.

Kim, T.J., 1983. A combined land use-transportation model when zonal travel demand is endogenously determined. Transportation Research 17B, 449–462.

Kim, K., Levine, N., 1996. Using GIS to improve highway safety. Computers, Environment and Urban Systems 20, 289–302.

Kim, T.J., Rho, J.H., Suh, S., 1989. Integrated Urban Systems Modeling: Theory and Applications. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Landis, J.D., Zhang, M., 1998a. The second generation of the California urban futures model. Part 1: Model logic and theory. Environment and Planning 25B, 666–675.

Landis, J.D., Zhang, M., 1998b. The second generation of the California urban futures model. Part 2: Specification and calibration results of the land-use change submodel. Environment and Planning 25B, 795–824.

Langran, G., 1992. Time in Geographic Information Systems. Taylor and Francis, London.

Langran, G., Chrisman, N., 1988. A framework for temporal geographic information. Cartographica 25, 1–14.

Lowry, I.S., 1964. A Model of Metropolis. RM-4035-RC. Rand Corporation, Santa Monica, CA.

Miller, H.J., Han, J. (Eds.), 2001. Geographic Data Mining and Knowledge Discovery. Taylor and Francis, London.

Miller, H.J., Shaw, S.L., 2001. Geographic Information Systems for Transportation: Principles and Applications. Oxford University Press, New York.

Miller, H.J., Storm, J.D., 1996. Geographic information system design for network equilibrium-based travel demand models. Transportation Research 4C, 373–389.

Miller, E.J., Kriger, D.S., Hunt, J.D., 1999. Integrating urban models for simulation of transit and land use policies: guidelines for implementation and use. Transit Cooperative Research Program (TCRP) Report 48, Transportation Research Board, National Research Council. National Academy Press, Washington, DC, USA.

Openshaw, S., 1994. Two exploratory space–time–attribute pattern analysers relevant to GIS. In: Fotheringham, S., Rogerson, P. (Eds.), Spatial Analysis and GIS. Taylor and Francis, London, pp. 83–104.

Payne-Maxie Consultants, 1980. The land use and urban development impacts of beltways. Final Report No. DOT-OS-90079, US Department of Transportation and Department of Housing and Urban Development. Payne-Maxi Consultants, Washington, DC.

Peng, Z.-R., Huang, R., 2000. Design and development of interactive trip planning for web-based transit information systems. Transportation Research 8C, 409–425.

Peuquet, D.J., 1994. It's about time: a conceptual framework for the representation of spatiotemporal dynamics in geographic information systems. Annals of the Association of American Geographers 84, 441–461.

Peuquet, D.J., Duan, N., 1995. An event-based spatiotemporal data model (ESTDM) for temporal analysis of geographical data. International Journal of Geographical Information Systems 9, 7–24.

Prastacos, P., 1986. An integrated land use-transportation model for the San Francisco region: 1. Design and mathematical structure. Environment and Planning 18A, pp. 307–322.

Ralston, B., 2001. Logistics. In: Miller, H.J., Shaw, S.L. (Eds.), Geographic Information Systems for Transportation: Principles and Applications. Oxford University Press, New York, pp. 380–400.

Sarasua, W., Jia, X., 1995. A framework for integrating GIS-T with KBES: a pavement management system example. Transportation Research Record 1497, 153–163.

Sinton, D.F., 1978. The inherent structure of information as a constraint to analysis: mapped thematic data as a case study. In: Dutton, G. (Ed.), Harvard Papers on Geographic Information Systems, vol. 6. Addison-Wesley, Reading, MA, pp. 1–17.

Southworth, F., 1995. A Technical Review of Urban Land Use-Transportation Models as Tools for Evaluating Vehicle Reduction Strategies, Research Report ORNL-6881, Oak Ridge National Laboratory, Oak Ridge, TN.

Tukey, J.W., 1977. Exploratory Data Analysis. Addison-Wesley, Reading, MA.

Wegner, M., Fürst, F., 1999. Land use transport interaction: state of the art. Deliverable 2a of the project TRANSLAND of the 4th RTD Framework Programme of the European Commission. Institut fur Raumplanung, Univeristat Dortmund.

Wilson, A.G., 1970. Entropy in Urban and Regional Modelling. Pion, London.

Worboys, M.F., 1992. A model for spatio-temporal information. Proceedings of the 5th International Symposium on Spatial Data Handling, vol. 2, pp. 602–611.

Worboys, M.F., 1994. Object-oriented approaches to geo-referenced information. International Journal of Geographical Information Systems 8, 385–399.

Worboys, M.F., 1998. A generic model for spatio-bitemporal geographic information. In: Egenhofer, M.J., Golledge, R.G. (Eds.), Spatial and Temporal Reasoning in Geographic Information Systems. Oxford University Press, New York, pp. 25–39.

Yuan, M., 1996. Modeling semantics, temporal, and spatial information in geographic information systems. In: Craglia, M., Couclelis, H. (Eds.), Geographic Information Research: Bridging the Atlantic. Taylor and Francis, London, pp. 334–347.

Yuan, M., 1999. Use of a three-domain representation to enhance GIS support for complex spatiotemporal queries. Transactions in GIS 3, 137–159.

Zeiler, M., 1999. Modeling Our World: The ESRI's Guide to Geodatabase Design. ESRI Press, Redlands, CA.

Zeiler, M. (Ed.), 2001. Exploring ArcObjects. ESRI Press, Redlands, CA.