INT. J. GEOGRAPHICAL INFORMATION SCIENCE, 2001, VOL. 15, NO. 6, 561–585

Research Article

A spatio-temporal data model for activity-based transport demand modelling

DONGGEN WANG

Department of Geography, Hong Kong Baptist University, Kowloon Tong, Hong Kong; e-mail: dgwang@hkbu.edu.hk

and TAO CHENG

Department of Geography, University of Leicester, Leicester, LE1 7RH, England, UK; e-mail: t.cheng@le.ac.uk

(*Received 4 May 2000; accepted 19 December 2000*)

Abstract. This paper develops a spatio-temporal data model to support activity-based transport demand modelling in a GIS environment. This so-called mobility-oriented spatio-temporal data model conceptualizes the spatial and temporal interaction of travel and activity behaviour using the concept of mobility. In other words, activity patterns are conceptualized as a sequence of staying at or travelling between activity locations. The model can support the analysis and queries of activities from different perspectives, i.e. queries can be location-based, time-based, and person-based. It can also support activity-based modelling by identifying spatial and temporal opportunities for activity participation. The conceptual and logical designs of the data model are presented. A prototype system based on the data model is implemented in ArcView. The prototype is illustrated and tested by a case study based in Hong Kong.

1. Introduction

Recently, the integration of activity-based transport demand modelling with Geographical Information Systems (GIS) has received substantial attention in both the GIS and transport communities (Miller 1991, Kwan 1997, Greaves and Stopher 1998, Bhat and Koppleman 1999, Miller and Wu 2000). This is inspired by the fact that GIS facilitates the representation and manipulation of spatial information, it is thus useful in modelling the spatial contexts of activity patterns and the interaction of temporal characteristics with spatial attributes. It is also encouraged by the successful integration between GIS and Transportation (GIS-T) in the past ten years or so. GIS-T, like GIS as a whole, benefited from developments in computer hardware, in management information systems and database techniques (Waters 1998). Besides highway mapping, GIS has been applied to managing bridges, networks, pavements, traffic volume and accident locations. As for transport demand modelling, among others, GIS software was developed to facilitate the development of the four-step urban transportation model system (Shaw and Wang 2000).

International Journal of Geographical Information Science
ISSN 1365-8816 print/ISSN 1362-3087 online © 2001 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/13658810110046934

Although most authors believe that GIS, through the capabilities offered for the collection, storage, manipulation, analysis, and display of spatially referenced data, could prove critical to the ultimate success of the activity-based approach, all agree that existing GIS techniques need to be further developed to meet the requirements of activity-based modelling. This is partly because compared with traditional trip-based models, activity-based models are dependent on detailed individual-level data, spatially more accurate representations of the physical environment, and the development of more efficient information processing technologies. More importantly, most models in GIS are static descriptions. They are not dynamic and do not describe spatial changes and/or change with time (Burrough and Frank 1995), but in activity-based modelling, the activity patterns of individuals are dynamic, and change in space and time. As Goodchild (2000) argued, current GIS are still inadequate in handling data analysis of flows, complex paths, and temporal changes. He believes that GIS-T has evolved in three stages: the map view, the navigational view, and the behavioural view. The map view is static in nature and favours application to inventory and description. It raises questions of accuracy and interoperability. The navigational view raises concerns for network representation and network topology and issues of representation related to scale, including the need for lane-level connectivity. The behavioural view treats transportation events as dynamic and occurring within the largely static transportation space. It deals explicitly with the behaviour of discrete objects to represent moving geometry. The behavioural view requires a new series of representation methods, beyond those required by either the map or navigation views. Appropriate representations for the behavioural view have still to be worked out.

To cope with the increasing demand for handling dynamic information, the GIS community has diverted substantial efforts to develop so-called 'spatio-temporal' data models with the aim of representing, analysing and predicting changes of spatial information over time (Langran 1992, Al-Taha and Frank 1993, Egenhofer and Golledge 1998). For example, Peuquet and Duan (1995) proposed an event-based spatio-temporal data model (ESTDM) to represent temporal information of landuse change. Several other authors including Raper and Livingstone (1995), Mason *et al.* (1994) and Cheng and Molenaar (1998) put forth object-oriented spatio-temporal data models to represent the dynamics of geomorphologic systems. Yuan (1995) developed a so-called three-domain model for forest and wildfire management, and Spery *et al.* (1999) suggested spatio-temporal models for cadastre management. All these models are intended for addressing and modelling the dynamic behaviour of natural phenomena, which is normally related to changes in spatial extent.

These models are, however, not tailored to the needs of activity-based research. This is because the dynamics of activity and travel behaviour are related to changes in locations of human subjects.

The objective of this paper is therefore to develop a spatio-temporal data model that can represent the dynamic behaviour of activity and to support activity-based modelling in a GIS environment. A mobility-oriented spatio-temporal data model is proposed. In the model, the behaviour of activities is represented as a sequence of two states—staying at and travelling between activity locations. The proposed model can support analysis and queries of activities from multiple perspectives, i.e. queries can be location-based, activity-based, time-based, and person-based. The conceptual and logical designs of the data model are presented. The multi-perspective queries and modelling function are implemented in ArcView. It is illustrated by a case study based in Hong Kong.

The next section of the paper introduces activity-based transport demand modelling. Section 3 discusses the requirements of activity-based modelling for GIS. Section 4 presents the conceptual and logical designs of the mobility-oriented spatio-temporal data model. Section 5 reports the physical implementation of the data model in a prototype and its application. Section 6 concludes the paper with a summary of findings and discussion.

2. Activity-based transport demand modelling

Since the late 1950s, transportation models have played an important role in forecasting transport demand and evaluating the impacts of plans and policies. Planners use transportation models to learn about the behaviour of transport systems. Over the past decades, the development of particular modelling approaches has closely followed planning needs, which in turn are closely related to dominant policy issues.

The first generation of transportation models was developed during the late 1950s and early 1960s. Their purpose was to facilitate the prediction of future transport demand, such that road capacity programs could be based on predicted demand. The first generation models are commonly referred to as four-step models. These models are typically formulated and calibrated at the level of the traffic zones. Individuals are aggregated by traffic zone. Traffic is considered to be the result of four sequential decisions: trip generation, trip distribution, mode split and traffic assignment. These decisions are modelled separately at successive stages. Although the four-step models have been widely used, even institutionalized in literally thousands of applications (Stopher *et al.* 1996), the major shortcoming of these large-scale, aggregate and supply-oriented models is their lack of behavioural content. Consequently, researchers could not evaluate alternative policies such as traffic demand management measures that are unrelated to investment proposals for major facilities, because the evaluation of these policies requires the prediction of individual behavioural responses.

Consequently, in the 1970s and 1980s, this aggregate approach was gradually replaced by a disaggregate modelling approach. The disaggregate approach focuses on decision-making and choice processes at the level of individuals or households. This shift was stimulated by a policy change from long-term supply strategies to short-term market-oriented traffic management initiatives. The major premise underlying this more decentralized and demand-oriented approach is that individual decision-making mediates the impact of transport policies on travel patterns. If the impact on an individual's behaviour can be predicted, the effects of transport policies can be easily derived by aggregating across individuals. The disaggregate approach was developed from random utility theory. Individual travel decision-making is represented by discrete choice models. Mode and destination choices are the two types of travel decisions that have witnessed most applications.

Although the theoretical underpinnings of the disaggregate approach were certainly stronger than those underlying the aggregate approach, the disaggregate approach also did not escape from major criticisms. Like the aggregate approach, the disaggregate approach is a trip-based approach which decomposes travel behaviour into a set of simple problems related to single trips, ignoring the interdependencies between individual trips. More importantly, the approach treats travel as a demand in its own right, avoiding the question why people travel. It has become increasingly evident, however, that travel choices fundamentally depend on choices to participate in activities (Jones *et al.* 1990), and on choices of related travel. A failure to account for these interdependencies will undermine the ability of the models to predict important decisions such as the trade-off between activities with and without travel, and between tours of single-stop and multi-stop. As a result, the approach was accused of not being able to predict the shift from single-stop tours to multi-stop tours and from non-travel activity patterns to patterns including travel. This limitation has become significant in the light of the need to assess a set of new policy initiatives proposed in recent years, including road pricing, information technologies, teleworking/teleshopping, etc. It has been argued that these policies may induce individuals to change their activity and travel behaviour by substituting out-of-home activities with in-home activities, chaining individual trips into home-based tours and changing the timing of activities and trips. Because of their inherent drawbacks, the trip-based aggregate and disaggregate approaches may be less appropriate to predict the effects of these potential behaviour changes.

It thus became necessary to explicitly address the fact that travel is derived from the decision to participate in particular activities at different locations. This so-called activity-based approach received some early attention in the late 1980s and became a dominant modelling approach in recent years. The approach considers travel decisions as derived from activity choices. Travel demand is thus accounted for by explaining and analysing individuals' and households' activity decisions. These decisions include whether, where, when, how, for how long and with whom activities are conducted. The interdependencies among these decisions are explicitly taken into consideration. The approach thus provides a more fundamental and comprehensive framework to examine travel behaviour than the trip-based aggregate and disaggregate modelling approaches.

The activity-based approach has also resulted in a wider range of issues that need to be addressed. According to Pas (1985), the major areas of investigation in activity-based studies include:

- demand for activity participation;
- activity scheduling in time and space;
- spatial-temporal, interpersonal, and other constraints;
- interactions in travel decisions over time;
- interactions among individuals; and
- household structure and roles.

Existing activity-based studies can be roughly classified into two categories. One stream of studies concerns empirically examining observed activity and travel patterns. These studies aim at formulating hypothesis about activity and travel behaviour. Another important stream has focused on developing activity-based models. These models intend to integrate the various decisions regarding activities and travel in a model framework with theoretical underpinnings and the possibility of being calibrated. In such a way, the models are able to predict how individuals may change their activity and travel patterns in response to changes in their travel environments.

To help readers, who are not familiar with the activity-based modelling approach to understand the terminology used in this paper, we shall first define some terms.

Following Axhausen (1994), an *activity* is defined as the main business carried out at a location including waiting time before or after the activity. For example, shopping is an activity carried out at a shop. Activities can be classified into types according to their purposes. For example, working is an activity for subsistence, while shopping is an activity for household maintenance.

The time of the day when activities are conducted is defined as the *timing* of activities. During a certain period, such as a month or a week, an activity may be conducted several times. The *frequency* of activities thus represents the number of times that a particular activity is conducted during a particular time period. An activity may only be conducted at a particular location where the necessary facilities and environment are provided. For example, one cannot conduct sporting activities in a shop, because the shop usually does not provide an environment for sport. The location where particular activities may be conducted is called the *destination*. Destinations are characterized by their locational and non-locational attributes, such as travel time to reach the location, the quality and quantity of facilities, etc. The fact that not all activities can be performed at the same destination implies that one has to move from one activity destination to another activity destination. Such a movement between two activity destinations is called a *trip*. The means used to make a trip is called a *transport mode*.

An *activity program* is defined as a list of activities to be performed on a particular day. For example, an individual's daily activity program on Monday may include the following out-of-home activities: working, sporting and visiting a friend. Before implementing an activity program, individuals need to organize the activities in time and space. They make decisions about where, when, in what sequence, in what home-based tours to organize their activities along with what transport modes to use. This detailed information regarding how activities are organized in space and time is defined as an *activity schedule*. Individuals do not necessarily perform activities according to the planned activity schedule. They may be involved in unplanned activities. We refer to the actual set of activities and the actual way in which activities were performed as an *activity pattern*. Thus, an activity pattern contains the information regarding activities, destinations, timings, sequence of activities, home-based tours, transport modes, etc.

Individuals' activity behaviour takes place within the context of their physical and institutional environments. The spatial configuration and transport connections between alternative destinations where individuals perform their commited activities constitute the *physical environment* in which individuals live. In other words, the physical environment refers to the home location, the work place, the locations of shopping centres, etc., and the roads and public transportation facilities connecting these places. The physical environment defines an individual's spatial opportunities but also the constraints to pursue particular activities. The *institutional environment* is defined as the set of formal rules that regulate on individual's time use. For example, the working time arrangement between an individual and employer, opening hours of shops and public facilities, time schedule of transport facilities, etc., are elements of the institutional environment. The individiual's institutional environment determines their time opportunities and constraints for activity participation. For example, a person who works until 6:00 p.m. will not be able to buy bread after work, if shops are open from 9:00 a.m. to 6:00 p.m. on weekdays.

3. Requirements of activity-based modelling for GIS

Section 2 demonstrated the complexity of activity-based modelling in terms of the number of entities involved and the complicated relationships among the entities. This complexity poses extreme demands on information handling. Since most activity data are location specific (geo-referenced), a GIS is particularly useful for activity-based modelling. As suggested by Greaves and Stopher (1998), it is likely that GIS will be used increasingly as a spatial decision support tool for activity modelling. In general, GIS has great potential to support activity-based modelling in data collection, data management (retrieving, updating, etc.), data manipulation, data output and visualization. Specifically, activity-based travel demand modelling will benefit from GIS in the following respects:

- Support for data collection;
- Provide cross-classification of activities by type, time, location, and socio-demographic characteristics of individuals;
- Define an individual's spatial and temporal opportunity set for conducting activities;
- Represent the space-time prism.

Traditionally, transport demand modelling is based on travel surveys that collect travel behaviour information such as trip purpose, transport mode and trip origin and destination. The spatial dimension of this information is normally referenced to traffic zones. For example, the origin and destination of a trip are recorded according to the traffic zones they belong to. It is not a big problem if you do not use a GIS to collect these information. On the other hand, a major part of an activity pattern is where individuals are doing what, and from where to where individuals travel. Because of these, information is required at a very detailed level, the traditional way of recording spatial information by traffic zones is not sufficient anymore. Instead, one needs to record the detailed address where activities are conducted. This will pose significant burdens to respondents because they need to recall detailed addresses where they have been. It can also be erroneous because individuals normally can not record exactly where they have been and where they are heading to by detailed address. A GIS that contains detailed information about the location and addresses of various facilities in a city is therefore desirable.

Descriptive analysis of activity and travel behaviour usually requires cross-classification of activities by time, location, and socio-demographic characteristics of individuals, etc. For example, it is a typical exercise to examine representative activity patterns and the frequencies and duration of individual activities by different kinds of people. In order to construct an activity pattern, it is important to record the topological relationships (in terms of time sequences) between activities and trips. To meet these requirements it is necessary for GIS to support multi-perspective queries. For example, in order to examine differences in activity patterns of different individuals, it is necessary to provide queries of activity related information based on individuals. Similarly, in order to caluclate the average duration of activities, it is necessary to retrieve information on the timing of activities by activity types.

As argued in the previous section, activity-based modelling intends to simulate individual decision making regarding activity participation and travel. The key information that is required in such modelling is the alternatives from which a choice may be made. These alternatives can be spatial or temporal opportunities. In terms of spatial opportunities, we refer to cases such as what are the potential destinations for shopping? While the case of temporal opportunities refer to what time slots are available to activity engagement? These spatial and temporal opportunities may be entailed in the concept of space-time prisms (Hagerstrand 1970). Miller (1991) proposed methods to use GIS for identifying space-time prisms.

Finally, visualization of activity patterns and space-time prisms is required to present activity information in a more appealing way and may help researchers to find out important regularities underlying activity patterns.

To support all the functions identified above, the GIS database must be structured and organized in an appropriate way that recognizes the dynamic nature of activity and travel related information. In this case, it is the spatial and temporal interaction and the complicated interactions between individuals and their environments. As will be argued in the next section, the recently proposed spatio-temporal data models cannot deal with the dynamics involved in activity patterns because that the dynamics handled by these models are normally related to changes of spatial extent in natural phenomena, while the dynamics in activty patterns are related to the change of locations. A new data model is therefore required.

4. A mobility-oriented spatio-temporal data model for activity-based transport demand modelling

In order to develop a spatio-temporal data model to support activity-based modelling, the dynamic behaviour of activity patterns should first be understood. As argued in §1, the dynamics underlying activity patterns are quite different from the dynamics of natural phenomena. In this section, we will firstly investigate this difference in detail in order to derive a proper model to accommodate the dynamics of activity patterns. Based on the investigation, a mobility-oriented spatio-temporal data model will be proposed.

4.1. *Types of spatio-temporal behaviour*

Based on the changing characteristics of the spatial attributes of objects, such as location, boundary or shape, three types of spatio-temporal behaviours can be differentiated (Tryfona and Jensen 1999, Hornsby and Egenhofer 2000, Renolen 2000):

A *continuous* change: objects of this type are always considered to be in a changing state. For example, the flow of water, the moving plume of an oil spill and a storm are usually modelled as 'moving' objects (changing location) with changing properties (e.g. intensity) and shape continuously.

A *discrete* change: objects of this type are always in static states but change instantaneously by events. This behaviour involves objects located in space, whose characteristics, such as shape, as well as their position may change suddenly in time. The land that a person owns is a typical example of this.

A *stepwise* change: objects of this type are sometimes static and sometimes change, for example, movement of people and vehicles (car, plane, ship, etc.). In this type of application, objects change in spatial position, but not in shape. For example, a 'car' moves on a road network, the location of the 'car' is changing, but its shape remains unchanged.

The three types of spatial-temporal behaviour are illustrated by figure 1. Panel (*a*) illustrates the continuous type of spatio-temporal behaviour by a slant line. Panel (*b*) describes the discrete change by several horizontal and vertical lines. The horizontal line means the static states, and vertical lines represent the sudden changes between two static states. Panel (*c*) shows the stepwise change by horizontal and slant lines with the horizontal lines representing the static states and the slant lines representing objects in motion.

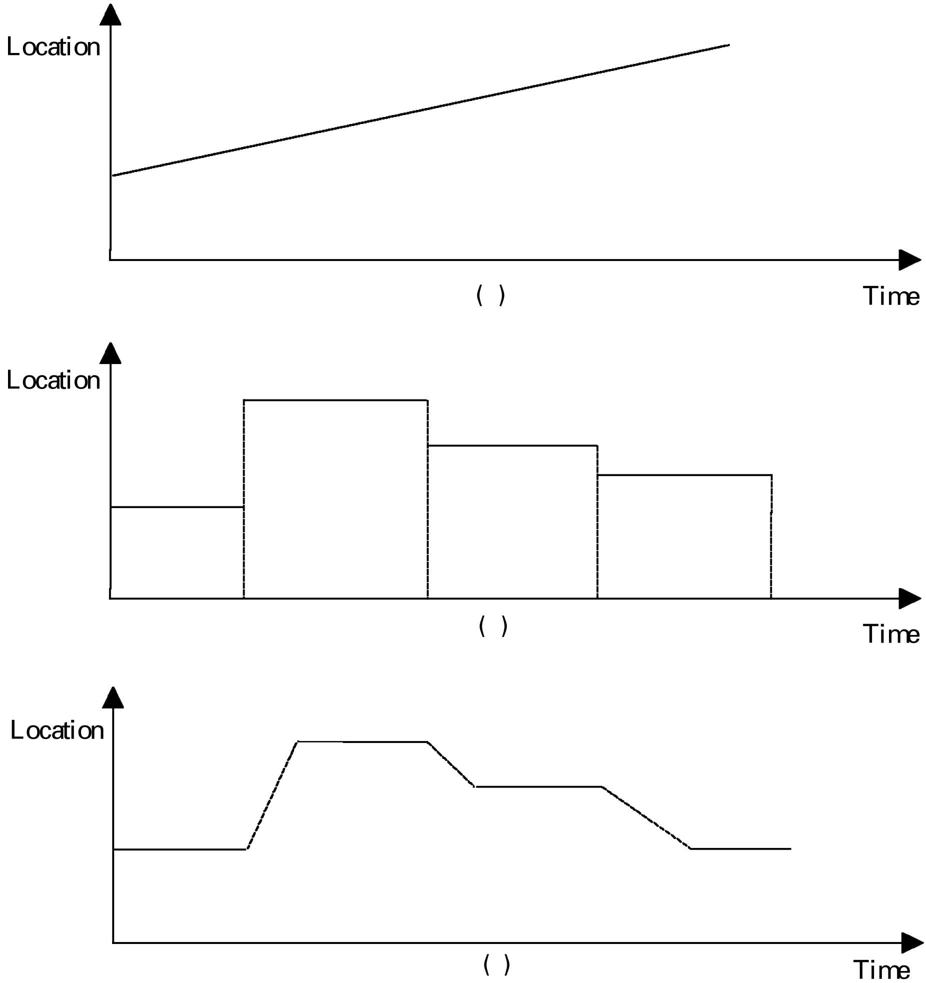


Figure 1. Three types of spatio-temporal behaviours (after Renolen 2000).

4.2. *The underlying dynamics of activity patterns*

In order to understand the underlying dynamics of activity patterns, let us examine a hypothetical activity pattern of a particular person in 24 hours:

8:30–9:00 travelling from home to office
9:00–12:00 working
12:00–12:15 going to restaurant
12:15–13:00 having lunch
13:00–13:15 going back to office
13:15–18:00 working
18:00–18:10 going to a shop
18:10–19:00 shopping
19:00–19:30 going back home
19:30–8:30 at home

We may display this activity pattern in a two-dimensional coordinate system with the horizontal axis representing the clock time and the vertical axis representing the spatial relations of the activity destinations. Figure 2 shows the graphic representation of the activity pattern. The horizontal lines indicate that the person stays in activity destinations (the length of the lines represents the duration of stays), while the slant lines suggest that the person is travelling between activity destinations. If we compare figure 2 with panel (*c*) of figure 1, it is easy to come to the following conclusion: the underlying dynamics of activity patterns can be classified as the *stepwise* type of spatio-temporal behaviour. The object, in this case the person, is sometimes static and some times in motion. The shape of the object (i.e. the size of the person) does not change during motion.

From the viewpoint of mobility status, activity patterns can be described by two types of state: *Stay_at* or *Travel_between*. We may apply these two states to represent the above activity pattern (table 1).

Therefore the activities of a person can be considered as the interaction of a person with locations, either *Stay_at* or *Travel_between* locations (as illustrated in figure 3). If we use mobility to represent the characteristics of *Travel_between*, and no-mobility to describe the characteristics of *Stay_at*, this view can be considered as a mobility-oriented view. This view treats activities as dynamic and occurring within the largely static transportation space. It deals explicitly with the moving behaviour of discrete objects (individuals). This view can also be used to describe the dynamics of vehicles (car, bus and airplane).

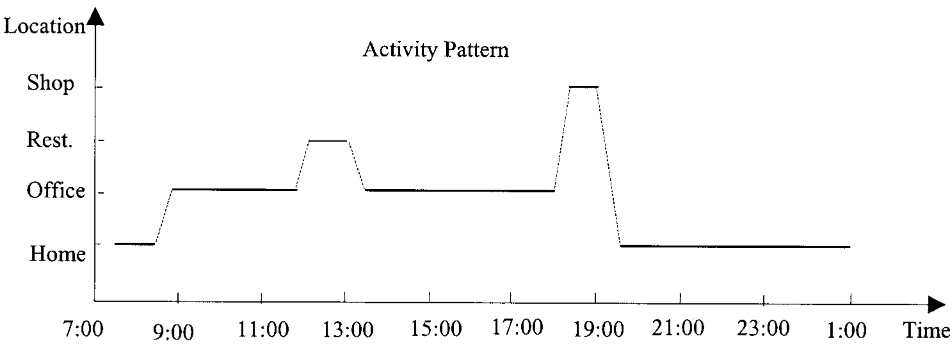


Figure 2. The spatio-temporal behaviour of an individual's activity pattern on a particular day.

Table 1. Representing daily activity patterns: *Stay_at* and *Travel_between*.

	Travel_between	
Stay_at	Location 1	Location 2
Home	Home	Office
Office	Office	Restaurant
Restaurant	Restaurant	Office
Shop	Office	Shop
Home	Shop	Home

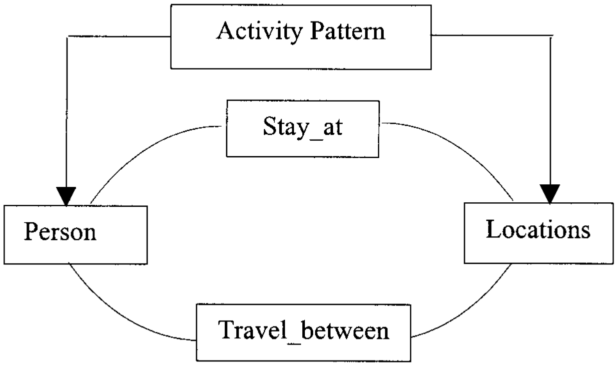


Figure 3. The mobility-oriented view of activity patterns.

4.3. *The conceptual model*

The types of dynamic behaviour discussed in §4.1 require different data models to represent, because of their differences in the natures of change, which demand different types of information to be represented. Many of the existing spatio-temporal data models address the *continuous* type of dynamics. For example, the model proposed by Raper and Livingstone (1995) focuses on the change of spatial extent (or boundary) i.e. the expanding or shrinking of objects in spatial extent. The dynamics of natural phenomena are usually manifested in this type of change. In terms of the information that should be captured for the continuous type of dynamics, since the change of spatial extent is continuous, it can only be recorded in the form of snapshots at particular times. Generally the time scale can be fixed (monthly, annually, etc) in order to analyse and model the change (Cheng and Molenaar 1999). Furthermore, for modelling natural phenomena, only physical environmental constraints should be considered.

The event-based model proposed by Peuquet and Duan (1995) is for modelling the *discrete* type of dynamics. Their model specifically addresses the change of land-use type in parcels. Models of this type are also suitable for modelling other discrete types of changes such as the change of ownership of land parcel. Since this type of change is random and discrete, the time when the event happened is usually recorded. The factors (either physical or institutional) that might result in the events causing the changes are usually included.

The stepwise type of spatio-temporal behaviour or dynamics, for example the dynamics underlying activity patterns, are revealed as the change in spatial positions, e.g. the moving of human objects in a city. Thus, the change of locations should be emphasized. Since this kind of dynamic is not always continuous, the time period over which the changes of location happened should be recorded explicitly. Further, the time scale is not fixed in the sense that activity patterns can be defined for a day or a week. Moreover, the activity patterns are influenced by the physical and institutional environmental constraints. The physical constraints are spatial constraints, which include the information of the home and work address, the locations of shopping centres and the network of roads. The institutional constraints require that the information about the opening hours, facilities of locations and household information of the persons should also be represented in the model. All these specialities make the spatio-temporal data model for activity-based modelling more complicated. We will follow the mobility-oriented view discussed above to design our model.

As discussed above, an individual's activity pattern can be considered as a series of *Stay_at* or *Travel_between* in space during a particular time period. Thus, we may present an activity pattern as a function of *Stay_at* or *Travel_between* of the following formula:

$$\begin{aligned} Activity\ Pattern = \{&Stay\_at(1),\ Travel\_between(1),\ \ldots,\ Stay\_at(\mathrm{i}),\ Travel\_between(\mathrm{i}),\\ &\ldots,\ Travel\_between(n-1),\ Stay\_at(n)\} \end{aligned} \quad (1)$$

$$Stay\_at(i) = f(SL_i, ST_i^s, ST_i^e, Aim) \quad (2)$$

$$Travel\_Between(i) = f(TL_i^s, TL_i^e, TT_i^s, TT_i^e, Path_i) \quad (3)$$

where, SL_i represents the location of *Stay_at*(i), ST_i^s and ST_i^e represent the starting time and ending time of *Stay_at*(i), respectively; *Aim* represents the activity of this stay, such as work or sport; TL_i^s and TL_i^e represent the starting location and the end location of *Travel_between*(i) respectively (i.e. the destination of the previous activity and the destination of the next activity); Similarly, TT_i^s and TT_i^e represent the starting time and end time of *Travel_between*(i). Finally $Path_i$ is the transport route of *Travel_between*(i).

The spatial and temporal constraints can be represented by equations (4), (5), (6) and (7).

$$SL_i = TL_i^s \qquad (i=1, .., n-1) \quad (4)$$

$$SL_{i+1} = TL_i^e \qquad (i=1, .., n-1) \quad (5)$$

$$ST_i^e = TT_i^s \qquad (i=1, .., n-1) \quad (6)$$

$$ST_{i+1}^s = TT_i^e \qquad (i=1, .., n-1) \quad (7)$$

Equation (4) means that the location of a stay is the start location of the next *Travel_between* and equation (5) means that the end location of *Travel_between*(i) is the location of *Stay_at*(i+1). Equation (6) states that the end of *Stay_at*(i) is the start time of *Travel_between*(i+1), whose end time is the start of the *Stay_at*(i+1) (equation (7)). There are cases that two stays are in the same location and there is no *Travel_between* between them. These equations still work for such cases because we may define $SL_i = SL_{i+1}$ and $TL_i^s = TL_i^e$. Still there might be other spatio-temporal constraints such as the time for sport should be within the opening hours of a sport studio, which is not discussed here since these constraints are more related to the methods of modelling.

The relationship between elements expressed in the equations can be represented in a hierarchical structure as illustrated in figure 4. Since activity-based modelling normally uses the household as the analytical unit because interactions between household members are an important factor determining activity engagement. In addition to the major elements of activity patterns, we include household and persons as two additional elements in the diagram. It shows that a *Household* consists of several persons. Furthermore, each *Person* has a planned activity program, which is then realized as an activity pattern. The fourth layer of the diagram illustrates the two major elements (*Stay_at* and *Travel_between*) of activity pattern and their topological relationships. Under the element of *Stay_at*, the location and duration (which is defined by the starting time and the end time) of the stay is indicated. The

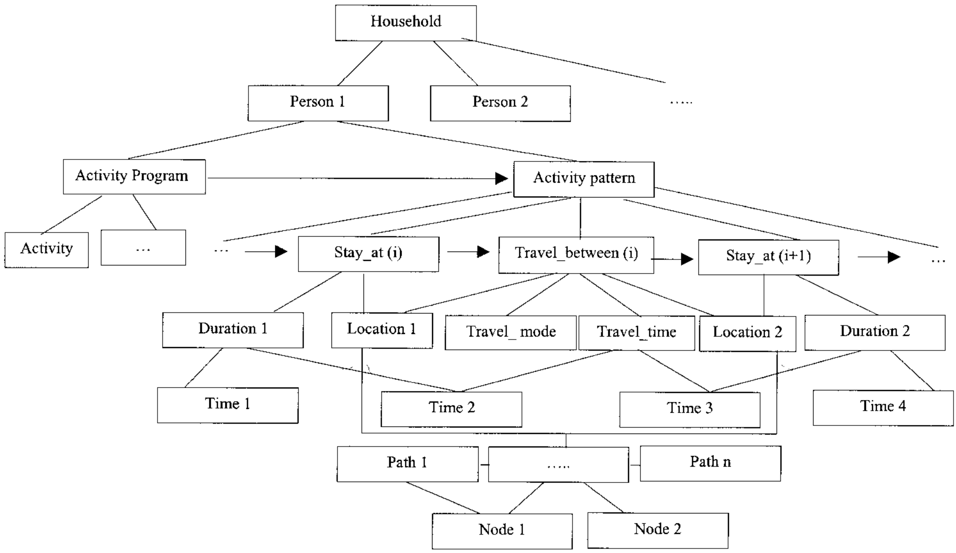


Figure 4. A conceptual framework of the hierarchical relationships between elements in activity-based transport modelling.

element of *Travel_between* is entailed by from where to where the travel takes place, how long the travel lasts (which is defined by the start and end time of the travel), what transport mode is used, and which path it traverses. All *Stay_at* and *Travel_between* are connected by topological relations between time and locations. For example, Location (i) of *Stay_at*(i) is the start location of *Travel_between*(i) (equation (6)) and the end location of *Travel_between*-(i)—Location($i+1$), is the location of *Stay_at*($i+1$) (equation (7)).

4.4. *The EER representation of the conceptual model*

The conceptual model proposed in the last section can be expressed by an extended-entity-relationship (EER) model, which describes the elements and the hierarchical relationships between the elements as entities, relationships and attributes. We adopt the notation of EER diagram used in Elmasri and Navathe (2000, p. 63). The EER representation of the conceptual model can then be illustrated as in figure 5. Ten entity types are defined. They are '*HOUSEHOLD*', '*PERSON*', '*ACTIVITY_PROGRAM*', '*ACTIVITY*', '*ACTIVITY_PATTERN*', '*LOCATION*', '*STAY_AT*', '*TRAVEL_BETWEEN*', '*NODE*', and '*PATH*'. Each of them is shown in a rectangular box. Among them, '*STAY_AT*' and '*TRAVEL_BETWEEN*' are defined as weak entity types, because their existence depends on another two entity types *PERSON* and *LOCATION*, which are the owner entity types. The interaction between *PERSON* and *LOCATION* at a particular *time* derives a *STAY_AT* or *TRAVEL_BETWEEN*. These two weak entity types are distinguished by being placed in rectangles with boundaries of double lines and by having their identifying relationship placed in diamonds with boundaries of double lines.

The relationship among these entity types are described by relationship types shown in the diamond-shaped boxes attached to the participating entity types with straight lines, such as *HAS* and *POSE*, etc. The cardinality ratio of each binary relationship type is specified by attaching a 1, M, or N on each participating edge.

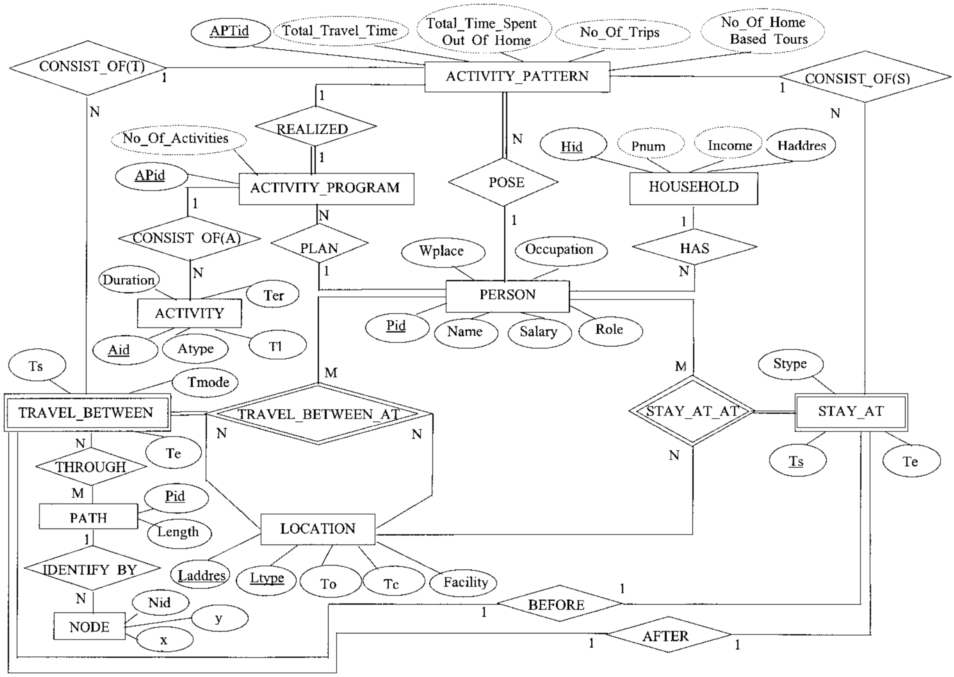


Figure 5. The EER diagram for the mobility-oriented spatio-temporal data model.

For example, the cardinality ratio of *HOUSEHOLD*:*PERSON* is 1:N, whilst it is 1:1 for *TRAVEL_BETWEEN* and *STAY_AT* for the relationship BEFORE. The participation constraint is specified by a single line for partial participation and by double lines for total participation.

The attributes are shown in ovals. Each attribute is connected by a straight line to its entity type of relationship type. Key attributes have their names underlined. For example, {Name} (the name of person), {Salary}, {Role} (the role of the person), {Wplace} (working place) and {Occupation} are the attributes of entity type *PERSON* and {Pid} (the identifier of a person) is the key attribute. For entity type *LOCATION*, there is a primary key {Laddress} (representing its address) and a partial key {Ltype} (representing its function types), because different function types of a location might have different opening time {To}, closing time {Tc}, and facility size {Facility}.

Derived attributes are shown in dotted ovals, as illustrated by the attributes {Pnum} (the number of persons in a household) and {Income} of *HOUSEHOLD*. In addition, *HOUSEHOLD* is described by its primary key attribute {Hid} (identifier of a household) and attribute ({Haddress} (its address).

4.5. *The logical model*

We transform the EER model to a relational schema as a logical data model. We will use the relational schema shown in figure 6 to illustrate the mapping steps as follows.

(1) Each entity type *HOUSEHOLD*, *PERSON*, *LOCATION*, *ACTIVITY*, *ACTIVITY_PATTERN*, and *ACTIVITY_PROGRAM* in the EER model is

HOUSEHOLD

Hid	Pnum	Income	Haddress

PERSON

Pid	Name	Salary	Role	Wplace	Occupation	PHid

LOCATION

Laddress	Ltype	To	Tc	Facility

ACTIVITY

Aid	Atype	Ter	Tl	Duration	AAPid

ACTIVITY_PROGRAM

APid	Na	APPid

(Na -- No_Of_Activities)

ACTIVITY_PATTERN

APid	Ttt	Tto	Nt	Nth	APTPid

(Ttt -- Total_Travel_Time; Tto -- Total_Time_Spent_Out_Of_Home; Nt -- No_Of_Trips; Nth -- Number_Of_Home_Based_Tours)

TRAVEL_BETWEEN

TBnum	Laddress1	Laddress2	Ts	Te	Tmode	BSAnum	ASAnum	TAPTid

STAY_AT

SAnum	Laddress	Ts	Te	Stype	SAPTid

REALIZATION

RAPid	RAPTid

Figure 6. Mapping the EER model of figure 5 to relational schema.

translated into a relation, which is given the same name. The relation inherits all the attributes of each entity, with the primary (and partial) keys underlined.

Since *NODE* and *PATH* are more related to spatial information and are usually available in a GIS database, we will not discuss the structure of these two entities.

(2) The weak entity type *TRAVEL_BETWEEN* together with the identifying relationship *TRAVEL_BETWEEN_AT* is translated into the relation *TRAVEL_BETWEEN*. All the attributes {Ts} (starting time of travel), {Te} (ending time of travel) and {Tmode} (transport mode) of the weak entity type *TRAVEL_BETWEEN* are mapped into the attributes of the relation *TRAVEL_BETWEEN*. In addition, the primary key attributes {Pid} and {Laddress} of the relation(s) corresponding to the owner entity types *PERSON* and *LOCATION* are included as foreign key attributes of the relation *TRAVEL_BETWEEN*. Now the primary key attributes of relation *TRAVEL_BETWEEN* are the combination of the primary keys of its owner

types and itself {Pid, Laddress1, Laddress2, Ts}. Since there are two Locations involved in the *TRAVEL_BETWEEN*, two location addresses (Laddress1 and Laddress2) are needed. In addition, the relation has its own attributes {Te} and {Tmode}.

The translation of weak entity type *STAY_AT* is similar to the translation of *TRAVEL_BETWEEN*. Similarly, the relation *STAY_AT* has primary key attributes {Pid, Laddress, Ts} and attributes {Te} and {Stype} (the activity type for the stay). In this case, only one location address is needed.

(3) For the binary 1:1 relationship REALIZED, which is an optional participation relation, we create a relation *REALIZATION* to represent it. We include the primary keys of the relations *ACTIVITY_PROGRAM* {APid} and *ACTIVITY_PATTERN* {APTid} as primary keys in *REALIZATION* and rename them as {RAPid} and {RAPTid}.

For the binary 1:1 relationships *BEFORE* and *AFTER*, we should include the primary key of the relation *STAY_AT* in the relation *TRAVEL_BETWEEN*. Since the primary key of the relation *STAY_AT* is the combination of the primary keys {Pid, Laddress, Ts}, we use {Sanum} as a surrogate key to represent their unique combination for simplicity and add it in the relation *STAY_AT*. {SAnum} is included in the *TRAVEL_BETWEEN* relation as {BSAnum} (which means the previous stay of this travel, representing the relation *BEFORE*) and {ASAnum} (which means the next stay after this travel, representing the relation *AFTER*). Similarly, we use {TBnum} as a surrogate key to represent the unique combination of {Pid, Laddress1, Laddress2, Ts} in the relation *TRAVEL_BETWEEN*.

(4) For the binary 1:N relationship *HAS*, we include the primary key {Hid} of relation *HOUSEHOLD* as a foreign key in the relation *PERSON* and call it {PHid}.

For the binary 1:N relationship *PLAN*, we include the primary key of the relation *PERSON* in the relation *ACTIVITY_PROGRAM* and call it {APPid}. Similarly, for *POSE* we include the primary key of the relation *PERSON* in the ACTIVITY_PATTERN relation and call it {APTPid} (This 1:N relation means that a person may have several patterns for different days of a week).

For the binary 1:N relationships *CONSIST_OF(T)* and *CONSIST_OF(S)*, we include the primary key (APTid} of *ACTIVITY_PATTERN* as the foreign key in the relation *TRAVEL_BETWEEN* and relation *STAY_AT* and call them {TAPTid} and {SAPTid}, respectively.

For the binary 1:N relationship *CONSIST_OF(A)*, we include the primary key {APid} of the relation *ACTIVITY_PROGRAM* as a foreign key in the *ACTIVITY* relation and call it {AAPid}.

After all the transformations we also check the functional dependencies in the relations. All the relations are in third normal form (3NF). Up to this point the procedure of the model design, including conceptual and logical designs, is finished.

5. Implementation

The aim of this section is to illustrate how to implement the data model proposed in the previous section. We will first describe the case study and creation of the database. Design of the user-interface of multi-perspective queries will then be reported.

5.1. *The Case*

We used the data collected from six families to test the data model. Table 2 reports the information about these six families, including household ID, number of persons, monthly income and address. The working members of these six families are portrayed in table 3. Each person has a daily activity pattern. Here are two examples:

The activity pattern of *Winter* is:

8:00–8:30 going to Baptist University by Train
8:30–12:00 working at Baptist University
12:00–13:00 having lunch at Baptist University
13:00–19:00 working at Baptist University
19:00–19:10 going to Festival Walk by walking
19:10–19:50 shopping at Festival Walk
19:50–20:00 going home (ParkView Garden) by Train
20:00–8:00 at home (ParkView Garden)

The activity pattern of Nancy is:

8:30–9:00 going to University by Train
9:00–12:00 working at University

Table 2. The table of *HOUSEHOLD*.

HID	PERSON_NUM	Income (HK$, month)	HADDRESS
1	3	70000	Parkview Garden
2	4	70000	Xiaoshui Chun
3	2	120000	Ma An Shan
4	4	60000	Royal Ascot
5	4	60000	University
6	4	100000	Sha Tin

Table 3. The table of *PERSON*.

Name	HID	ROLE	OCCUPATION	WORKING_PLACE
Winter	1	Husband	Teacher	Baptist University
Nancy	1	Wife	Researcher	University
Jone	2	Husband	Teacher	University
Krystal	2	Wife	Secretary	University
Samen	3	Husband	Teacher	Baptist University
Ingeberg	3	Wife	Housewife	At-home
Mike	4	Husband	Teacher	Baptist University
Linda	4	Wife	Housewife	At-home
Lincon	5	Husband	Teacher	University
Karin	5	Wife	Student	University
Peter	6	Husband	Teacher	Baptist University
Amy	6	Wife	Business	Central

12:00–12:30 having lunch at University
12:30–17:30 working at University
17:30–18:00 going home (ParkView Garden) by Train
18:00–8:30 at home (ParkViewGarden)

In addition to the types of activities listed above, the activity patterns of other persons may involve other activities, such as sporting or having dinner in a restaurant. Similarly, in addition to the activity destinations listed above, the patterns of other persons may involve other destinations.

5.2. *The database*

We now apply the spatio-temporal data model presented in §4.5 to organize the data. First a database including only the major information is built.

Data describing the household are the same as those stated in table 2, although a person identifier column (Pid) is added to that describing persons (table 3). Table 4 is used to encode the activity type (used as *Atype* in *ACTIVITY*, *Stype* in *STAY_AT* and *Ltype* in *LOCATION*), with six records representing six activity types. Table 5 is used to encode the travel mode (used as *Tmode* in *TRAVEL_BETWEEN*).

Table 6 and table 7 show the information about *STAY_AT* and *TRAVEL_BETWEEN*. Data presented in these two tables are central information to describe the dynamics underlying activity patterns, because they represent the moving of persons in space (locations) and time in the transport system (by travel mode).

Table 8 and table 9 show data about the planned activities and activity programs for two persons.

Table 10 shows the information about the locations. The information of *ACTIVITY_PATTERN* is not listed since it can be derived from tables 6 and 7.

These tables can be built in either the ArcView environment or some other database management system (DBMS) e.g. Microsoft Access, and then converted into ArcView.

Table 4. The table of activity types.

Atypeid	Type
1	Working
2	Shopping
3	Sporting
4	At home
5	Having lunch

Table 5. The table of *TRAVEL_MODE*.

TMode	TRAVEL MODE
1	Train
2	Bus
3	Car
4	Walking
5	Bike

Table 6. Part of the table of *TRAVEL_BETWEEN*.

TBnum	Pid	Laddress1	Laddress2	Ts	Te	Tmode	BSAnbu	ASAnu
1	1	Parkview Garden	Kowloon Tang	8:00:00 AM	8:30:00 AM	1	1	2
2	2	Parkview Garden	University	8:30:00 AM	9:00:00 AM	1	9	7
3	1	Kowloon Tang	Festival Walk	7:00:00 PM	7:10:00 PM	4	4	6
4	1	Festival Walk	Parkview Garden	7:50:00 PM	8:00:00 PM	1	6	5
5	2	University	Parkview Garden	5:30:00 PM	6:00:00 PM	1	10	11
6	3	Xiaochui Chun	University	8:40:00 AM	9:00:00 AM	3	12	19
7	4	Xiaochui Chun	Kowloon Tang	8:00:00 AM	8:30:00 AM	1	18	20
8	4	Kowloon Tang	University	8:40:00 AM	9:00:00 AM	1	21	13
9	4	University	Xiaochui Chun	12:30:00 PM	1:00:00 PM	1	14	15
10	4	Xiaochui Chun	Sha Tin	3:00:00 PM	3:30:00 PM	1	15	16
11	4	Sha Tin	Xiaochui Chun	5:00:00 PM	5:30:00 PM	6	16	17
…	…	…	…	…	…	…	…	…

Table 7. Part of the table of *STAY_AT.*

SAnum	Pid	Laddress	Stype	Ts	Te
1	1	Parkview Garden	4	7:00:00 AM	8:00:00 AM
2	1	Kowloon Tong	1	8:30:00 AM	12:00:00 PM
3	1	Kowloon Tong	3	12:00:00 PM	1:00:00 PM
4	1	Kowloon Tong	1	1:00:00 PM	7:00:00 PM
5	1	Parkview Garden	4	8:00:00 PM	11:59:00 PM
6	1	Festival Walk	2	7:10:00 PM	7:50:00 PM
7	2	University	1	9:00:00 AM	12:00:00 PM
8	2	University	5	12:00:00 PM	12:30:00 PM
9	2	Parkview Garden	4	7:00:00 AM	8:30:00 AM
10	2	University	1	12:30:00 PM	5:30:00 PM
11	2	Parkview Garden	4	6:00:00 PM	11:59:00 PM
…	…	…	…	…	…

Table 8. The table of *ACTIVITY.*

Aid	Atype	Te	Tl	Duration (hours)	AAPid
1	1	9:00 AM	9:30 AM	3	1
2	1	13:00 PM	13:30 PM	3	1
3	2	9:00 AM	6:00 PM	0.75	1
4	3	9:00 AM	7:00 PM	2	1
1	1	8:45 AM	7:30 PM	3	2
2	1	12:30 AM	1:00 PM	3	2
3	2	9:00 AM	6:00 PM	1	2
4	3	9:00 AM	7:00 PM	1	2

Table 9. The table of *ACTIVITY_PROGRAM*.

APid	Na	APPid
1	4	1
2	4	2

Table 10. The table of *LOCATION*.

Laddress	Ltype	Facility	To	Tc
Mei Shong Yuan	2	L	0:00:00 AM	12:00:00 PM
Parkview Garden	3	L	7:30:00 AM	7:30:00 PM
Mei Lin Chun	2	M	8:30:00 AM	10:30:00 PM
Parknshop [Tai Wei]	2	M	9:00:00 AM	10:00:00 PM
Festival Walker	2	H	9:00:00 AM	9:00:00 PM
Baptist University	3	H	9:00:00 AM	8:00:00 PM
University	5		0:00:00 AM	12:00:00 PM
Ma An Shan	3		7:30:00 AM	9:30:00 PM
Parkview Garden	4		0:00:00 AM	12:00:00 PM
Sha Tin Station	2	H	9:00:00 AM	9:00:00 PM
Ma An Shan	2	M	9:00:00 AM	9:00:00 PM
Baptist University	1		7:30:00 AM	10:30:00 PM

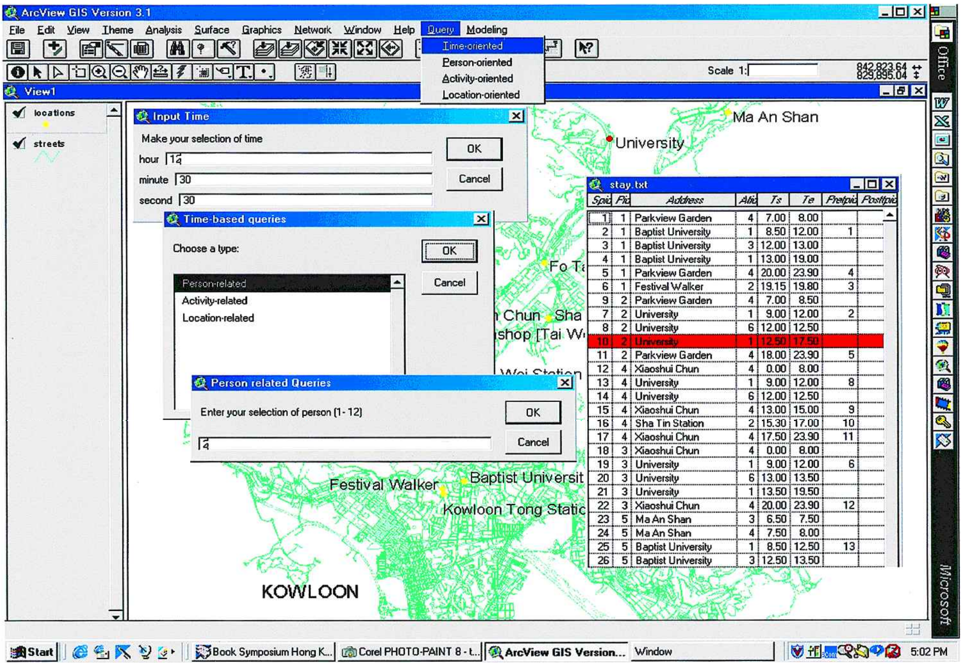


Figure 7. The user-interface and result of the time-based query.

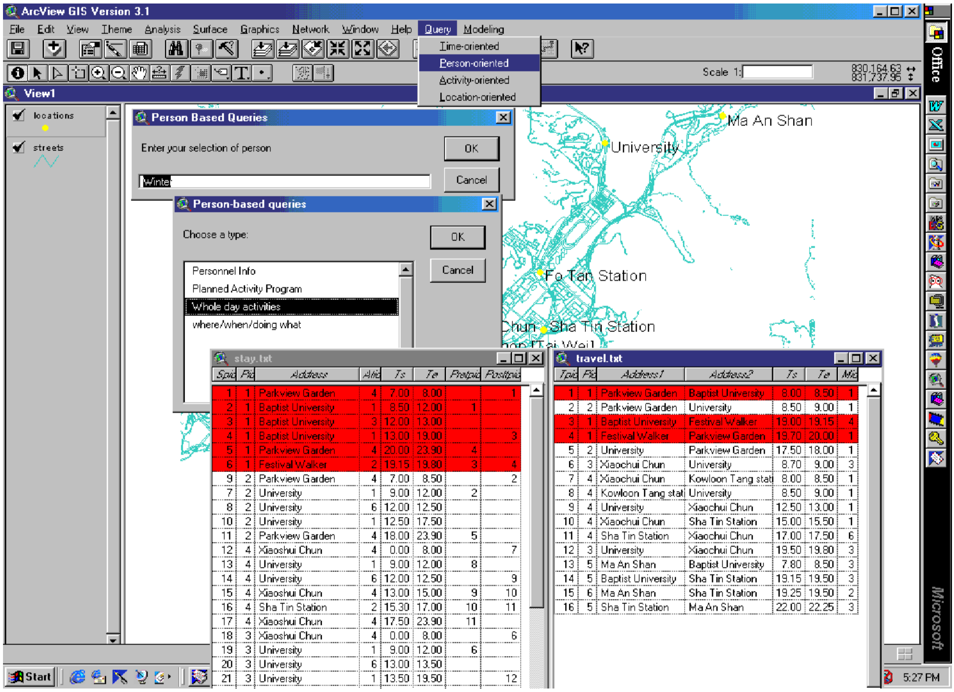


Figure 8. The user-interface and result of the person-based query.

5.3. *User interface for multi-perspective queries*

To simplify the operations for users to query and to visualize the query result, a window-based query prototype was implemented based upon the function of Network Analyst and Avenue provided by ArcView. In the following paragraphs, we will demonstrate how the prototype may support the cross-classification of activities by type, time, location, and socio-demographic characteristics of individuals. The prototype may be easily extended to support other tasks of activity-based modelling.

We may organize the queries into four groups, i.e. time-based, person-based, activity-based and location-based. Major functions of these four groups are listed below:

- *Time-based* queries search for time related information, for example:

  (*a*) 'Where is person A and what is he/she doing at 10:00 a.m.?'
  (*b*) 'Which shops are open at 10:00 p.m.?'

  Figure 7 shows the result of a time-based query, 'Where is person 2 and what is he doing at 12:30 p.m.? The result shows that this person was working at University (indicated on the map) at this time.
- *Person-based* queries look up information about a person, including personal information, the types of activities he/she is engaged in and activity programs, for example:

  (*a*) What is the income of person B?
  (*b*) What is the activity program of person B?
  (*c*) Where person B is doing between 10:00 a.m. and 12:00 p.m.?

  Figure 8 illustrates the result of a person-based query. The two tables in this figure show all activities that person *Winter* was engaged in for a whole day.
- *Activity-based* queries search for information on when and where an activity is conducted and by whom, for example:

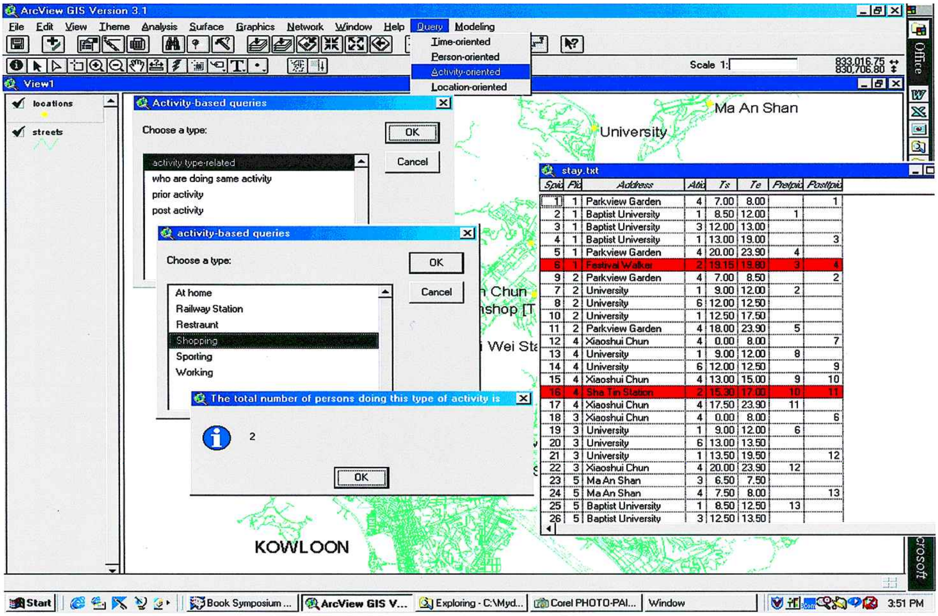
  (*a*) Where can shopping activities be conducted?
  (*b*) How long did person C work?
  (*c*) What is the probability that person C does shopping activity on Saturday?
  (*d*) Which activity person C did before he/she came home?

  The result of an activity-based query is presented in figure 9. Panel (*a*) shows the user-interface of querying activity *Shopping*. Two persons *Shopped* and the result is reported in the table '*stay.txt*'. Panel (*b*) shows the locations where shopping activities were conducted: '*Festival Walk*' and '*Sha Tin Station*'.
- *Location-based* queries find information on activity locations, for example:

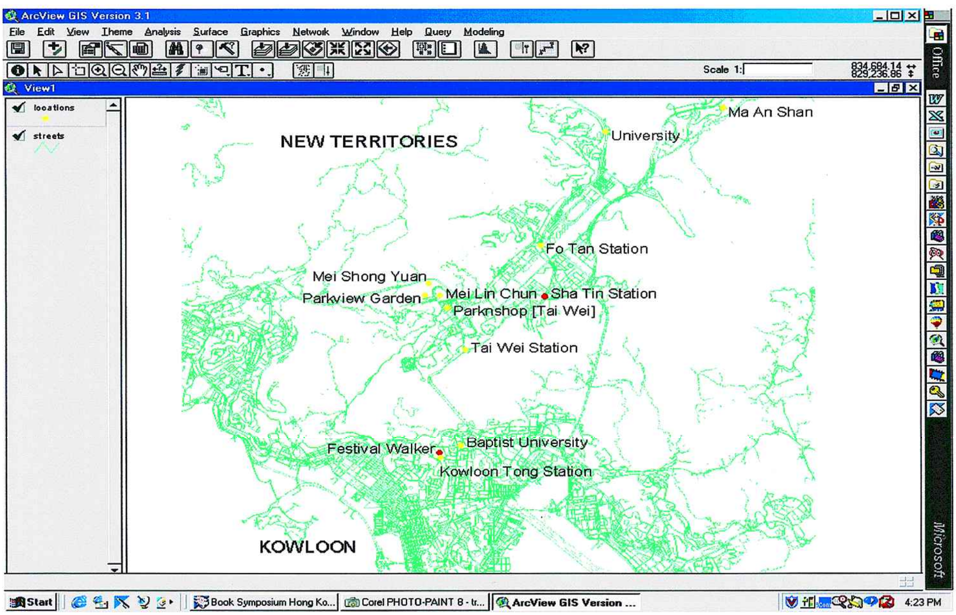
  (*a*) What are the opening hours of Festival Walk shopping centre?
  (*b*) Where is the Baptist University located?
  (*c*) What kind of activities may one conduct at Baptist University? Sporting? Dinning?

Figure 10 illustrates location-based queries. The figure displays the location of shopping centres where a shopping activity could be conducted.

There are still other types of queries that the prototype supports. These queries provide the information for calculating the frequency of activities, the average duration of activities, travel times to different activity types, time use patterns of different

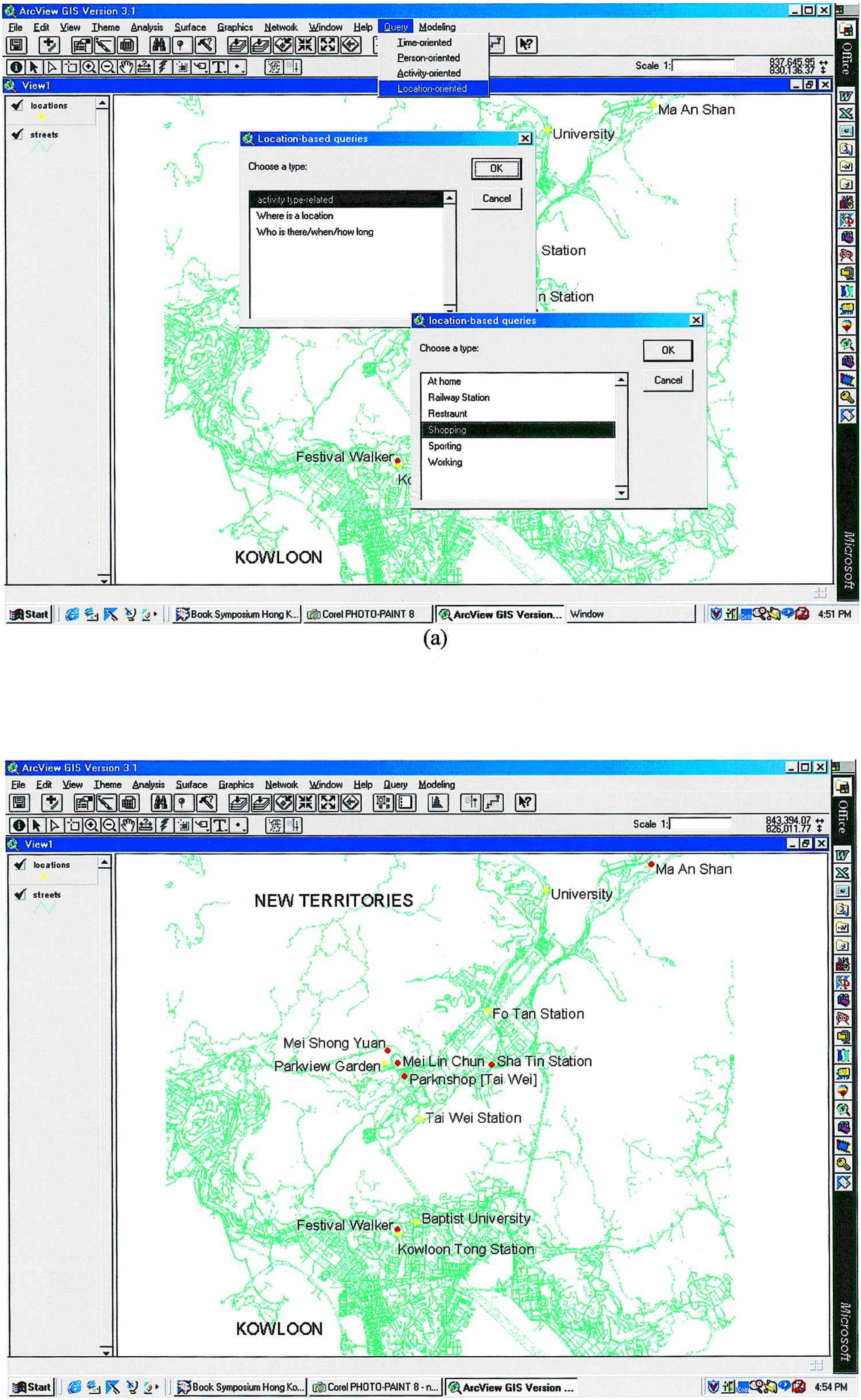


(a)



(b)

Figure 9. The user-interface and result of the activity-based query.



(a)

(b)

Figure 10. The user-interface and result of the location-based query.

types of persons, the relationships between activity participation patterns and the socio-demographic characteristics of individuals, etc. All of these are important topics in activity-based transport demand modelling. The time- and location-based queries directly provide information on spatial and temporal opportunities (or constraints) for activity participation, this information is essential for defining choice alternatives in activity scheduling models.

6. Discussion and conclusions

This paper presents a so-called mobility-oriented spatio-temporal data model for activity-based transport demand modelling. The conceptual and logical designs and prototype system are reported. The prototype supports queries from time-based, person-based, activity-based and location-based perspectives. These query functions are illustrated and tested by a case based in Hong Kong. The case study proves that the data model is powerful in organizing, managing and manipulating data for activity-based modelling. In the future, the prototype will be extended to support activity scheduling and policy change evaluation, by providing functions to find out activity schedules for giving activity programs and to identify impacts on activity patterns of changes in opening hours, level of service of the transport system, etc. In other words, the proposed data model is capable of supporting all aspects of activity-based modelling.

Although the case used to illustrate the application of the data mode is simple, it has all the essential data that one may encounter in activity-based transport modelling. The model should be able to manage large amounts of activity data, although the search time might increase if the data size is very large. The proposed data model should also be able to handle GPS (Global Position System)-derived data and easily establish links with the data types included in the model. First, for the entity having locational information such as *Stay_at*, we assigned a location attribute, which records the name of the location but the name is linked to a pair of coordinates in the map. If GPS-derived coordinates are available, they may simply be linked to the location attributes. Secondly, if the GPS-derived coordinates are used to construct a moving *Path* of a person, these coordinates can be used as nodes constituting the *Path* for the *Travel_between* relation. This 'Path' is not necessarily the shortest path in our model.

While the data model is developed to support activity-based transport modelling, we believe that this model can be applied to represent and model the dynamical behaviour of objects with step-wise changes in general.

Acknowledgments

This study is supported by the Faculty Research Grant of the Hong Kong Baptist University, No. FRG/9899/II-34. Thanks are due to the anonymous referees for their comments on an earlier version of this paper.

References

Al-Taha, K., and Frank, A. U., 1993, What a temporal GIS can do for cadastral systems. In *GISA'93 in Sharjah*, pp. 13-1–13-17.

Axhausen, K. W., 1994, Travel Diaries: An Annotated Catalogue. Working Paper, Imperial College, London.

Baht, C. B., and Koppelman, F. S., 1999, A retrospective and prospective survey of time-use research. *Transportation*, **26**, 119–139.

Burrough, P. A., and Frank, A. U., 1995, Concepts and paradigms in spatial information:

are current geographical information systems truly generic? *International Journal of Geographical Information System*, **9**, 101–116.

Cheng, T., and Molenaar, M., 1998, A process-oriented spatio-temporal data model to support physical environmental modelling. In *Proceedings of the 8th International Symposium on Spatial Data Handling*, edited by T. K. Poiker and N. Chrisman (Somon Fraser University, Vancouver), pp. 418–430.

Cheng, T., and Molenaar, M., 1999, Diachronic analysis of fuzzy objects. *GeoInformatica*, **3**, 337–356.

Egenhofer, M. J., and Golledge, R. G., 1998, *Spatial and Temporal Reasoning in Geographic Information Systems* (Oxford: Oxford University Press).

Elmasri, R., and Navathe, S. B., 2000, *Fundamentals of Database Systems*, 3rd Edition (Massachusetts: Addison-Wesley).

Goodchild, M., 2000, GIS and transportation:status and challenges. *GeoInformatica*, **4**, 127–139.

Greaves, S., and Stopher, P., 1998, A synthesis of GIS and activity-based travel-forecasting. *Geographical Systems*, **5**, 59–89.

Hägerstrand, T., 1970, What about people in regional science? *Papers of the Regional Science Association*, **23**, 7–21.

Hornsby, K., and Egenhofer, M., 2000, Identity-based change: a foundation spatio-temporal knowledge representation. *International Journal of Geographical Information Systems*, **14**, 207–224.

Jones, P. M., Koppelman, F., and Orfeuil, J. P., 1990, Activity analysis: state-of-the-art and future directions. In *Developments in Dynamic and Activity-Based Approaches to Travel Analysis*, edited by P. M. Jones (Avebury: Aldershot), pp. 34–55.

Kwan, M. P., 1997, GISCAS: An activity-based travel decision support system using a GIS-interfaced computational-process model. In *Activity-Based Approaches to Travel Analysis*, edited by D. Ettema and H. Timmermans (Oxford: Pergamon), pp. 263–282.

Langran, G., 1992, *Time in Geographic Information System* (London: Taylor & Francis).

Mason, D. C., O'Conaill, M. A., and Bell, S. B. M., 1994, Handling four-dimensional geo-referenced data in environmental GIS. *International Journal of Geographical Information Systems*, **8**, 191–215.

Miller, H. J., 1991, Modelling accessibility using space-time prism concepts within geographical information systems. *International Journal of Geographical Information Systems*, **5**, 287–301.

Miller, H. J., and Wu, Y. H., 2000, GIS software for measuring space-time accessibility in transportation planning and analysis. *GeoInformatica*, **4**, 141–159.

Pas, E. I., 1985, State of the art and research opportunities in travel demand: another perspective. *Transportation Research*, **19A**, pp. 460–464.

Peuquet, D. J., and 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.

Raper, J., and Livingstone, D., 1995, Development of a geomorphological spatial model using object-oriented design. *International Journal of Geographical Information Systems*, **9**, 359–383.

Renolen, A., 2000, Modelling the real world: conceptual modelling in spatiotemporal information system design. *Transactions in GIS*, **4**, 23–42.

Shaw, S. L., and Wang, D., 2000, Handling disaggregate travel data in GIS. *GeoInformatica*, **4**, 161–178.

Spery, L., Claramunt, C., and Libourel, T., 1999, A lineage metadata model for the temporal management of a cadastre application. In *Proceedings of the International Workshop on Spatio-temporal Models and Language SDTDML'99*, edited by A. M. Tjoa, A. Cammelli and R. R. Wagner (Florence: The IEEE Computer Society), pp. 466–474.

Stopher, P. R., Hartgen, D. T., and Li, Y., 1996, SMART: simulation model for activities, resources and travel. *Transportation*, **23**, 293–312.

Tryfona, N., and Jensen, C., 1999, Conceptual data modelling for spatio-temporal applications. *Geoinformatica*, **3**, 245–268.

Waters, N., 1998, Transportation GIS: GIS-T. In *Geographical Information Systems*, edited by P. A. Longley, M. F. Goodchild, D. J. Maguire, D. W. Rhind, second edition (New York: John Wiley & Sons), Vol. 2, pp. 827–844.

Yuan, M., 1995, Wildfire conceptual modelling for building GIS space-time model. In *Temporal Data in Geographic Information Systems*, compiled by A. U. Frank, W. Kuhn and P. Haunold (Department of Geoinformation, Technical University Vienna), pp. 47–56.