Visualizing and Analyzing Activities in an Integrated Space-time Environment: Temporal GIS Design and Implementation

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ABSTRACT

An integrated space-time environment is demanded by activity-based travel studies to facilitate the investigation of spatial and temporal characteristics of activities. Current GIS, which has been very successful in supporting trip-based travel analysis, does not include an explicit time representation and therefore is incapable of supporting activity-based travel analysis efficiently. This study proposes a temporal GIS design, which incorporates the space-time path concept of Hägerstrand's time geography, to facilitate the analysis of activities in a space-time context. The space-time path concept provides an efficient approach of organizing activities/travels in their space-time contexts and supporting the investigation of spatio-temporal relationships between individuals. This study adopts the three-dimensional orthogonal space-time system in the temporal GIS design and develops representation and analysis functions related to space-time paths and individual activities. The proposed design is successfully implemented in a prototype system. The system provides an integrated space-time environment to effectively visualize activities/travels in their space-time contexts and analyze their spatio-temporal characteristics. Such a system offers useful tools to facilitate activity-based travel studies.

INTRODUCTION

Transportation has been a major application field of geographic information system (GIS) since 1960s when GIS started to emerge (*1*). An acronym, GIS-T, has been coined to represent GIS applications for transportation. Over the years, GIS has been offering researchers useful tools to solve various transportation problems. For example, off-the-shelf GIS-T software packages (e.g., TransCAD from Caliper Corp.) are available to support the traditional four-step approach to the urban transportation planning process.

Current GIS-T applications are designed mostly to facilitate data representation and manipulation used in the traditional trip-based aggregate travel analysis. However, researchers have long recognized that travel is a derived demand (*2*, *3*) and trip-based approaches cannot catch this important nature of travel. In response to this concern, researchers have been proposing activity-based approaches since 1970s. These approaches formed the new paradigm in transportation study. Fundamentally different from the traditional trip-based approach, the activity-based approach believes that activity is the reason behind travel and the study of travel behavior therefore relies on the understanding of the distribution of activities that are involved in an individual's daily life (*4*). Such an approach requires a new GIS design that can explicitly represent the connections between activities and travels. Also, time has drawn increasing concerns in the activity-based approach because activities are available only at specific time durations as well as locations. Different distribution of activities in space and time can lead to different travel behaviors and patterns. Therefore, the activity-based approach requires an integrated space-time environment to analyze activity and travel patterns. This new paradigm in transportation research brings up challenges to the current GIS design. Since GIS has been quite successful in supporting trip-based travel analysis, researchers consider it a potential candidate for supporting activity-based travel studies (*5*, *6*). However, the design of GIS needs improvements to address the new requirements of representing and analyzing the spatial and temporal characteristics of activities/travels before it can efficiently support the activity-based approach.

Current GIS designs do not include an explicit representation of a time dimension and they work well only for static spatial phenomena (*7*, *8*). Such GIS designs are insufficient to support activity-based travel analysis, which involves the temporal aspect of travel/activity. Therefore, the objective of this study is to develop a GIS design with an integrated space-time representation, which can support visualization and exploration of activities/travels with their spatio-temporal characteristics and eventually be used to facilitate activity-based travel studies.

ACTIVITY, TRAVEL, AND SPACE-TIME PATH

The activity-based approach was first studied in depth in the 1970s as an effort to replace the conventional trip-based aggregate approach of travel analysis (*9*, *10*, *11*). It presents a philosophy rather than a practical method towards travel studies. Under this philosophy, "travel decisions are activity based, and … any understanding of travel behavior is secondary to a fundamental understanding of activity behavior." (*4*, p54) Therefore, trips made by an individual are not independent, but closely related and organized to fulfill the individual's specific daily schedule (*12*). The activity-based approach brings back various characteristics of trips that have been ignored in the trip-based aggregate models (*5*).

The activity-based approach enhances the concept of treating travel as a derived demand and ties travel to its contextual background. In the conventional trip-based approach, trips are taken out of their contexts and treated as independent behaviors. However, from an activity perspective, people travel because they need to participate in their daily activities distributed at different locations, such as home, work, and grocery stores (*13*, *14*). Also, people often arrange multiple purposes and make multiple stops along their trips. For example, a working mother may do grocery shopping and pick up her child at a day-care center on her way home from work. This is known as a trip with multiple stops (*3*). A simply defined trip classification (e.g., a home-based work trip or a shopping trip) in the conventional trip-based approach can hardly capture the complexity of this trip's purposes.

The activity-based approach also puts more emphasis on the temporal aspect of a trip (*5*). Activities usually take place at specific times and travel is required to take an individual to an activity location in a timely manner. Therefore, the temporal distribution of trips is of great importance to travel studies. For example, morning rush-hour congestion occurs because too many individuals are on the road at the same time when they all need to reach their work places around the same time.

The activity-based approach emphasizes on the relation between travels and activities (*15*). Wang and Cheng (*16*) conceptualized the activity pattern of an individual's daily life as a sequence of staying at or traveling between locations. Travel is the means for people to reach specific locations on time in order to conduct activities. Each individual may have a different set of daily activities, and even if two individuals have the same set of activities, they may assign different priority to the same activity. Therefore, each individual has a specific activity schedule, which determines the individual's travel pattern. Kitamura and Fuji (*17*) classified daily activities into two types. Activities related to work or school are usually conducted at fixed locations and fixed times, and they are considered as *fixed activities* and require *blocked periods*. Activities related to shopping and entertaining are *flexible activities*, which can be carried out in *open periods* with higher flexibility. The spatio-temporal distributions of an individual's fixed activities can impact how the individual carries out flexible activities. How people arrange and conduct their daily activities presents a very complex and challenging research issue (*5*). A tool that can help examine human activities in a space-time context can offer researchers opportunities to gain a better understanding of spatial and temporal characteristics of activities and reveal the mysteries of human travel behavior.

With these new views of travel behavior, the activity-based approach brings up many new space-time related inquiries on travel/activity patterns, which cannot be efficiently carried out in datasets for trip-based approaches. Such inquiries can be about the sequence of an individual's activities (e.g., what did Adams do after he drove to the downtown area?), the activity organization of an individual (e.g., what activities was Betty engaged in between 9AM and 4PM and where and when did those activities take place?), temporal features of activity locations (e.g., how many times did Carl visit a selected grocery store last week and when did those visits happen?), and bundles of activities among individuals (e.g., did Dave and Evan happen to participate in the same activity or share the same trip yesterday?). Although these questions are only a small set of inquires in the activity-based approach, they make it very clear that a proper theoretical framework with an integrated space-time analysis environment is essential to activity-based travel analysis.

Time geography provides an elegant framework to support activity-based travel analysis by representing trips and activities with their space-time contexts (*5*). Originally proposed by Torsten Hägerstrand (*18*), time geography was developed to study the relationships between human activities and their constraints in a space-time context (*19*, *20*). Hägerstrand (*18*) argued that time should not be considered only as an external factor when examining human activities;

time, as essential as space, should be involved in the examination process. The time-geographic framework adopts a three-dimensional (3D) orthogonal coordinate system, with time as the third dimension added to a two-dimensional spatial plane. The space dimensions are used to measure location changes of objects, while the time dimension is used to order the sequence of events and to synchronize human activities. Using this system, time geography is ready to model human activities and travels with their spatial and temporal characteristics.

The space-time path concept is a fundamental concept of time geography. A space-time path is a trajectory recording an individual's movements in physical space over time. As a linear feature in the 3D space-time system, a space-time path provides a continuous representation for the history of an individual's location in space (FIGURE 1). A path is composed of a set of connected vertical segments and tilted segments. Each vertical segment indicates a person's stay at a specific location for a time period. The individual may conduct activities at the location during the time period. Each tilted segment refers to a travel activity and the slope of the segment indicates the travel speed. Thus, a space-time path can be considered as a container of various activities and travels (which can be considered a special type of activities) conducted by an individual during an observed time period. Travel activities can be easily retrieved from a space-time path by locating the tilted portions along the path. Activities other than travel can be located along a path according to their temporal information (i.e., starting/ending time of activities). Therefore, a space-time path can provide detailed information about the spatial and temporal characteristics of an individual's actions, including the starting/ending times and locations of activities, the duration of each activity, and the sequence of activities. Moreover, it offers an integrated space-time system to organize these activities (*20*). Therefore, the space-time path concept addresses the requirements of activity-based travel analysis in the following ways:

1) The integrated space-time system provides an effective approach to the representation of activities with their spatio-temporal characteristics;

2) The concept of travel as a derived demand is represented in a space-time path with an alternating pattern of vertical segments (activities) and tilted segments (travels) along the path;

3) The issue of trip-chaining and trips with multiple stops/purposes is solved by connecting all activities and trips according to their time sequence in a space-time path.

In addition, space-time paths can also help represent and analyze bundles of activities among individuals. Bundles among people can be recognized as overlaps of space-time paths. FIGURE 2 represents two types of bundles. Case 1, where the vertical portions of space-time paths overlap, indicates a static bundle scenario in which both individuals stay at the same location partaking activities (e.g., people attending a meeting together). Case 2, where the tilted portions of paths overlap, describes a dynamic bundle scenario (*21*) in which individuals stay together while moving (e.g., people carpooling or riding the same bus to work). Therefore, examining overlaps among paths can help conduct inquires regarding bundles of activities.

The space-time path concept of time geography offers an effective means to represent activities with their space-time contexts and supports spatio-temporal analysis applied to them. This study adopts the concept to organize activities/travels and proposes a temporal GIS design to visualize and analyze the spatio-temporal characteristics of activities and travels which are represented in the form of space-time paths.

TEMPORAL GIS DESIGN FOR VISUALIZING AND ANALYZING SPACE-TIME PATHS WITH ACTIVITIES AND TRAVELS

Although the structure of time geography is simple and clear, most studies adopt the framework as a conceptual model only, and limited progress has been made so far to operationalize the framework in a computer system (*22*). Recent improvement of GIS in representing geographic phenomena and the reviving interests in time geography have prompted new attempts of implementing the time-geographic framework in GIS (e.g., *23*, *24*, *25*, *26*). These studies provide valuable experiences on incorporating the time-geographic concepts in GIS to support activity studies. Building on these existing studies, this paper provides detailed discussion on developing a temporal GIS to support the representation and analysis of activities and travels with their spatio-temporal characteristics.

Representation of Space-time Paths and Travels/Activities

Hägerstrand's time geography adopts a 3D space-time system to study the spatial and temporal constraints of human activities (*18*). In order to represent space-time paths, a GIS design must include an explicit representation of the time dimension. Therefore, a 3D GIS environment, which simulates the space-time system in time geography, is required to represent space-time paths. In this 3D GIS environment, a 2D plane is used to record spatial information of time-geographic objects, and a third dimension is used to represent temporal information in a linear time structure.

Features in such a 3D system are named spatio-temporal features. Two types of spatio-temporal are defined in this system. A spatio-temporal point feature, which occupies a single position in the 3D framework, is represented with a triplet of $<x, y, t>$, where x and y are used to define a location in the 2D plane and t is used for time. A spatio-temporal line feature is represented as a sequence of triplets ($\{<x_0, y_0, t_0>, <x_1, y_1, t_1>, \ldots , <x_n, y_n, t_n>\}$, where $t_0 < t_1 < \ldots < t_n$). FIGURE 3 shows how these spatio-temporal features are represented in the temporal GIS framework. With these basic spatio-temporal features, time-geographic concepts can be explicitly represented in GIS with their spatial and temporal characteristics.

A space-time path records the observed movements of an individual in physical space over time. Due to the indivisibility constraint, each individual can only have one observed trajectory in physical space over time. In this GIS design, each individual will be associated to one space-time path, which is represented as a spatio-temporal line feature. The triplets ($<x, y, t>$) stored at vertices along the line explicitly record the spatial and temporal information of the individual's movements. Space-time paths are containers of activities (including travels) because each activity, as an episode in one's life, occupies a portion on the individual's space-time path. With an individual's space-time path and the temporal information (i.e., starting/ending times) of an activity conducted by this person, the activity can be located along the space-time path by a temporal dynamic segmentation method (*26*). Extra spatial and temporal information of the activity then can be derived from the path. Therefore, individual activities can be represented as spatio-temporal line segments attached to space-time paths.

Basic Operations Applied to Spatio-temporal Line Features

The temporal GIS design needs to support spatio-temporal analysis on space-time paths and activities in order to facilitate the exploration of spatial and temporal characteristics of activities. However, most operations developed in current GIS are applied to features in a 2D plane. Analysis on space-time paths demands extra effort to handle a third dimension of time. This study adopts a *space-first-time-second* strategy to develop operations on spatio-temporal line features. Using this strategy, spatio-temporal features are first projected into the 2D plane, and existing GIS operations are employed to examine certain spatial relationships among them. Examinations of temporal relationship are then processed on the resulting features from the previous step to finalize the spatio-temporal operation.

Spatio-temporal intersection is a basic and important operation applied to spatio-temporal line features. Because it will be frequently used to support various inquiries of activity-travel patterns (e.g., activity bundles), detailed discussions on conducting the intersection operation between two spatio-temporal lines are provided below.

In the 3D temporal GIS framework, the spatio-temporal intersection operation can be considered as a process of locating 3D intersections among features. Because a line is usually constructed as a collection of connected straight-line segments in GIS, the discussion of this operation focuses on straight-line cases. Adopting the space-first-time-second strategy, two spatio-temporal lines are first projected into the 2D plane for spatial analysis. Depending on its position, a 3D line could be a point (for a vertical line) or a line (for a tilted line) after projected into the 2D plane. Therefore, the projection of two 3D lines in the 2D plane can be two points, a point and a line, or two lines. These scenarios are discussed separately.

Two-Point Scenario

When the projected shapes of two 3D lines are both points, it indicates that both lines are vertical 3D lines. If the two vertical 3D lines intersect, their projected points must overlap in the 2D plane. Conventional GIS operations can help ascertain whether the two projected points overlap. Also, the two lines must overlap in the time dimension. Such a temporal overlap can be identified by comparing the minimum and maximum time represented by the spatio-temporal lines. Denoting A_s, A_e, B_s, B_e, R_s, and R_e as the minimum and maximum time for lines A, B, and a possible intersected segment R between them (FIGURE 4), the temporal overlap can be determined by simple calculations.

$$\text{Let } R_s = \text{Maximum}(A_s, B_s); \quad R_e = \text{Minimum}(A_e, B_e) \qquad [1]$$

If $R_s \leq R_e$, the two lines have temporal overlap, which starts at R_s and ends at R_e. When the two vertical 3D lines also overlap in the 2D plane, they have spatio-temporal intersections. If the location of their projected point in the 2D plane is represented as $<x_0, y_0>$, the 3D line resulting from the spatio-temporal intersection of the two vertical 3D lines can be represented as $\{<x_0, y_0, R_s>, <x_0, y_0, R_e>\}$. In the case of $R_s = R_e$, the result becomes a 3D point instead of a 3D line.

One-Point-One-Line Scenario

When one of the two original 3D lines is a vertical line and the other is a tilted line, their projected shapes in the 2D plane will be a point and a line respectively (FIGURE 5). If these two lines have a 3D intersection, their projected shapes must overlap. Conventional GIS operations can be used to check whether a point overlaps a line. If they do overlap, it indicates that the tilted 3D line must, at the very least, pass through the location where the vertical 3D line resides in the 2D plane. According to the location of the intersection in the 2D plane, a time value can be calculated for that location on the tilted 3D line through a linear interpolation method based on the time values at the end points of the tilted line. For example, if the tilted 3D line and the vertical 3D line are represented as $\{<x_1, y_1, A_s>, <x_2, y_2, A_e>\}$ and $\{<x_0, y_0, B_s>, <x_0, y_0, B_e>\}$ respectively, and they have an intersection in the 2D plane at $<x_0, y_0>$ as shown in FIGURE 5, the time value (t_0) for the location of <x_0, y_0> on the tilted 3D line can be achieved from the following formula:

$$t_0 = A_s + (A_e - A_s) * \frac{\sqrt{(y_0 - y_1)^2 + (x_0 - x_1)^2}}{\sqrt{(y_2 - y_1)^2 + (x_2 - x_1)^2}} \qquad [2]$$

If $B_s \le t_0 \le B_e$, the two lines will have a 3D intersection at a point of <x_0, y_0, t_0>.

Two-Line Scenario

Finding 3D intersections between two tilted 3D lines is more complex. In this case, their projected shapes in the 2D plane are two lines. Again, conventional GIS operations can be used to find intersections between the two projected lines in the 2D plane. If the projected lines have only one intersection, the time value for the intersected location on each tilted 3D line can be interpolated using formula [2]. If the two interpolated time values are the same, the two original 3D lines have one intersection and its coordinates can be achieved from the 2D intersection and the interpolated time value. Otherwise, the two 3D lines only pass the same location at different times.

If the projected lines overlap one another instead of having just one intersection, there are various possibilities for the relationship between the two 3D lines (FIGURE 6). Six situations between the two 3D lines are classified based on their directions and temporal relationships. A_s, A_e, B_s, and B_e are used to denote the minimum and maximum time for two tilted 3D lines, *A* and *B*. In FIGURE 6a, two 3D lines have the same direction and they share the same time range (i.e., $A_s = B_s$ and $A_e = B_e$). In this case, the two 3D lines completely overlap and either of them is the result of the 3D intersection operation between them. When $A_s > B_e$ as in FIGURE 6b, the two 3D lines will not intersect no matter what their directions are.

When the time range of one 3D line covers the other one (i.e., $A_s < B_s$ and $A_e > B_e$) as shown in FIGURE 6c and 6d, the two 3D lines will have one 3D intersection. Depending on the directions of the two lines, the time value (t_0) for the intersection is calculated using different formulas. In FIGURE 6c, a ratio relationship can be set up among A_s, A_e, B_s, B_e, and t_0.

$$\frac{B_s - A_s}{A_e - B_e} = \frac{t_0 - A_s}{A_e - t_0} \qquad [3]$$

Therefore, the time value (t_0) for the intersection in this case is

$$t_0 = A_s + \frac{(A_e - A_s)(B_s - A_s)}{A_e - A_s + B_s - B_e} \qquad [4]$$

Similarly, when the two lines have different directions as displayed in FIGURE 6d, the time value (t_0) for the intersection can be calculated using the following formula.

$$t_0 = A_s + \frac{(A_e - A_s)(B_e - A_s)}{A_e - A_s + B_e - B_s} \qquad [5]$$

Once the time value (t_0) is calculated, it can be used to calculate x_0 and y_0 for the intersection based on the coordinates of one original 3D line. For instance, representing line *A* as {<x_1, y_1, A_s>, <x_2, y_2, A_e>}, the value of x_0 and y_0 can be calculated by the following formulas.

$$x_0 = x_1 + (x_2 - x_1)\frac{t_0 - A_s}{A_e - A_s} \qquad [6]$$

$$y_0 = y_1 + (y_2 - y_1)\frac{t_0 - A_s}{A_e - A_s} \qquad [7]$$

In both cases, the two 3D lines intersect at the point of $<x_0, y_0, t_0>$.

When the time ranges of the two lines overlap (i.e., $B_s < A_s \le B_e < A_e$), the directions of the lines will determine whether they have a 3D intersection. When the two lines have the same direction as displayed in FIGURE 6e, they will not intersect. When the two lines have different directions as in FIGURE 6f, they will have one 3D intersection. The coordinates of the intersection can be calculated using the same process for the case in FIGURE 6d.

With these operations, the temporal GIS design is able to explore spatial and temporal characteristics of activities and travels and help researchers answer space-time related questions in activity-based travel analysis.

IMPLEMENTATION OF THE DESIGN

As a prove-of-concept test, a prototype system with selected functions is created following the temporal GIS design discussed in this paper. The prototype system is developed in ArcGIS, which is a commercial GIS software package. ArcGIS supports a 3D spatial system, which is similar to the 3D orthogonal space-time system of time geography. The third spatial dimension (z) in ArcGIS is adjusted and used as the time dimension (t) in the space-time system. Therefore, the spatio-temporal features are represented as adjusted 3D features in ArcGIS. Customized functions applied to spatio-temporal features are created in the system. A small hypothetical activity dataset is generated and used in the prototype to test the capability of the system. The prototype can successfully perform functions of interactively visualizing individual activities in their space-time contexts and analyzing spatio-temporal characteristics of activities. Examples of several analysis functions in the prototype are provided below.

The prototype can generate space-time paths for individuals based on the complete sets of their travel records. A customized procedure is created to connect all trips of an individual in their sequential order to create a space-time path. Vertical links, which represent an individual's stays at particular locations, are added to the path between every two consecutive trips. The actual shapes of trips and extra vertical links are used to construct the geometry of a space-time path. Once an individual's space-time path is available, other non-travel activities of the individual can be located along the path by a temporal dynamic segmentation method using the temporal information of the activities (*26*). FIGURE 7, which is a screen capture of the prototype system, shows a generated space-time path and activities attached to the paths by the temporal dynamic segmentation method. The prototype system provides an interactive environment to effectively visualize activities in their space-time contexts. The sequential relation among activities of an individual is maintained by the activities' position in the path and such a relation can be conveniently visualized in the prototype system.

A customized function in the prototype system can help researchers explore individuals' visiting pattern at selected locations. This function can report how many times an individual visited a selected activity location, when the individual made the visit, and how long each visit lasted by executing the spatio-temporal intersection operation between space-time paths and selected point locations. FIGURE 8 displays a sample report generated from such an inquiry. It indicates that the person (Prof D) visited the interested location (Department of Geography) twice during the observed period. Information of the two visits is derived from calculation and included in the report. In this case, the person arrived at the department at 8:30AM and left at 12:15PM for the first visit, and returned to the department at 1:48PM and stayed until 4:30PM. Information from the result can help researchers reveal different visit patterns of different individuals at the same or similar activity locations and provide insights on the understanding of people's activity scheduling process.

As socialized beings, people cannot avoid interacting with one another. People who are connected through family or social relationships usually share many activity/travel bundles, such as attending a conference with colleagues (static bundle) or having a family road trip (dynamic bundle). The prototype system includes a function which can identify static and dynamic bundles among people by executing the spatio-temporal intersection operation and searching for overlaps of space-time paths. FIGURE 9 shows a sample report generated after the analysis. It indicates that the two individuals (GS A1 and GS A3) share three bundles, one static bundle and two dynamic bundles. The first and third bundles are dynamic bundles, which represent carpooling activities of the two individuals. The static bundle was generated when the two individuals stayed at the same shopping center. The start/end time and duration of each bundle are also listed in the report.

CONCLUSIONS

Traditional GIS has been very successful in supporting trip-based travel analysis. However, the activity-based approach, which represents the new transport research paradigm, requires an integrated space-time environment to examine the distribution of activities for analyzing travel behavior. The current GIS design needs improvement to efficiently support activity-based travel analysis. In response to this challenge, this study proposed a temporal GIS design which provides an integrated space-time representation environment and supports basic functions for activity-based travel analysis. Hägerstrand's time-geographic framework is adopted in the system design and the space-time path concept is used to organize individual activities/travels in a space-time context. Methods of representing activities/travels with space-time paths and conducting spatio-temporal intersection operations between spatio-temporal features are discussed in this paper. Feasibility and effectiveness of the design are proved with a successfully implemented running prototype system. This study presents an initial effort of developing a temporal GIS, which incorporates the time-geographic framework, to support activity-based travel studies. Based on the result of this study, such an approach is proved to be capable of providing an efficient GIS environment to facilitate activity-based travel analysis. Further studies can focus on developing more robust GIS applications which can help explore and reveal complex spatial and temporal patterns of human travel behavior.

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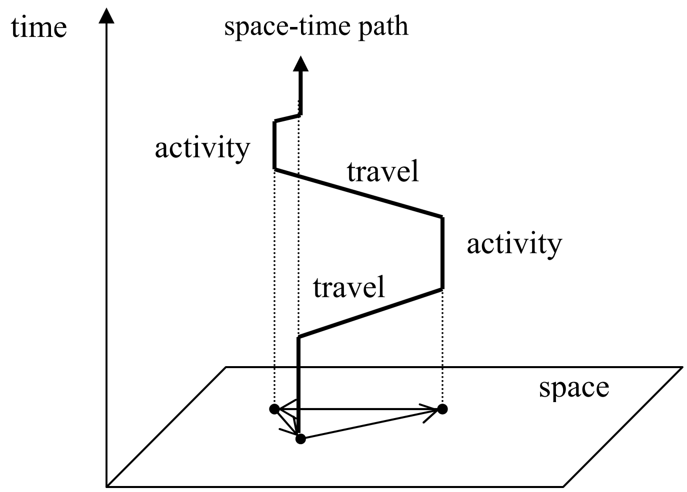

FIGURE 1 Space-time path and activities.

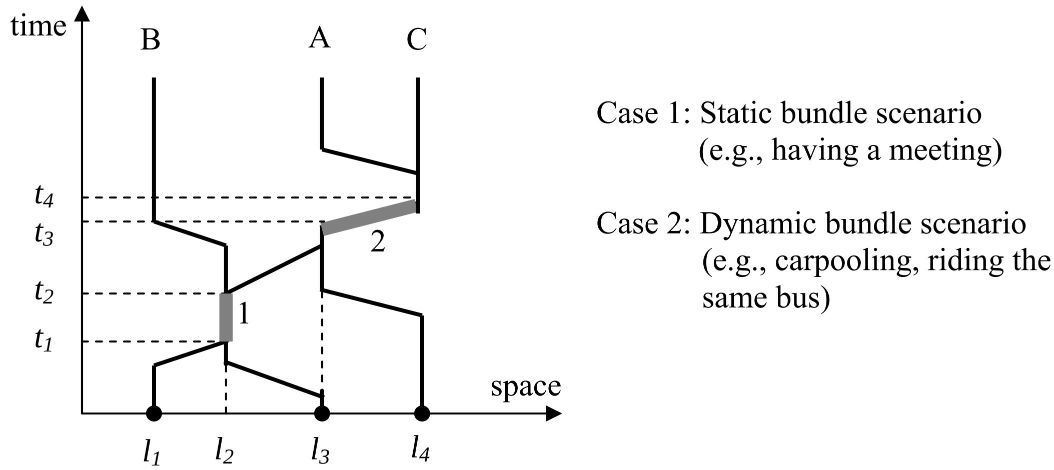

FIGURE 2 Representing activity bundles with overlaps of space-time paths.

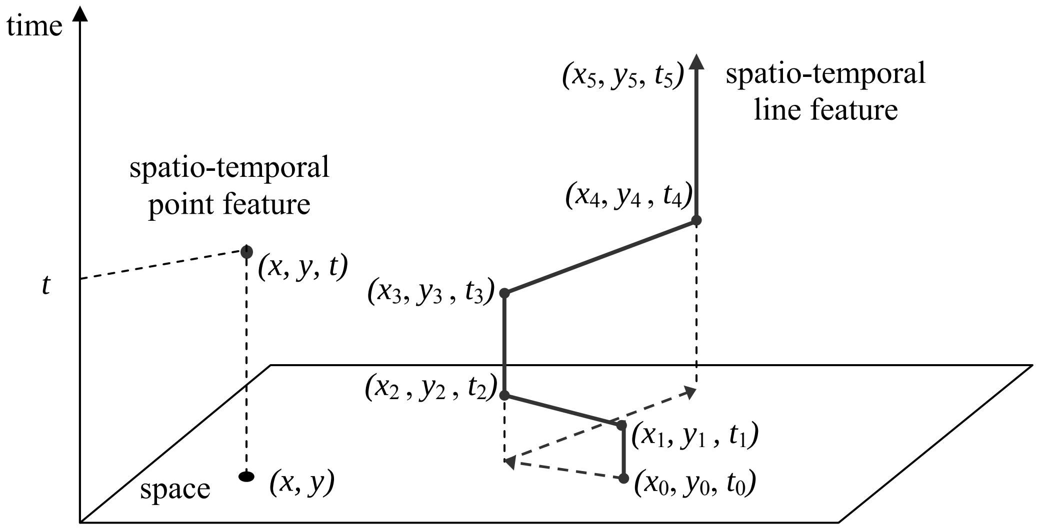

FIGURE 3 Spatio-temporal features in a 3D GIS environment.

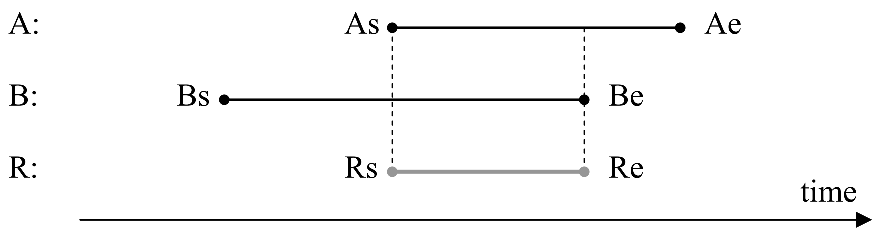

FIGURE 4 Temporal overlap.

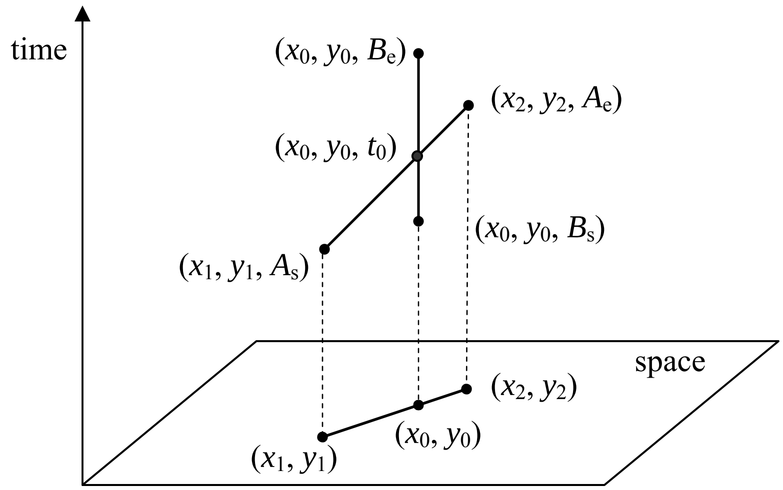

FIGURE 5 A spatio-temporal intersection between a vertical 3D line and a tilted 3D line.

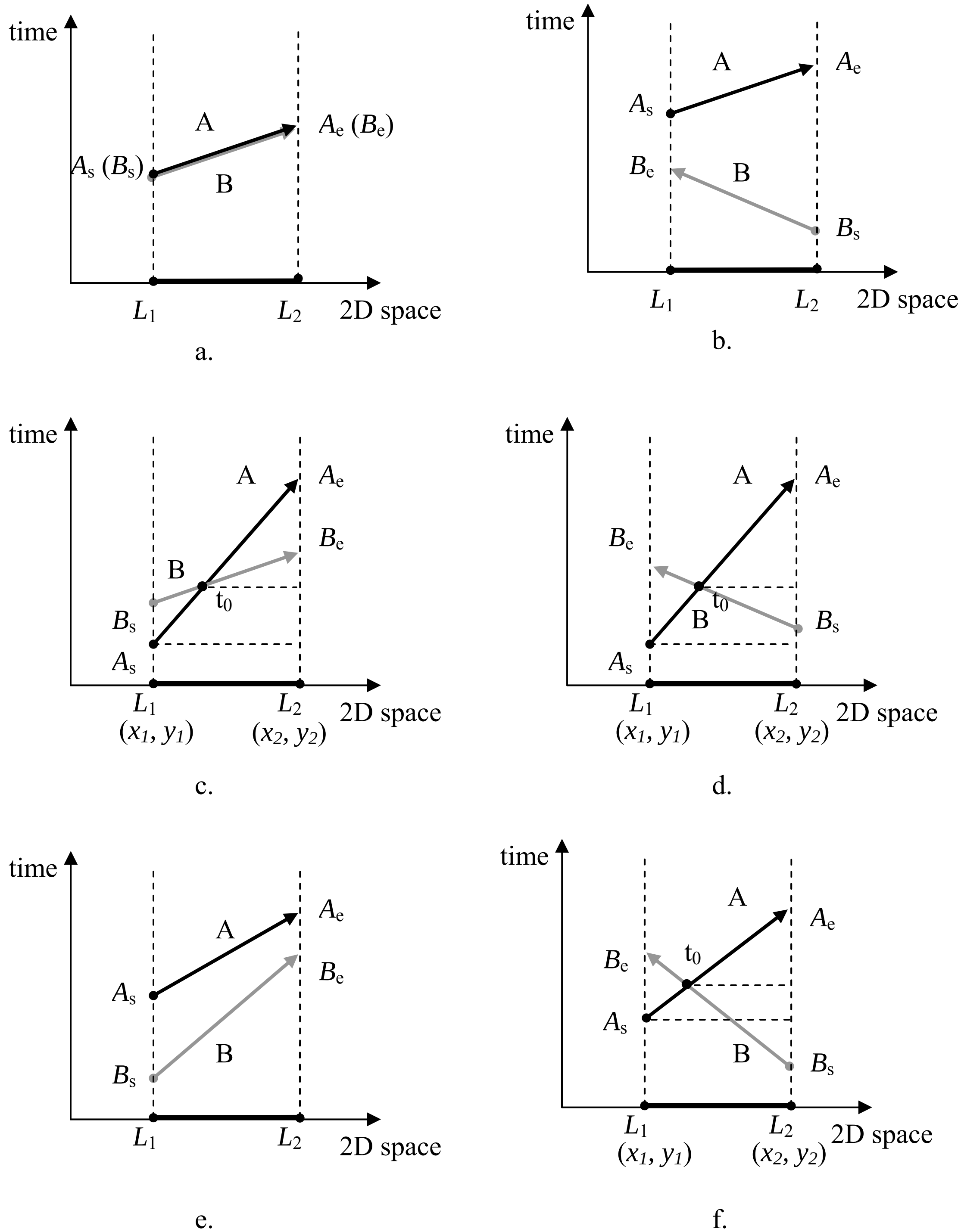

FIGURE 6 Spatio-temporal intersections between two tilted 3D lines.

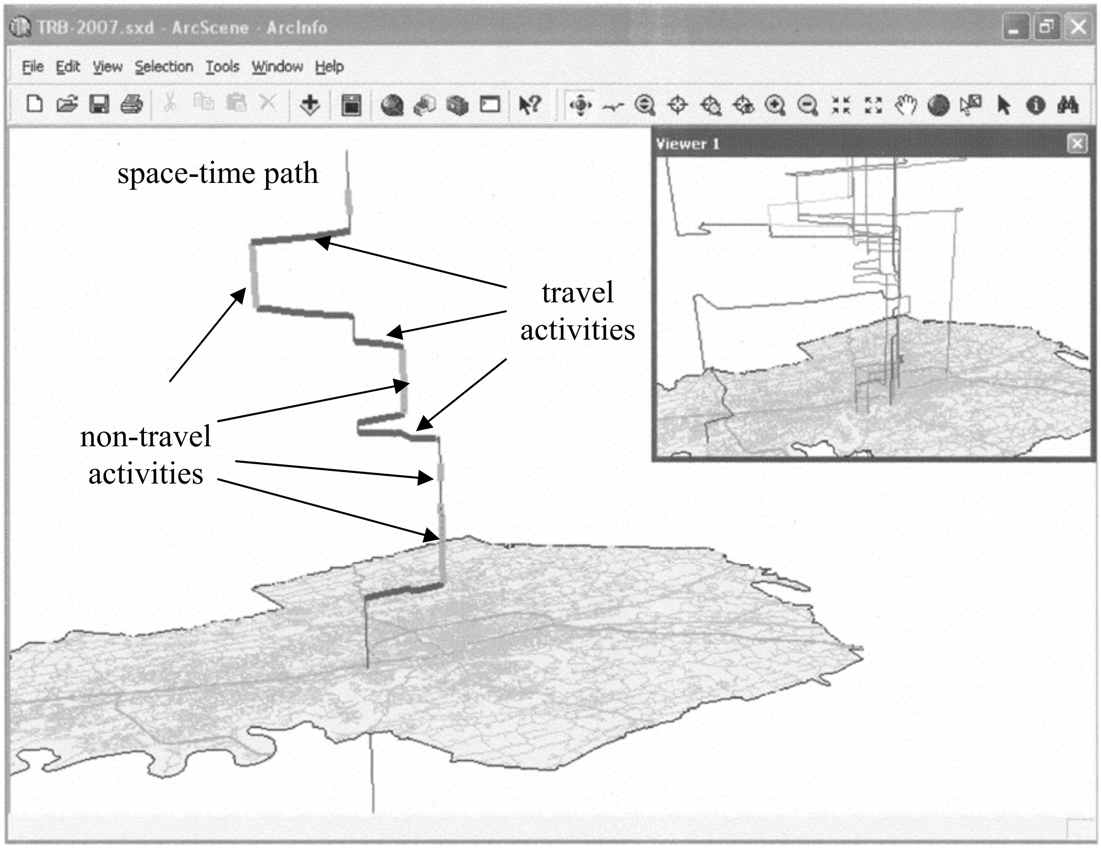

FIGURE 7 Visualization of space-time paths and individual activities.

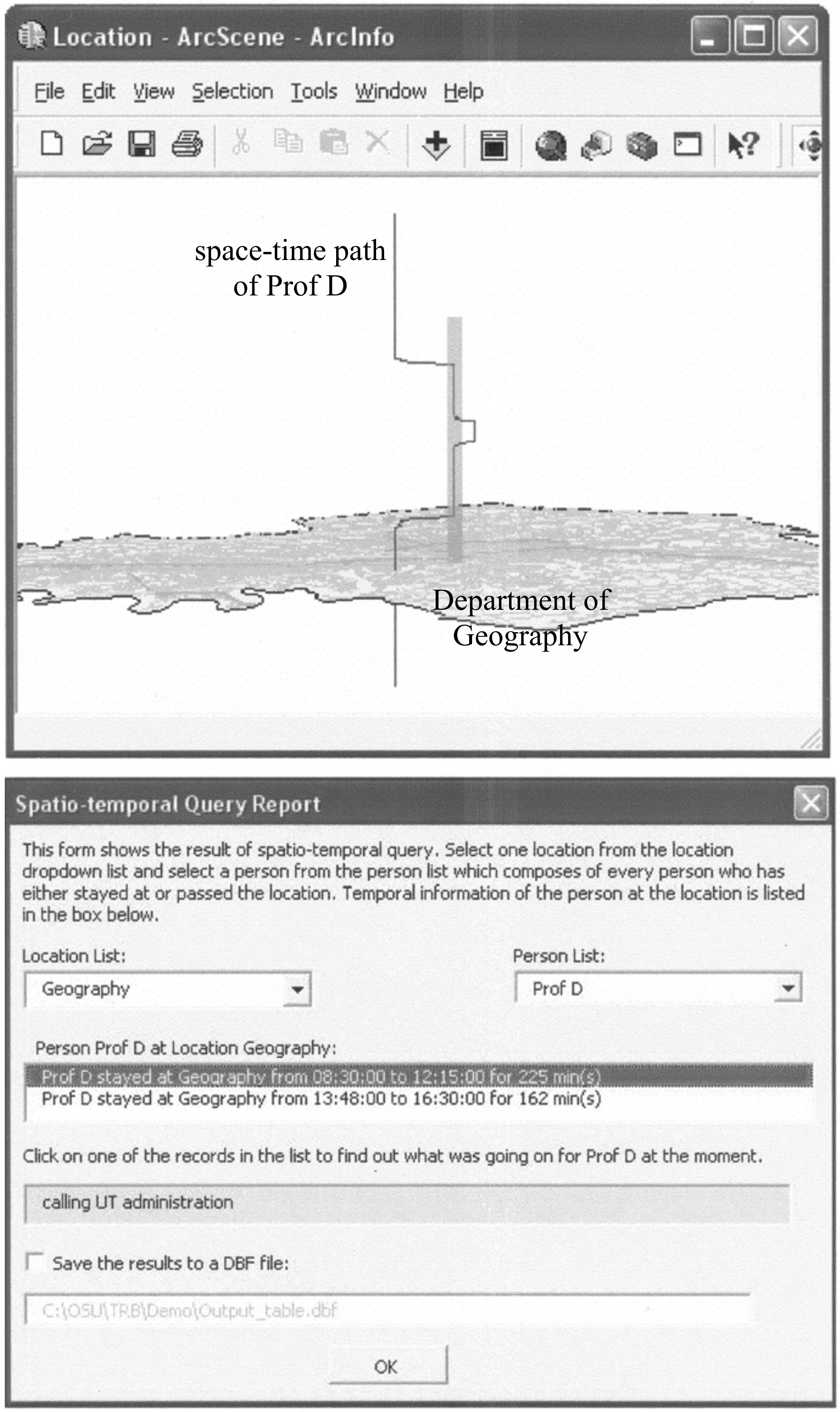

FIGURE 8 A sample report of an individual's visit to a selected location.

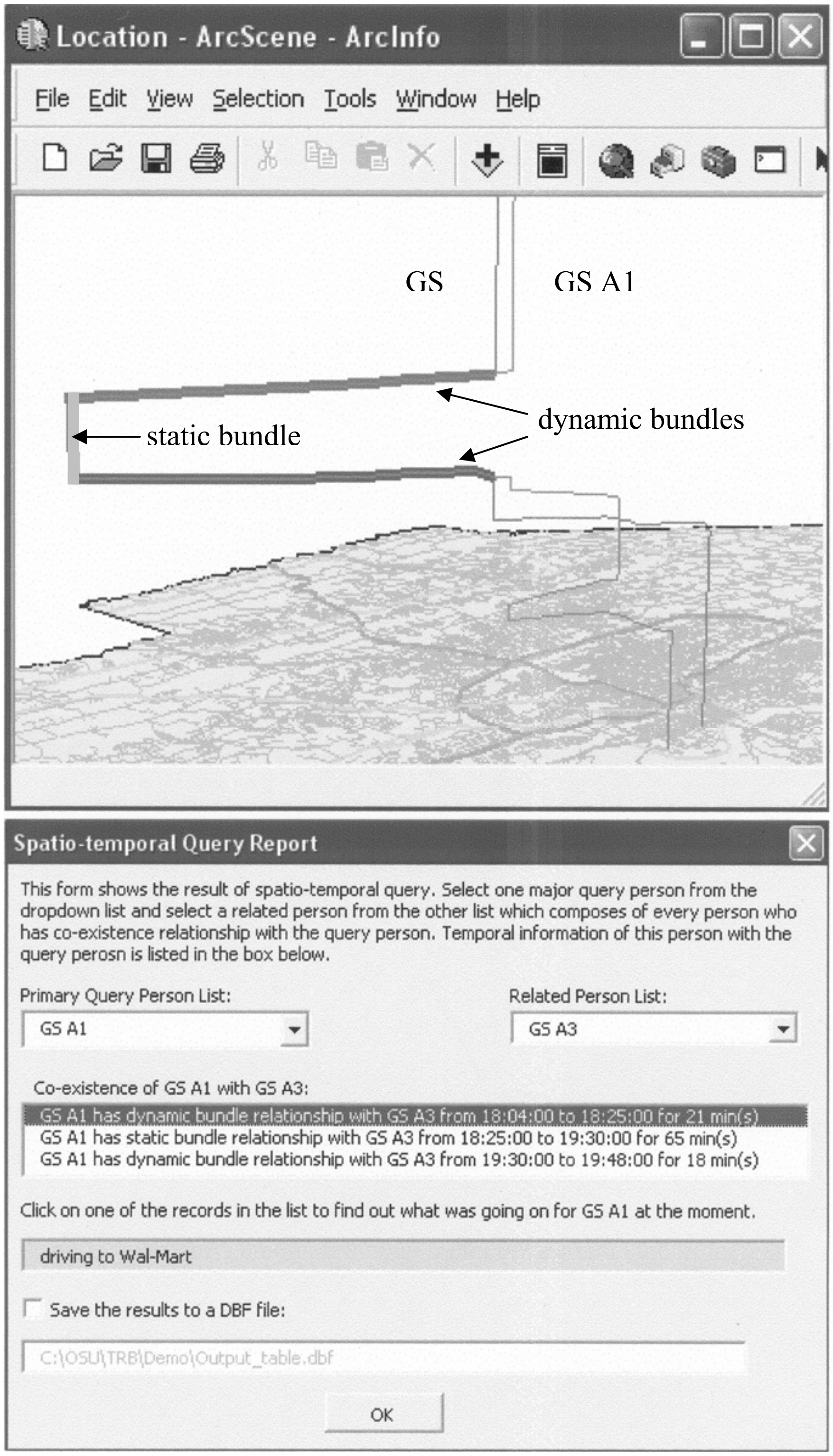

FIGURE 9 A sample report of bundles between two individuals.