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Representing and Visualizing Travel Diary Data: A Spatio-temporal GIS Approach

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Abstract

Travel diary data (TDD) is an important disaggregate data source for transportation research. It is an example of multi-dimensional data that combines spatial, temporal, and attribute information. A proper representation of TDD can help researchers extract useful information from the data set. Current GIS is mainly designed to handle spatial and attribute data, lacking the representation of temporal aspect of spatial objects. In this paper, we present a time-enabled GIS design to represent and visualize TDD. Space-time path concept of time geography is adopted to organize the trips in TDD. The proposed design is implemented on the ArcGIS 8 platform. Under this approach, space-time paths can be generated from TDD and stored as a feature class in ESRI's geodatabase data model. Using time as the third dimension, visualization of space-time path is provided in a customized ArcScene environment. This spatio-temporal GIS design offers an effective approach for representation and visualization of TDD. It also provides researchers with useful tools to explore and extract spatio-temporal information hidden in TDD.

Key Words: Travel diary data, spatio-temporal GIS, time geography, space-time path, 3D visualization

1. Introduction

Travel diary data (TDD), which records the trips made by individuals in sampled households, serves as an important data source for transportation research. Different from the aggregate traffic data such as annual average daily traffic (AADT), TDD describes detailed travel activities at the individual level. TDD not only provides a data source to derive useful statistical information of trip characteristics (e.g., trip length, trip frequency), but also offers opportunities to gain a better understanding of individuals' travel patterns and travel behavior. As the focus of travel demand modeling shifted from the conventional four-step models based on aggregate travel data to activity-based approach using disaggregate data during the recent decades, TDD has received increasing attention in the transportation research community (Wang and Cheng, 2001). In addition, the development and adoption of modern technologies (e.g., Global Positioning System and Geographic Information Systems) have made the collection and analysis of TDD an easier task than before. These changes provide better opportunities for in-depth transportation research at the disaggregate level. In the meantime, the research community also encounters new challenges of handling and analyzing the spatially-explicit disaggregate data in an efficient and effective way. These challenges include representation, exploration, and understanding of the data in order to derive useful information from the data sets.

Geographic Information Systems (GIS), which provide powerful functions for storing, managing, analyzing, and visualizing spatial data, have been used in transportation research since the early days of GIS (Goodchild, 2000). A specific term, GIS-T, has been coined to represent GIS applications for transportation. With their functions of dealing with spatial data, GIS have been suggested as a potential approach to managing TDD and assisting in activity-based travel analysis (Greaves and Stopher, 1998). Several studies have demonstrated the use of GIS to represent and analyze TDD (e.g., Shaw and Wang, 2000; Wang and Cheng, 2001). However, the currently available GIS software works well only for representations of static spatial phenomena (Spaccapietra, 2001; Peuquet, 2002). TDD, on the other hand, is multi-dimensional data that includes spatial, attribute, and temporal information. Many dynamic characteristics of travel data cannot be properly represented in a standard static GIS environment. Special GIS design therefore is required to deal with the multi-dimensional TDD. In this paper, we present a GIS design that enables the representation and visualization of TDD in a spatio-temporal framework. We also demonstrate this spatio-temporal GIS design through an implementation that uses ArcGIS 8.3, ArcScene (ArcGIS 3D extension), and customized Visual Basic for Applications (VBA) programs with ArcObjects.

2. Research Background

TDD is an important source of disaggregate travel data for transportation studies. It records individuals' movements in space and time and has specific characteristics that are different from the aggregate travel data. Under the conventional TDD collection method, each individual is asked to fill out a form with information about every trip made by the individual during a survey period. Each person normally records the origin location, destination location, starting time, ending time, trip purpose, and travel mode of each trip. Some recent surveys also employed GPS, which can automatically record not only origin/destination location and starting/ending time, but also the route of a trip. Each data record collected from the survey represents a single trip, which contains geographic information of the trip (i.e., origin/destination location, and possibly travel route), temporal information of the trip (i.e., starting/ending time), and non-spatial attributes of the trip (e.g., trip purpose, traveler information).

One important characteristic of TDD is the relationships among trip records. A person can make multiple trips during a day. Although each record in TDD represents a separate trip, it should not be treated as an independent record. Trip records of an individual represent a trip sequence over time. As an individual can only be at a single location and perform a single trip in physical space at a given time, complete trip records of an individual have the following characteristics: 1) time periods associated with an individual's trips are mutually exclusive (i.e., no two trips can be performed during the same time period); and 2) the origin location of a trip corresponds to the destination location of its previous trip. In other words, trips made by a person form a trip sequence that moves the person from one location to another location so that the person can carry out different activities. This is consistent with the suggestion of "travel as a derived demand" discussed in the literature (Miller and Shaw, 2001). It is also common to observe that people organize a multi-purpose trip chain, instead of separate single-purpose trips, to carry out their activities. For example, a person may go grocery shopping on the way back home from work. This indicates that we should focus on the activities performed by a person, rather than on the individual trips made by a person, as suggested by the activity-based travel analysis that has gained increasing attention among transportation researchers.

Time geography, which was first proposed by Hägerstrand (1970) and consolidated by himself and his collaborators at a later time (Wachowicz, 1999), suggests concepts that are applicable to handling TDD as trip sequences with spatio-temporal characteristics. Time geography presents a conceptual framework that guides the study of an individual's movements in a space-time context according to various constraints applied to an individual (Golledge and Stimson, 1997). It recognizes that time, as well as space, should be involved when examining activity participation and accessibility (Miller and Shaw, 2001). Treating time as an equal term as space, the framework considers space and time as orthogonal dimensions. Time dimension is used to order the sequence of events and to synchronize human activities, while space dimension deals with the location changes of objects. Space and time are connected under the concept of *space-time path* (Miller, 2003), which depicts an object's history over space (see Figure 1). This framework covers information about spatial and temporal characteristics of an individual's activities, including starting and ending time and place, duration, sequence of activities, and relative locations of activities. Transportation is considered as a means to trade time for space since physical movements in space take time. Given a location and a time period, a person can stay at a location for the entire time duration. If the person wishes to move to a new location, he/she must trade time for physical movements and the time available for performing activities at the new location is shortened accordingly. The possible locations that a person can travel within a given time duration form a continuous space in the orthogonal space-time coordinate system, which is called *space-time prism* (Lenntorp,

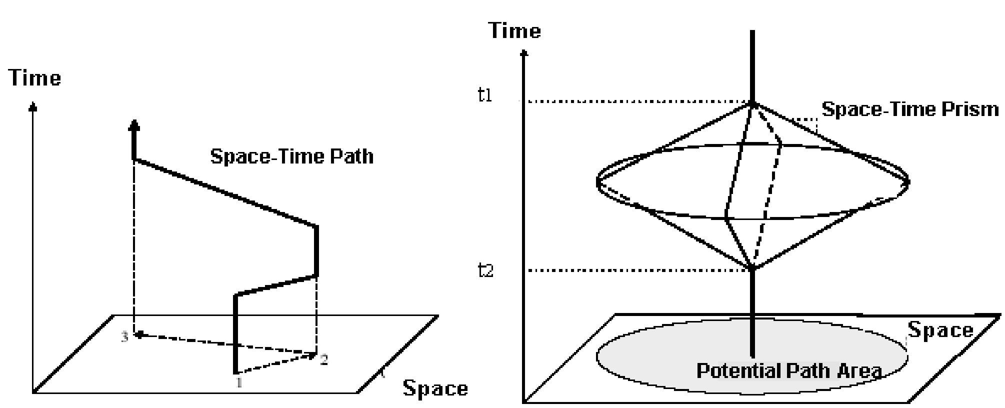


Figure 1. Space-time path, space-time prism, and potential path area.
(Source: Miller, 2003)

1976). Projection of a space-time prism on the two-dimensional space is a region, which is known as *potential path area* (PPA).

Space-time path provides an efficient representation of trip sequence in TDD. Constructed in an orthogonal space-time coordinate system, space-time path can capture the spatio-temporal characteristics of trips. As a space-time path records an object's history of movements in physical space, it tracks the spatio-temporal sequence of a person's trips. Non-vertical line segments on a space-time path indicate trips made by an individual, while vertical segments on a space-time path represent that a person stays and takes certain activities at a particular location for a given time period. Representation of spatio-temporal features has been a major research challenge in GIS. Due to its cartographic representation origin, current GIS are designed to deal with static geographic phenomena (Spaccapietra, 2001). Thus, it is cumbersome to represent time-geographic concepts and objects in the current framework of GIS. Miller (1991) first brought time-geographic concepts into GIS to calculate accessibility under the concept of space-time prism. Applying time geographic concepts in a GIS environment to study space-time dependent accessibility and to visualize space-time paths has received additional research attentions in recent years (e.g., Miller and Wu, 2000; Kwan and Hong, 1998; Kwan, 1999; 2000).

Current static-scenario-oriented GIS framework cannot support efficient treatment of spatio-temporal data, such as space-time path. Efforts have been made to extend the current static GIS framework to a spatio-temporal one, which include snapshot model (Armstrong, 1988), space-time composite model (Langran and Chrisman, 1988), object-oriented approach (Worboys, 1992), event-based approach (Peuquet and Duan, 1995), and three-domain model (Yuan, 1996). These models attempt to build a GIS framework that can manipulate spatio-temporal data, catch the changes of spatial features, and describe the dynamics of geographic phenomena. Nevertheless, a widely accepted spatio-temporal GIS framework has not surfaced yet and it remains as an on-going research topic.

Space-time path is a simple type of spatio-temporal features, as it portrays the location change history of a point object. In the spatio-temporal GIS literature, "moving object" has been used to refer to an object that changes locations without changing its shape (or no shape as it is represented as a point feature) (Tryfona and Jensen, 1999; Erwig et al., 1999). A number of papers have focused on modeling moving objects (e.g., Porkaew et al., 2001; Vazirgiannis and Wolfson, 2001; Brinkhoff, 2002). Despite of these efforts, design of a spatio-temporal GIS data model for efficient and effective visualization and analysis of space-time path remains an open research topic.

3. Spatio-temporal GIS Design and Implementation for TDD

In this section, we first discuss a spatio-temporal GIS design for representation and visualization of TDD based on the space-time path concept of time geography. An implementation of the system design in ArcGIS 8 environment is then presented using a sample TDD data set.

3.1 Spatio-temporal GIS Design for TDD

As mentioned above, TDD contains spatial, temporal, and attribute information about individual trips and the people who made these trips. Records in TDD are not independent and some of them are closely related to each other. We organize trip records from TDD based on the space-time path concept of time geography. Thus, spatial and temporal characteristics of trips made by a person are integrated into a space-time path of that person. Adopting the space-time path concept, we can organize TDD data in a conceptual framework as shown in Figure 2.

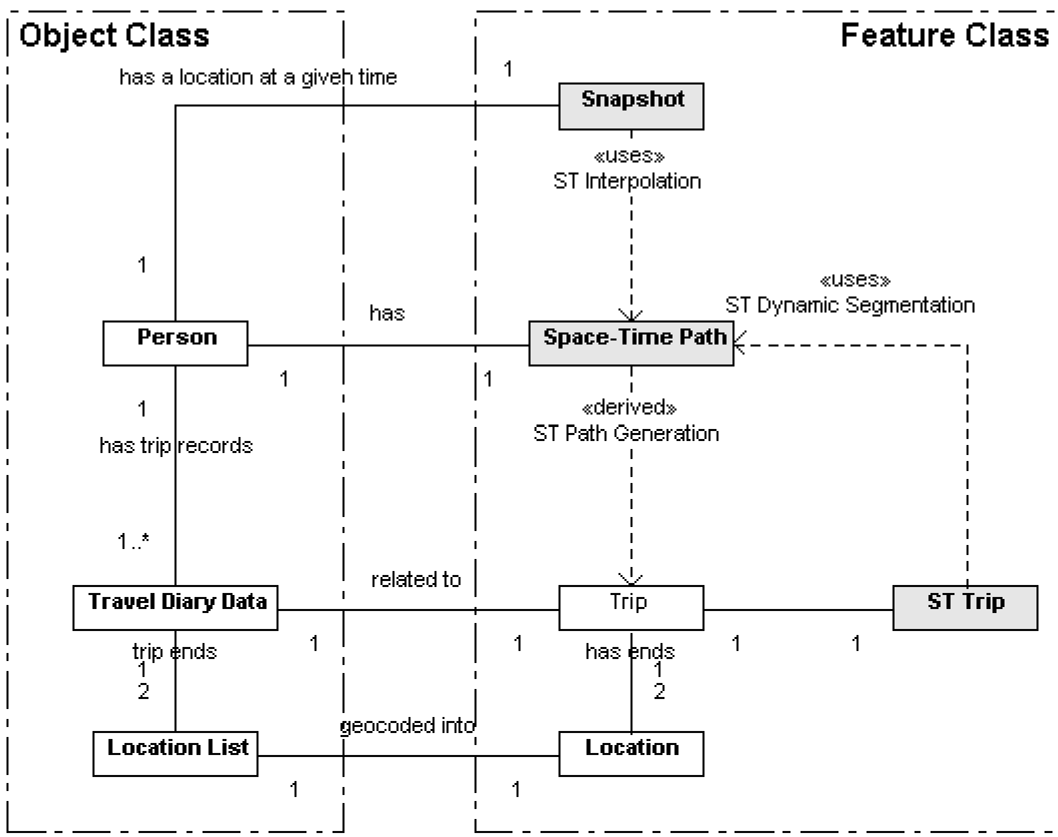


Figure 2. Conceptual model for Representation of Travel Diary Data

In this framework, *Person*, *Travel Diary Data*, and *Location List* are treated as objects without geometric representations (i.e., Object Classes). *Location*, *Trip*, *Space-Time Path*, *Snapshot*, and *ST Trip* are objects with explicit geometric representations (i.e., Feature Classes). Among them, *Space-Time Path*, *Snapshot*, and *ST Trip* are spatio-temporal features. A spatio-temporal feature contains not only geometric shape but also temporal information, in which spatio-temporal information is represented as either a set of triplet ({<x, y, t>}) for a point feature or a sequence of triplet sets ({<x_0, y_0, t_0>, <$x_1, y_1,$

t_1>, … }) for a line feature. Two basic time types are included in the framework, which are *Time Instance* and *Time Interval*. A *Time Instance* is a point temporal feature (e.g., 16:30:00, May 12, 2004), and a *Time Interval* is a continuous linear temporal feature defined by a starting time and an ending time (e.g., from 14:30:23, May 12, 2004 to 15:07:45, May 12, 2004). *Time Instance* is shown as a timestamp field in the database, while *Time Interval* is stored as two separate fields (i.e., StartTime and EndTime fields) in the database. Descriptions of each object in the framework are provided below.

Object classes:

Person: A table containing information about individual persons, such as age, gender, and occupation of a person. A unique ID is assigned to each person.

Travel Dairy Data: A table composed of trip information, including the origin/destination, starting/ending time of a trip, trip purpose, person who takes this trip, etc. A unique trip ID is used as the identifier for each trip.

Location List: A list containing location information (e.g., address, name, description) of the origin/destination of trips.

Feature classes:

Location: A point feature class that is generated from Location List via geocoding. Each point represents either the begin point or the end point of a trip. Location ID is the unique identifier for each point in this feature class.

Trip: A line feature class representing the route of each trip. This feature class is created from Travel Diary Data through a path-generation process. If the original Travel Diary Data has only origin and destination locations for each trip record, the shortest path for each pair of origin and destination is used as the route for that trip. If the original data set contains GPS data for the route, the GPS data is used to generate the route for that trip. For each trip, starting time and ending time are stored in the attribute table of the feature class. Trip ID, the same one as in the *Travel Diary Data* object class, is the unique identifier for each trip.

Space-Time Path (ST Path): A spatio-temporal line feature class representing space-time path for each person in the data set. A space-time path is created from trips made by the same person, where the trips are organized according to the time sequence. This line feature class contains both geometric shape and temporal information for each space-time path. Person ID is used as the unique ID for each ST Path.

ST Trip: A spatio-temporal line feature class representing trips with spatial and temporal information. As each trip is a segment on its corresponding ST Path, ST trip is generated from ST Path with spatio-temporal dynamic segmentation. Again, Trip ID works as the unique identifier for each ST trip.

Snapshot: A spatio-temporal point feature class representing locations of persons at a time instant. It is generated from ST Path using spatio-temporal interpolation at a given time instant. Person ID is the unique identifier for each point in the Snapshot feature class.

Relationships among the classes in this framework are shown in Figure 2. As a person can make multiple trips, a one-to-many relationship exists between the *Person* object class and the *Travel Diary Data* object class. Since a trip has one origin and one destination, a one-to-two relationship exists between the *Travel Diary Data* object class and the *Location List* object class. A similar relationship also exists between the *Trip* feature class and the *Location* feature class. One-to-one relationship exists between the *Travel Diary Data* object class and the *Trip* feature class, the *Location List* object class and the *Location* feature class, the *Trip* feature class and the *ST Trip* feature class, the *Person* object class and the *Space-Time Path* feature class, and the *Person* object class and the *Snapshot* feature class. Relationships among these classes are maintained through the unique identifier of each class.

3.2 System Implementation Using ArcGIS 8

To implement the system design in ArcGIS 8, the geodatabase data model is used to store and mange all data sets. The space-time path concept of time geography is based on a 2D space with an orthogonal third dimension for time (i.e., 2D space + 1D time). This space-time coordinate system structure is similar to the 3D Cartesian coordinate system used in ArcScene for displaying 3D features. ArcScene provides basic visualization functions for 3D features. We take advantage of the existing functions in ArcScene to visualize TDD, which is organized as spatio-temporal features in our model. In addition, we write several VBA programs with ArcObjects to implement the system design and to customize the user interfaces in ArcScene for displaying and processing of spatio-temporal features.

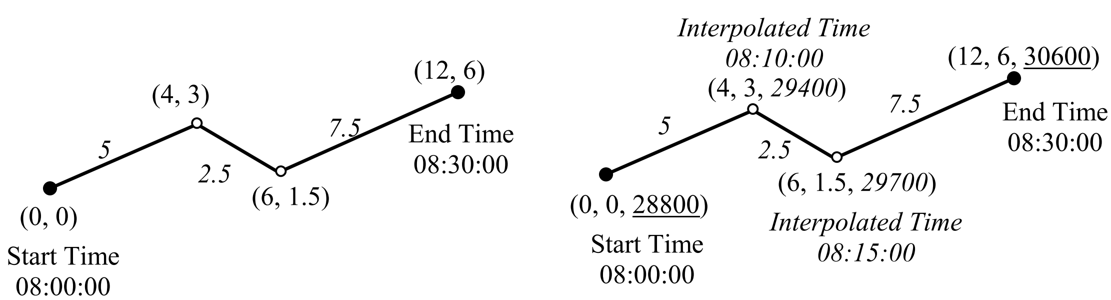
In order to properly represent and visualize spatio-temporal features in ArcGIS 8, several technical challenges must be overcome during the system implementation. As we use ArcScene to display spatio-temporal features, time values of a spatio-temporal feature must have a similar format as *z* values in 3D features. A conversion program is developed to deal with the changes between the format of a time value in real world and the format in a computer system. Based on this defined time representation, we implement the representations of spatio-temporal features (i.e., space-time paths, ST trips, and snapshots) within the geodatabase data model. All the spatio-temporal features are stored as feature classes in a personal geodatabas. Functions for generating space-time paths from original TDD data and creating other spatio-temporal features from space-time paths are coded using VBA with ArcObjects. A customized visualization environment in ArcScene is developed to display spatio-temporal features and other non-temporal features that serve as backgrounds for spatio-temporal features. These custom functions are organized into a toolbar to facilitate data processing and visualization of TDD represented in a spatio-temporal GIS environment. The following five steps describe the system implementation.

(1) Represent time in geodatabase data model

In order to display time as the third dimension in ArcScene, we store the temporal data as z values in the geodatabase data model. Since *z* values are represented as real numbers in the geodatabase data model, a conversion program is developed to translate time strings into real numbers. We use the midnight as the 0 location in our time reference system and convert all time strings into the unit of seconds. Thus, any given time in a day is represented as a real number of cumulative seconds from the midnight. For example, 08:30:15 is converted into a *z* value of 30615 (i.e., 8x3600+30x60+15=30615 seconds). Similarly, given a real number, the program can convert it back to the time format.

(2) Build space-time paths

Trip features generated from Travel Diary Data are 2D line features with extra fields of timestamps for the beginning and the ending trip locations (i.e., *StartTime* and *EndTime*). The 2D information and timestamps of trip features are used to generate space-time path. First, the timestamps are converted into real numbers and assigned as *z* values for the beginning point and the ending point of each trip. *Z* values for the intermediate points along a line can be computed by a linear interpolation method. If a constant travel speed is assumed, the time at an intermediate point is proportional to the *StartTime* and *EndTime* with respect to its position on the given line. For example, in Figure 3, the total length of a trip route is 15, which costs 30 minutes. As the length of the first segment on the route is 5, it will cost 5/15x30=10 minutes to travel through. Thus, the second vertex on the route will have a timestamp of 08:10:00 based on the trip start time (08:00:00). After converted into a real number, a *z* value of 29400 is assigned to the second vertex. These values can be computed using the *MSegmentation* method of Polyline feature class in ArcObjects (Zeiler, 2002). Through this method, a spatio-temporal line feature is generated and all vertices in the line have *z* values (i.e., time values) assigned to them.



(a) Original line feature

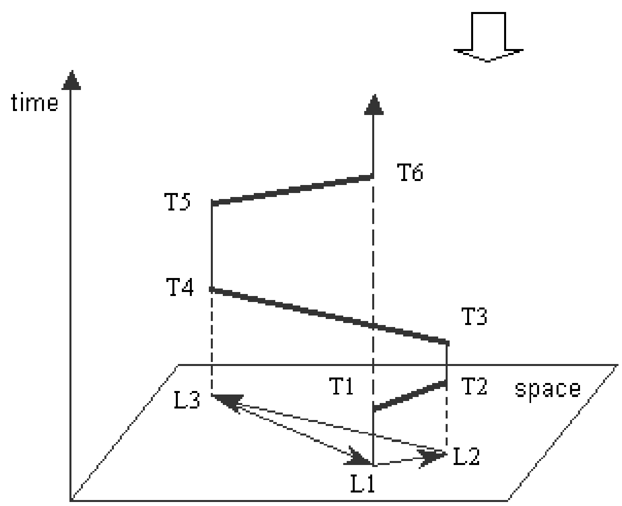
(b) Spatio-temporal line feature after spatio-temporal interpolation

Figure 3. Convert line feature to spatio-temporal line feature

A space-time path (ST path) in the implementation represents a person's daily movements. The time span for every ST path starts at 00:00:00 and ends at 24:00:00. All trips made by the same person within a given day are selected from the TDD data set and sorted by time. Each trip is then converted into a spatio-temporal line feature through the method mentioned above and these spatio-temporal lines are linked to form an ST path. Since the origin location of a trip is the destination location of the previous trip made by the same person. A vertical line segment is used to connect the destination point of the previous trip to the origin point of the next trip in a space-time path. A vertical line segment on an ST path therefore indicates that the person stays at the given location for a specific time period. On the other hand, non-vertical line segments on an ST path represent movements (i.e., trips) made by a person. Together, they represent both stationary and moving activities performed by a person recorded in the Travel Diary Data. A person ID is assigned to each generated ST path. Figure 4 shows the process of generating an ST path from TDD. The original three trips (polylines in the Trip feature class) of a person (Alan) are converted into spatio-temporal lines and, based on their time sequence, these spatio-temporal lines are connected by vertical lines to form a space-time path (a polylineZ in the Space-Time Path feature class).

Trip feature class:

OID	Shape	TripID	PersonID	Name	Origin	Destination	StartTime	EndTime
1	Polyline	101	1	Alan	L1	L2	T1	T2
2	Polyline	102	1	Alan	L2	L3	T3	T4
3	Polyline	103	1	Alan	L3	L1	T5	T6
…	…	…	…	…	…	…	…	…



Space-Time Path feature class:

OID	Shape	PersonID	Name
1	PolylineZ	1	Alan
…	…	…	…

Figure 4. Generate space-time path from trips

(3) Generate spatio-temporal point and line features

Since we treat time values along an ST path as a linear referencing system, standard dynamic segmentation functions can be applied to ST paths for locating point and linear spatio-temporal events. Given a time instance and a space-time path of a person, we can use dynamic segmentation functions to interpolate the location of that person. A spatio-temporal snapshot feature class can be created from space-time paths from this interpolation method. For example, we can create a snapshot feature class to display the spatial distribution of all people at 5pm on a particular day. Using the same method with time intervals, we can also locate spatio-temporal line features from ST paths. Customized functions are generated in VBA with ArcObjects to handle sptio-temporal dynamic segmentations.

(4) Assign timestamps to non-temporal feature layers

For visualization of ST paths, we may want to display other non-temporal feature layers (e.g., street network, landmarks, land use) as background layers in ArcScene. This can be accomplished by assigning a base height (i.e., temporal *z* value) to each background layer in ArcScene. For example, Figure 5 shows the street network layer displayed at 8:00 AM with respect to the ST paths. After assigning a time value to the background layers, users can easily visualize locations of surveyed people where their space-time paths intersect with the background layers. Users can assign different time values to these background layers to compare location changes of the surveyed people.

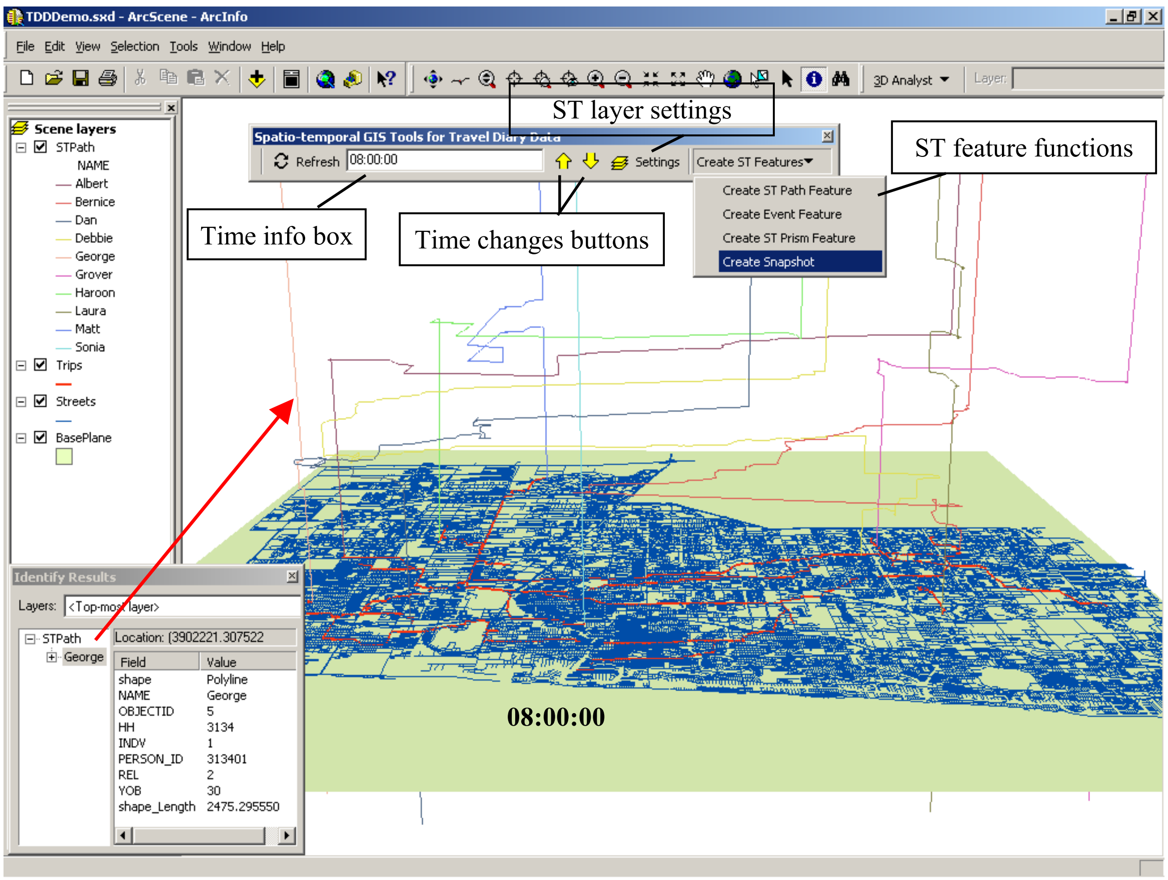


Figure 5. Customized interface of spatio-temporal GIS prototype for TDD in ArcScene

(5) Create customized user interfaces in ArcScene

Functions for creating spatio-temporal features and tools for manipulating display of spatio-temporal features are organized into a customized toolbar in ArcScene (see Figure 5). A drop-down menu of *ST Feature functions* contains programs to create spatio-temporal features, such as space-time paths, snapshots, and ST trips. Each function in the drop-down menu will bring up a dialog box to guide users through the creation of spatio-temporal features. Since the created features are stored as feature classes in the geodatabase data model, users can use the *identify* tool to find information of each spatio-temporal feature. For example, as shown in Figure 5, attributes of a space-time path are displayed in the identify result window. Other components in the toolbar are used to assign time values to non-temporal background feature layers. Users can set the time value of background layers by changing the time displayed in the *Time info box*. A click on one of the *Time change buttons* can move the background layers upward or downward along time by a user-specified time step. After each click, the time value displayed in the *Time info box* will be automatically updated. Users can set the time step for the time change buttons and which layers will be used as background layers through the *ST layer settings*. The customized interfaces provide an integrated environment to handle TDD under a spatio-temporal GIS approach.

4. Conclusions

This paper presents a spatio-temporal GIS design for representation and visualization of travel diary data. The space-time path concept of time geography is used in this study to organize travel diary data. A conceptual spatio-temporal GIS framework is designed for representation and visualization of TDD. This conceptual framework is implemented in ArcGIS environment using the geodatabase data model. Space-time paths and other spatio-temporal features are realized as 3D features, where the 3D is represented as 2D space + 1D time. With this representation, spatio-temporal features carry both inherited spatial characteristics and extended temporal characteristics through the customized environment. Visualization of spatio-temporal features of TDD is operationalized in ArcScene, the 3D viewer of ArcGIS. Through these customized visualization tools, spatio-temporal features of TDD can be effectively displayed and users can gain better understanding of spatio-temporal patterns of travel diary data.

Design and implementation of this conceptual spatio-temporal framework make the following contributions. For GIS, it offers an explicit representation of the space-time path concept of time geography and provides an operational GIS system. This stud also demonstrates that our design is a feasible approach of extending the currently space-only GIS to a spatio-temporal GIS for handling certain types of spatio-temporal problem. For transportation studies, our efforts offer a flexible and powerful way to represent and visualize individual's movements with both spatial and temporal characteristics as space-time paths in a GIS environment. This GIS design allows transportation researchers to explore and analyze travel diary data in a more efficient and effective way.

However, the GIS design and implementation presented in this paper can be further improved. In this study, temporal information is represented as attribute fields in the database and only linear time structure is considered. Time can be in other structures such as cyclic time. A more complete representation of time should be included in the data model to handle representation and conversion of multiple time structures. In addition, this study implements only simple spatio-temporal data analysis. Users may need functions to identify spatio-temporal relationships among space-time paths, execute spatio-temporal queries, or find spatio-temporal clusters of space-time paths. Further efforts are needed to make the system design and implementation capable of handling these complex analyses and enhancing the analytical power of the system.

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